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Dairy farming within planetary boundaries: re-thinking dairy cows into landscapes and food systems

Photo: Kari Bækgaard Eriksson

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PhD thesis

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Preface

I had no idea what this PhD journey would entail. It has been a wild ride, encompassing everything from soils, measurement of terrestrial GHG fluxes, and nature conservation to degrowth, political science, a multitude of qualitative research methodologies, pastures, grazing management, cow manure, and farm designs. It has provoked a fundamental reflection of what it means to be an animal scientist, of past learnings and experience and new insights, doubts and motivations. I have learned more than I imagined.

Through my time as a PhD student (2021-2025) we have seen major crises around the world. From the widespread pandemic to wars, wildfires and continued wildlife extinction. It has been a whirlwind of hope and despair, curiosity and doubts.

I am wholeheartedly grateful to my supervisors, Liza, Nathalia and Dorte. Thank you for your support and encouragement in so many ways. Liza for always taking the time to listen and suggest possible ways to address whatever problem I was having and for helping me get my writing started in your summer house. Nathalia for extraordinary and infectious enthusiasm and curiosity in all things of cattle and beyond and for all our shared conversations. And to Dorte for understanding and putting words to the difficulties of balancing the different roles one has in life. Thank you to the rest of the Cattle Crossroad research group, Frida, Signe and Camilla, for all the eye-opening conversations, shared field trips and much needed laughs. To Katy for joining forces with me in understanding the life of cows on pastures. To Alice for helping with presenting data in R. To Laurence and Nick from University of Reading for letting me stay and work with them for a while, which gave valuable insight into development trajectories for agriculture and cattle in the UK. To colleagues, office buddies and fellow PhD students. To Mossa and Maj who were the only ones in the entire office building when I started during corona lock down and who gave me a warm welcome. To Roi for listening to my (at times) many frustrations.

I am thankful for my two boys, Mattias and Alexander, for being a reliable source of distraction, hugs and meaningfulness. To my parents for helping out when time wasn't enough to cover all that needed my attention. To my garden for much enjoyment and for keeping me grounded in times of frustration. And to my partner, Jacob, for all the support, for believing in me and for being an inspiration in work discipline.

Finally, I am deeply thankful to the farmers who have let me in in their daily lives with their cows, provided farm data, insights, experiences and ideas and answered my steady stream of questions over more than three years. Thank you!

Frederiksberg, October 2025

Kari Bækgaard Eriksson

Summary

The purpose of this PhD project was to investigate how green transition of dairy cattle production can be understood through an absolute understanding of sustainability. This understanding is based on whether planetary boundaries and local carrying capacities are respected, rather than the more common relative comparison across time and place based on productivity and efficiency estimates (for example, when some consider Danish dairy cattle production more sustainable than elsewhere based on higher milk yield per cow or lower greenhouse gas emissions per kg of milk produced compared to other countries).

Opportunities and limitations for achieving absolute sustainability were explored through fieldwork on and around dairy farms, where production was based on different goals and perceptions of sustainability than those typically encountered in intensive Danish dairy production. This included the use of permanent grasslands, a focus on soil health, low or no use of concentrate feed, and integration of cattle and plant-based food production.

The PhD project was part of the transdisciplinary research project, "Cattle Crossroads. Researching Danish livestock production for the future," which consisted of a research group where researchers from animal and veterinary sciences collaborated with anthropologists. The Cattle Crossroads-project was funded by the Danish Independent Research Foundation from a themed call for research towards a 'green transition'. This thesis builds on the premise that reducing the consumption of animal-derived food products is necessary to achieve a more land-use efficient food system and greater environmental balance in Denmark and other countries with similar production and consumption patterns.

The research processes were iterative and drew on a mix of qualitative and quantitative methods. This process inspired a new approach to animal science research, where close collaboration within the research group and across other relevant knowledge disciplines led to significant (self)reflection on methods, research questions, underlying societal structures, historical development, and other elements important in discussions about the green transition. The empirical foundation of this dissertation consists of a mix of field notes, transcribed interviews, and production- and animal-based data from the case farms.

The first presented study challenge common assumptions about land-use efficiency in dairy farming, showing that some farms with dairy cows would be positioned differently in green transition debates, if the types of land and farm purposes were considered. Using detailed data from four organic case farms, we quantified land use, food output, and feed-food competition through a land-type adjusted land-use ratio calculation approach. The findings indicate that marginal land-based dairy farming and mixed livestock-crop systems can outperform high-yielding dairy farms in food-production efficiency, depending on measurement methods, land characteristics, and assumed alternative uses of the land. The study integrated quantitative data with farmer insights and field observations, highlighting often

overlooked factors such as nutrient flows, nature-care, and landscape development, offering a more nuanced perspective on dairy farming's role in sustainable food systems.

Next, this thesis presents a 3.5-year longitudinal study of two pasture-based, low-input dairy case farms. The study was based on an integrated approach mixing qualitative and quantitative data to assess and qualify potentials and risks of multifunctionality for cows and pastures, and to enhance our knowledge on the everyday dynamics that relates to them. Through body condition scores (BCS), milk yield data, observations as well as formal and informal interviews with the farmers, the study finds that the cows can adjust milk production to feeding conditions, however that it demands high level of attention, skills and experience from the farmers to manage and adjust feeding management. Biodiversity screening reports made by visiting biologists established that some pastures aligned with what the biologists' emphasised as valuable for biodiversity loss mitigation (flowing plants, variation, indicator plants), but that others were too productive or overgrazed. The study further unfolds relationships and dynamics between pasture development, milk production, BCSs, cow management and the ideas and goals of the farmers to emphasise the contextual and entangled nature of outcomes for cows and pastures in these farms. Overall, this case-study demonstrate promising potential to align multifunctional land use and food production goals with animal welfare, warranting further research of such systems.

The third study presents an inquiry into ways of re-thinking dairy farming through an increasingly recognised new economic theory, "Doughnut Economics" (today also known as "Wellbeing Economics") first launched by Economist Kate Raworth in 2017. Observations and interviews from fieldwork at Danish dairy farms employing low-input, pasture-based, and regenerative principles formed the primary empirical foundation for the study. Raworth's seven 'steps' for transforming what she describes as an outdated 20th-century economic discourse – and for retooling the discipline of economics – served as inspiration for making visible alternative ways of thinking about and practicing dairy farming. From this, the study proposes seven ways in which livestock agronomy – including animal science – can broaden its perspectives and considerations regarding farm optimisation and development.

This thesis can serve as a stepping stone for further investigation into holistic approaches and the opportunities they offer for supporting the agricultural sector's green transition. Such approaches require active engagement from agricultural actors, organisations, and knowledge institutions. This includes making space for diverse dairy production systems that consider both local carrying capacity and globally relevant environmental impacts.

Sammendrag

Formålet med dette ph.d.-projekt var at undersøge, hvordan grøn omstilling af malkekvægsproduktion kan forstås gennem en absolut forståelse af bæredygtighed. Denne forståelse er baseret på, om planetære grænser og lokal bæreevne respekteres, frem for den mere almindelige relative sammenligning på tværs af tid og sted der typisk baseres på produktivitets- og effektivitetsestimater (eksempelvis når nogle vurderer dansk malkekvægsproduktion som mere bæredygtig end andre steder på baggrund af en højere mælkeydelse per ko eller en lavere drivhusgas-emission per kg mælk, sammenlignet med andre lande).

Muligheder og begrænsninger for at opnå absolut bæredygtighed blev undersøgt via feltarbejde i og omkring malkekvægsbedrifter, der har valgt at producere ud fra andre mål og bæredygtighedsforståelser end dem, man typisk møder i den intensive danske mælkeproduktion. Dette inkluderede brug af vedvarende græsmarker, fokus på jordsundhed, lavt eller intet forbrug af kraftfoder, og samtænkning af kvæg og plantebaseret fødevareproduktion.

Ph.d.-projektet var en del af det transdisciplinære forskningsprojekt, "Cattle Crossroads. Researching Danish livestock production for the future", som bestod af en forskningsgruppe, hvor forskere fra husdyr- og veterinærvidenskab samarbejdede med antropologer. Cattle Crossroads-projektet var finansieret af Danmarks Frie Forskningsfond fra et tematiseret opslag om forskning i den grønne omstilling. Denne forskning tog udgangspunkt i præmissen om at forbruget af animalske fødevareprodukter skal reduceres i fremtiden for at opnå en mere areal-effektiv fødevareforsyning og en større miljømæssig balance i Danmark og andre lande med sammenlignelig produktion og forbrugsmønstre.

Forskningsprocessen var eksplorativ, iterativ og baseret på en blanding af kvalitative og kvantitative metoder. Denne tilgang inspirerede til at afprøve nye forskningsmetoder indenfor husdyrvidenskab, hvor det tætte samarbejde i forskningsgruppen og med andre relevante vidensdiscipliner, medførte stor (selv)refleksion omkring metoder, forskningsspørgsmål, underliggende samfundsstrukturer, historisk udvikling og andre elementer, der er vigtige i diskussionen om grøn omstilling. Det empiriske datamateriale, afhandlingen er baseret på, består derfor af en blanding af feltnoter, transskriberede interviews, og produktions- og dyrebaserede tal og målinger fra case-gårde.

Det først præsenterede studie udfordrede almindelige antagelser om arealeffektivitet i mælkeproduktion. Det viste, at nogle malkekvægsproduktioner kunne blive anskuet anderledes i den grønne omstillingsdebat, hvis kvaliteten af det anvendte areal samt bedrifternes formål blev taget i betragtning. Ved at bruge detaljerede data fra fire økologiske case-bedrifter med malkekvæg blev arealanvendelse, fødevareoutput og konkurrence mellem foder og fødevarer kvantificeret med en justeret "land-use ratio"-beregning, der tager højde for forskelle i de anvendte arealers egnethed og potentialer. Resultaterne indikerer, at mælkeproduktion på marginale jorde og integrerede systemer med kvæg- og afgrøder til

humant konsum kan være mere effektive end højtydende mælkeproduktion, afhængigt af målemetoder, jordens karakteristika og antagelser om alternative anvendelser af arealet. Undersøgelsen kombinerede kvantitative data med landmændenes indsigt og feltobservationer, hvilket fremhævede ofte oversete faktorer som næringsstofstrømme, naturpleje og landskabsudvikling. Dermed giver studiet en mere nuanceret forståelse af mælkeproduktionens rolle i bæredygtige fødevaresystemer.

Næste del af denne afhandling er et 3,5-årigt longitudinelt studie af to græsningsbaserede, lav-input mælkeproduktionsbedrifter. Studiet bygger på en integreret tilgang, hvor kvalitative og kvantitative data kombineres for at vurdere og kvalificere potentialer og risici ved multifunktionalitet for køer og græsningsarealer. Analyse af huld-vurderinger, mælkeydelsesdata, observationer samt formelle og uformelle interviews med landmændene viste at køerne dels tilpassede mælkeproduktionen efter fodringsforholdene, men også at dette krævede en høj grad af opmærksomhed, faglig kunnen og erfaring fra landmændenes side at løbende justerer fodringen. Biodiversitetsscreenings udført af besøgende biologer viste, at nogle græsningsarealer stemte overens med det, biologerne fremhævede som værdifuldt for at modvirke biodiversitetstab (blomstrende planter, struktur, indikatorplanter), mens andre var enten for produktive eller græsset for intensivt. Studiet viser relationer og dynamikker mellem græsningsarealernes udvikling, mælkeproduktionen, management og landmændenes idéer og målsætninger, og fremhæver dermed hvordan resultater omkring køer og græsningsarealer på disse bedrifter er indviklet i kontekstuelle faktorer. Overordnet viser casestudiet lovende potentialer for at forene mål om multifunktionel arealanvendelse og fødevareproduktion med dyrevelfærd, hvilket understreger behovet for yderligere forskning i sådanne systemer.

Den tredje undersøgelse præsenterer en undersøgelse af måder at gentænke mælkeproduktion på gennem en stadig mere anerkendt ny økonomisk teori, "Doughnut Economics" (i dag også kendt som "Wellbeing Economics"), først lanceret af økonom Kate Raworth i 2017. Observationer og interviews fra feltarbejde på danske mælkekvægsbedrifter, der anvendte lav-input, græsbaserede og regenerative principper, dannede det primære empiriske grundlag for studiet. Raworths syv 'trin' til at transformere det, hun beskriver som en forældet økonomisk diskurs fra det 20. århundrede – og til at gentænke økonomifaget – fungerede som inspiration til at synliggøre alternative måder at tænke og praktisere mælkeproduktion på. På baggrund af dette foreslår studiet syv måder, hvorpå husdyragronomi – herunder husdyrevidenskab – kan udvide sine perspektiver og overvejelser i forhold til optimering og udvikling af landbrugsbedrifter.

Denne afhandling kan fungere som et springbræt for videre undersøgelser af helhedsorienterede tilgange til malkekvægsproduktion og de muligheder, de rummer for at understøtte landbrugssektorens grønne omstilling. Sådanne tilgange kræver aktiv involvering fra landbrugets aktører, organisationer og vidensinstitutioner. Det er afgørende at skabe plads til mangfoldige former for mælkeproduktion, der tager hensyn til både lokale bæreevner og globale miljømæssige påvirkninger.

List of abbreviations

BCS	Body condition score
CH_4	Methane
CAP	Common Agricultural Policy
CO_2	Carbon dioxide
CO_2eq	Carbon dioxide equivalents
HOL	Danish Holstein
DIAAS	Digestible Indispensable Amino Acid Score
DIM	Days in milk
DMI	Dry matter intake
ECM	Energy corrected milk
FAY	Finnish Ayrshire
GHG	Greenhouse gas
HDE	Human digestible energy
heFCR	Human edible feed conversion ratio
JER	Danish Jersey
LCA	Life-cycle-assessment
LUR	Land-use ratio
eLUR	Land-use ratio for HDE
pLUR	Land-use ration for QP
MIX	Mixed breed
N_2O	Nitrous oxide
PBF	Planetary boundary framework
QP	Quality adjusted protein
RDM	Red Danish milking breed
SOC	Soil organic carbon

Table of contents

1 Introduction

This thesis is about green transition within alternative dairy production in Denmark. It is a subproject to a broader transdisciplinary research project "Cattle Crossroads. Researching Danish livestock production for the future" (2021-2025), financed by the Independent Research Fund Denmark, which sets out to find novel avenues to a green transition. A premise for the project was that it is not only *more* knowledge about the relations between cattle, environment, climate and society which is needed, but also to understand them *differently*, hence the ambition to study alternative farms. I have addressed my sub-project "Low-input Cattle Production. An animal science demonstration of unconventional dairy farms" with three studies (one published, two under submission) focussing on land-use and food supply, relational dynamics between animals, farmers, and land in pasture-based dairy farming, and lastly, knowledge paradigms in the science of livestock agronomy.

In 1950 there were almost 200,000 farms in Denmark and around 89% of these had dairy cows (Bjørn, 2025; Kristensen et al., 2015). Today, there are currently just over 2,000 farm properties with milk-producing cows in Denmark (Statistics Denmark, n.d.). The Danish dairy landscape is dominated by specialised farms with year-round indoor housing and high-yielding Danish Holstein cows (Kristensen et al., 2015; van den Pol-van Dasselaar et al., 2020) and the Danish average milk yield per cow ranks in the top compared with the other European Union (EU) member states (Eurostat, 2024). Over the past century, the Danish dairy and beef sector has undergone a tremendous development, driven primarily by techno-scientific advancements, promoting or enabling intensive genetic selection, feed and digestion modelling, and supported by advancements in veterinary knowledge (Kristensen et al., 2015; Leisner and Larsen, 2024). Based on its high productivity, the Danish cattle sector has been singled out as one of the most climate efficient among the EU countries in terms of greenhouse gas (GHG) emissions per produced product (Lesschen et al., 2011), and is often referred to as such in discussions on how to mitigate the environmental impact of the Danish livestock sector (Hastrup et al., 2022). Thus, is it among the most optimised, knowledge-based and efficient dairy sectors in the world and yet it is not sustainable according to recent quantifications of GHG emissions and nutrient use (Hjalsted et al., 2021; Nielsen et al., 2025). Livestock production, and especially the production of dairy and beef, is highlighted as having one of the largest environmental impacts within agriculture due to the potent GHG – methane – primarily stemming from the enteric fermentation of the ruminating cattle, but also through low resource use efficiency compared to other food sources (Leip et al., 2015; Shepon et al., 2016; Steinfeld et al., 2006; Weiss and Leip, 2012). Thus, despite having a *relatively* low level of GHG emission per kg milk compared to others, the total emissions are still high – constituting around 30 % of GHG emission from Danish agriculture (Nielsen et al., 2025). At the same time, with an increasing human population coupled with economic growth, especially in low- and middle-income countries, projections are showing increasing future demands for animal-derived food products (Bodirsky et al., 2015). This leaves major challenges for the development of animal-based agricultural systems, where a prevailing idea seems to be that production levels must increase further, while environmental impacts per produced unit of food must be reduced, without compromising the welfare of the animals (Capper and Bauman, 2013; Dorca-Preda et al., 2024; Gerber et al., 2011).

Relative measures, where sustainability in part is assessed through productivity or product based efficiency measures relative to other places or times, have been the focus in livestock production development over the past 100 years, and transition to alternative farming practices have at large been overlooked and not supported (Hoes and Aramyan, 2022). The issue at stake is that relative measures fail to acknowledge the finite nature of the planet. The development in global food systems have roughly halved the number of undernourished people since the mid-20th century through increases in productivity and distribution, however, it has been achieved at the expense of planetary health while also doubling the number of overnourished people (Gordon et al., 2017). Indeed, agricultural activities have become a major driver of the anthropogenic pressure on biosphere integrity, posing a significant threat to the stability of the planet (Campbell et al., 2017). At the same time, it has been pointed out that it *is* possible to sustainably feed the growing world population, although it will demand considerable rewiring of production and consumption practices and patterns (Gerten et al., 2020). This points to the necessity of rethinking development approaches, as well as the metrics and perspectives used to measure agricultural progress. Along these lines, the Danish Council on Climate Change has stated that exploring entirely new paths is needed to achieve the ambitious Danish goal of a 70% reduction in GHG emission by 2030 (DCCC, 2020).

This PhD thesis has, through premisses defined in the overall Cattle Crossroads project, sought such new paths and perspectives, by researching cattle and the green transition through research approaches that differ from ideas of further intensification and technology-driven mitigation strategies. Inspired by a conceptual division of sustainability as either relative or absolute made by chemical engineer, Michael Hauschild, and his research group, this includes a different understanding on what sustainability entails. In contrast to the above-mentioned relative perspectives, the principle of 'absolute sustainability' puts special weight on absolute numbers, and argues that sustainable operation can only be achieved if the activity does not exceed environmental limits (Bjørn et al., 2019; Hauschild et al., 2020). Absolute sustainability is therefore not defined by the activities of others, but by so-called 'carrying capacities', which has been defined as "*the maximum sustained environmental intervention a natural system can withstand without experiencing negative changes in structure or functioning that are difficult or impossible to revert*" (Bjørn and Hauschild, 2015, p. 1007).

Such fundamental environmental limits have been defined and estimated on a global scale in the planetary boundary framework (PBF), first described by Rockström et al. (2009). It consists of nine interconnected and essential processes for maintaining liveable conditions on the planet. Seven out of these are now pressured by human operation beyond their safe boundaries (PBScience, 2025; Richardson et al., 2023). While these processes, which will be described in the following chapter, are assessed and presented individually, they are deeply interconnected. This was stressed by Rockström et al. (2009), who wrote: "*We do not have the luxury of concentrating our efforts on any one of them in isolation from the others. If one boundary is transgressed, then other boundaries are also under serious risk*." Thus, the PBF offers an important insights and overview of the ecological limits and interconnections that agricultural food production systems must navigate.

However, agricultural systems are not only rooted in land and ecosystems – they are also deeply embedded in societies. Development to achieve sustainability requires balancing the ecological 'ceiling' with an acceptable social foundation as was emphasised and illustrated by economist Kate Raworth in her model from '*Doughnut Economics – seven ways to think like a 21st century economist*' (Raworth, 2017). The image of a doughnut is shaped by the outer and inner ring, representing ecological and social limits, respectively. Where the ecological limits are formed by the PBF, the social limits are the set of basic socioecological conditions that will ensure human well-being. Residing in the space between the inner and outer limits – inside the doughnut – is the safe and just space for humanity. The concept of the doughnut is also known as *Wellbeing Economics* (Wellbeing Economy Alliance, 2022). Raworth identified seven key shifts in economic thinking that are necessary for humanity to transition into this space. These have been an inspiration and provide a useful, comprehensive and operational framework (described in more detail in section 2.3) to use for viewing development of dairy farming through new perspectives.

An assessment of the global impact of the livestock sector suggested that achieving a sustainable food production on an absolute scale, will require both consumption and production-based interventions (Bowles et al., 2019). When coupled with a transition towards more plant-based diets, the prospect of downscaling the population of production animals emerges as an effective tool for mitigating climate change and biodiversity loss, as well as reducing overall land use (Danmarks Naturfredningsforening et al., 2023; Prag and Henriksen, 2020; Röös et al., 2017). Thus, rather than making projections on likely future demands for certain food types, the absolute perspective urges us to ask first, what can the planet, or indeed, specific places, carry, and then second, how might we then live and act to respect such boundaries. The prospects of feeding a large and growing population on limited land demands finetuned attention to the degrees of feed-food competition, as sustaining an animal production with feed grown from land suitable for crop production, leads to a net loss in the potential global food supply (Foley et al., 2011; van Zanten et al., 2016). Accordingly, it was the task in this PhD project to conduct fieldwork at alternative dairy farms, where the cows were kept on marginal land not suited for cultivation of crops – so-called 'low-input dairy farms' – representing a pathway alternative to the dominant model of intensive dairy production and its reliance on large-scale arable feed cultivation. However, such farms turned out to be extremely difficult to find in Denmark. Therefore, the inclusion criteria for the case farms were expanded to include farms that focused on other important eco-system functions such as improving biodiversity and soil health.

The fieldwork at these farms were framed by the strong message put forward by the PBF and Doughnut Economics, specifically that of paying attention to limits and interrelations within ecological and societal systems. Thus, Raworth's emphasis on how changing underlying ways of thinking and measuring human activities can leverage change, provided an important frame for how to engage with the socioeconomic aspects of dairy farming. While the PBF is a quantitative and global framework, it effectively communicates the scale and magnitude of the ecological crises and stresses the need to consider the fundamental processes that ensure planetary health and stability. Together, the two frameworks have served as a guide for shaping the focus of the research. Thus, rather than seeking to produce quantitative measures of such limits and interrelations, this thesis aims to *qualify* what it means to think and work with limits and the complexity of socio-ecological systems within practical dairy farming and research. It explores how, within concrete dairy farming contexts, it might be possible – or impossible – to reconcile the goal of feeding a growing population with the imperative to maintain liveable conditions on a finite planet.

Research in sustainability within classic animal science tend to either conduct experimental studies or develop farm models or assessment frameworks (Maigaard et al., 2024a; Schader et al., 2016; van der Linden et al., 2020). They typically aim to identify causal relationships, synergies, and trade-offs among predefined sustainability dimensions – useful for benchmarking and comparing outcomes across farm types and large datasets. However, they often rely on broad generalisations and rigid categories that can obscure underlying drivers, barriers, and contextual nuances, and may not align with the realities and diversities of the measured farms. In doing so, complex farming systems are reduced to measurable entities to enable the production of scalable results. The American anthropologist Anna Tsing argues that assumptions of scalability have contributed to environmental degradation, as nature is inherently diverse and entangled in webs of relations – making it non-scalable. She proposes a theory of non-scalability, which emphasises that entities (e.g. farms or farm designs) cannot be scaled without being fundamentally altered, due to the diversity and specificity of their relational contexts (Tsing, 2012). Working with qualitative data is a way to engage with such complexities.

Qualitative research remains a relatively novel approach within dairy science, with a recent review indicating that such studies only began to emerge in mainstream dairy science journals around 2013 (Ritter et al., 2023). The studies found in this review addressed a relatively narrow range of research topics, all centred around biosecurity, animal health and/or diseases, veterinary work, or animal welfare. Non addressed themes such as sustainability, land use, or green transition. However, another search was made by the same authors, but through broader collection of journals which were not directed specifically at (or used by) dairy science researchers. Here a wider range of topics were found, including studies addressing dairy farming in ecological landscapes, in food landscapes and in human society (Vaarst et al., 2024). One study investigated barriers to change in the Norwegian dairy/beef sector regarding GHG mitigation, using semi-structured interviews with 29 dairy farmers. It found that many farmers pursued intensification – such as increased productivity and use of arable land – to finance automatic milking systems, motivated by a desire for greater flexibility and time for family and leisure (Burton and Farstad, 2020). Another study analysed (knowledge) discourses around the practice of grazing in relation to sustainable development in the dairy sector in Ireland and the UK, through document analysis and interviews with different stakeholders of the dairy sector (from industry, government, NGOs, and academia) (Shortall, 2019). This study found both a coherence between dominating beliefs and the dominating dairy practices in the two countries (which differed), but also contradictory arguments within the two, emphasising how knowledge production and its conclusions are entangled in socioeconomic politics. Both studies show how qualitative research can bring important depth and nuance to questions of sustainability and green transition. While deductive, quantitative evaluations based on predefined categories remain important for generating tangible measures of production outcomes, the relational insights offered by qualitative inquiry are equally vital. This PhD therefore seeks to integrate the richness of qualitative approaches into the dominant focus on quantitative outcomes and optimisation within animal and agricultural sciences.

Followingly, the ambition of this PhD was to explore how green transitions of dairy farming can be practiced, understood, and evaluated when researched through ideas of absolute sustainability. Employing an iterative, fieldwork-based and methodologically open research approach, with close collaboration and inspiration between researchers, actors and stakeholders in the transdisciplinary Cattle Crossroads project – including researchers from anthropology, veterinary- and animal science – this thesis sets out to address the aim and objectives outlined in the following section.

1.1 Aim and objectives

The funding for Cattle Crossroads originated from a themed call for research towards a 'green transition' from the Independent Research Fund Denmark. As such, this project came with an explicit ambition and commitment to produce knowledge that can support green transition of dairy farming in Denmark. The overall aim of this PhD was to contribute with new qualitative and mixed-method insights to sustainability research within the field of animal science. Specifically, it sought to engage with ongoing discussions about the future of Danish dairy cows and the agricultural systems they are a part of and rely on. At the same time, it explored how animal science as a discipline can broaden and adapt its approaches to absolute sustainability within agricultural systems.

To pursue this aim, the PhD addressed the following research questions:

- What are the opportunities and challenges for alternative dairy farming, specifically low-input, pasture-based dairy systems, when investigated at farm level and through land-use analysis?
- How might holistic studies of selected case farms, including both quantitative and qualitative data on animals, landscapes and farmers, produce new data and hitherto overlooked features of alternative dairy farming?
- How can animal science as a discipline support green transition of livestock production through research at alternative dairy farms as analysed through the lens of limits and absolute sustainability?

The research questions have been addressed through the following three specific objectives:

- To explore and evaluate food production, land-use efficiency and practises of selected alternative dairy farms.
- To describe and characterise the operation of low-input, pasture-based dairy farming with attention to animal-farmer-land relations of relevance for green transition and sustainability.
- To qualify needed shifts in the knowledge basis and use of the livestock agronomy to encompass perspectives of green transition within livestock production.

1.2 Contribution and delineation

This PhD contributes to the knowledge and discussion of the green transition in dairy farming by questioning how such transitions can be researched. It does so by making visible and critically discussing the fundamental assumptions that shape how researchers and experts in agronomy and animal science measure and evaluate the sustainability of dairy farming. These assumptions, in turn, influence the conclusions we can draw. The thesis exemplifies and explores alternative ways of thinking about and practicing efficiency and value in relation to dairy cows. It also foregrounds the relationships between animals, land, and humans, which are often overlooked in the intensive and specialised dairy systems that dominate in Denmark. All analyses are situated in the context of concrete farms and their everyday practices.

It has been an ambition of this PhD to cover a broader array of connections to dairy farming and through different knowledge paradigms, than what is usually attempted in animal science research on sustainability. The entry point for the study at the case farms have thus been to include perspectives from land, animals, and people and to allow the fieldwork to inform the content and direction of the research. Such iterative designs contrasts more typical approaches to sustainability in livestock science research, as previously discussed. By starting from a different, and to animal science, novel point of departure, the intention was to allow for generation of different ways of knowing and viewing possible green pathways for dairy farming in the future through the animal science lens. Accordingly, it is not a study that aims to provide estimates for extrapolation from representative farms, but rather to provide examples and context-embedded data that unfold new perspectives and encourage new ways of thinking about food production with dairy cows involved. The case-farms provide real-life material to explore different ways of thinking and measuring potentials for green transition. As such, the work in this thesis does not aim specifically at adding to existing knowledge on alternative dairy farms and farmers per se, but rather to study and expand on literature from dairy science and agroecology (Gliessman, 2018) on sustainability and green transitions, by enriching the field through new perspectives, knowledge collaborations, and thus new outcomes.

1.3 Outline of the thesis

Three manuscripts form the scientific basis of this thesis. These are incorporated as chapters 4-6. The thesis has the following structure:

Chapter 2 provides an overview of the agricultural development in Denmark over the past 100-150 years that has led to the ways in which most Danish dairy farmers operate their productions today. It further outlines the processes in the PBF, their relevance in relation to the Danish context, and lastly present the ideas behind Doughnut Economics.

Chapter 3 presents the research approach and provides and overview of the used methods.

Chapter 4 is themed around 'Land and Food production' and presents the published Manuscript I: "*Situated analysis of food supply, land-use dynamics, and feed-food competition at organic farms with dairy cattle*".

Chapter 5 explores the relational dynamics and outcomes between cows and pastures, and how these are managed by farmers in two pasture-based dairy production systems, presented in Manuscript II: "*Balancing Dairy Production and Biosphere Integrity: A Mixed Method Case Study of Pasture-Based, Low-Input Dairy Farms in Denmark".*

Chapter 6 contains Manuscript III: "*Doughnut Agronomy. Dairy farming and Well-being in 21st century Denmark"*. Building on economist Kate Raworth's Doughnut Economics-framework, this manuscript argues for making visible alternative dairy farming systems as practices worthy of agronomic attention and proposes that livestock agronomy needs to expand it knowledge base for it to become a science for the 21st century.

Chapter 7 forms a discussion of the findings presented in chap. 4-6 in relation to the objectives and aim of the thesis.

Chapter 8 presents the conclusions.

Chapter 9 presents the perspectives.

Chapter 10 contains the references.

Chapter 11 contains an appendix.

2 Study context

This section gives an overview of knowledge I find important to consider, when researching possible futures for dairy production. However, it also gives a more thorough outline of the perspectives which form the basis of the work presented in the thesis. The section includes a brief review of the most recent agricultural development (the past 100-150 years) that has led to the ways in which most dairy farmers in Denmark operate their productions today, a description of the PBF as well as a short review of each of processes in the PBF and their relevance in relation to the Danish landscapes and mitigation attempts, and finally a short presentation of Doughnut Economics and how it is relevant for this thesis.

2.1 The development of the Danish dairy sector

The ways in which we keep dairy cows has undergone a drastic change during the past 150 year together with the rest of the agricultural sector. The history of the dairy sector cannot be separated from the development in agricultural land use and cultivation. Hence, this section engages in topics usually not considered part of the animal science field and will go through the development in different – although highly interconnected – areas. This includes the following subsections: 1) Cows in numbers and milk production, 2) Farm numbers, sizes and designs, 3) The agricultural land' 4) Grazing dairy cows in Denmark, 5) Livestock and dairy technology and 6) Challenges of Danish dairy farming today.

2.1.1 Cow numbers and milk production

In the beginning of the 20th century, the total milk production in Denmark was around 1700 million kg of milk per year (Kristensen et al., 2015). At this point in time, the dairy and slaughterhouse cooperative movement already dominated the sector , after Denmark under a relatively short period of time had shifted its agricultural production and export from grains to butter, bacon and egg, exported to a global market in ever greater numbers (Lampe and Sharp, 2015; Sørensen, 2011). The Danish butter production had gained a considerate share of the UK butter market, likely in part due to the development of 'winter dairying' in Denmark, where early winter calving and sufficient stable feeding enabled a year-round butter export, where the high winter-prices made the feeding at stable economically profitable (Henriksen and O'Rourke, 2005; Lampe and Sharp, 2015). Altogether, this formed the basis of the establishment of the feedstuff and fertiliser industry, initiating the import of especially maize, soybean cake and artificial (inorganic) fertiliser and during the 1920s the sale of feed mixes for cattle gained traction (Christensen, 2014). In this period the number of dairy cows and the total milk production in Denmark increased. The total national production reached its to date highest level in the period 1930-60 (although with a significant drop during WWII), delivering around 5400 million kg per year. This level was hereafter reduced slightly and stabilised just below 5000 million kg after the introduction of the EU milk quotas in 1984 (Kristensen et al., 2015).

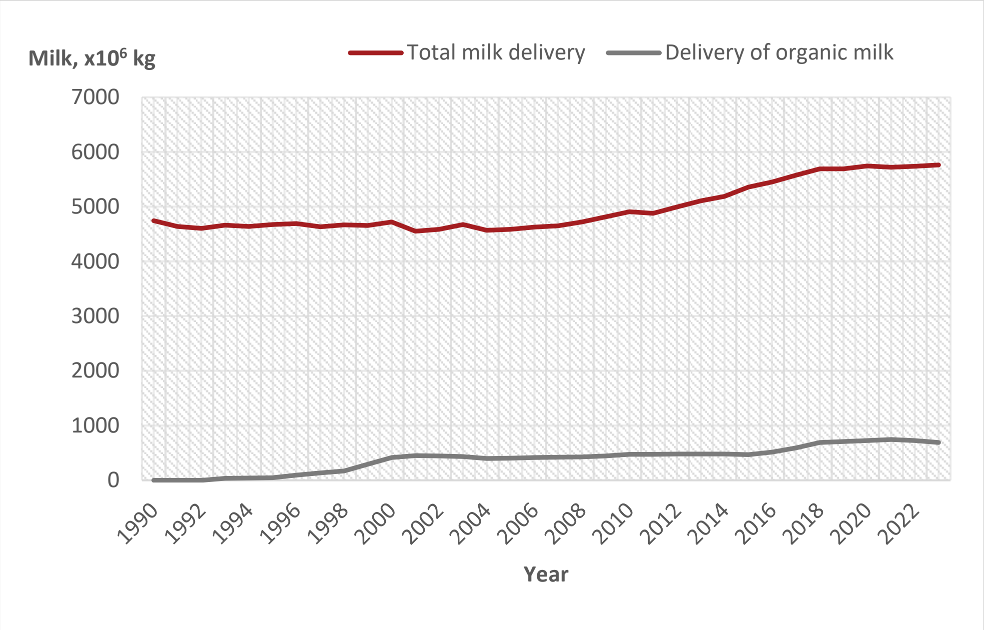


Figure 2.1. Total milk production (delivered milk) in Denmark, and the amount of this which was organic milk from 1990-2023, in Mio. kg (Denmark's Statistics, n.d.).

The more recent data for the Danish milk production show that the total production has increased, reaching around 5,700 Mio. kg milk a year in 2018 (corresponding an increase of 21%), after a gradual increase starting in 2008 (see Figure 2.1). This was likely related to the gradual expansion of the EU milk quotas leading up to the final abolishment in 2015 (Salou et al., 2017).

Since 1930, where the dairy cow population in Denmark was 1.7 Mio. (Kristensen et al., 2015), the number of cows has steadily decreased to a third of that number, counting 545,709 individuals by the end of 2024 (Statistics Denmark, n.d.). This development together hints at the considerable increase in animal productivity. The milk yield per cow (delivered milk) steadily increased between 1900-1970 from ~2000 to 4000 kg/cow/year followed by a steep increase in the milk productivity per cow between 1970-2010 from 4000 to 8500 (milk delivered/cow/year). This development has accelerated up until the present date, where the average amount of milk delivered per cow per year was 10,416 kg in 2023 (Statistics Denmark, n.d.). Thus, the increase in the average milk yield per cow in these three periods (1900-1970, 1970-2010 and 2010-2023) has accelerated by 28.6, 112.5 and 147.4 kg milk/year, respectively. Note that this data on milk yields from delivered milk differs slightly from the annual records from the Danish yield control, which performs at farm yield recordings throughout the years, covering around 92% of all dairy cows in Denmark (Viking Data- & Ydelsesservice, 2024).

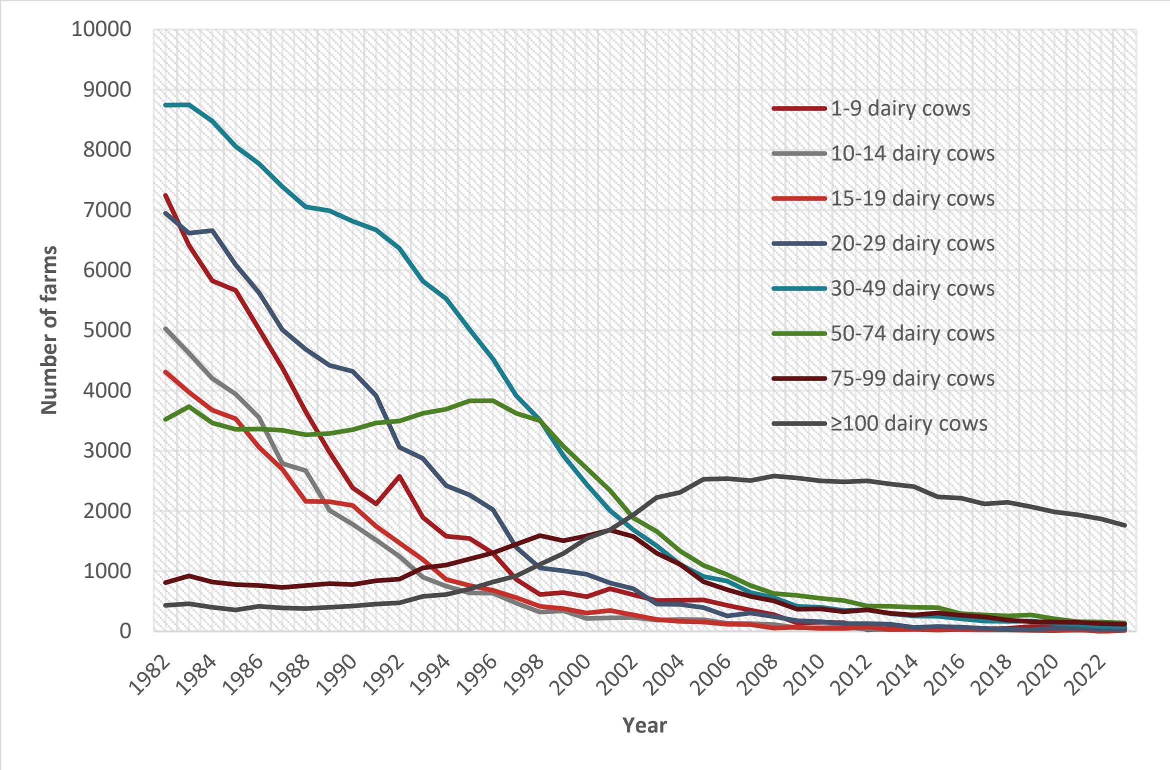
2.1.2 Farm numbers, sizes and designs

Besides the development directly related to the cows, the ways farms and landscapes have been designed and used have also undergone considerable change. In 1950, there was – as mentioned in the introduction – almost 200,000 farms in Denmark (Bjørn, 2025), of which 89% had dairy cattle, typically 6-7 dairy cows in mixed systems (Kristensen et al., 2015). Following the structural changes of agriculture, where the total number of farms decreased rapidly in Denmark, as it happened in many other countries (Otte Hansen, 2016), the share of farms with dairy cows decreased to 36% of all farms in 1982, as the farms were undergoing production specialisation. This development has continued up until the present, where only 8% (2,228 farms) of all Danish farms had dairy cattle in 2023 (Statistics Denmark, n.d.).

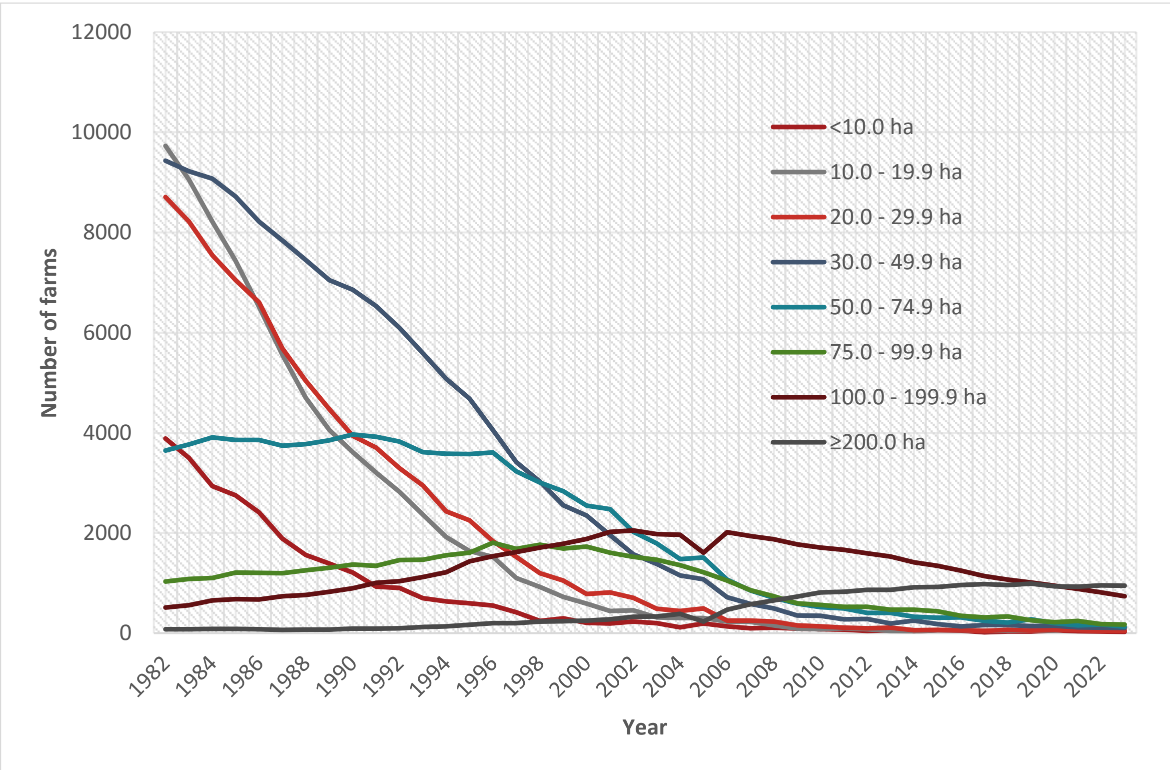
However, while both the total number of dairy cows and the proportion of agricultural farms with dairy cows decreased, the herd sizes of the remaining have increased. This development is clearly shown by the number of dairy farms of different herd sizes seen in Figure 2.2a, showing data from 1982 up until 2023. Just after the turn of the millennium, dairy farms with more than 100 cows became the norm and in 2002, 22% of dairy farms were in this category, just surpassing the number of farms with 50-74 cows. As of 2023, farms with more than 100 cows constitute 79% of all dairy farms in Denmark, where the average herd size is 246 cows (Statistics Denmark, n.d.), effectively surpassing the herd size categories established by Statistics Denmark in 1982. A similar trend has been observed in the land area of dairy farms, with most now managing 200 hectares or more (see Figure 2.2b). This also applies to organic dairy farms, which in 2024 had an average size of 325 hectares. (Danish Agriculture Administration, 2025).

2.1.3 The agricultural land

Looking into the specific changes during the 20th century, several major changes deserve to be highlighted. The mechanisation from the 1950's rapidly replaced horses as drought power in agriculture, which was clearly seen in the population of horses in Denmark, which dropped from over 600,000 in 1945 to just below 50,000 in 1965 (Jensen and Reenberg, 1986). The use of artificial fertiliser, which was without any significance by the beginning of the 20th century, increased drastically after the second world war. In the time from 1945-1980 the yearly use of artificial nitrogen fertiliser increased from around 40 to 380 Mio. kg N (850% increase), with the steepest increase occurring in the 60s (Jensen and Reenberg, 1986). The use peaked in the 80s at almost 400 Mio. kg. N and was later, through environmental regulations (Dalgaard et al., 2014) reduced throughout the 90s to level around 200 kg N per year just after the millennial change. The sale seemed to have increased slightly again after 2017 (see Figure 2.3).



(a)



(b)

Figure 2.2. Development in dairy farm characteristics from 1982-2023 in Denmark in terms of **(a)** number of farms with specific herd sizes, and **(b)** the number of farms of different land area sizes (Statistics Denmark, n.d.).

For phosphorous the increase in use through artificial fertiliser was less steep, increasing from approximately 30 Mio. kg P per year in 1945 to around 50 Mio. kg P by the end of the 1970s. Since then, the use of P has decreased to a level around 12 Mio. kg. P per year. However, the purchase has also in the most recent years fluctuated towards increased uses (see Figure 2.3).

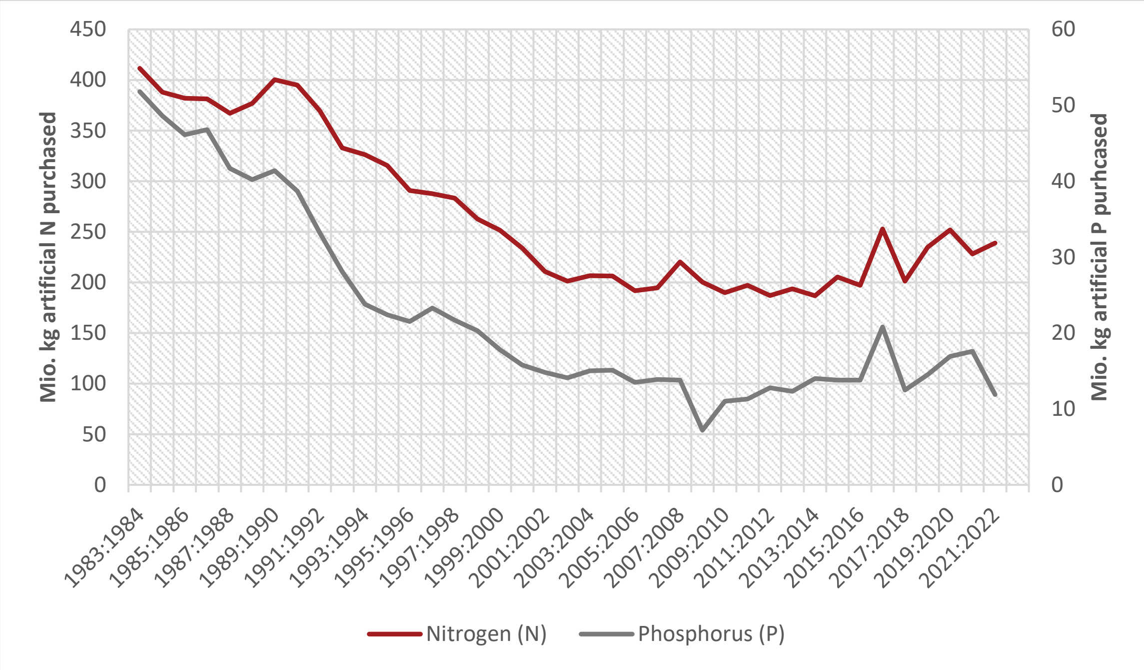


Figure 2.3. The total purchase of artificial N (left y-axis) and P (right y-axis) measured in Mio. kg pure nutrients in Denmark from 1983-2022 (Denmark's Statistics, n.d.).

Livestock manure was the main source of N and P in agriculture by the beginning of the 20th century. The annual application of fertiliser through livestock manure increased up until 1980s. Manure-sourced N was dominating up until 1960, where it was surpassed by the steep increase in use of artificial N. Thus, at its peak, artificial N was used in twice the amount compared to N from manure. After the second world war the manure-sourced and artificial P were used in approximately similar amounts and were both increasing steadily following the general development (Jensen and Reenberg, 1986).

Today, approximately 70% of the phosphorous applied to the Danish soils comes from livestock manure, 20% is from artificial fertiliser and the remaining is from industrial waste and sewage sludge. Livestock manure (including a considerable amount of pig slurry) could in theory sustain the national need for P. However, since the majority of livestock are located in the western part of Denmark, import of artificial P still needed (Poulsen et al., 2019).

Use of pesticides (herbicides, fungicides, insecticides) also increased in the post-war period and peaked during the 1980s (Bichel-udvalget, 1999). Generally, usage is highest among plant producers, but also particular crops, such as potatoes and sugar beets.

The cultivated landscape and the crops in the fields also changed considerably. The decrease in the horse population was followed by a corresponding decrease in the amount of cultivated oat (Jensen and Reenberg, 1986). While area cultivated with fodder beets were high in the 1960s and 70s, the extent decreased during and especially after the 1980s and has to a large extent been replaced by maize for wholecrop silage, which increased considerably over the millennial change (see Figure 2.4). Maize silage is today often an important part of dairy cattle feeding.

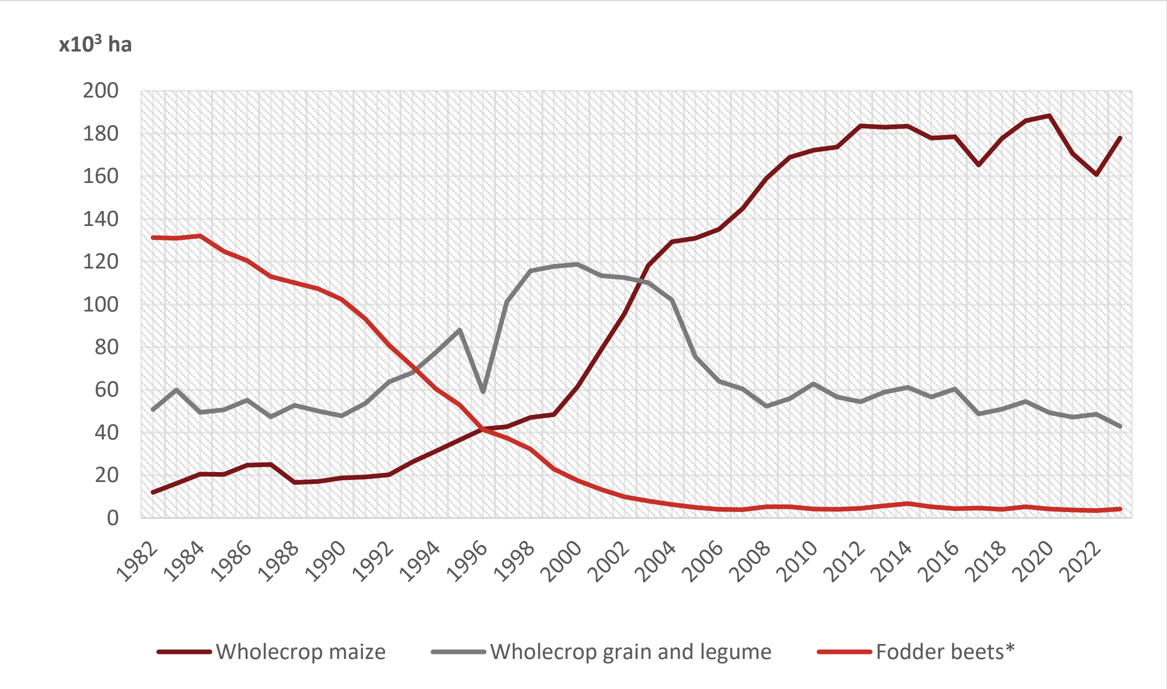


Figure 2.4. Development in the total area (ha) cultivated with wholecrop maize, wholecrop grain and legumes and fodder beets (*including other root vegetables used as fodder) in Denmark from 1982-2023 (Denmark's Statistics, n.d.).

Mechanisation of feed and manure handling related to stable buildings were rolled through the country during the 1970s (Jensen and Reenberg, 1986) and feeding with a total mixed ration (TMR) systems generally increased in popularity throughout the late half of the 20th century (Schingoethe, 2017). At the same time, the importance of grazing decreased over the course of the 20th century (Kristensen et al., 2015) and open permanent grassland areas such as meadows, heaths, bogs, and dunes decreased from constituting 25% of the Danish land area by the end of the 19th century to constituting less than 10% in year 2000 (Levin and Normander, 2008).

2.1.4 Grazing dairy cows in Denmark

Today, around 70% of all Danish dairy cows are housed indoor year-round (Statistics Denmark, 2021). However, this figure does not necessarily mean that 70% of dairy farms practice continuous indoor housing. This is because farms that keep cows indoors year-round are likely to have larger herd sizes. Consequently, a smaller number of large-scale farms may account for the majority of cows, while a greater number of smaller farms may still practice grazing to some degree.

Of all dairy farms, 14% were organic in 2023 (Danish Agriculture Administration, 2024; Statistics Denmark, n.d.), which – dictated by legislation – all must have pasture access in the grazing season. However, a relatively recent survey suggested that 30% of the conventional dairy farms in Denmark also put dairy cows on pasture (Kristensen and Sørensen, 2017). This indicate that approximately 44% of all dairy farms in Denmark have grazing cows and thus a corresponding 56% have year-round indoor housing for the cows, confirming that the non-grazing dairy farms are more likely to have larger herd sizes. Indeed, among conventional producers, grazing dairy cows is most common with herd sizes below 100, whereas grazing youngstock is more common also with higher herd sizes (Kristensen and Sørensen, 2017).

Two surveys with Danish dairy farmers from 2008 and 2015, respectively, found that the most frequent reasons for not grazing dairy cows were challenges with logistics and time consumption related to pasture and grazing management as well as an expectation of reductions in milk yields and economic returns (Kristensen et al., 2010; Kristensen and Sørensen, 2017). Other reasons reported in the latest survey was related to the distance between stable and pasture and a general lack of pasture area. These, however, were not found to be correlated with increasing herd sizes, but expressed by similar numbers of farmers in the small and large herd size groups, respectively.

Although Denmark is among the European countries with the lowest proportion of grazing dairy cows, the practice of grazing is in decline across much of Europe. As noted by European grassland experts, this trend is driven by a complex set of challenges, including issues related to knowledge transfer, research and development, and prevailing farmer mindsets (van den Pol-van Dasselaar et al., 2020). Research from the UK and Ireland also suggests that institutionalised discourses on whether grazing are important in relation to sustainability can play an important role as to whether or not grazing is practiced (Shortall, 2019). It is thus likely that – apart from the structural development leading to higher herd sizes in Denmark – dairy science research, knowledge and knowledge sharing institutions such as farm advisory services also play a significant role. Indeed, education and knowledge work as well as the increasing use of (and need for) consultancy services in the dairy sector has been suggested to have played an important part in the development of the specialised, knowledge and technology heavy Danish dairy sector (Lampe and Sharp, 2015; Ranestad, 2021). Moreover, the high milk yields found in most Danish dairy farms, have in part been achieved through feed optimisation using measures of energy content (feed units) and chemical compositions (Brieghel et al., 2022). Grazing, regardless of the type of pasture, does not fit well into such finetuned optimisation.

Taken together, the low prevalence of grazing in Denmark reflects the broader trend toward an increasingly consolidated and intensive dairy sector, where knowledge and technology play a central role. Beyond advancements in feed optimisation, have both developments in veterinary care, reproductive technologies, and breeding been fundamental in shaping this highly specialised production system. This will be outlined in the following.

2.1.5 Livestock and dairy technology

The work and research in veterinary bacteriology were likely one important area of technology that has shaped livestock production in Denmark. For example, bovine tuberculosis and brucellosis (both diseases found in cattle caused by bacterial infections) were eradicated in 1952 and 1959, respectively, through targeted eradication programs. This was a research area which increased in importance following the challenges with animal pathogens that followed the structural changes in livestock production (Leisner and Larsen, 2024).

In the field of reproduction and genetic development, a number of technologies has contributed significantly in changing dairy production and dairy cows over the past century, as was reviewed by the animal scientists Moore and Hasler (2017), which will be outlined in the following. One of these was artificial insemination, where Denmark was a front runner in the initial development in the early 1900. Although commercial application began as the first place in the world in Denmark in 1936, widespread use did not gain traction until the 1950s, where the development of sperm cryopreservation, using liquid nitrogen, enabled long-term storage of semen. This last discovery increased the opportunities and speed of genetic selection, as high-performance bulls could be widely used in breeding efforts, without the practical limitation of having to transport the bull or semen with limited storage potential around. As such, bulls could suddenly be used in breeding across long distances. Several other reproduction technologies have been important throughout the past century, e.g. semen extenders, plastic insemination straws, protocols for superovulation, embryo transfer, cloning techniques, and computer-based semen analysis. The ability to produce sexed semen was another impactful discovery made by the end of the 20th century, significantly driven by American researchers and laboratories. It was first made commercially available in the UK, however, the Nordic breeding company VikingGenetics were among the first to follow (VikingGenetics, n.d.). In the 21st century, genomic selection has accelerated the speed of breeding even further, by enabling prediction of an animal's genetic potential based on DNA information accessible through the bovine genome sequence first described in 2009 (Elsik et al., 2009). Such technological abilities eliminate the need to wait for phenotypic traits to appear, thereby shortening the generation interval.

Taken together, veterinary and reproductive knowledge, stemming from research activities in Denmark and elsewhere, have together with focus on feed optimisation been forging the shape of the Danish dairy industry of today. Not only has productivity and housing changed considerable, the genetic makeup has changed from being 70% of the Red Danish Milking breed (RDM) in the

1950s, to now being dominated by the high-yielding Danish Holstein breed (Sørensen and Nielsen, 2017). Of all dairy cows in 2010, 72% were of the Danish Holstein breed, whereas 13% were of Danish Jersey breed (JER) and 7% were of RDM breed, more recently also known as Viking Red (Kristensen et al., 2015).
Given that this research is conducted in a country where the dairy sector is broadly optimised through advanced technologies, the following section will explore the challenges present in such systems and the types of dairy research they inspire. This will serve as context and a reference point for the radically different systems and research approaches examined in this PhD.

2.1.6 Challenges of Danish dairy farming today

The major advancements in animal productivity achieved especially through the genetic selection in the latter half of the 20th century came with trade-offs on fertility and longevity and increased the prevalence of mastitis and lameness (Rodriguez-Martinez et al., 2008). These, together with metabolic 'production' diseases such as ketosis and milk fever (hypocalcaemia), but also infectious diseases, including mastitis, are among the challenges frequently found at typical dairy farms in Denmark.

A recent study showed how an infectious disease such as *Salmonella* Dublin is endemic and continues to spread in the Danish dairy cattle population despite intensive efforts in the form of a national surveillance and eradication program to control the spread of the bacteria (Conrady et al., 2024). Likely causes for this can be that the infrastructure of the production system, where the large herd sizes, high density of dairy farms in some parts of the country, and frequent movements of animals and manure to and from farms, facilitate the spread of pathogens among and within farms (Pedersen et al., 2023). Research in dairy science typically fall into a specific area in relation to dairy farming. Besides the study of infectious diseases, studies aiming to reduce the use of antimicrobial use and thus the risk of antimicrobial resistance through e.g. analysis of usage through register data or alternative mastitis treatment practices (Henningsen et al., 2024; Svennesen et al., 2023) and aims to address overall health of cows and calves and thus both improve welfare, animal productivity and production economy e.g. through reviewing lameness prevalence and developing dairy calf health monitoring protocols (Otten et al., 2023; Thomsen et al., 2023) are other topics typically found in dairy science research. However, a more radical aim for animal welfare is the studies on the prospects, implications and work of adopting cow-calf contact systems, where calves stay together with the dam or a nurse cow for a prolonged period (Mogensen et al., 2022; Vaarst and Christiansen, 2023). In relation to environmental mitigation, there is an overwhelming focus on how to reduce enteric CH_4 emissions to decrease climate impacts, mainly through experimental studies with feed additives. One of the remedies that is considered most effective in this, is the artificial feed additive 3-nitrooxypropanol (3-NOP), the active ingredient in the commercial feed additive Bovaer, which was approved in the EU in 2022 (Danish Veterinary and Food Administration, n.d.). A recent Danish study investigated the reduction potentials of 3-NOP, fat and nitrate supplementation, which was found to reduce enteric methane emissions by 18-23%, 10-15%, and 15-22%, respectively (Maigaard et al., 2024a).

All of these examples are research conducted within the Danish dairy science research community. As such, it is research which typically work to improve a particular area of interest (medical use, health, productivity and welfare, welfare as natural needs, and environmental mitigation through precision feeding initiatives). Usually, such studies are performed within the current production frames, aiming for representativeness, to produce solutions, improvements or assessments which are likely to fit or be possible and effective in the majority of the Danish farms. However, this approach also creates reinforcing feed-back loops of system-preservation, as alternatives are rarely explored.

In 2021, researchers in the Danish Public Sector Service were asked by the Danish Agricultural Agency (Landbrugsstyrelsen), under the Ministry of Food, Agriculture and Fisheries of Denmark, to estimate the effect of reducing animal based production (including cattle, pigs, sheep and poultry) by 10, 20, 30, 40 and 50% on GHG emissions, nitrogen leaching and ammonia evaporation under two different scenarios – one where feed is imported as today and one of 100% feed self-sufficiency (Jørgensen et al., 2021). The researchers ended up, after an expectation-alignment meeting, estimating the scenario with 10% reductions for the cattle, pigs, and 'other animals'. The researchers included the following statement in the very end of the requested response note (translated from Danish to English):

> *"It has not been possible, within the short deadline of the request, to analyse the desired interactions between a greater degree of reduction in livestock production and self-sufficiency in feed. Moreover, these are highly complex interactions within a dynamic agricultural system, where the uncertainty of very specific combinations can quickly overshadow the calculated effects."* (Jørgensen et al., 2021, p. 23)

This statement and several remarks in the response note makes it clear how the effects of such reductions are dependent on the assumptions on what then will come instead. In the presented response of 10% reductions, it was assumed that plant production with artificial fertiliser would replace the feed production with animal manure. The reduction potentials of GHG emissions were estimated to 6.6%. The impact on nitrate leaching was on the other hand estimated to slightly *increase*. The note also mentioned the risks of production leakage when reducing animal numbers and thus production, as it potentially can lead to a global increase in GHG emissions if the animal production is moved to less efficient countries to maintain global production levels.

Indeed, prospects of deviating from the intensive animal-based production paradigm are reluctantly explored within animal production research in Denmark. Still, other researchers have explored the GHG emission reduction potentials by transitioning the Danish food production towards more plant-based food in accordance with the EAT-lancet diet (Willett et al., 2019), also known as the "planetary health diet". Through such a transition, entailing a significant downscale of the production animal population in Denmark, the study found reduction potentials for GHG emission from agriculture ranging from 58.2–86.5%, depending of the degrees of feed self-sufficiency, restoration of drained organic soils and levels of afforestation on 'surplus' soils (Prag and Henriksen, 2020).

While this PhD is not aiming to perform such national estimates, it does insist on going beyond the arguments of representativeness, risks of production leakage and too great complexity, which effectively creates a lock-in for maintaining a high level of intensive animal production in Danish agriculture. Approaching green transition through the perspective of absolute sustainability and socio-ecological interconnection demands an attention which goes beyond the animal and the stable and extent into landscapes. In this regard, understanding the PBF has been important. Hence, the following section will provide an overview of the framework, its development since it was first described, as well as the nine interlinked processes and their relevance for Denmark and green transition of dairy farming.

2.2 The planetary boundary framework

At the time the PBF was first described (Rockström et al., 2009), seven of the processes were quantified (missing novel entities and atmospheric aerosol loading) and three processes were assessed to be transgressed beyond the safe limit. Figure 2.5 shows the development to the latest update in 2025, where all processes have been addressed, and seven out of nine boundaries are transgressed by human activities.

The development of this framework over time speaks a clear language about the need for radical actions to mitigate the planetary pressures. For each process researchers have defined a safe boundary, marking the limits for human activities to avoid threatening the resilience of the Earth system, through a control variable chosen for each process. These can be found in Table 2.1. The work on determining appropriate variables and quantifying limits and current use of the respective processes have been ongoing since the first publication in 2009. Hence, some processes have been renamed or expanded for more nuances. For example, the control variable and defined boundary used for freshwater use in Richardson et al. (2023) changed from "blue water consumption" to "human disturbance of blue and green water flows compared to preindustrial variability". Blue water represents (extractable) surface and underground freshwater pools, such as groundwater and lakes, where green water refers to the water held in soils. The inclusion of green water and the change in boundary indicators meant that the boundaries were transgressed already in 1905 and 1929 for blue and green water, respectively. The previously used control variable would have been shown to be within safe levels, also in the 2023 update (Richardson et al., 2023).

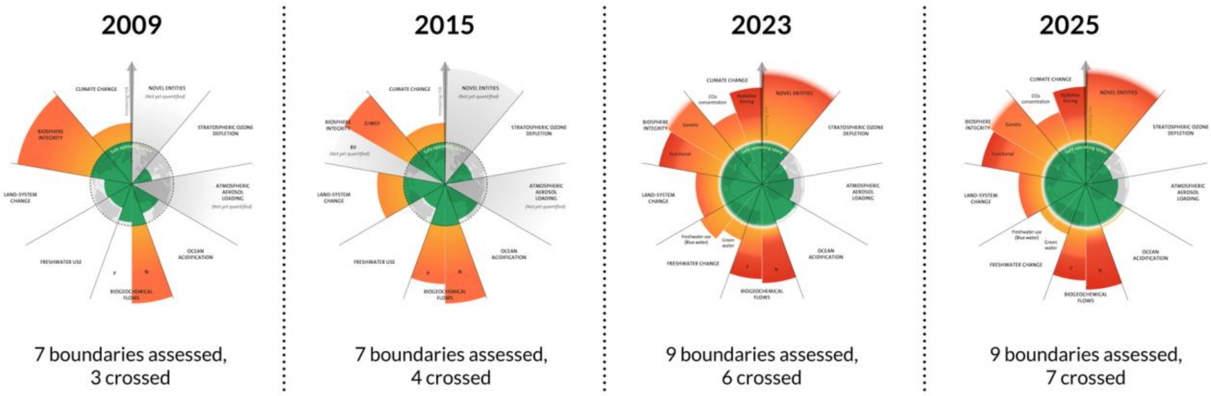


Figure 2.5. The evolution of the planetary boundaries framework. Licenced under CC BY-NC-ND 3.0 (Credit: Azote for Stockholm Resilience Centre, Stockholm University. Based on Sakschewski and Caesar et al. 2025, Richardson et al. 2023, Steffen et al. 2015, and Rockström et al. 2009).

It is evident that such large-scale quantifications are based on broad assumptions and covers huge variation and uncertainties. To illustrate this, Steffen et al. (2015) introduced the 'zone of uncertainty', where PB are set in the "safe" end of this zone, representing low probability for challenging thresholds and tipping points. On the other hand, moving towards and beyond the "danger end" of the zone is associated with increasing and high probability of provoking irreversible thresholds and tipping points. To emphasise this, this zone was renamed 'the zone of increasing risk' in the latest framework publication (Richardson et al., 2023). An overview of processes and PB indicators used in the framework over time can be found in Table 11.1 in Chapter 11.

Of the nine processes in the framework, climate change and biosphere integrity are considered the two core processes, where climate change is used as a proxy for the geosphere. These two processes together regulate the state and stability of the planet system, as they represent the functions which manage the flows of energy between the biosphere and geosphere. To be able to work with the framework, it has been important to understand the nine processes, and how they are relevant to the context of Denmark and agricultural development. Each process will be further described from this perspective in the following sections, with particular emphasis on those most relevant to this project – namely climate change, biosphere integrity, biogeochemical flows, land-system change, water use and novel entities.

Table 2.1. Overview of the nine interlinked planetary boundaries and the control variable(s) used to quantify them, as described by (Richardson et al., 2023).

Planetary process	**Control variable(s)**
Climate change	Atmospheric CO2 conc., ppm
Biosphere integrity: genetic diversity and functional integrity	Genetic diversity: extinction rate, number of species gone extinct per million of species per year (E/MSY) Functional integrity: energy available to ecosystems (net primary production, NPP) Limit variable: % HANPP (Human Appropriation of the biosphere's NPP)
Biogeochemical flows: nitrogen and phosphorus	Nitrogen: Anthropogenic N (industrial and intentional biological fixation), Tg N yr-1 Phosphorus: Global: P flow from freshwater systems into the ocean (Tg P yr-1). Regional: P flow from fertilizers to erodible soils, Tg P yr-1 mined and applied to erodible (agricultural) soils
Stratospheric ozone depletion	Concentration of ozone (O3), Dobson unit (DU)
Ocean acidification	% of mean pre-industrial aragonite saturation state (Ω_{arag}) of surface ocean. Aragonite is a crystalline form of calcium carbonate, which constitutes part of the shells and skeletons of many marine organisms.
Freshwater use: Blue and green	Blue: human induced disturbance of blue water flow (% of global land area with deviations greater than during preindustrial) Green: human induced disturbance of water available to plants (% land area with deviations from preindustrial variability)
Land-system change Global and biome	Global: Area of forested land as the percentage of original forest cover Biome (tropical, temperate and boreal): Area of forested land as the percentage of potential forest (% area remaining)
Atmospheric aerosol loading	Interhemispheric difference in Aerosol Optical Depth (AOD)
Novel entities (use of synthetic substances and material)	Percentage of synthetic chemicals released to the environment without adequate safety testing

2.2.1 Climate change

Climate change is by far the most discussed process and is caused by an increasing concentration of GHG in the atmosphere, primarily carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). In discussions on green transition of the cattle sector, this process has received major attention in scientific livestock research (Beauchemin et al., 2022; Boadi et al., 2004; Hristov et al., 2022; Knapp et al., 2014; Steinfeld et al., 2006), due to the CH_4-emission from the enteric fermentation, which has been estimated to constitute over half of the total CH_4-emission from agriculture globally (Knapp et al., 2014). Among many other parties, Denmark signed the Paris Agreement form 2015, committing to reducing total national GHG emissions for "*holding the increase in the global average temperature to well below 2 °C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5 °C above pre-industrial levels*" (United Nations, 2016).
This has led to further political action and in 2021 nearly all political parties in Denmark reached an agreement to reduce the agricultural sector's climate impact by 55-65% (compared to 1990) by 2030 (Finansministeriet, 2021). The agreement stated that there currently were few tools to achieve the reductions and that "*further reductions in agriculture's emissions of greenhouse gases and nutrients must be achieved through the development and not the dismantling of Danish agriculture, based on a technology-neutral approach. For this, new technologies and solutions are needed to reduce agriculture's emissions of greenhouse gases and nutrients".* Precisely what was meant by "*development*" and "*dismantling*" was not specified, but the wording suggests that solutions that would reduce current production levels were not of interest – or maybe not politically viable. The agreement also included reduction goals on nitrogen emissions to water environments through establishment of wetlands and forest, although on a voluntary basis.
The Danish national inventory report from 2025 stated that the GHG emissions from the agricultural sector in Denmark contributed with 29% of the total national emissions in 2023, an increasing percentage as other sectors rapidly have decreased their climate impact (Nielsen et al., 2025). Reviewing the development of GHG emissions from the agricultural sector between 1990-2023, showed a 23% reduction in the total GHG emissions. However, this can primarily be attributed a large (40%) reduction in N_2O emissions from soils through a decreased use of inorganic fertilisers between 1990-2003, as depicted in section 2.1.3 in this thesis.
The majority (64%) of agricultural GHG emissions in 2023 came from CH_4 emissions and was primary related to the large Danish livestock production of pigs and cattle, mainly from enteric fermentation and manure management. While reductions in the total CH_4 emission from enteric fermentation from dairy cows was reducing between 1990-2007, there has been an increasing trend from 2008-2023 (see Figure 2.6). This can be explained by the large increases in milk yield per cow, which has increased the total feed consumption, which in turn has increased the implied emission factor (increasing from 128 kg CH_4 per dairy cow per year in 1990 to 162 kg CH_4 in

2023). The decrease in cow numbers and improvements in feed efficiency have to some extent offset some of these increases resulting in a 10.8% reduction of CH_4 from enteric fermentation in 2023 compared to 1990.

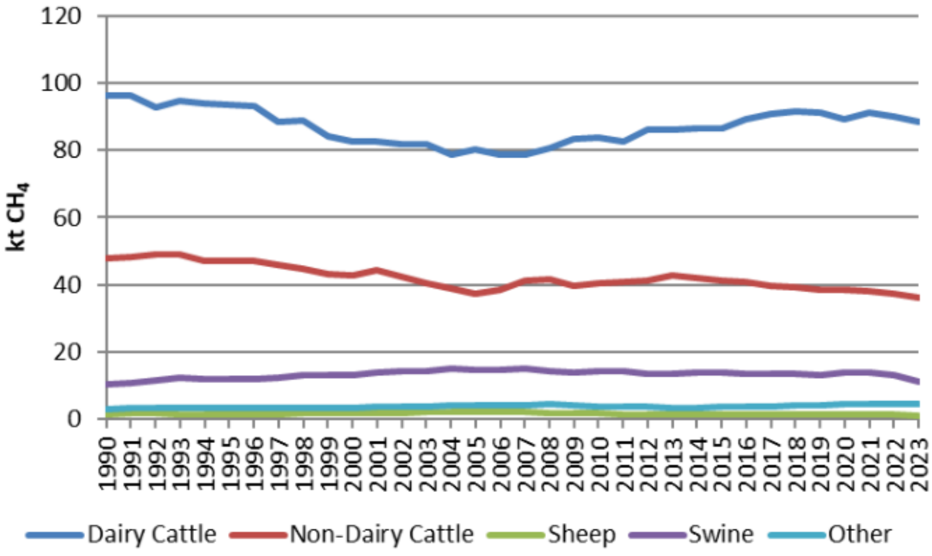


Figure 2.6. Emission of CH_4 from enteric fermentation, 1990-2023. (Credit: Nielsen et al. (2025, p. 436)).

The CH_4 emissions from livestock manure management – of which around half originated from cattle production (including dairy and non-dairy) – has on the other hand increased by 4.8% between 1990-2023. This has primarily been caused by a change from solid to liquid manure handling systems, but also the increases in feed intake in dairy cows and the following higher manure excretion has contributed to increases in CH_4 emissions from manure management from 1990-2018. However, from 2019-2023 decreases were found through slurry treatment in biogas plants. The report concludes that net CH_4 emissions from agriculture have decreased by 4.6% since 1990. The remaining discrepancy of 1.4% may indicate an increase from other minor sources.

The slow reductions in GHG emissions from the sector, not even halfway to the 55-65% reduction goal, led – among other things – to a new agreement called "The Green Tripartite" in 2024. It was negotiated between governmental and non-governmental actors and agreed to put a carbon tax on agricultural GHG emissions from manure and enteric fermentation (Grøn Trepart, 2024). The tax will be gradually introduced by 2030 and reach its full amount by 2035. However, already from January 1st, 2025, all conventional dairy farms with more than 50 cows are legally required to use CH_4 reducing feed additives for at least 80 days per year – either Bovaer (mentioned in section 2.1.6) or increased levels of fat in the feed ration (Landbrug & Fødevarer, n.d.). Farmers who choose Bovaer can apply for financial compensation to cover the costs of meeting this requirement.

In this way, the Danish government actively supports the agricultural sector through targeted technical solutions that enable the continuation of current production levels and herd sizes.

2.2.2 Biosphere integrity

Regulating the flows of nutrients to water environments is connected to goals on improving the diversity and functionality of the Danish environments. In other words, to mitigate impacts on the integrity of the biosphere, the other core process of the PBF.

This process is formed by two defined areas: the genetic variation and the functioning of the biosphere. Where the genetic diversity refers to the overall species richness, the functional integrity refers to the intactness and adequacy of the cycling and storage processes of the biosphere. The genetic variation is measured by extinction rates, and the functional integrity is assessed through human appropriation of net primary production (HANPP). The HANPP indicates the extent to which human activities (through land conversion and harvest of biomass) impact the availability of biomass energy (produced through photosynthesis) to ecosystems, which in turn supports genetic variation and regulating functions important to sufficiently maintain the stability of the planet. This includes the regulation of flows of water, nutrients, and other substances, each of which also form a process of their own within the PBF.

With Denmark being the world's second most cultivated land with almost 60% of the land in agricultural cultivation (The World Bank Group, 2024), consideration to this process is highly relevant. Only 9.2% of the Danish land area is constituted by permanent open nature areas (Statistics Denmark, 2022) and only 2.3 % of the Danish land area is estimated to be in a state that aligns with international goals for protected areas (Biodiversitetsrådet, 2022). Followingly, the diversity of butterflies (an insect species which has been suggested to be especially sensitive to the intensification of land-use) has been rapidly declining in Denmark over the past 100 years, with sedentary butterflies that are habitat or host plant specialists and which overwinter in an immature stage, showing the highest regional extinction rates (Bjerregård et al., 2023; Eskildsen et al., 2015). In addition, most streams, lakes, and costal water environments are in moderate or poor ecological condition due to excessive nutrient leaching (Ministry of Environment, 2023).

Further, loss of organic matter content, soil erosion and compaction have been evaluated to pose significant drivers for soil degradation in Denmark (Schjønning et al., 2009). Researchers from the Department of Agroecology at Aarhus University have investigated soil organic carbon (SOC) content in the Danish agricultural fields from 1987-2009, finding a small annual loss (0.2 t C $ha^{-1}year^{-1}$) in a depth of 0-100 cm. However, while the SOC decreased in loamy soils, it tended to increase in sandy soils. This was suggested to be explained by the fact that dairy production is most frequent on sandy soil and typically has clover-grass leys in the crop rotation, whereas loamy soils are more likely to be subjected to continuous cultivation of cash crops (Taghizadeh-Toosi et al., 2014).

Altogether, this suggests that human activities in Denmark, primarily through agricultural practices, are overshooting local liveability and carrying capacities in several directions, including human encroachment on land areas, land-use practises, and the use and flows of nutrients.

2.2.3 Biogeochemical flows and land-system change

The process for biogeochemical flows represents the anthropogenic alteration and control of cycling of elements, which currently include flows of phosphorus (P) and nitrogen (N). The latter encompasses both industrially and intentional biologically fixed N, e.g. the N produced from temporary clover-grass leys in crop rotations. Balancing the use of these elements is an important factor in relation to ecosystem diversity (Le Clec'h et al., 2019). In addition, as opposed to N, P is a non-renewable resource which is mined from phosphate rock only present in few areas of the world and have thus been described as 'life's bottleneck' (Cordell and White, 2014). This further makes recycling of nutrients an essential consideration in agriculture.

A study estimating national use, impact and performance of different environmental and social indicators in the period from 1992 to 2015, found that the Danish use of N and P was massively overshooting allocated boundaries in 1992 (by 312 and 427% for N and P, respectively). However, in 2015 the degree of overshooting was decreased considerably for P, overshooting only by 12.5%, whereas N were still transgressing the allocated threshold by 273% (University of Leeds, 2025). In approximately the same period, 1990-2013, the use of artificial P in the Danish agriculture was reduced by 70%. In addition, the P contribution from livestock manure was reduced by 25% following general improvements in feed efficiency, but also due to the introduction of a tax on the use of mineral feed phosphate in 2005 (Andersen et al., 2016). Phosphorus has the ability to accumulate in soils as it is chemically bound to soil particles up to a certain level and thereby is more 'sticky' compared to the 'slippery' N (Bouwman et al., 2017). However, following many years with a high use, the P content in the Danish soils has accumulated (more on this later). High saturation of P increases the risks of leaching in soluble form, but P can also be lost to water environments via soil particles through erosion, surface runoff, and drains (Andersen et al., 2016). Thus, despite reductions in use, both N and P from agricultural activities are still a significant driver for the degraded ecological conditions in the Danish water environments (Ministry of Environment, 2023).

The Green Tripartite mentioned before in section 2.2.1 in relation to GHG emissions, also aimed to take 400,000 ha targeted land area out of cultivation to contribute to reduced nutrient leaching and increase area for nature (Grøn Trepart, 2024). This agreement was politically agreed on in November 2024 (Socialdemokratiet et al., 2024). Thus, initiatives on mitigating the pressure on climate change, biosphere integrity and nutrient use in Denmark are current and much needed events. These are also linked to the process ‘land-system change’, which covers human alternation of terrestrial biomes (e.g. forest, grasslands, tundra and more (Champreux et al., 2024)). The PBF process for land-system change uses the different forest biomes (tropical, temperate and boreal, see Table 2.1) as a proxy for this, due to its strong connection to climate change. However, the aim to convert cultivated land to both open and forested nature areas found in The Green Tripartite agreement also addresses this process.

2.2.4 Novel entities, freshwater use, ocean acidification, aerosol loading and ozone depletion

Novel entities are defined as human made or altered substances, which includes a wide array of chemicals, substances and human mobilised radioactive material. In relation to agriculture, this would cover for example pesticides, artificial fertilisers, synthetic feed additives, antibiotics and microplastics.

Freshwater use covers land-based water cycling and regulation divided into blue and green water, where blue water refers to surface freshwater and groundwater, and green water is the flow of water through precipitation, evaporation and soil root zones moisture (Wang-Erlandsson et al., 2022). Drinking water in Denmark is abstracted from the groundwater, where agriculture some years consume a considerate part of the abstracted water – in dry years up to one third of the total amount. The average amount of precipitation has increased by 4.4% when comparing the period of 1961-1990 with that from 1991-2015, which in drained areas are likely to increase the flow of water to wetlands and near coastal areas. The groundwater monitoring program in 2017 found traces of pesticides down to 50 meter in depth in 24-39% of the sampled monitoring points samples (GEUS, n.d.). This shows how these flows of both nutrients and the novel entities from agriculture also are affected by the changing climate patterns, here increases in the average yearly precipitation.

As of finalising this thesis, the status for the process ‘ocean acidification’ was changed to also be transgressing the defined safe boundary (PBScience, 2025). Ocean acidification is the decrease of ocean pH which mainly is caused by CO_2 absorption from the increasing concentrations in the atmosphere. Thus, only two processes are currently assessed to be within planetary safe limits: ‘aerosol loading’ and ‘ozone depletion’. Aerosol loading is the concentration of dust particles in the air related to regional climate, precipitation patterns and monsoon systems. And last, ozone depletion is caused by release of certain novel entities and have recovered somewhat since the regulation of the depleting entities through the Montreal Protocol from 1987.

This overview of the PBF processes situated in the current states in Denmark, emphasise the need for changes, especially in the ways we use land and nutrients. Together with the background of how dairy farming has developed in Denmark, this information has been important for my reflections on how to change developmental patterns in dairy and agricultural production, something that economist Kate Raworth – mentioned in chapter 1 – emphasised as essential in her work on Doughnut Economics. The following section will bring an overview of the doughnut model and Raworth's framework for how to transition society into a safe and just space of operation.

2.3 Doughnut Economics

The doughnut-shaped model effectively directs attention to the balance of goals that green transitions must consider. Since the publication of the conceptual model depicted in Figure 2.7, efforts have been put into quantifying global as well as national operation statuses.

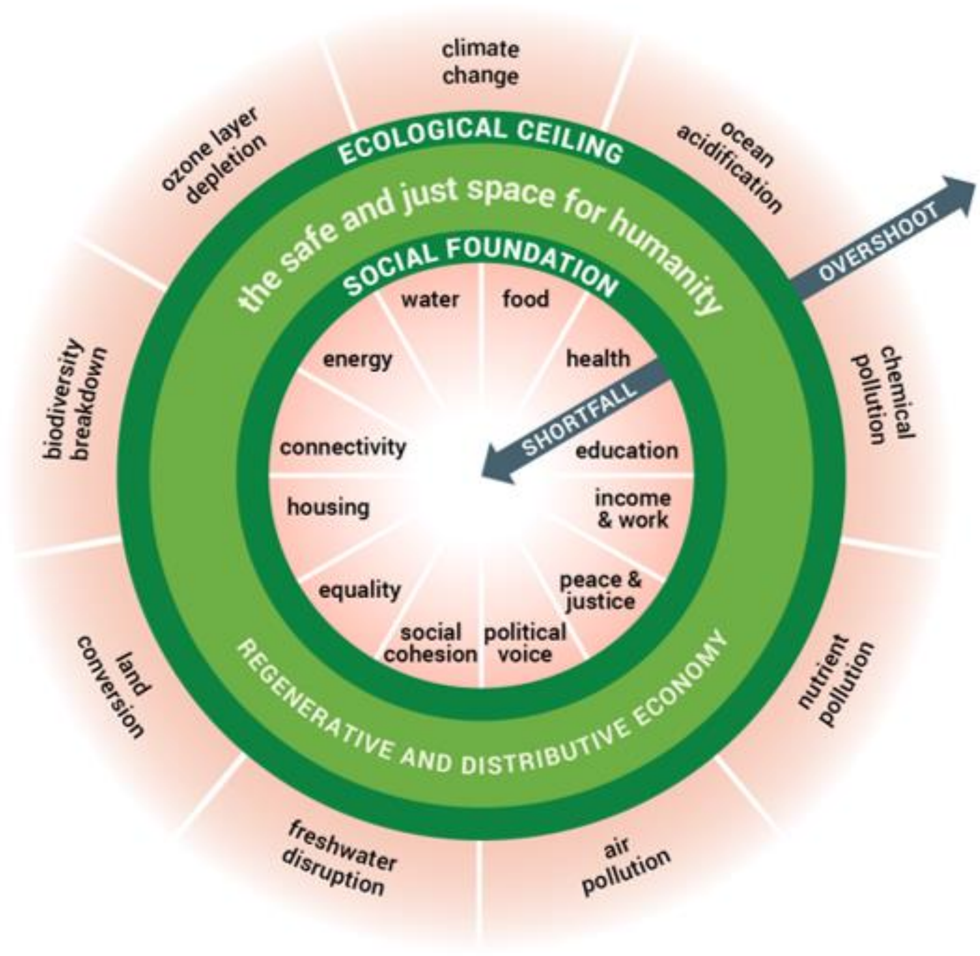


Figure 2.7. The Doughnut of social and planetary boundaries. Licenced under CC-BY-SA 4.0 (Credit: Kate Raworth and Christian Guthier. Based on Raworth (2017)).

A recent publication on such quantifications found that while the global social foundations have improved slightly between 2000-2022, the collective pressures on the planet have significantly increased on all processes apart from ozone depletion (Fanning and Raworth, 2025). Of the 21 dimensions quantified in the social foundation, 13 were improved, 5 largely unchanged, 1 unknown (due to missing data), and 2 had worsened. One of the latter was food insecurity.

In dairy farming, the concept of 'just' transition within the doughnut model can be interpreted in multiple ways. Farming is deeply embedded in complex socioeconomic relations. For example the import of soy from South America – a practice that risks supporting or driving illegal deforestation of rainforest (Vasconcelos et al., 2020). Another critical aspect is access to land, subsidies, and the issue of land grabbing (Van Der Ploeg et al., 2015), which remains a highly relevant and contested topic. However, in this thesis, the doughnut model is primarily used to illustrate the balancing act agriculture must perform, with a particular focus on the social foundation of ensuring food security for all. A just transition, in this sense, involves integrating strategies that maximises food production, aiming to contribute as much as possible to global goals for food security. Accordingly, a 'safe and just transition' will in this thesis be understood as an agricultural system which transition with attention to ecological carrying capacities, while optimising for food total output.

The quantitative measures of current operations are important to guide attention towards critical areas. However, it does not qualify *how* to address these urgent matters. The seven critical shifts in our ways of thinking, forming the content of Raworth's book on Doughnut Economics, specifically aim to qualify the types of changes needed to leverage a different developmental path for the 21st century. The shifts in the mindset of economists Raworth suggests are depicted in Figure 2.8.

Raworth's seven steps – referenced in the third manuscript (chapter 6) – offer a framework for rethinking economics in service of a safe and just future. First, she calls for changing the goal: shifting from a narrow focus on economic growth to operating within safe and just boundaries. Second, she urges us to see the big picture, recognising that society is embedded within a finite, living world. Third, she emphasises nurturing human nature by supporting community, reciprocity, and collaboration, rather than relying on the image of the rational economic man. Fourth, she advocates becoming savvy with systems, highlighting the importance of understanding dynamic interactions between stocks and flows in complex socio-ecological systems. Fifth, she proposes designing to distribute, using grassroots networks to share various forms of wealth – including knowledge. Sixth, she promotes creating regenerative systems and enterprises, inspired by nature's circular processes. Finally, she argues for being agnostic about growth, encouraging societies to rewire their economies for adaptability rather than dependence on growth.

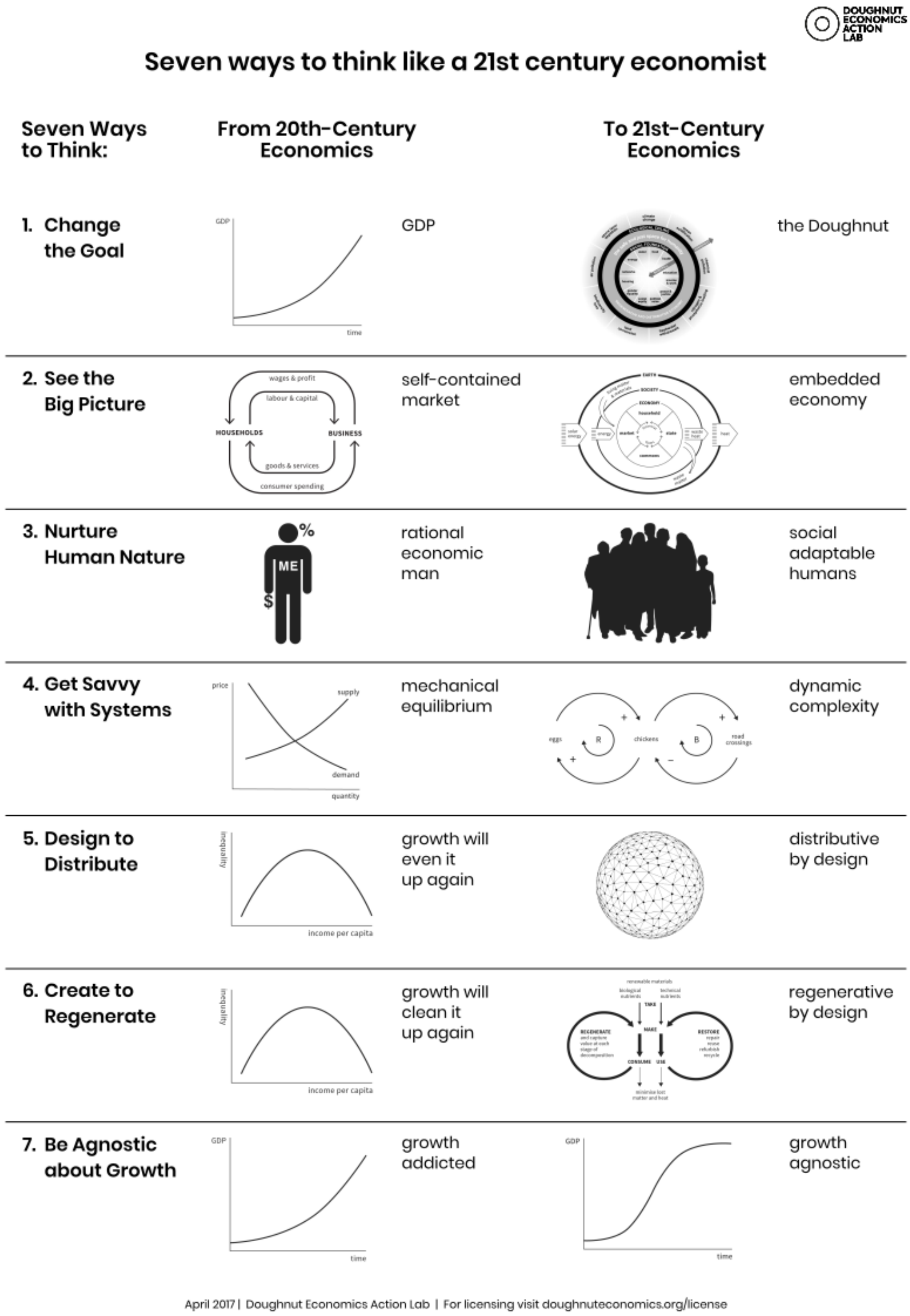


Figure 2.8. Seven ways to think line a 21st century economist. Licenced under CC-BY-SA 4.0 (Credit: Raworth (2017)).

With researchers already working hard to quantify the current status and developments of social and planetary boundaries – showing how progress is both too slow and still causes further pressure on planetary processes – it is clear that different ways of achieving and rationalising progress are needed. This PhD is an attempt to pursue that. The following chapter will describe the research approach adapted in this PhD.

3 Research approach

The encompassing challenges outlined in the previous chapters can be termed a 'wicked problem'. This has been characterised as a problem with no 'right answer', which cannot be addressed by one scientific field or one knowledge form alone, but which calls for diverse mitigation efforts across scales, stakeholders and analytical paradigms (Achiam et al., 2021). The Cattle Crossroads project was a transdisciplinary research project, merging anthropology with animal and veterinarian sciences employing a fieldwork-based with a stakeholder inclusive approach. Transdisciplinary research is thus defined as the involvement of different academic disciplines as well as non-academic actors (society) (Jahn et al., 2012; Tress et al., 2007).

The joining of researchers with diverse backgrounds entailing that very different perspectives were brought into conversation in the group, was a deliberate design in the Cattle Crossroads projects. My background as an animal scientist with experience from mainstream livestock production through the animal science lens was therefore an important aspect, as it in many ways shapes what I notice and consider important in animal production. The different disciplinary perspectives often became the source of discussion, where e.g. the anthropologists questioned the underlying assumptions of typical knowledge production in animal science, based on ideas of objectivity, sharp definitions of units of study, and narrow hypothesis testing. Such reflexivity had not been articulated through my education, but was something that I became aware of through the Cattle Crossroads set up and close collaborations within the project group. However, it is an increasing practise – at least in qualitative research – to include author reflexivity or positionality statements (Ritter et al., 2023). Academic practices of reflexivity are an attempt to recognise such relations and influences. As such, in the following section I will state my background and experiences gained before I enrolled as a PhD student.

3.1 Author reflexivity

As a former student of Animal Science at the University of Copenhagen (UCPH), I have gained knowledge and experience from conventional Danish animal science research and thinking, particularly within cattle and pig production. My academic and professional background has involved collaborations with agricultural innovation institutions, fieldwork in commercial farms, and roles spanning research assistance, technical support, and farm labour. All within intensive, conventional livestock systems and production frames – although primarily pig productions – in both Denmark and Sweden. Altogether, the experiences from working with pig production from several places (education, private and public research, practical farm work) had left me increasingly frustrated and sceptical of my own discipline. I found the conditions seriously lacking considerations for the needs of the animals in the prevailing indoor systems, even when it looked best. Efforts to improve them by tweaking conditions I saw as practically meaningless, as the conditions remained confined within the frames and limits of existing production designs. As such, my critique of livestock systems primarily came from an animal welfare perspective. However, in private – especially after working at a conventional hedge plant production, needing a break from livestock systems, where I found extensive use of both pesticides, artificial fertilisers, and imported peat soil for potting – I was to an increasing extent occupied with environmental interests of biodiversity, growing vegetables, composting, soil health, and limiting resource use. Altogether, when offered the opportunity to research *green transition* of cattle production development through the lens of my animal science knowledge base, but with a radically new angle and point of departure, I took on the challenge excitedly.

In the following, the motivation behind the research approach, the research process, case farm selection, as well as the methodological entry points are outlined.

3.2 Animal science in transdisciplinary research

From the beginning, it was recognised that there would be a need for both qualitative and quantitative methods, including methods found within animal and veterinary sciences, to achieve the intended integration of the different science and knowledge forms. The anthropologists in the project were practiced in ethnographic research, which is characterised by an open immersive approach, where the researcher studies a specific field (in our case green transition in alternative dairy farming), while being in the field of study, with an awareness of the personal knowledge-basis they bring with them which colour what they notice (Hammersley and Atkinson, 2019). Further, the ethnographic approach is most often inductive-iterative with flexible study boundaries that leave space for the emergence and adaptation to unexpected findings (O'Reilly, 2012). In particular, I have been inspired by the relatively recent emergence of multispecies ethnography where other species and ecologies – domestic animals, plants, fungi and microbiotas alike – are brought into the study of human cultures, studying entanglements of organisms, interspecies dependencies, and reciprocity in creations of cultures and livelihoods (Kirksey and Helmreich, 2010).

The close collaboration with anthropologists challenged the research approaches typically found in livestock science, which – as outlined in the previous chapter – often focus on optimisation of isolated parts (extracted from the greater context) of the specialised dairy system. Often aiming the research towards singular goals, e.g. often economic optimisation through knowledge on feeding, genetics, management or diseases. Including different sciences and practices to question and supplement each other was a way to expand the attention and invite novel ways of thinking about the challenges and potentials of different forms of dairy farming. This resulted in an attention to a much wider range of drivers and activities than animal science research usually would do.

These exchanges occurred through shared field trips and recurrent discussions of fieldwork material and literature, which is specified in section 2.5.1. Further, the project offered engagement with other disciplines besides the ones represented in the research group. Correspondences and shared field trips with researchers and experts outside the project group were important to understand the nuances of the environmental challenges and potentials. As such, it entailed fieldwork and engagement with a variety of stakeholders, where people from different backgrounds could discuss, reflect, and influence each other in multiple directions.

Throughout the project, I have participated in PhD courses within environmental research, learning about GHG measurements from soil and ecosystems, as well as interactions between plants, microorganisms and soil in terrestrial ecosystems. I engaged in discussions and field trips with soils scientists and biologists, both at some of my case farms, and in other places. I participated in farm visits and excursions with organic farm consultants and talked with other relevant stakeholders from the industry and attended Danish cattle and agricultural seminars and conferences. These different fieldwork activities added to my understanding of what it entails to run a dairy farm in the Danish landscapes today, what it means to be a cow – and a farmer – in different contexts, what interests and aspects of ecosystem functioning are important to whom, and how these collide and synergise with mainstream and alternative animal agriculture in Denmark.

3.3 Iterative research process

Working with change and development of complex systems demands a shift in perspectives, adapting linear and mechanistic ways of thinking (which is dominating the field of animal science research), where assumptions and study designs may rule out discovering important aspects of the problem of interest, to more non-linear and organic ones, allowing for understanding of otherwise not observed relations to emerge from a field of study during deep and longitudinal investigation (typical for ethnography) (Hjorth and Bagheri, 2006). Thus, it calls for both an understanding of the complexity and 'wickedness' of the system of study and incorporation of complexity into project processes (Sellberg et al., 2021), making the project process flexible and iterative, allowing for learning experiences, keeping porous boundaries between the field of study (dairy production) and potential connection to other domains. Further, having an adaptive and iterative research process has been suggested important for the success of One Health and transdisciplinary initiatives, including research projects (Rüegg et al., 2018). It is a way to recognise that when working with projects on complex and dynamic systems, one cannot know beforehand what will emerge as key analytical focal points.
In practice, this meant that the study of alternative dairy farming in this PhD project was guided by the overarching and broad premise of 'green transition' and the previously described understanding of absolute sustainability. As such, the intention was that the observations and conversations about green transition and dairy production during initial fieldwork should co-determine the direction and

scientific content. The direction and later in-depth studies were therefore defined and constructed from the encounters between me as an animal science researcher and the field of alternative dairy farming. This contrasted my previous more deductive animal science research experiences, where the experimental setups were predefined, and the direction, design, and required data were specified based on gaps identified in existing scientific literature. When operating with close-ended aims of hypothesis testing through such setups using statistical analyses, many farms and/or iterations of data collection is required. Predefining data collection is therefore also a practical requirement in such quantitative research, as it takes time to obtain the large number of data needed. Thus, the iterative approach involved a necessary loss of control over the scientific outcomes and also limited the scope of quantitative activities due to practical time constraints.

Three project phases, or rather *research modes*, can be defined as essential parts of the research approach; an explorative, an analysing, and a reflection mode, as outlined in Table 3.1.

Table 3.1. Description of the three research modes followed throughout the PhD work. The research moved through these three modes repeatedly, successively getting deeper into the understanding of the field of study.

Research mode	Description
1	The explorative mode is characterised by a relatively open approach to fieldwork. This includes farm visits where both formal/structured and informal conversations and observations simultaneously guided the research interests and part of data collection. These insights were continuously discussed with researchers and experts across scientific disciplines in the field. This mode allows space for newness and the emergence of themes that reach beyond existing ideas, diminish sharp distinctions between both scientific areas and farm system boundaries, and potentially challenge preconceived expectations.
2	The analysing mode encompasses an engagement in deep analysis of a few chosen themes. This involves working with data materials from field activities, as well as performing further targeted fieldwork and data collection on the chosen themes, employing methods according to the type of data, which best enable answering the sought questions, and new questions that emerged.
3	The reflection mode includes the presentation and discussion of preliminary findings (from fieldwork and analyses) in different settings (with farmers, academic researchers, students and other relevant stakeholders), for validation of interpretations and generalisations, further qualification, and deepening of the analysis based on responses of the presented findings as well as findings in literature.

The movements through these three modes were not linear, but more like spiralling movements, getting progressively deeper into the field and materials, with new quantitative and qualitative questions generating data that feed additional information and insights to the work. These movements between the modes, conceptualised in Figure 3.1, continued throughout the entire study period (beginning in 2021). While the figure communicates the research processes and dynamics well, it portrays a more orderly version than the actual tangled and intertwined real-life process.

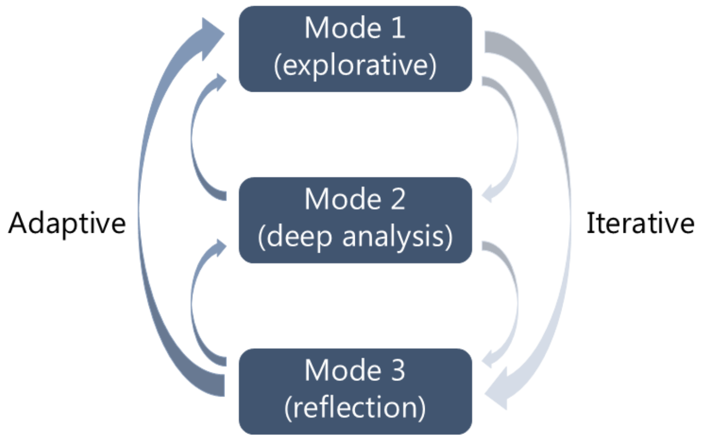


Figure 3.1. The figure shows a stylised picture of the dynamic movements between the three defined research modes, illustrated by iterative progressions and adaptive feedback loops, allowing for learning experiences and adjustments.

Central to the project was the collaboration with a few case farms, which constituted the primary fieldwork sites. The selection and role of these farms will be discussed in the following section.

3.4 Case farm selection

The initial idea in the overall Cattle Crossroads project was to find cases that represented dairy productions, as they yield both milk and meat, using marginal soils – land not suitable for cultivation. However, such criteria were mostly suited to robust beef cattle, and it proved difficult to find dairy cow productions in Denmark that met them. Thus, inspired by the dramatic overshooting of several planetary boundaries – such as the functional and genetic integrity of the biosphere, as well as fertiliser use as depicted by the PBF – the selection criteria evolved to also include practices that support landscape and soil health and reduce feed-food competition through grass-feeding and minimal use of concentrate.

Before the onset of the study, we discussed within the research team the number of farms to be included. The tradition with long-term fieldwork in anthropology argued to focus on one or two case farm(s), to allow for deep insights into daily routines and unforeseen events to increase the different heterogenous practises and character – both verbalised and non-verbalised knowledge production generated at farm level. This was for example done by food system scholar Caitlin Morgan (2025), who through ethnographic research on a single farm, studied the possibilities of

embracing holistic sustainability in one farm. On the other hand, the veterinary and animal science tradition is concerned with the limited coverage of the types of 'alternative dairy farms' such a case study could produce, as it would not be representative for all the different ways of practicing alternatively. Four case farms were identified as collaborators before the project initiation, including dairy productions characterised by low-input approaches, grass-based feeding, regenerative thinking, and a large organic production experimenting with agroforestry.
Upon enrolment in the PhD project, it was agreed to try to reach 4-10 farms aiming to including more farms through the snowball method, where one farmer or farm advisor points to other potential participants fitting the enrolment criteria, and thereby reach a higher level of saturation in the information gained from different types of alternative dairy farming.
As the project progressed and themes emerged through the initial explorative and preliminary analytical modes, the project evolved around a few themes which repeated themselves. Two of the initial case farms ended up being the main farms of investigation. Additional both alternative and intensive farms were encountered and visited throughout the project and served as valuable reference farms to widen the field. Two of these additional farms were included for a deeper land-use analysis alongside the two main case-farms used in Manuscript I, and all formed valuable insights for writing Manuscript III.

As such, I ended up with a combined set of materials, by having two main case farms for deeper study, and visiting in total 19 other cattle-keeping farms (or locations) at least once during the project process. Of the reference farms, six were other 'alternative' dairy farms, eight were more typical dairy farms within a Danish context (five organic and three conventional), two were beef producers (either with beef or dairy/beef genetics), two were vegetable or bread grain producers depending on cattle for recycling nutrients to soils and crops, and finally one was a rewilding project with a cattle breed ideal for nature conservation.

3.5 Methodological entry points

Fieldwork has, together with a wide engagement across scientific disciplines and referencing a wide pallet of scientific literature along the way, formed the core elements of the approach adapted during this PhD work with ongoing activities throughout the entire project period, as described in section 3.3. The use of case farms is a common practise within animal science, although fieldwork in that context is usually called 'data collection', reflecting the more deductive research designs.

In this section, I will go through the different methodologies I have engaged with in the fieldwork, including the use of qualitative research methods and data and how they were interacted with quantitative measures.

3.5.1 Qualitative research

Qualitative methods such as observations, informal and semi-structured interviews have formed a cornerstone in the exploration of the case farms and contributed to all three manuscripts presented in the following chapters. Contrary to most quantitative research, qualitative research often includes explicit statements about and discussions of research paradigms, recognising that a broad spectrum of perspectives can shape both data generation and analysis (Ritter et al., 2023). In other words, what the qualitative data is taken to mean depends on the specific analytical interest. Traditional animal science in which I was trained, to the contrary, usually builds on assumptions of independent research, objectivity and distance between researcher and the research subject/field, and works from more singular interpretations of data.

As part of the overall Cattle Crossroads project, I wanted to draw on insights from other disciplines, while firmly situating my research within animal science. Put differently, I needed to draw on inspirations that are not usually part of the animal science tool kit. Accordingly, this PhD has been influenced by ideas found in social science literature on pasture-based and regenerative dairy farming and multispecies ethnography. For example research on grazing and pastures in relation to questions of sustainability in the UK and Ireland, has unfolded values, perspectives and discourses around the practice of grazing or not grazing through interviews with farmers and other dairy stakeholders, relevant for engaging in the socio-ecological dynamics of farming (Shortall, 2024, 2019, 2022). Shortall used different theoretical frameworks ranging from sociotechnical imaginaries (Jasanoff and Kim, 2015), the good farmer concept (Burton et al., 2020) and relational approach (Darnhofer, 2020), employing thematic analysis and iterative inductive, deductive analytical processes. Further, research on regenerative farming, which often involves cattle, describes how the practices and mindset characteristic of farms and farmers in the regenerative movement operate with specific attention to soil health, multispecies care, and spatial imaginaries related to fields, ruminant feeding, and living soils, thus describing the rationales, circumstances, and attentions in place when questions of planetary health are foregrounded by farmers (Cusworth et al., 2024; Kallio and LaFleur, 2023; Seymour and Connelly, 2023). These studies employ the analytical frameworks of more-than-human ethics of care (see also Krzywoszynska, 2019; Puig de la Bellacasa, 2015), relational approach and the concept of (un) knowing landscapes (see Ingold, 2012), as well as a combination of the concept of the patchy Anthropocene (Tsing et al., 2019) and the attention to space and scale in human geography. In many ways – but most true for the lenses with emphasis on relations – these frameworks are similar to the ethnographic literature which, as a product of the close collaboration within the research group, has been especially important and influential of this PhD work. Particularly the text on *situated knowledge* by philosopher of science Donna Haraway (Haraway, 1988) was central and will be further addressed later in this chapter.

However, other ideas and texts such as *"The Actor-Enacted: The Cumbrian Sheep in 2001"* where Law and Mol (2008) showed how the ways we think about and relate to an animal (how it is enacted) affects the actions it evokes (its agency), in this case the Cumbrian Sheep during the foot-and-mouth disease epidemic in the UK in 2001. Other areas of thinking, too, including ideas of non-scalability (Tsing, 2012), liveability and multispecies landscapes (Tsing, 2017) and how the concept of the holobiont (Gilbert and Tauber, 2016) and multispecies co-development brought up views that were never addressed in my training as an animal scientist at UCPH. For that matter, reflexivity about the paradigms or narratives residing underneath the ways of optimising separate units of specific animal systems was not a subject of discussion.

A shared element of the inspirational texts and ideas I listed in the above was the strong focus on relations. Without unfolding these ideas in detail, for now at least, they all come together in nurturing a focus on webs of relations and their intertwined dynamics – instead of parcelling out entities ignoring their relations that make them appear as such. Further, they put emphasis on the consequences of foregrounding some relations and qualities, while backgrounding or even ignoring others – sometimes out of habit or ignorance and at other times rooted in interests (often presented as neutral). A focus on such foregrounding and backgrounding shows how research questions always come with specific valuations, drivers and perspectives (Brichet and Hastrup, 2011; Mol and Mesman, 1996). Perhaps more than anything, what this PhD project gained from exposing the discipline of animal science to social science literature on livestock, grazing, care, multispecies insights and ideas from science and technology studies (Brown and Webster, 2004) is a fundamental relational thinking and situated analysis, thereby opening up new ways of conducting animal science research that situates itself actively in the major challenge of ensuring enough food within the limits of the ecological capacities.

Accordingly, the intention with this thesis was not to do an ethnographic or social scientific study, but rather to cross-fertilise my animal science research with the dynamics, relational approaches and depth of ethnographic method and theories. The qualitative approaches along with the relational thinking spurred by the texts and concepts mentioned above thus "comment" on and enhance the analytical expertise in the study of outcomes and optimisation of livestock productions that is characteristic for animal science. Similarly, a recent study suggested that engaging with ethnography in mixed-methods research can *"function as a theoretical catalyst, re-configuring the underlying assumptions of quantitative tools and reshaping the conceptual frameworks applied"* (Lowis, 2025, p. 11).

What that looked like in this PhD will be outlined in the following two sections.

3.5.2 Situated analysis

The introduction to the idea of situated (and embodied) knowledge and in the same breath, the critique of the idea of objective, untouched data as a representation of the real world that Haraway provided through terms and wordings such as "*disembodied scientific objectivity*" and "*to be from everywhere and so nowhere",* led me to explore what embodied knowledge would look like in animal science. In other words, how to do animal science research through a different research paradigm.

The literature research prompted by the initial fieldwork led me in the direction of research estimating land-use efficiency of dairy production based on different metrics, however all were based on modelled farms or farm data disconnected from the perspectives of land, animals and people (Hennessy et al., 2021; Ineichen et al., 2023; van Zanten et al., 2016). I explored and developed a situated approach to these forms of data analysis by combining the quantitative estimations with the contextual data of the places and situations where they originated, including the specificities of the farms investigated, the nuances of the local landscape, the farmers' background, ways of thinking, and approaches to dairy farming.

The inclusion of land specificities has previously been suggested by the Canadian agronomist H. Henry Janzen, as an important method for qualifying the opportunities of green transition of cattle production, advocating for what he termed 'place-based research' in his review *"What place for livestock on a re-greening earth?"* (Janzen, 2011). However, a situated analysis of land-use found in the following chapter not only interweave insights from quantitative and qualitative estimations but also interrogates its own knowledge production by paying attention to the elements foregrounded (and backgrounded) by farmers, consultants, researchers and other involved parties, making the analysis more than a product of a 'data-extraction', but a product of combined efforts and perspectives. As such becoming, in the words of Haraway, "*...the joining of partial views and halting voices into a collective subject position that promises a vision of the means of ongoing finite embodiment, of living within limits and contradictions – of views from somewhere.*"

First and foremost, I understand the situated analysis to mean a form of reflexive analysis that is both informed by and questioned through specific contexts. It serves as a method for exploring how certain outcomes may be evaluated differently, depending on the perspective, and for considering alternative ways of thinking dairy cows within the landscape and food system

3.5.3 Body condition scoring

The initial exploration of alternative dairy production, revealed to primarily encircle an attempt to base the dairy production on grazing and grass-feeding (to different degrees). However, we encountered expressions of doubt if typical high prolific dairy breeds, developed to fit another type of feeding and production scheme, really could thrive under low-input conditions. The concern (and experience in relation to the Holstein breed) was that these cows would lose excessive amounts of body fat due to the large 'pull' for high milk yields coded by the genetic material.

The body condition score (BCS) of a cow provides a rough measure of the amount of body fat (energy reserve) the cow possesses. It is influenced by a number of factors, both internal (e.g. genotype, parity, age, health) and external (e.g. stocking rate, feed composition, feed level) (Roche et al., 2009). As such, the BCS provides a good measure for the overall compatibility between the animal and the environment (system design and management). The method adopted was a 5-point BCS scale from 1 to 5 with 0.25 increments (1 = emaciated, 5 = severely over-conditioned), where scoring entailed inspection of specific body locations at the individual animal, primarily around the pelvic and tail head area, following procedures described by Edmonson et al. (1989).

I performed a longitudinal study of cow BCS at the two main case farms, aiming to incorporating an animal-based measure to the research on the inner workings, potentials and challenges of pasture-based and low concentrate input production types. In a review on BCS in dairy cows by Roche et al. (2009) presented a figure of the optimal BCS profile range across a lactation, which would *"…allow cows to produce near maximum milk production for their genetics and production systems, while ensuring reproduction, health and animal welfare are not compromised"*. This range went from BCS of 2.5-3.25, depending on lactation stage, on a 5-point scale. In Manuscript II, I used this range to discuss the BCS findings from the two included case farms, however situated within qualitative empirical data on cow and pasture management practises, and biodiversity potentials. As such, this methodological integration enabled a thick description of both outcomes and dynamic relations between cows, pastures, and farmers.

3.6 Data and data analysis

While the PBF and ideas of safe and just transition formed an overall direction of the analyses of the empirical data, the analyses were not limited to any one defined analytical method but can instead be characterised as 'iterative analysis'. Fieldnotes written before, during and after fieldwork, constituted a large part of the data material generated in this project. Six rich semi-structured interviews (varying from 20 min to 2.5 h) were recorded and transcribed allowing me to later consider – both my own and the farmers' – pauses, intonations and wordings to describe various situations. This also proved valuable to qualify and direct the quantitative parts of my research. Other data sources included production and land-use data and the longitudinal body condition scorings.

Contrary to quantitative, experimental research where data collection and data analysis typically fall into two distinct phases, working with qualitative data, the analysis part was more fluid – as

was also indicated in iterative research process in Figure 3.1. More specifically, the analysis started already in the field, through the observations and conversation parts I chose to writing down (i.e. already subjected to an analytical choice) and only ended, formally at least, when the last punctuation in the writing was done (Hammersley and Atkinson, 2019). The large body of analytical work in between these events was in this PhD characterised by moving between the field of study, the heterogenous empirical data, and literature, using writing and discussions of data and findings, as part of the analysis.
In Manuscript III, we actively used the framework from economist Kate Raworth book 'Doughnut Economics – seven ways to think like a 21st century economist' (Raworth, 2017) and her suggestions on how to rewire economic thinking – as described in section 2.3. – to critique and suggest changes in the epistemological foundation for livestock agronomy and animal science.

When analyses involve qualitative data, the line of thoughts, reasonings, and arguments for methods, interpretation, and analysis serves to establish the reliability of the research. Even though doing fieldwork on very few sites meets critique in my field, for not being representative, the thorough and continuous study of a site comes with other advantages. I can revisit the same field and informants many times over an extended period of time (in this case 2-3 years) with different purposes and in different forms, which increases the likelihood of a deeper (and broader) understanding of the specific case, as the information gained will become increasingly predicable and bring fewer surprises. This will in the end make a stronger argument for interpretations (Lund, 2014). However, the needed number and characteristics of the case farms are closely linked to the purposes behind the conducted research. An exploration of alternative practices and methods of evaluation methods such as was the aim of this PhD, does not need the same number of replicants compared to a research project aiming to describe a population or test a specific intervention within a certain population – say dairy farms in Denmark.

3.7 Ethics

The qualitative methods used in the exploration of the farmers' knowledge and practices involved handling of personal information. It was therefore important to ensure correct handling and storage of the data. The recommended procedures of systematic anonymisation of the data was undesirable, as the data was to a larger degree co-created and nuanced through the conversations with the farmers. Thus, the actual people (the researcher and the farmers) were relevant for the data created. However, to comply with the guidelines for responsible conduct of research (Jensen et al., 2020), an agreement for all data to be anonymised in any publication of data – if nothing else was agreed upon – was made with the participating farmers, although none expressed a wish for such measures. Furthermore, all personal information was handled with confidence and respect, complying with the European Commission's guide on Research Ethics in Anthropology (Iphofen, 2021). Participation in the project was not considered to put any informants at risk.

All data (field notes, pictures and other farm documents) were digitalised and stored on the personal drive on the university's network. This ensured safe storage of personal information and prevented loss of data.

The Cattle Crossroad research project was, with Professor Frida Hastrup as Principal Investigator, hosted at the Saxo Institute and was approved by The Research Ethics Committee at the Faculty of Humanities and the Faculty of Law, University of Copenhagen. The Research Ethics Committee at the Faculty of Health and Medical Sciences found that approval sufficient and did not find it necessary to proceed with other ethical approvals.

4 Manuscript I: Situated analysis of food supply, land-use dynamics, and feed-food competition at organic farms with dairy cattle

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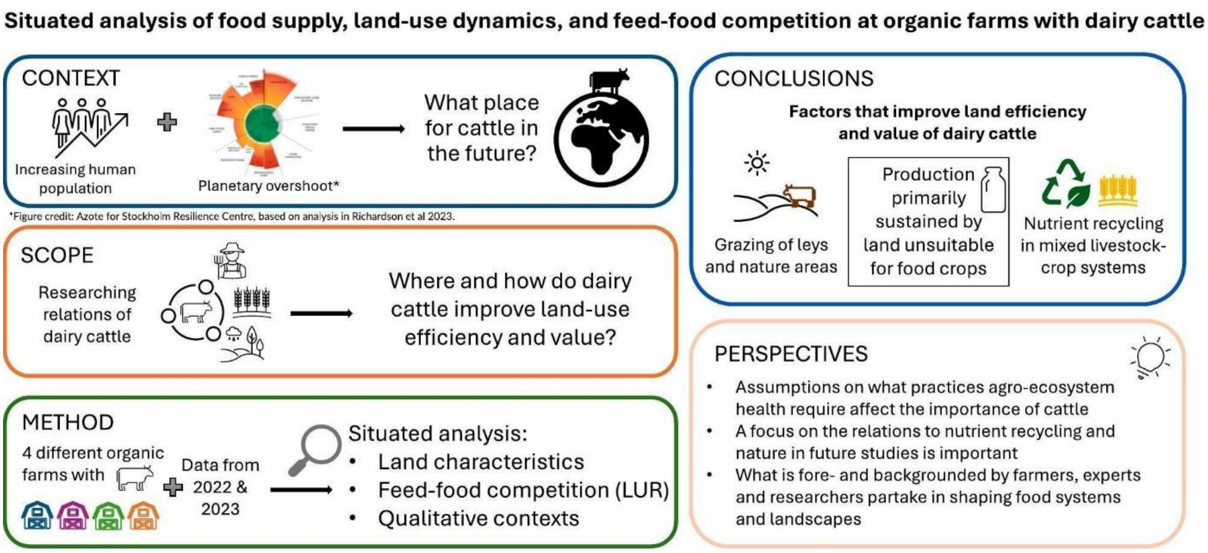
Highlights

- New perspectives on land-use efficiency of organic dairy cattle farming needed.
- Situated analysis of land-use and food outputs from organic farms with dairy cattle.
- Linking quantitative land-use estimates to qualitative contextual farm data.
- Feeding cattle from land unsuitable for cultivation has highest land-use efficiency.
- Dairy cows' role in land-use efficiency depends on agro-ecosystem health assumptions.

Graphical abstract



Abstract

Context

The increasing competition for land calls for new perspectives on land-use efficiency. Prioritisation must be discussed, as scientists and policymakers focus on food security with reduced environmental harm. Some farms with dairy cattle may not be resource-inefficient when compared to plant-based production, as generally believed, if the farm purpose and type(s) of land used are considered.

Objective

This study aims to provide nuanced and often ignored perspectives on agricultural land-use efficiency and the ways this is assessed, through situated analysis of organic farms with dairy cattle. It considers landscape characteristics, farm designs, land uses, food outputs, weather conditions, and farmer considerations and motivations, to produce context-dependent land-use insights.

Methods

Using detailed data from four organic case-farms, we quantified the total land use and food output at the farm gate and estimated the land-based feed-food competition through a land-use ratio (LUR). The LUR was used to compare current animal-based or mixed production outputs to potential plant-based food outputs from the same area, while maintaining an organic perspective. The quantitative results were qualified by insights from farmers and observations from multiple farm visits. The characteristics of the analysed farms were A) dairy production on marginal soils, B) regenerative grass-based dairy production, C) feed-no-food mixed livestock-crop system, and D) high-yielding dairy farm with crop production.

Results and Conclusions

The results showed how a feed-no-food mixed livestock-crop production (C) or dairy production primarily supported by land unsuited for food crop cultivation (A) can be as or more land-use efficient and have lower feed-food competition than a high yielding dairy production (D). The conclusions on efficiency were strongly influenced by the measuring unit, underlying assumptions on what constitutes a healthy agro-ecosystem as well as the fluctuations between years. Most important for the conclusion was the characteristics of the used land, the share of land use assessed suitable for cultivation, and the assumed yields for the estimated alternative pure plant-sourced food productions. Through the situated and mixed method perspectives, we furthermore showed how other relations such as flows of nutrients, nature-care, landscape development and farmers' considerations are relevant.

Significance

Combining quantitative estimations with qualitative knowledge about farmers and their landscapes bring relations that are often ignored from similar studies into the analyses and provides a nuanced basis for discussion of the relevance of dairy cattle in future food production systems.

Keywords
Organic dairy production; Land use; Food systems; Production efficiency;Food security; Feed-food competition;

4.1 Introduction

"*As we face the twin challenges of feeding a growing world while charting a more environmentally sustainable path, the amount of land (and other resources) devoted to animal-based agriculture merits critical evaluation*."

This call for a critical evaluation of the scale of global livestock production by Foley et al. (2011) in the paper "Solutions for a cultivated planet" is still urgent and part of the motivation for this article. It is well-established knowledge that ruminants have an ability to produce nutrient dense foodstuff (milk and meat) from feed that is not edible to humans, i.e. grasses and crop residues. Several studies have emphasised this ability and suggested an efficiency measurement that considers the net food contribution of livestock systems, measuring the achieved food output in relation to the human edible fraction of the feed input; called 'the human edible feed conversion ratio' (heFCR) (Ertl et al., 2015; Laisse et al., 2018; Mottet et al., 2017; Wilkinson, 2011). This way of viewing production efficiency contrasts with the focus on optimising yields per animal and reducing total inputs per yield gain in the animals. The narrow focus on yield has dominated the intensive livestock production for over a century, and is the result of enormous efforts by farmers, cattle, industry and researchers working to improve animal productivity and feed-efficiency (Bach et al., 2020; Brito et al., 2021; Schingoethe, 2017). This, in turn, backgrounds feed-food competition, land use and biogeochemical flows. The critical evaluation called for by Foley et al. (2011) foreground a concern with ensuring sufficient food supply for a growing human population, thus emphasising the need to evaluate the efficiency of livestock systems in a way that considers the degree of feed-food competition.

However, the heFCR does not consider that feed inedible for humans can be grown on land suitable for food crop production, and thereby still contribute to feed-food competition. To consider differences in the suitability of land to be cultivated for food crops, another group of researchers introduced a land-use ratio (LUR) evaluation method (van Zanten et al., 2016). This ratio compares the nutritional output from an animal production, with what a food crop production could have yielded from that same area. It reveals whether there is a food provision opportunity cost to the animal production. A LUR < 1 means that the animal production contributes with more human edible nutrients than a food crop production could have yielded. Based on modelled dairy systems, van Zanten et al. (2016) estimated LUR on Dutch systems relying on peat soils and showed results in favour of dairy – at least when it came to protein output. Another dairy model study, carried out in Ireland, found similar results (Hennessy et al., 2021). Together, these findings appear promising for dairy production as a valuable production form for protein supply when primarily kept on non-arable land.

Yet, a study of 25 Swiss dairy farms, ranging from mountainous to lowland farms, found that only 2 (8%) of the farms had a LUR for protein below 1 (Ineichen et al., 2023). Furthermore, they found great variability at farm level meriting a closer look into the characteristics of productions at specific farms; a point that we will come back to.

Interestingly, none of the mentioned studies estimating LUR paid attention to rotations including leys. Yet, since they do not use artificial fertilizers and pesticides, many organic farmers depend on leys as part of their crop rotation, as clover-grass leys will provide both nitrogen for the consecutive crops and reduce perennial weeds and crop rotation diseases (Kremen and Miles, 2012; Watson et al., 2011). The omission of leys from existing studies on land-use efficiency is unfortunate, and we find them important to consider in an analysis of different agricultural systems and how they perform feed-food balances most efficiently according to an increasing demand for food on a limited planet – not least in view of the latest updates of the assessment of the planetary boundaries (Richardson et al., 2023). Beyond doubt, the boundaries for biogeochemical flows (nitrogen and phosphorous nutrients) and novel entities (the use and emission of synthetic chemicals and substances, e.g. pesticides) are transgressed on a global scale, suggesting that drastic reductions are needed.

Indeed, reducing biogeochemical flows and residues of pesticides into the ground water is a serious challenge in a low-lying country such as Denmark where 58.9% of the land was under cultivation in 2021, only exceeded by Bangladesh with 62.3% land under cultivation (The World Bank Group, 2024). This large-scale cultivation of the land mass has negatively impacted land and water environments due to nutrient and chemical leaching (Baumane et al., 2021; GEUS, n.d.; Ministry of Environment, 2023; Voutchkova et al., 2021).

A political strategy to meet the necessary reduction goals and bring the nation into safe operating space on the two transgressed boundaries, is to increase the organic production. We have therefore chosen to investigate organic dairy production relying on agro-ecological approaches to fertiliser use and weed and disease control, rather than chemical inputs.

The farm level variability found by the field study of Ineichen et al. (2023) has been inspirational for our study by challenging the previous LUR studies that have used data from model dairy farms. We take up the challenge of field-based and farm-specific studies in a rather radical way – namely by focussing on four different farms. Not so much as scalable model farms, but as concrete and inspirational sites that show the many choices, settings and conditions involved in dairy farming and efficient land use. We have welcomed the qualitative differences between the four farms as part of our analysis, incorporating insights and practices that might be well-known to many, but for numerous reasons often are forgotten or ignored by researchers. By foregrounding some of these different practices in different farm settings, our ambition is to find ways that may – ultimately – point us towards other kinds of solutions for future sustainable food productions with dairy cattle.

We call this field-based and field-generated method a “situated analysis”, inspired by philosopher of science Donna Haraway (Haraway, 1988). This implies an analysis that takes place at a specific site and at a particular time, in this case four different organic farms with dairy cattle. Their specificities will be considered in the analysis of the material, with the aim to investigate their total food contribution, feeding system, and land-use practices, and finally to compare how their internal differences reflect on land-use efficiency. The objective of this study is therefore twofold: first, to perform a situated land-use analysis at four organic farms with dairy cattle, including estimating total land use, food production and adapting and qualifying the LUR-method with a system-oriented perspective. Second, to discuss these quantitative estimates in light of a qualitative understanding of the farms and their internal differences. On this basis, we explore how our methods to assess land use and feed-food competition affect our conclusions, and thereby our choices to create future food production systems that enable us to stay within the planetary boundaries.

4.2 Material and methods

Based on an interdisciplinary research project on dairy production and opportunities for green transition, merging animal and veterinary sciences with anthropology, four organic dairy cattle farms in Denmark were selected as case-farms for further land-use and food-output analysis. They represented different combinations of local landscape context, soil quality, production design, history, farmer experience and use of consultancy services. The farms were therefore selected for their differences and not for being representative for the Danish dairy production population. These differences are described in section 4.2.2.

4.2.1 Data collection

This was a mixed-method study using both qualitative and quantitative data. Observations in the field together with semi-structured interviews and informal conversations with the farmers were made on several occasions over two years. This way we not only obtained a deeper understanding of life on the farm, but also had the opportunity to qualify and discuss both the quantitative and qualitative information obtained in the field. The qualitative data were processed as transcriptions of the recorded interviews and personal field notes from the informal conversations. For production data, a “cradle to farm-gate” system boundary was chosen. Data were obtained from 2022 and 2023 with the help from the farmers and their farming consultancy companies.

The two years provide a basis for insights in the fluctuations of farming performance as for example the weather conditions in Denmark differed substantially. During 2022 and 2023 the annual national precipitation was 694 and 977 mm, respectively. Where the growing season of 2022 showed favourable growing conditions, 2023 was characterised by drought in May and June, followed by a historically wet July and a wet and overcast harvest season (DMI, 2024).

4.2.2 Farm descriptions

In natural and agricultural sciences, humans are often reduced to informants providing raw data to be used by the researcher for later calculations and models. However, ‘raw data’ and the farmers who provide it are embedded in concrete and complex contexts where the interests and questions that we as researchers come with foreground and background particular things. Therefore, discussions with the farmers of our main concern for a sustainable dairy production that considers feed-food competition and reduces biogeochemical and chemical flows were highly rewarding. Not least because our talks have directed our attention towards relations between land use, food-feed competition, dairy cows, farm management and systems health all at once. Through this comprehensive field-generated and qualitative approach, where relations that are often ignored in other studies of similar issues were foregrounded, we were able to make a more nuanced and thorough analysis of the quantitative data obtained. The technical production characteristics of the farms are outlined in Table 4.1. Table 4.2 shows the direct land use managed by the farmers themselves, and Appendix 4A, Table 4A.1, provides a rough outline of the imported biomass at the farms. A more in-depth description of the four farms and farmers follows here.

4.2.2.1 Farm A

With approximately 40 cows, this was considered a small-scale dairy farm compared to Danish standards (average 246 cows per farm (LF Oksekød, 2023)). Located in a hilly landscape with sandy soils and fields framed by fences, forest, or shrubbery. In 1990, after graduating from an agricultural school the farmer bought the farm that has approximately kept the same size throughout the more than 30 years of production, with around 50–55 cows, and a small herd of sheep. The cows were downscaled to around 40 during the study years. While the farmer first attempted to continue the cultivation of the fields in the early 1990's, he quickly stopped due to too low yields and left the fields to be permanent pastures that developed over time with no reseeding done by the farmer.

Table 4.1 Production characteristics for the years 2022 and 2023 from the four Danish organic dairy farms used as study cases.

	Farm A		Farm B		Farm C		Farm D	
Item	2022	2023	2022	2023	2022	2023	2022	2023
Dairy breed(s)	RDM, Jersey, few mixed breeds		Mixed breeds, RDM and Jerseys		Crossbred (Holstein X RDM x Jersey)		Holstein	
Dairy cows / year (heads)	41.4	39.1	30.1	40.7	131.3	124.6	223.0	218.0
Heifers / year (heads)	20.9	18.1	25.4	34.8	179.4	186.9	171.3	175.4
Steers / year (heads)	0	0	0	0.4	107.1	76.4	0	0
Bulls / year (heads)	1	1.1	4.9	4.5	13.3	14.8	7.1	4.5
Sheep / year (heads)	10	10	-	-	-	-	-	-
Lambs / year (heads)	16	14	-	-	-	-	-	-
Milk sold / cow / year (kg ECM)[1]	4 831	5 525	4 717	4 651	4 805	4 718	11 057	11 228
Food output								
Milk sold (kg whole milk / year)	184 095	206 086	129 265	159 525	558 733	523 502	2 410 079	2 339 455
Protein content (%)	3.66	3.56	3.61	3.93	3.74	3.72	3.47	3.55
Fat content (%)	4.55	4.3	4.68	5.2	4.85	4.81	4.15	4.29
Meat sold (kg / year)								
Beef	2 354	2 988	3 831	4 311	29 912	26 789	23 669	25 011
Lamb meat	161	141	-	-	-	-	-	-
Crops sold (kg / year)								
Wheat	-	-	-	-	60 402	16 220	143 666	24 980
Barley	-	-	-	-	73 203	61 560	-	-
Rye	-	-	-	-	132 878	150 800	-	-
Oat	-	-	-	-	38 400	-	-	-
Field peas, yellow	-	-	-	-	32 256	57 344	-	-
Potatoes, white	-	-	-	-	720 554	777 015	-	-
Rapeseeds	-	-	-	-	-	-	58 500	35 000
Broad beans	-	-	-	-	-	-	45 176	-
Lupins	-	-	-	-	-	-	19 755	-
Other outputs								
Wood chips for energy (GJ)	-	-	-	-	2120	-	-	-
Ryegrass seeds (kg)	-	-	-	-	9 936	-	-	-
Straw (kg)	-	-	-	-	-	-	256 000	-

Abbreviations: RDM = Red Danish Dairy breed; ECM = Energy corrected milk,

[1] Energy corrected milk calculated from kg wholemilk, fat and protein content accordance to formula B described in Sjaunja et al. (1990).

Table 4.2 Characteristics of the direct land use at the included farms in 2022 and 2023. In 2023 new EU requirements of fallow land were implemented, requiring 4% of the arable land to be fallow (non-productive areas).

	Farm A		Farm B		Farm C		Farm D	
Item	2022	2023	2022	2023	2022	2023	2022	2023
Total direct land use (ha)	46.83	46.83	57.18	57.18	354.13	375.59	423.53	423.53
Cultivated land (ha)	0	0	10.08	0	145.89	151.33	177.37	166.57
Ley (ha)	6.56	0	27.36	35.94	119.48	114.55	187.97	185.70
Fallowland (ha)	0	0	0	1.5	0	20.9	0	14.16
Permanent grass[1] (ha)	40.27	46.83	19.74	19.74	88.76	88.81	58.19	57.10
Forest etc.[2] (ha)	0	0	0	0	21.37	11.63	0	0
Area allocated to exported byproducts (ha)	0	0	0	0	0	0	11.69	4.24
Area of permanent grass with nature protection or nature-like appearance[3] (ha)	11.5	11.5	3.9	3.9	49.5	60.2	28.3	28.2
Soil type(s)[4]	Sandy soils of varying characteristics		Fine sandy clay + organic soils		Sandy soils of varying characteristics + organic soils		Fine sandy clay, fine clayey sand + organic soils	

[1] More than 5.5 years since tilling. This number includes small areas of 'nature areas' such as small clusters of trees or bushes.

[2] Note that this area is not included in the 'Total direct land use', as the area was not directly contributing to the food output.

[3] Based on expert observations or either the area of fields with §3 nature protection at the map 'Paragraf 3 i IMK with updated data from 2023' (Danish Agricultural Agency, n.d.) (Farm A and B) or the area of fields that received subsidies though the 'Environmentally friendly farm measures'-schemes (MVJ-ordninger) (Farm C and D).

[4] Soil types are based on a triangulation of the soil map from the Danish Agricultural Agency from 2019 (Danish Agricultural Agency, n.d.), the surface geology map from Denmark's Geology Portal (GEUS, 2023), and personal communication with the farmers and at farm observations.

Some of the fields had during this time been assigned with nature protection, §3, under the Danish Nature Conservation Act, which means that they due to considerable nature value could not be changed from their meadow-like state and or fertilised. In general, the farmer was very attentive to how his cattle created a landscape that was also welcoming for insects and told us that a biologist a few years earlier had said that the nature development on his land was impressive despite the dairy production. To this the farmer had replied, "*it is not despite, it is because of my production*". To him this dialogue exemplified the usual dichotomies between nature and agriculture – which in his eyes was a balancing act and more than anything a matter of having too many animals on limited land.

Another example of his attentiveness to multispecies life can be illustrated with a piece of land that he manged during the study period, which had previously been covered by a 'Christmas tree plantation'. When the farmer started leasing the area in 2006, the trees were cut down, the fields were thoroughly tilled, and barley with an undersown pasture-grass mix were grown in 2007. Under the management of the farmer and animals, these areas transformed into a dry-meadow-like state. Seventeen years after the deforestation, two biologists, invited by the authors of this paper to assess the farm's biodiversity value, declared that the habitat had developed significant value and ought to be protected.

In contrast to the early days of his production, the farmer no longer optimised the feeding as known from Danish best practice recommendations, balancing according to norms for energy, protein, and other chemical components of the feed. Not striving for top milk yields, he was content with a relatively low yield around 5000 kg energy corrected milk (ECM) per cow per year and pointed to a study that showed that feed efficiency is higher at lower feed intake levels. For reference, updates at the time of writing showed that the average Danish national milk yields were 11,310 kg ECM per cow per year across all types of dairy productions (Viking, n.d.).

The feeding during the study years was based on wrap silage, pasture-grazing, and a concentrate mix for the lactating cows. The farmer found that it made sense to feed the cows with what humans cannot eat but recognised that he had to supplement lactating cows with some concentrate, because he did not have enough fresh pasture to sustain the number of cows he had. "*If I was paid twice as much for the milk, then I could halve the stock, and then it might be possible to feed 100% grass-based*" he once said. During the study years he also bought clover-grass and alfalfa wrap silage from local farmers through the machinery station.

All calves were born from March to July and were fed and cared for by nursing-cows until sold around the age of 1 month to a local nature-based calf-rearing farmer. When calves were sold, one or two of the nursing-cows were usually sold to go with them. The replacement heifers were weaned at 3–5-month of age. All animals, besides the calves, had access to pasture every day all year round, although only in rotation during the grass growth period, April to November.

The farmer gave the deep litter bedding from the barn to a local organic vegetable producer, thereby creating connections to local, organic vegetable supply, who treasured the fertility-building quality of the cow manure.

4.2.2.2 Farm B

Similar in herd size, Farm B was located in a slightly sloping landscape with sandy clay soils. This production was young and run by a young farmer in his early thirties. With his partner, a dairy technology specialist, he started the dairy production and an accompanying small scale farm dairy in 2019 where they processed all the produced milk. Inspired by voices such as Allan Savory on YouTube and farmers he had visited and worked with in Norway and Sweden, the farmer embarked on the idea and desire to create a dairy production taking radical responsibility to land, soils and animals, while producing healthy and high-quality dairy food products.

This entailed using cattle to regenerate soils through holistically managed grazing of permanent and diverse grasslands, thereby creating a positive impact of the grazing and trampling of the cattle. The method was a rotational grazing system based on frequent movements of the herd (as minimum twice per day), and long resting periods for the pasture. When the production started out, the cattle were 100% grassfed, and calves stayed together with their dams until weaning several months from birth. Cows were milked once a day. The reproduction was based on selected bulls from the herd and natural mating and the cattle kept their horns. With a few employees, the farmer and his partner initially managed all of this, including all sales, marketing, and deliveries and the operation of the new farm dairy.

Throughout the 2 years we followed the production, the ideas and practices have morphed with experience or practical circumstances. The farmer once said: "*We have made many hard learned mistakes, but we do have a strong brand. No matter what the consumer wants, we can give it to them*".

During the study period, the farmer shifted to insemination-based production, calves reared by nursing-cows, with flexible dam-calf separation typically occurring a few weeks after birth, when he assessed that both the dam and her calf seemed strong and healthy. Where the intention from the start was to keep all calves and rear them to slaughter on farm, practicalities ended up meaning that the farmer started selling surplus calves after approximately 14 days for rearing elsewhere. Calves were born primarily in spring and autumn, although not strictly. The herd was housed at pasture 24 h a day at least 5 months of the year and milked with a mobile milking parlour-system. The heifers grazed a leased area a few kilometres from the farm, with permanent pastures and organic soils, which the farmer reported as always being wet or moist, even during the drought period. During the winter, the cattle were housed in a deep litter barn fitted with an outdoor concrete area and feeding table.

The lactating cows were milked twice a day and supplemented with rolled barley each day to keep the energy supply sufficient. Some pastures were ploughed and re-established in 2022, whereas others were close to entering the permanent grass category by the end of the study period.

Discussing feeding strategy the farmer explained: "*My job is just to give them the best possible plate to choose from, but what they choose, I don't care. They know what to eat and what not to eat*", thereby also taking an alternative stance to feed optimisation. However, he also pointed to the challenge of grass-fed dairy cows; *"…it just takes so much [energy] to produce milk. If we were doing beef, it would be a completely other story*". This is why they started feeding the lactating cows more rolled barley at milking.

Collaborating with a local plant producer, the farmer bought the cuttings from their clover-grass leys to make silage for the winter, and the straw from the grain production. The plant producer in turn bought slurry and the deep litter bedding from the winter barn to fertilize his plant production.

This farm appeared as a dairy farm still in the process of establishing a farming practice that would work for the owners.

4.2.2.3 Farm C

This farm included around 400 ha of diverse land, with a mix of sandy soils of varying characteristics and organic soils kept as permanent pastures. Even though these pastures were once drained and cultivated, the farmer did not assess them to be suitable for cultivation, and most of the drainage pipes had not been maintained for many years. Today these permanent pastures stood as wet meadow-like landscapes, and many were under the nature protection law, §3 (see Table 4.2).

The farmer was the fifth generation at the farm, and with an academic education in agronomy he started the process of taking over the production after his father in 1997, where the production also converted to organic dairy production. At that time the farm had Holstein dairy cows and were self-sufficient with feed, feeding a ration optimised for high milk yields.

In 2017, the farmer changed the production to its current feed-no-food concept, with 100% grass-fed dairy cows and crops sold for human consumption. The change was motivated by calculations he had made on how many people the farm could feed, based on an average person's caloric need, if he either maximised the number of cows on the farm to 250, the maximum number he could feed from the farm's land, or if he changed the production design to the mixed feed-no-food system. He found that he would be able to feed around 200% more people with the latter compared with an upscale to 250 high-yielding cows.

Changing the production, he down-scaled the cow herd from approximately 160 high-yielding Holstein cows to 120–130 lower-yielding 100% grass-fed cows. At the same time, he started following a rotational breeding strategy with Holstein, Red Danish dairy breed (RDM) and Jerseys. The number of animals was dimensioned from what he could sustain with feed from the ley area, needed in the crop rotation, and the meadow areas at the farm. In contrast to the other farms in this study, no living animals were sold from the farm. All surplus calves were raised for beef and slaughtered at the age of 26–28 months. The young stock and dry cows grazed the permanent pastures, whereas the milking herd grazed and were moved between leys in small paddocks, inspired by the idea of holistic grazing.

A typical crop rotation on these fields was 2 years with grazed and/or cut clover-grass ley, then followed by three years with crops, such as potatoes, spring wheat, winter rye and intercropped barley and field peas. To increase options for sale to human consumption, the farmer reported that in 2024 he would experiment with intercropped wheat and pea, instead, because, as he said, "*wheat is much easier to sell for human consumption*".

The relatively large area with permanent meadow-like pastures was an essential part of the farm. The farmer explained: "*Now, if we didn't have those meadows, then all our young animals and our steers and all this, then they would all have to be on high ground [the arable land], where you otherwise can have crops for human consumption (...) And then there may be a period of drought, where the meadows still produce a yield (...) you cannot just take those areas out*".

All calves were born during the summer months June and July, mostly out on the pastures. For as long as the weather allowed, cows, heifers and steers spent their days and nights on the pastures, while the calves, separated from the dam approximately five days after birth, were housed in a barn with deep litter group-pens.

4.2.2.4 Farm D

At approximately the same size in hectares of land as Farm C, this farm had been operated as an organic dairy production since 1998, where the farmer bought the place together with his father. The farmer himself grew up with dairy farming, went to agricultural school and bought his first dairy farm in 1985.

The farmer was praised among farm consultants to have a very well-run dairy production, referring to his achieved production results in terms of milk yield and cattle health. One of the farmer's goals was that the fields "*should not look too organic*", meaning that he wanted them to be free of weeds.

The crop rotation was typically 2–3 years of ley followed by 2–3 years of crops, usually wheat, rape, barley, and rye. He had a lot of ley area, which comprised just over half of the arable land managed by the farmer. He explained that it was important for the crop rotation in relation to nitrogen supply and weed control.

Even though he saw himself as a dairy farmer, most years he also sold cash crops, e.g. bread wheat and rape seeds, however he expressed that "*the cattle are always priority one and then I sell the surplus*". He had chosen this model instead of aiming for complete self-sufficiency, because it for practical reasons was much easier to make this trade, than to manage drying, storing and processing of local protein crops such as broad beans. He also found that the soy in the concentrate mix he bought really boosted the milk yield: "*It is more fun to do the milking if you really get something out of it*". Farm D was the only one of the four farms using feed containing soy.

He had a close collaboration with farming consultants using them for feed optimisation, making ration plans for both lactating cows, dry cows and heifers, but also for advising on his crop production and rotation. With this, he was the only one of the farmers in this study, who made full use of the many years of dairy science research into genetic development in the Holstein breed and feed management optimised for high milk yields.

In the grazing season from April to October the cows grazed ley pastures combined with a total mixed ration fed indoors. During the winter, they were fully housed in the loose-housing stable, fitted with cubicles and slatted floor. Calvings happened throughout the entire year. Calves were separated from the dam approximately 24 h after birth and housed in group-pens. Surplus calves were sold once a month, at approximately 10–35 days old.

The replacement heifers were in the grazing seasons, through agreements, used for nature maintenance in areas owned by the municipality and a few private landowners. Apart from this, the farmer expressed that he thought it was fun to do nature projects on his own land. However, he saw the focus on nature as something separate from his job, being a dairy farmer, and it was mostly time that was the limit for what he could do in this area: *"…our most limited resource here, is time… and our time is spent being farmers*".

The area where the farm was situated was a ground water extraction area and the farmer recently signed an agreement with the municipality on ground water protection, which meant that 60 ha of the land belonging to the farm became protected against exposure to any pesticides.

Asked if he could see something like a feed-no-food dairy concept as a way the dairy sector could develop towards, the farmer answered "*Well… I'm just a farmer, after all, affected by the upbringing I've had and the agricultural school I've attended… and this thing about getting the most out of the least possible… it runs deep. But I also have the opinion that society can get whatever it wants… if people are willing to pay for it. After all, we can't work for free*".

4.2.3 Estimating total land use

Information on the direct land use was found through the field plan that each farmer had their consultant make each year, combined with personal communication and observations at the farm visits. For example, most of the nature areas grazed by the replacement heifers from Farm D were not included in the field plan, but still part of the direct land use, as they were used for the farmer's animals.

Data on imported biomass were obtained from the farmers' accounting and, where it was possible, data on actual use in the two years were obtained, balancing the bought material with the stock of the material at the beginning and end of the year.

Data on the use of imported feed in the beginning of the year 2022 at Farm B were not obtainable. As the farm operated in seasons and not calendar years, it was easier to get accurate data on bought and used feed for the winter 22/23 and 23/24. The imported biomass for this farm therefore represents what was bought in 2022 and 2023 but used over the two mentioned winters.

Data on the amount of bought clover-grass seeds in 2023 at Farm C were missing, but since the farmer reported that the amount was usually stable from year to year, it was assumed to be similar to 2022.

The land-use areas was divided into the categories 1) cultivated land, 2) ley (which includes all clover-grass and other grasslands with less than 5.5 years since last tilled, 3) permanent grass (which includes all grassland or nature like areas which have not been tilled for more than 5.5 year), 4) fallow land (non-productive land), 5) forest etc. (areas not part of the food production). This categorisation was assigned for both direct and indirect land use. The 'forest etc.' land-use category, however, was not directly contributing to the food output and therefore not included in the analysis, although we are aware that forests and a heterogenous landscapes in general are valuable for healthy and biodiverse lands and to limit bio-geochemical run-off. Additionally, the category included a field with the production of perennial rye grass seeds at Farm C in 2022. While not contributing directly to the food output, the production of ley seeds is an essential part of the ley-based rotation system, which we did not find a good way to consider in the present paper.

Estimating the indirect land use, based on data for all imported land-sourced biomass including feed, seeds and bedding, comprised the largest amounts of assumptions. Figure 4.1 shows a schematic presentation of how the indirect land use was estimated. All biomass was assumed produced under organic conditions. All data on substrate amounts, except silage and seed grass cutting, were received in kg. For these, dry matter contents were based on literature.

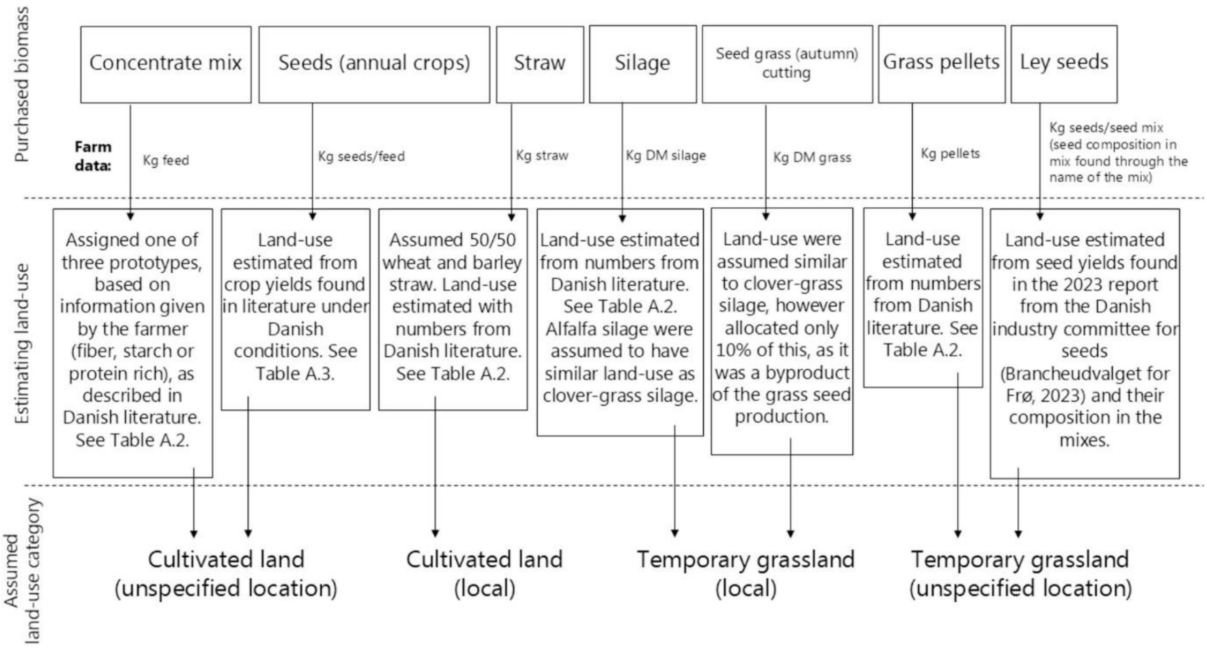


Figure 4.1 Schematic presentation of the estimation of indirect land-use and the assignment of land-use category.

Although the total amount of imported concentrate mix was easy to obtain, the specific contents were not, which was both not listed and varied from batch to batch. Optimally we would have had the feedstuff company provide a typical ingredient list for each feed mix and state the originating country of production for the different feedstuffs. In this way, the total amount of land used to produce the feed mix, could have been calculated from data on average yields for the specific crops and countries. However, this information was not possible to obtain. Therefore, we ended up with the method depicted in Figure 4.1. For the imported rolled barley, it was assumed that 1 kg barley also yielded 1 kg rolled barley. Production yields for some of the herbs in the ley seed mixes were not found. In these cases, we used the average yields for clover, alfalfa and birdsfoot trefoil.

All land use from imported concentrate mixes, seeds from annual crops (for feeding or sowing) and straw were assumed to be cultivated land. The estimated land use from imported grass- or herb-based biomass were assumed to be temporary grassland (ley). While straw, silage and seed grass cuttings were purchased locally, typically through machinery stations, concentrate mixes, seeds and pellets were purchased through feed stuff and seed distribution companies, where the country of origin was unknown and could come from anywhere. The indirect land use was therefore divided into 'local' and 'unspecified' origin.

Land allocated to none-food byproducts exported (rape seed cake – a byproduct from the rape seed oil yield and straw – a byproduct from the grain production) was subtracted from the direct land use. For rape seed cake, this area was estimated from the amount of sold rapeseeds (Farm D, see Table 4.1) and literature numbers for rape seed cake product share, DM content and land use (68%, 89% and 2.0 m2/kg DM, respectively (Mogensen et al., 2018)). Land use of the exported straw was estimated from the amount sold (Farm D, see Table 4.1) and the land-use estimates in Table 4A.2.

4.2.4 Estimating total food production

To estimate the direct food contribution from the farms, only human edible foodstuff that left the farm gate directly for human consumptions was included. This encompassed milk and meat (beef and, for Farm A, lamb meat) and food crops (the latter only relevant for Farm C and D). The farmer at Farm C intentionally attempted to grow and sell crops for human consumption, while the focus at Farm D was primarily on the dairy production and the end use of the cash crops was not actively considered. However, in the two years included in this study, Farm D sold wheat, rapeseeds, lupine and broad beans. Wheat was sold as '*bread wheat'*. The oil yielded from the sold organic rapeseeds were assumed to be most likely to be used for human consumption and were included in the food output. Both broad beans and lupins were included as food crops, as they both are suitable for direct human consumption, despite that they under the prevailing food market realities were most likely to be used for animal feed.

All sales of crops were registered under the production year, even though some were sold during the winter in the following year. Some crops at Farm C were not yet sold and still in stock. The amount was estimated from the measured volume in stock and the farmers estimate for kg per m3.

The amount of milk delivered to the dairies, and the year and farm-specific fat and protein contents, were obtained from the farmers' digital management tool, ‘DMS’ (SEGES, 2023), which nearly all Danish dairy farmers use and which receives data from the dairies. However, since Farm B had their own small scale farm dairy, no data on delivered milk was recorded in their farm management tool. Instead, the total amount of ‘delivered milk’ was found in their own registrations of milk flow through the dairy. The fat and protein content for this, was not recorded. These numbers were obtained from data from the milk yield control service performed 11 times per year, where the yield and milk composition of all milked cows are recorded.

The number of slaughtered animals was also obtained from the management tool. However, there were only data available on the slaughter weight of the slaughtered heifers, steers and bulls, not the culled milking cows. From Farm B, we received the slaughter lists, but for the three other farms, the average slaughter weight was obtained from a project that recorded slaughter weight results from culled cows of similar or comparable breeds. The average slaughter weight from a Holstein x RDM x Jersey-crossbred was 250 kg per cow, which we used for Farm A and C, and 298 kg for the Holstein breed, which we used for Farm D. The average slaughter weight for the lamb at Farm A was by the farmer estimated to be 15 kg per lamb on average. To estimate the boneless meat yield from slaughtered animals, it was assumed that 81% and 67% of the bone-in carcase weight, for beef and lamb meat, respectively, was edible meat (Wilkinson, 2011).

The meat contribution of the farms through live sold surplus calves and other young stock, which were sold for fattening or production elsewhere, was estimated from their sales-weight. Liveweights were either averaged from farm records or estimated by the farmers. Following the methodology used by Ineichen et al. (2023), surplus calves and older young stock for fattening at another farm was assumed to yield 410 g meat per kg liveweight. Heifers sold for milk production elsewhere were assumed to yield 310 g meat per kg liveweight, as the assumed slaughter of the animals would be as a culled milking cow. Live sold nurse-cows were assumed to have a similar slaughter weight as the culled cows of the farms.

4.2.4.1 Energy and protein output

The human digestible energy (HDE) and crude protein (CP) content of the food products are listed in Table 4.3 and found in the Frida food database (DTU, 2024) and USDA food database (USDA, 2018). For oat, output values for rolled oats were used. It was assumed that 1 kg of harvested oat also yielded 1 kg of rolled oats. In the processing of the rapeseed to produce the two products oil and rape seed cake, 31% of the seed weight was assumed to yield oil, 68% cake and 1% waste (Mogensen et al., 2018).

Table 4.3 Content of human digestible energy (HDE), crude protein (CP) and the protein quality adjusting score (DIAAS) in foodstuff outputs from the farms. The energy and protein content in the milk is specific for both farm and year.

Heading	Food ID[1]	HDE (MJ / kg product)	CP (kg / kg product)	DIAAS[2] (%)
Milk				115.9[a]
Farm A, 2022 / 2023		3.1 / 3.0[3]	0.0366 / 0.0356[2]	
Farm B, 2022 / 2023		3.14 / 3.39[3]	0.0361 / 0.0393[2]	
Farm C, 2022 / 2023		3.23 / 3.21[3]	0.0374 / 0.0372[2]	
Farm D, 2022 / 2023		2.92 / 2.99[3]	0.0347 / 0.0355[2]	
Meat				
Beef	1053	10.12	0.197	111[a]
Lamb	1234	13.65	0.139	111
Crops				
Wheat, whole	189	14.38	0.107	40.2[a]
Barley, whole	176	14.76	0.092	47.2[b]
Rye, whole	143	14.01	0.09	47.6[a]
Oat, rolled	480	15.41	0.133	56.7[a]
Yellow field peas, dry	592	14.7	0.22	64.7[b]
Potatoes, white	4	3.26	0.02	95.02[b]
Rapeseed oil	1483	37.0	0	-
Broad beans, raw	175205	14.2	0.261	57[a]
Lupins, whole, raw	172423	15.5	0.362	64.7[b]

[1] Data on HD energy and protein content were obtained from Frida food database (DTU, 2024) with the exception of broad beans and lupins, which were not available in the database. These were instead found in the USDA food database (USDA, 2018).

[2]Sources: [a]Hennessy et al. (2021), [b]Ineichen et al., (2023). DIAAS for lamb meat were assumed similar to beef as factor for lamb meat were not found

[3] Farm specific energy and protein content. The energy content was calculated using the Atwater general factors on the basis of the farm and year specific fat and protein contents (see Table 4.1) and a carbohydrate content of 47 g/kg milk found in the Frida food database for organic milk, 3.5% fat, Food ID: 1266 (DTU, 2024).

The quality of protein, in terms of digestibility and amino acid composition differs between foodstuffs (Gilani et al., 2005). To consider this in the estimation of the food security value of the protein from different food stuffs, this has been corrected for by applying the 'Digestible Indispensable Amino Acid Score' (DIAAS) for the individual foodstuff (see Table 4.3). As it has been discussed (Craddock et al., 2021) whether it is appropriate to use the DIAAS system (because the scores are based on pig models and do not consider the complementary effect of a divers diet), we have included all results on protein based on CP in the Supplementary material, Appendix 4A (Table 4A.5–7), but will work with the quality (DIAAS) adjusted protein (QP) throughout the paper.

4.2.5 Land-use ratio

The LUR method was, as mentioned, first described and performed by van Zanten et al. (2016) who described the method in four steps: 1) quantify land use of the animal production, 2) evaluate the suitability of that land for food crop cultivation, 3) assess the food output potential for a food crop production on that area, and 4) relate the assessed food crop output with the output from the animal production, see eq. (4.1).

$$LUR = \frac{Potential\ plant\ sourced\ food\ production}{Actual\ animal\ sourced\ food\ production} \qquad (4.1)$$

4.2.5.1 Land suitability

For the two farms with crop production, all fields in arable rotation were considered suitable. For the remaining permanent area as well as the area at the two smaller farms, which only or primarily managed grasslands, suitability was assessed through interview, soil and nature protection maps as well as personal observations of the fields. Here, we made a qualitative assessment based on information on feasibility and the potentials for other essential environmental functions within the local landscape (e.g. biodiversity potentials or nutrient leaching mitigation). This additional level in the assessment, which goes beyond the physical and feasibility perspective, we argue, is crucial when working towards agricultural systems operating within the environmental capacities of local landscapes.

In 2023 it was made a requirement to leave at least 4% of the arable area in fallow (non-productive areas) by the EU standards on good agricultural and environmental condition of land (GAEC) in the new CAP (Common Agricultural Policy: 2023–27). Fallow land areas in 2023 were therefore assumed unsuitable, as they were not available for food crop cultivation.

All indirect land-use in arable rotation (land estimated from imported biomass, which were assumed to origin from either cultivated land or land in ley, see section 4.2.3) were assumed suitable. Land allocation to exported byproducts or imported straw was not included in the LUR estimations. Similarly, the indirect land use from purchasing sowing seeds for annual crop production was excluded, as a potential pure food crop production would also require such land. Therefore, it could not be considered part of the area available for generating a direct food output.

We estimated the share of suitable area under two different ley assumptions: 1) that ley areas are necessary for healthy and fertile organic crop rotations and thus not available for food crop cultivation, and 2) that leys are not needed, and therefore that the total land area in arable rotation is available for food crop production.

4.2.5.2 Alternative production scenarios

Rather than making this estimation on "the animals vs. the plants" as described in eq. (1), we used the method as a tool to compare the different food production designs, allowing for whole system inclusion of mixed systems. We computed two different LUR-estimates for all farms and production years, for both HDE (eLUR) and QP (pLUR) under organic production practices.

We estimated a LUR between the current production output and the theoretical output a pure food crop production could have on the area assessed suitable for cultivation. A LUR estimate was calculated under both ley assumption, see eq. (4.2).

$$LUR_{ley/no\ ley} = \frac{Potential\ plant{-}sourced\ food\ output,\ \ with/without\ leys}{Current\ food\ output} \qquad (4.2)$$

The theoretical plant-sourced production output was estimated using the crops and their nutritional yields listed in Table 4.4, inspired by the crop rotations on Farms C and D. The difference in the LUR estimations between the two ley assumptions was determined by the area used for calculating the theoretical plant-sourced food output. Under assumption one, this area included only cultivated land and under assumption two, it included both cultivated land and ley areas (land in arable rotation).

Table 4.4 Crops in rotation and their yield of HDE and QP per hectare cultivated land. The average HDE and QP yield per hectare is highlighted in bold.

Crops in rotation[1]	Potatoes	Peas	Winter rye	Wheat	Broad beans	Oats	Avg. yield / ha cultivated land
HDE yield, GJ/ha	65.2	65.0	68.1	73.1	58.8	56.1	**64.4**
QP yield, kg/ha	380	630	208	219	616	275	**388**

[1]Modelled after the crops in rotation at Farm C and D. Yields from Table 4A.3 and content of HDE and QP of the different crops estimated from numbers in Table 4.3, were used to calculate the nutrient yields per area.

The same rotation was used on all land assessed suitable, even though, in practice, some of the indirect land use of the farms were likely to be located outside of Denmark. This was certainly the case of the soy in the concentrate mix at Farm D. However, differentiating crop rotations based on a guess of land-origin of the 'unspecified' land, was not considered appropriate. Nor did we differentiate the crop yields by soil type.

4.3 Results

4.3.1 Land characteristics

The characteristics of the total land use for the farms differ substantially among the analysed farms, see Figure 4.2, which includes both direct and indirect land use. Farm A relied primarily on permanent pastures, Farm B on leys, and Farm C and D on a mix of cultivated land and grassland. Although the average share of cultivated land and grasslands for the two largest farms were somewhat similar, the characteristics of the grassland differed, with Farm C proportionally having more permanent pastures and fallow land, and Farm D having more ley.

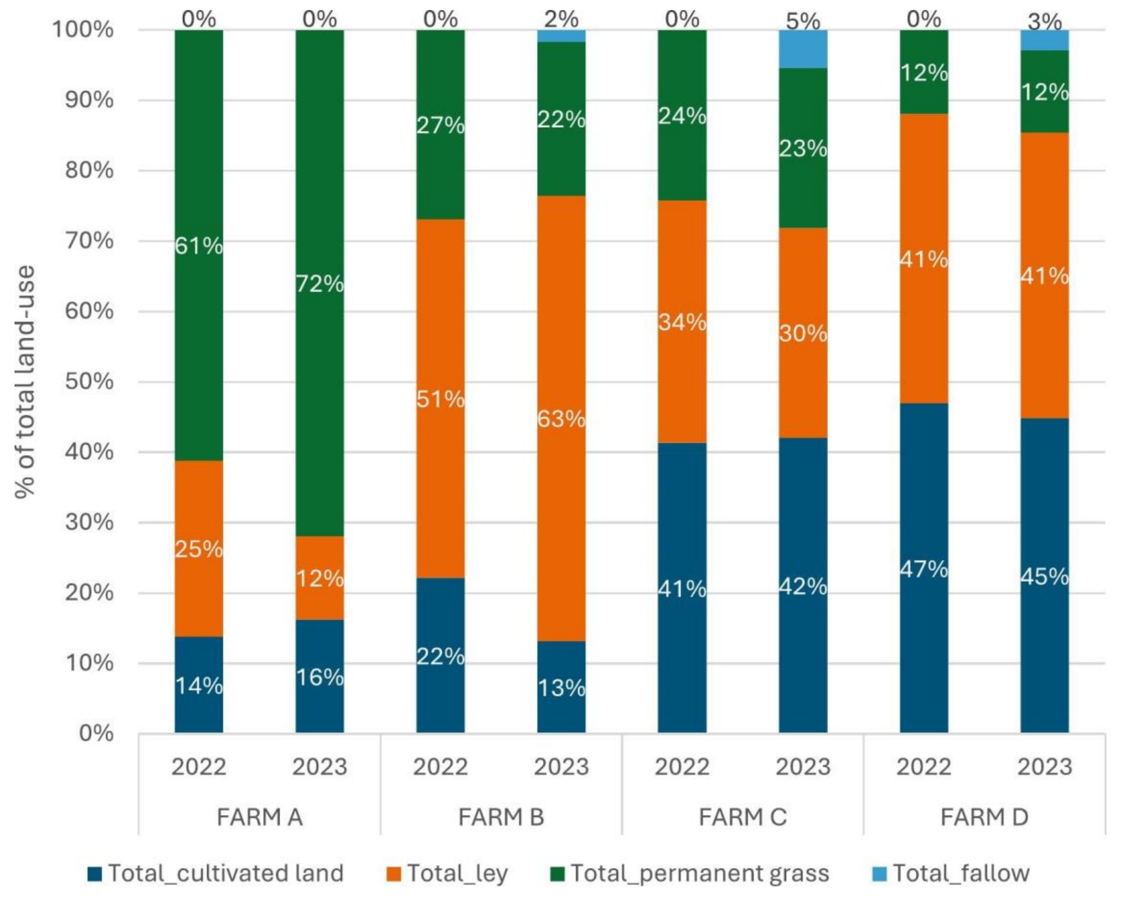


Figure 4.2 Land-use characteristics of the total land use (includes both direct and indirect land-use) at the four farms in 2022 and 2023, divided into cultivated land, ley, permanent grass, and fallow land.

The location, and who managed the land, also varied. While Farm D relied on most indirect land in absolute terms, the land self-sufficiency degree was relatively high, with 85–86% of the total land use managed by the farmer himself. Farm C had the highest land self-sufficiency degree, managing 96–97% of the total land use (Table 4.5). Note that the reported percentages disregard the land allocation of exported non-food byproducts). The two smallest farms had a lower degree of self-sufficiency, managing 63–78% of their total land use themselves. However, they both collaborated with farmers in their local communities, through purchase of silage and straw from known, local areas. This accounted for 16–25% of their total land use. The use of land of 'unspecified location' for Farm A, B and D were therefore quite similar, around 11–14% of the total land use (see Table 4.5). Farm C only relied on 1–2% of 'unspecified land', through the import of sowing seed for food crops and herbal leys.

Table 4.5 Estimations of indirect land use and the characteristics of this. The total land-use, the sum of direct (see Table 4.2) and indirect land use is stated, as well as the share of total land-use which is managed by the farmers, locally managed, or is of 'unspecified' location.

	Farm A		Farm B		Farm C		Farm D	
Item	2022	2023	2022	2023	2022	2023	2022	2023
Total indirect land use (ha)	24.63	23.06	16.19	33.05	12.49	14.59	72.95	69.38
Indirect cultivated land (ha)	9.87	11.34	6.18	11.90	5.65	12.83	60.72	56.02
Indirect ley (ha)	11.32	8.27	10.01	21.15	6.84	1.76	12.23	13.36
Indirect perm. grass[1] (ha)	3.44	3.44	0	0	0	0	0	0
Total land-use (ha)[2]	71.5	69.9	73.4	90.2	366.6	390.2	484.8	488.7
Location of total land-use								
Direct land use	66%	67%	78%	63%	97%	96%	85%	86%
Indirect land use, local	23%	19%	16%	25%	2%	2%	2%	2%
Indirect land use, unspecified	12%	14%	7%	11%	1%	2%	13%	12%

[1] More than 5.5 years since tilling. This number includes small areas of 'nature areas' such as small clusters of trees or bushes.
[2]Subtracted land use allocated to byproducts (see Table 4.2, only relevant for Farm D).

As mentioned in the farm descriptions, both Farm A and B exported manure to support local grain and vegetable productions. The exchange of silage and straw from arable farmers with manure from the small-scale dairy farms, means that the value of the animals at these farms extended to other products, although this were not included in this study. Farm C and D on the contrary had imported slurry in addition to the manure from their own animals, although, the farmer at Farm D reported that they had previously managed without importing manure and that they also at times exported slurry to the neighbouring farm.

All farms were to some degree contributing to management of nature areas (see Table 4.2). Farm A and C had the largest share of grasslands with nature value as part of their production system, comprising around 16% of their total land use.

4.3.2 Food yields and land-use efficiency

The total energy and protein output from the case-farms can be found in the Table 4A.4. Where the food outputs from Farm A and B were 100% animal based, 77% of the HDE output and 51–54% of the QP output from Farm C were plant sourced. At Farm D, the plant sourced share varied substantially between 2022 and 2023, with 9–34% of HDE and 1–15% of QP output, respectively, being plant sourced. This was caused by a decreased sale of food crops in 2023, due to low yields caused by unfavourable growing conditions.

It can be viewed in different ways how efficiently the farms used the land resources. Land-use efficiency depended on the perspective of the measuring (Table 4.6). Viewing land-use efficiency as the total land area used, Farm C and D achieved the lowest use for energy supply, with 393 and 442 m2/GJ HDE, respectively in 2022.

Table 4.6 Land-use efficiency measures of the four case-farms viewed as the use of 'total land', 'arable land', and 'cultivated land' per output of human digestible energy (HDE) and protein quality adjusted protein (QP). The three lowest values within a row are highlighted in bold.

	Farm A		Farm B		Farm C		Farm D	
Item	2022	2023	2022	2023	2022	2023	2022	2023
Land-use per HDE output								
Total land (m^2 / GJ)	1196	1076	1648	1543	393	455	442	610
Arable land (m^2 / GJ)	464	302	1205	1180	298	327	389	521
Cultivated land (m^2 / GJ)	165	175	365	203	162	191	206	273
Land-use per QP output								
Total land (m^2 / kg)	86	76	117	110	58	64	41	48
Arable land (m^2 / kg)	33	21	86	84	44	46	36	41
Cultivated land (m^2 / kg)	12	12	26	14	24	27	19	21

The variation between the production years was large, especially at Farm D. For protein supply, Farm D used the least amount of total land per produced kg QP. Viewing the efficiency as the use of arable land, the lowest amounts per HDE output were found at Farm C and A. Farm A followed by Farm D used least arable land per QP output. Farm B had a considerably higher use of arable land for both HDE and QP outputs, as the farm relied primarily on herbal leys, either managed by the farmer or other local farmers.

The leys at farm, although planned to remain permanent, were yet too young to be categorised as permanent pastures during the study period. Finally, when viewing land-efficiency as the use of cultivated land, Farm A and C appeared most land-efficient producers of HDE with 165 and 162 m2/GJ HDE, respectively in 2022. Considering protein, Farm A and Farm B (only in 2023) used the least amount of cultivated land per kg QP output.

4.3.3 Feed-food competition

As can be seen in Table 4.7, only Farm A had estimated $eLUR_{ley}$ values (slightly) below 1, indicating that it produced more HDE than a pure food crop production would have on the suitable area used by the farm, given that leys were considered unavailable for cultivation.

Table 4.7 Share of land assessed suitable (available) for cultivating food crops under different assumptions concerning the importance of ley and the corresponding estimated land-use ratios for human digestible energy (eLUR) and quality adjusted protein (pLUR).

	Farm A		Farm B		Farm C		Farm D	
Item	2022	2023	2022	2023	2022	2023	2022	2023
Suitable share of total land-use								
With ley	0.12	0.14	0.38	0.36	0.40	0.39	0.46	0.44
No ley	0.28	0.26	0.74	0.77	0.74	0.69	0.87	0.84
Land-use ratio								
$eLUR_{ley}$	0.91	0.99	4.04	3.59	1.01	1.14	1.35	1.74
$pLUR_{ley}$	0.39	0.42	1.74	1.54	0.89	0.96	0.75	0.82
$eLUR_{no\ ley}$	2.13	1.81	7.82	7.70	1.88	2.01	2.52	3.34
$pLUR_{no\ ley}$	0.92	0.77	3.36	3.30	1.67	1.70	1.39	1.57

The estimates for Farm C were also close to 1, ranging from 1.01 to 1.14. Farm D had slightly higher values and Farm B, which had a combination of animal production only, low milk yields and a relatively large percentage of soils suitable for food crop cultivation (36–38% of the used land), showed considerable higher feed-food competition. Farm A, C and D had a $pLUR_{ley} \leq 1$, with Farm A having the lowest ratios. Farm B had $pLUR_{ley}$ at 1.85 and 1.63.

The $LUR_{no\ ley}$ estimates showed considerably larger values (higher plant-based food provision opportunity cost). All farms had an $eLUR_{no\ ley}$ around 2 or over and only Farm A had $pLUR_{no\ ley}$ below one (0.98 and 0.83 over the two years), and that only if applying the DIAAS protein quality adjustment (see Table 4A.7 for pLUR-values for CP).

4.4 Discussion

This study has illustrated how dairy farming can be practiced with different implications and potentials for improved land-use efficiency. Our findings reveal that farms, which may appear similar when certain parameters are foregrounded (e.g., number of cows, milk yield per cow, or crop rotation management), can show considerable variation in land-use efficiency and feed-food competition due to differences in local topographies and cattle feeding practices. Farm A with the lowest land-use share of area suitable for cultivation and Farm C with the largest percentage of plant-sourced food output, had the best land-use efficiency for food production, when measured as the use of arable or cultivated land, and the least land-based feed-food competition.

The high relevance of the characteristics of the used land is consistent with the previously cited LUR-studies (Hennessy et al., 2021; Ineichen et al., 2023; van Zanten et al., 2016). Another recent study estimated the pLUR of 10 intensive, indoor dairy farms in Northern Italy (Palladini et al., 2024). That study found, like Ineichen et al. (2023) and our study, great farm variability, but also surprisingly low pLUR-values (0.2 and ~ 0.25) for two of the five farms with pLUR<1. The study pointed to a high use of byproducts and high animal productivity as viable approaches to decreased feed-food competition and noted that no substantial difference in land suitability was found between the 10 lowland farms. The study excluded area allocation to the used byproducts, including soybean and sunflower meal. This complete exclusion is a likely cause for the discrepancy in the results. While handling byproducts in this type of studies is tricky, the assumption that soybean production is driven purely by oil demand can be questioned, as it overlooks the significant value soybean meal represent in many livestock production (Fraanje and Garnett, 2020).

In the present study we did, in contrast, not find a particular advantage in high milk yields per cow (Farm D) when compared to low milk yields in combination with a food crop production for human consumption (Farm C) or a low share of land suitable for cultivation (Farm A). These different conclusions emphasise how we as researchers can point to two contrasting pathways for dairy cattle by the factors and relations, we choose to foreground and background.

4.4.1 Land-use ratio

The LUR measure is easy to interpret, communicate and use to indicate the land-based feed-food competition of a food production with livestock. Yet, the method is highly sensitive to the combination of the following three factors: 1) the crops chosen for the ‘theoretical food crop output’ estimation, 2) the assumed yield for these crops, and 3) the suitability assessment and assumptions around agro-ecosystem health.

We used five crops for computing the theoretical output inspired by the crops cultivated at Farm C and/or D. This rotation gave an average yield from the cultivated land of 64.4 GJ HDE/ha and 388 kg QP/ha (Table 4.4). The choice of crops affects the potential yield of dietary energy and protein, as some food crops yield considerably more of one or the other. Based on the assumption that the average person needs 9450 kJ energy (National Health Service, 2022) and 51.2 g protein per day (Webb, 2020), the kg protein/GJ energy ratio is 5.4. The rotation we used had a ratio of 6.0 kg QP/GJ HDE, meaning that this rotation could potentially feed more people based on their protein than their energy needs. In addition, the differences might not always be as large as initially assumed. For example, the protein/energy output ratio from potatoes is relatively similar to the rotation output, with a QP/HDE-ratio of 5.8.

The assumed yields for the crops are, however, highly determining for the dietary output of such a rotation. Under the ley-based production assumption, Farm C only cultivated food crops on the suitable area, and all of this was located at the farm, due to the exclusion of land for sowing seeds and land allocated straw. The cattle produced 23% and 47–48% of that farm's HDE and QP output, respectively (Table 4A.4.). The $eLUR_{ley}$ and $pLUR_{ley}$ would therefore be expected to be (well) below one but was estimated to 1.01 and 1.14 for HDE and 0.89 and 0.95 for QP over the two years. This indicates that the yields were assumed too high compared to what was possible to achieve in the real-life production context on the sandy soils of Farm C.

In addition, the LUR variation between the two years of production shows how sensitive situated LUR estimates are to variations in production due to weather conditions or other management or resource changes. Despite these uncertainties, the LUR that we calculated, clearly pointed to the previously stated underlying dynamics of land-use efficiency of farms with dairy cattle, namely relying of land unsuitable for growing food crops.

This puts a lot of weight to the suitability assessment. As described in section 4.2.5.1, we tried to consider not only the practical suitability, but also the suitability in relation to environmental functions, qualities and potentials. Exemplifying this, one of the permanent pastures at Farm A (9.33 ha) was evaluated as unsuitable, despite having been successfully cultivated 25 years prior to the present study. This decision was motivated by the biodiversity potential of the field and the surrounding area. The farmer reported observing numerous Glanville fritillary butterflies (Melitaea cinxia) on the field, which depend on the narrowleaf plantain (Plantago lanceolata) that was abundant in the sward. Although this butterfly species was not endangered at the time of the study, it was in drastic decline in Denmark. If this additional level of suitability assessment had not been considered and the area had been included as suitable, the LUR estimates for Farm A would have been considerably higher, with only $pLUR_{ley}$ remaining below 1 (0.76 and 0.82).

Still, the largest impact of the suitability assessment on the LUR came from whether the traditional use of ley was considered necessary, with only Farm A avoiding feed-food competition under 'no ley' production forms (Table 4.7), and only in relation to protein output. While the use of ley is beneficial for agro-ecosystem health (Martin et al., 2020) it requires a trade-off between short term maximisation of farm system plant-based food output and the adoption of low-input approaches to sustain good crop growing conditions and soil functions (Williams et al., 2006).

4.4.2 Food security indicators

All farms performed better when assessed on protein supply, especially with QP, compared to the HDE measures. This confirms previous studies (Ineichen et al., 2023; van Zanten et al., 2016). Several studies have focused entirely on the protein supply of cattle systems (Ertl et al., 2016; Hennessy et al., 2021; Laisse et al., 2018), where the quality of proteins were approximated and discussed. The LUR results of QP and CP (crude protein, without amino acid adjustment, Table 4A.7) showed notable differences. The amino acid correction reduced the farm's pLUR values by 26–49%, with larger reductions observed as the animal share of the protein supply increased.

However, it is unclear to which degree the protein output from food productions is an essential indicator for food security, despite the frequent use of this parameter. Webb (2020) argued that the focus on protein and the 'protein gap' resulted from earlier exaggerated estimates of protein needs of small children based on experiments on fast-growing animals. He stated that the protein needs usually are covered well when the caloric intake is sufficient. This suggests that dietary energy should be the main indicator for food security, making the discussion on protein quality redundant. Giving less attention to the protein indicator does not change the overall conclusions of this study, but it does narrow down the places and situations where the use of dairy cattle as part of the food production would be the most land-efficient choice. It might be that the greatest value of integrating dairy cattle into our food systems lies in aspects beyond the direct food contribution, particularly via their role in nutrient cycling and nature conservation and restoration.

4.4.3 The value of grazing animals

4.4.3.1 Nutrient flows

At farms prioritising large areas for fertility-building ley, cattle provide both a food output and an economic input from the ley fields (Cooledge et al., 2022) and recycle nutrients to the land either directly or through slurry and deep litter bedding (Wilkins, 2008). Other studies estimating LUR have not commented on these relations, likely because they (without directly specifying it) assumed conventional production methods with the use of artificial fertiliser, but as mentioned in the introduction, the planetary poly-crises that we are facing urges us to explore systems that can reduce biogeochemical flows and the use of pesticides.

The suggested alternative production scenario in section 4.2.5.2 represented a livestock-free food crop production. However, we did not consider specificities of the nutrient supply, which, considering that organic production depends on organic fertilizers, is an essential part of the discussion. Without livestock, where should the nutrient supply come from? In the ley-based alternative, the clover-grass fields would contribute to the nitrogen-supply through nitrogen fixation. The 'no ley' alternative would have to use other measures, e.g. autumn green manure and catch crops. Thorup-Kristensen et al. (2012) experimentally tested a conventional (C), a nutrient import based organic rotation (O1) and two green manure organic rotations (O2 and O3) of continuous cropping in Denmark from 2006 to 2009. Their crop rotations included rye, oats, lettuce, carrots, onion and white cabbage for all treatments. The O2 treatment achieved yields similar to the O1 treatment (yields 81 and 83% of that in the C rotation, respectively). The O3 treatment, which included leaving part of the green manure as intercrops, had a decreased total food output from the grown vegetables, as the green manure occupied some of the land (yields 63% of that in the C rotation). While the study suggest that organic food crop production is possible without the use of traditional leys, both low-input rotations did receive a yearly average of 25 kg N/ha from slurry and thus were not entirely independent of production animals.

The question is how soil health and plant nutrition would fare long-term, if no livestock were part of the organic systems to recycle nutrients and organic matter?

We stress the importance of including measures of the use of manure or estimate key nutrient balances of the farms (e.g. nitrogen, potassium and phosphorus) in future studies.

4.4.3.2 Intersection between production and nature

All cattle can graze. Yet, it is far from all that are given the opportunity. Around 70% of the Danish dairy cows are housed indoor all year (Statistics Denmark, 2021), but all Danish organic dairy cows must have access to pasture between April and November. All the farms in this study provided nature care of protected grasslands through grazing, but to different degrees. While Farm B, C and D primarily used youngstock for this purpose, all cattle at Farm A engaged daily with the nature-like dry meadow landscape around the farm.

Conflicting interests are present when a commercial food production is engaged in nature care. Such productions typically aim for high fertility and biomass production whereas nature conservation requires natural stocking rates (recommended: 70–250 kg ha^{-1}, maximum: 400 kg ha^{-1}) and fields free from fertilisation, drainage, and human-controlled plant species composition through (re)seeding (Ejrnæs et al., 2023). The question is whether we have the kinds of knowledge and insights needed to aim for less damaging production while also producing food products?

4.4.4 Perspectives

4.4.4.1 (Food) system resilience

Besides the agro-ecosystem benefits of herbal leys and potential nature benefits of having cattle graze permanent semi-natural pastures, an important perspective in relation to resilience is the value of grass, a resilient plant good for feeding ruminants. All four case farms had grasslands as a vital part of their production. What was lost in forage growth during the months of drought in the late spring and early summer of 2023, were compensated for by an increased growth later in the season, as the wet and relatively overcast high summer and warm autumn were good conditions for good pasture growth. All farmers pointed to this characteristic of grass and the farmer at Farm D commented that despite the unstable weather of 2023: *"…we ended up landing on our feet (...) [because of] the grass's ability to compensate… and we know that very well, it saves us every time*". What this suggest is that cattle and pastures can serve as a security when crop harvests are poor or fail due to extreme weather conditions – an insight that might be valuable in the future.

4.4.4.2 The farmers behind the productions

As we have seen in the presentations of the farms, the farmers' ideas and concerns shape the farms that they have in various ways. This points to how the ways of knowing and thinking play important parts in the shaping of agricultural systems. Linking reflections of assessment metrics with specific farming and landscape contexts, as we have done here, may inspire new and broader ways of thinking, as it is presented in a form relatable for the individual actor. For example, when the farmer from Farm B read the results of this paper he commented; "*Considering the soil I have, I really should grow food crops instead. It is just too bad that it is cattle and dairying that I am passionate about*". In a world where fewer people choose to work in agriculture, the interests and passions of the people matter, so how can we as researchers contribute to foreground some of the relations that are important to meet the feed-food competition of the future while reducing environmental harm?

4.4.4.3 Limitations, future and large-scale perspectives

Including more than four case farms would have been preferable to cover a wider spectrum of farm diversities. Of course, data from more years of production would also enable more confidence in the results and conclusions. Yet, the idea with this article is not to make an exhaustive analysis but more than anything to engage with former analyses on feed-food competition and add aspects that have been backgrounded and ignored. Further, due to the time consuming, multi-source data collection, resource-dependent priorities led us to include four farms representing different production choices and styles, while still allowing us to illustrate the method, and to identify and discuss methodological benefits and limitations.

The study was primarily intended to inspire and provide insights into land-use dynamics for farmers, consultants and knowledge producers. As the farms were not selected to ensure representativeness of the full dairy population, extrapolation of the estimations should be done with caution. For further qualification of trade-offs and futures for livestock, the land-use indicators presented in this study could be used in multicriteria frameworks, together with other important indicators, e.g. for nutrient, water and energy use, as well as emissions and pollution impacts, in connection to local environmental capacities.

4.5 Conclusion

Dairy production based on grass feeding in a mixed livestock-food crop system and/or supported by soils unsuitable for food crop cultivation showed the highest land-use efficiency and lowest feed-food competition, while also creating most nature value. Important functions of dairy cattle seen in organic systems are recycling of nutrients to food crops, the productive use of fertility building leys, and grazing of permanent nature areas. Such connections might be of high(est) importance when considering the future role of cattle in food production and landscapes, given the current challenges of planetary health.

CRediT authorship contribution statement

K.B. Eriksson: Writing – review & editing, Writing – original draft, Visualization, Project administration, Methodology, Investigation, Data curation, Conceptualization. N. Brichet: Writing – review & editing, Supervision, Funding acquisition, Conceptualization. L.R. Nielsen: Writing – review & editing, Supervision, Funding acquisition, Conceptualization.

Ethics approval

The research project, Cattle Crossroad, in which this work was carried out, was approved by The Research Ethics Committee at the Faculty of Humanities and the Faculty of Law, University of Copenhagen. All the farmers enrolled in the study signed a declaration of consent for the use of their data and provided information. Complying with the orderly conduct of research used in anthropology, all farmers were presented with the manuscript for approval and adjustments of any misconceptions of data or statements.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

None of the data were deposited in an official repository. Upon reasonable request data is available from the corresponding author.

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4.6 Appendix 4A. Supplementary data

Content

This document contains supplementary tables which include additional data (Table 4A.1), numbers used in land-use estimations (Table 4A.2-3), food output estimations (Table 4A.4) and alternative results for protein estimates, if the protein was not quality adjusted (Table 4A.5-7).

Table 4A.1 A rough outline of the land-based imported biomass at the four case farms

	Farm A		Farm B		Farm C		Farm D	
Item	2022	2023	2022	2023	2022	2023	2022	2023
Concentrate[1] (tonnes)	53.2	55.7	15.9	42.1	-	-	305.2	288.5
Roughage/bedding								
Silage[2] (tonnes DM)	78	57	-	-	35	-	-	-
Grass pellets (kg)	90	60	-	-	-	-	-	-
Seed grass cutting (tonnes DM)	-	-	40	-	-	-	-	-
Straw (tonnes)	81.0	78.3	100	100	190.4	373.5	-256	-
Seeds								
For crops[3] (tonnes)	-	-	2.5	-	26	116.3	35.3	27.2
For leys[4] (kg)	-	-	299	-	1 191	1 191	2 000	2 510
All biomass harvest from a specific area[5] (ha)	3.4	3.4	9	21.2	-	-	10	10

[1] Different organic concentrate mixes at Farm A and D, rolled barley at Farm B.

[2] Included both clover-grass and alfafa silage.

[3] Solely yellow field peas for Farm B 2022, for Farm C it included potatoes, wheat, and in 2022 oat, at Farm D it included spring wheat, spring barley, winter rye, rapeseeds and in 2022 also broad beans and lupins.

[4] Includes primarily different clover-grass mixes for cutting and grazing, but also mixed herb seeds.

[5] The area at Farm A, is permanent nature-like grass, the areas for Farm B and D are crop rotation leys. All biomass were ensiled, either as wrap silage or in stacks at the farms.

Table 4A.2 Land-use estimates for concentrate feed mixes, grass pellets, clover-grass silage, straw, and rapeseed cakes based on organic cultivation. All based on numbers from Mogensen et al. (2018).

Substrate	m^2 use / kg DM
Fiber rich concentrate mix, 87.9 % DM	1.80[1]
Starch rich concentrate mix, 87.4 % DM	2.04[1]
Protein rich concentrate mix, 89 % DM	1.92[1]
Grass pellets, 92 % DM	1.58
Clover-grass silage	1.45
Rapeseed cake, 89 % DM	2.00[1]
Straw	0.18[1]

[1] Land-use for conventionally cultivated substrates adjusted for organic production by multiplying with 1.2 to adjust for an average of 20% lower yields in organic compared to conventional production (De Ponti et al., 2012)

Table 4A.3 Yields used to estimate indirect land-use of imported seeds. All based or adjusted to organic cultivation.

Substrate	Yield (kg per ha)
Spring wheat	5 085[1]
Spring barley	4 029[2]
Winter rye	4 741[1]
Oat	3 643[2]
Field peas, yellow	4 425[1]
Potatoes, white	20 000[3]
Rapeseeds	2 651[2]
Broad beans	4 143[1]
Lupins	2 430[1]

[1] Source: SEGES INNOVATION (2022). Yields for winter rye were the average of the 2016-2022 conventional trials multiplied with 0.8 to adjust for organic production in accordance with De Ponti et al. (2012). Yield for field peas were the average of the 2021-2022 organic trials and broad bean yield were the average of the tested varieties in 2022.

[2] Source: Mogensen et al. (2018).

[3] Source: H. Pedersen, AKV Langholt, personal communication, 22 March 2024.

Table 4A.4 Total food output measured as GJ of human digestible energy (HDE) and kg Quality adjusted Protein (QP). The percentage share of each food category (milk, meat and crops) of the total HDE and QP output is listed in brackets.

	Farm A		Farm B		Farm C		Farm D	
Item	2022	2023	2022	2023	2022	2023	2022	2023
Total HDE (GJ)	**598**	**649**	**445**	**585**	**9 333**	**8 583**	**10 972**	**8 008**
HDE_milk (GJ)	572	617	406	541	1 804	1 681	7 048	6 995
	(96%)	(95%)	(91%)	(93%)	(19%)	(20%)	(64%)	(87%)
HDE_meat (GJ)	26	32	39	44	303	271	240	253
	(4%)	(5%)	(9%)	(7%)	(3%)	(3%)	(2%)	(3%)
HDE_crops (GJ)	0	0	0	0	7 226	6 631	3 685	761
	(0%)	(0%)	(0%)	(0%)	(77%)	(77%)	(34%)	(9%)
Total QP (kg)	**8 349**	**9 178**	**6 246**	**8 209**	**63 410**	**61 189**	**119 630**	**102 799**
QP_milk (kg)	7 809	8 503	5 408	7 266	24 219	22 571	96 927	96 256
	(94%)	(93%)	(87%)	(89%)	(38%)	(37%)	(81%)	(94%)
QP_meat (kg)	540	675	838	943	6 541	5 858	5 176	5 469
	(6%)	(7%)	(13%)	(11%)	(10%)	(10%)	(4%)	(5%)
QP_crops (kg)	0	0	0	0	32 650	32 760	17 527	1 074
	(0%)	(0%)	(0%)	(0%)	(51%)	(54%)	(15%)	(1%)

Table 4A.5 Total protein output measured as crude protein (CP), without adjusting for protein quality. The percentage share of each food category (milk, meat and crops) of the total CP output is listed in brackets.

	Farm A		Farm B		Farm C		Farm D	
Item	2022	2023	2022	2023	2022	2023	2022	2023
Total CP (kg)	**7 224**	**7 945**	**5 421**	**7 119**	**78 561**	**73 879**	**122 607**	**90 651**
CP_milk (kg)	6 738	7 337	4 666	6 269	20 897	19 474	83 630	83 051
	(93%)	(92%)	(86%)	(88%)	(27%)	(26%)	(68%)	(92%)
CP_meat (kg)	486	608	755	849	5 893	5 277	4 663	4 927
	(7%)	(8%)	(14%)	(12%)	(8%)	(7%)	(4%)	(5%)
CP_crops (kg)	0	0	0	0	51 771	49 127	34 315	2 673
	(0%)	(0%)	(0%)	(0%)	(66%)	(66%)	(28%)	(3%)

Table 4A.6 Land-use efficiency measures of the four case-farms viewed as the use of 'total land', 'arable land', and 'cultivated land' per crude protein output. The three lowest values within a row is highlighted in bold.

	Farm A		Farm B		Farm C		Farm D	
Item	2022	2023	2022	2023	2022	2023	2022	2023
Land-use per CP output								
Total land (m^2 / kg)	99	88	135	127	**47**	**53**	**40**	54
Arable land (m^2 / kg)	38	**25**	99	97	**35**	38	**35**	46
Cultivated land (m^2 / kg)	**14**	**14**	30	**17**	19	22	18	24

Table 4A.7 Estimates for pLUR without protein quality adjustment.

	Farm A		Farm B		Farm C		Farm D	
Item	2022	2023	2022	2023	2022	2023	2022	2023
$pLUR_{ley}$	0.76	0.82	3.37	2.99	1.21	1.34	1.22	1.56
$pLUR_{no\ ley}$	1.79	1.50	6.52	6.41	2.26	2.37	2.29	2.99

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5 Manuscript II: Balancing Dairy Production and Biosphere Integrity: A Mixed-Methods Case Study of Pasture-Based, Low-Input Dairy Farms in Denmark

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Abstract

Considering current environmental challenges and the need for more effective land use in food-producing systems, pasture-based dairy production with limited use of concentrates offers opportunities for environmentally friendly agriculture. This article draws on a 3.5 year longitudinal mixed-methods case study of everyday operations at two pasture-based farms in Denmark, aiming to enhance the understanding of system-cow compatibility and mitigation of biodiversity loss within such farms. We analysed qualitative and quantitative data from interviews, farm visits, repeated body condition scoring of cows, production data, and biodiversity screening reports. We found that the cows at the two pasture-based farms generally adjusted milk production to the feeding conditions over time without excessive body-fat mobilisation. This was supported by the farmers' attentive care and adaptive management. The farmers both paid attention to land and animals within organic frameworks but optimised their farms differently. One farmer aimed for pasture fertility and productivity through orchestration of natural processes, while the other to a larger extent, balanced the production around the dynamic interplay of land and animal outcomes, with a lower degree of human interference. While both approaches seemed to meet the cows' nutritional needs, the latter involved a greater proportion of pastures which aligned with what biologists assessed as valuable for biodiversity loss mitigation. Still, approximately 90% and 59% of the grazed pastures at the two farms were evaluated as either too productive or overgrazed. Notably, the analysis suggested that even highly productive pastures, when managed through the orchestration of natural processes, might hold indirect value for nature by exerting minimal impact on the surrounding landscape. We emphasise that the dynamics of the cow-pasture relation are shaped by situated contexts and multiple interests, making the practice of grazing dairy cows and the cow-pasture relation an important interface for negotiating balances between production, animal welfare, and the integrity of the biosphere. In conclusion, the two studied low-input, pasture-based dairy farms demonstrate promising potentials to integrate multifunctional land-use and food production goals with animal welfare, exemplifying a viable pathway for a green transition in dairy farming.

Keywords: multifunctionality; pasture-based dairy; biodiversity loss mitigation; biosphere integrity; body condition; mixed-methods

5.1 Introduction

Attention to the many functions and interests in land areas in cattle research is timely, as the topic is high on the agenda across all scales. Global studies highlight an overall need for focusing on Earth system health and food provision efficiency (Foley et al., 2011; Richardson et al., 2023; Rockström et al., 2025). Regional initiatives, for example The European Union (EU) Green Deal from 2020, aims to place a minimum of 30% of EU's land- and sea-areas under protection as nature areas by 2030 (Europarc Federation, 2024). In Denmark, the national agreement named 'the Green Tripartite' aims to take out at least 17% of the total arable land area to mitigate nutrient pollution of water environments and increase the national forest and nature area (Grøn Trepart, 2024).

Transitioning livestock production away from arable land and changing feeding practices has been suggested as a necessary shift for livestock in these times of increasing demands for renewable energy and competition for arable land (Benoit and Mottet, 2023). Research on pasture-based dairy productions sustained by permanent grasslands or temporary clover-grass with low external nutrient inputs points to a wide range of potentials. Such farms provide an opportunity for food provisioning from land areas which are unsuitable – or for environmental reasons – undesirable to use for cultivation of crops (van Zanten et al., 2016; Hennessy et al., 2021; Eriksson et al., 2025). Having grass as a main feed input can, moreover, reduce risks of nitrate leaching from fields compared to dairy systems with feeding based on large quantities of cultivation-based feed, e.g. maize forage, grains and oilseeds (Smit et al., 2021). Further, low concentrate allocation has been found to be related to higher diversity in permanent grassland at dairy farms (Bettin et al., 2020). Generally, it is well established that low-intensity land use, with low or no application of nutrients, and grazing with low stocking densities is positive for plant species richness and nature conservation (Klimek et al., 2007; Kleijn et al., 2012; Van Vooren et al., 2018). However, practices supporting pasture development with potentials for mitigating biodiversity loss within a production framework are not well studied or documented.

Regenerative grazing practices, such as holistic or rotational grazing, may not universally enhance biodiversity, but they might promote beneficial habitat heterogeneity when management is adapted to areas of special conservation concerns (Morris, 2021).

Pasture-based dairy systems also have potentials to benefit animal health, longevity, and welfare compared to confinement systems, and cows in general (especially at night) show preferences towards pastures as opposed to stables (Burow et al., 2011, 2013; Arnott et al., 2017). Furthermore, there are studies suggesting that grass-fed dairy cows produce milk with a healthier fatty acid composition for the consumer (Alothman et al., 2019).

Despite the multiple potentials of more extensive dairy systems, they are becoming rare. As has occurred many places in the world, dairy farming in Denmark have developed towards relatively large, highly productive and specialised systems, with high feed input of feedstuff originating from cultivated land, locally as well as imported. Efforts to increase animal productivity through genetic selection, feed optimisation, and building and management changes, have long dominated the field of dairy research in Denmark and elsewhere, and more than tripled the Danish average milk yields per cow over the past 100 years (Reijs et al., 2013; Kristensen et al., 2015; Brito et al., 2021). Alongside this development, the role and place of grazing dairy cows have decreased considerably in Denmark, leading an overall trend for dairy systems in Europe (Reijs et al., 2013; van den Pol-van Dasselaar et al., 2020). Today, around 70% of all adult dairy cows in Denmark are housed in-door all year round (Statistics Denmark, 2021).

Extensive paradigms for dairy farming meet varying perceptions including scepticism from several stakeholders. Some voices from the dairy industry, researchers and farmers question whether the genetics of the most frequently used dairy breeds today (i.e., Danish Holstein, Jersey, and Red Milking Breed) can thrive in low-input systems with 'sub-optimal' feeding, without excessive mobilisation of fat deposits due to their genetic potentials for high milk yields. For example, in an ethnographic study of dairy production in the midwestern United States, producers and nutritionists described pasture-based feeding as insufficient for high-producing Holsteins (Overstreet, 2018). A similar perspective has also been found among Dutch dairy producers (Vogel, 2025). Further, animal welfare scientists have noted that pasture-based systems may carry a higher risk of nutritional stress for cows, particularly in the form of negative energy balance (Arnott et al., 2017).

Body Condition Score (BCS) is a general indicator of a cow's body fat reserve and a BCS ranging between 2.5-3.25 (on a 5-point scale) across a lactation has been recommended to support optimal productivity without compromising health, reproduction, or welfare (Roche et al., 2009). Thus, BCS-values persistently lower could indicate nutritional stress, potentially stemming from a mismatch between the feeding regime and the cow's genetic makeup (system-cow incompatibility), although BCS also is influenced by factors such as age, parity, stocking rate, and season. Some studies have found that two breeds, i.e., Jerseys or the

New Zealand Holstein strain, maintain their body condition better in dairy systems relying heavily on pasture-based nutrition compared to the larger North American Holstein strain (Washburn et al., 2002; Schori and Münger, 2021). The same has been found for a 3-way cross (Holstein x Jersey x Norwegian Red) compared to Jerseys x Holstein and Holstein cows (McClearn et al., 2020). However, variation in BCS was greater between the studies than among the breeds assessed within each study. In addition, they only provided average BCS-values – potentially obscuring a large individual variation – and had little information on the daily management with cow nutrition and grazing. As such, there are no studies to the authors knowledge that both quantifies and qualifies risks of excessive body fat mobilisation in low-input, pasture-based dairy farming.

At the same time, the potential of extensive dairy production to contribute to nature areas valuable for biodiversity loss mitigation meets scepticism from conservation experts. This is due to the typical high stocking rates risking overgrazing, but also that most dairy cows have a high intake of energy-rich feed, resulting in substantial manure excretion and thus elevated nutrient levels in the pastures. Even the value of pas-ture-based beef cattle production have been found limited in practice due to over-stocking and -grazing (Ejrnæs et al., 2023). To contribute to halting the loss of species in Denmark, there is a need for habitats which are open and infertile and either wet or very dry, as it is primarily species associated with such landscapes which are declining (Finderup Nielsen et al., 2021).

As such, alternative modes of dairying have struggled to gain traction in Denmark, a country dominated by intensive, specialised, and indoor dairy farming. In addition, even in the context of a green transition (Hastrup et al., 2022), the potential of pasture-based dairy farming to meet aims of multifunctionality, i.e., both for food production and ecosystems functions such as biodiversity, has received little attention in scholarly research as well as public discourse on sustainability. Thus, knowledge on the practical operation and dynamics, potentials, and challenges in a broad context is necessary to demonstrate whether and how alternative dairying can contribute to the twin aims of producing food and supporting biosphere integrity (genetic diversity and functional integrity in ecosystems).

It is therefore the ambition of this paper to offer a deep description of such systems and to provide context rich data on these two main concerns towards multifunctional pasture-based dairy farming – the risks of nutritional stress for dairy cows and the biodiversity potential of the pastures. In this, farmers play a central role as their ways of thinking and decision-making strongly shape land-use practices and outcomes (Glenna, 1996; Beedell and Rehman, 1999; van den Pol-van Dasselaar et al., 2020). At the same time, the management of the system – regardless of type – is likely to be just as important as its design when it comes to ensuring good animal welfare. (Mee and Boyle, 2020). It is therefore highly relevant to include the farmers' perspectives and practical management in the study of cow-pasture dynamics in multifunctional pasture-based dairy farming.

Drawing on qualitative research with farmers and biologists as well as body condition and milk production data, this study takes a case-based approach to investigate the potentials of pasture-based dairy systems to promote biodiversity while supporting adequate dairy cow nutrition for milk production. As such, we aim to address the following four research questions at two low input, pasture-based dairy farms:

- Do BCSs and milk yield data across the seasons indicate risks of excessive nutritional stress for the cows?
- How do qualitative data on how the farmers attend to cows in relation to feeding and well-being compliment the BCS and milk yield data for a more encompassing system-cow compatibility evaluation?
- What characterises the farmers' management of pastures and grazing in relation to their multifunctionality goals?
- How do experts on biodiversity evaluate the nature value of the pastures grazed by dairy cows in relation to potentials for biodiversity loss mitigation?

The research questions will be addressed through integration of the different qualitative and quantitative data, an approach which will be specified in the following section together with a description of the case farms.

5.2 Materials and Methods

Two case farms (Farms A and B) were selected for their choice to produce milk within a low-concentrate-input and pasture-based production frame. Farm A was a well-established farm with over 30 years of experience and Farm B had been operating for two years at the time when this study was initiated and was still in the establishing phase. Limiting the farm number allowed for the development of deep and exemplary insights rather than more superficial knowledge across a larger sample of farms. As such, while the number of cases is small, the information power (Malterud et al., 2016) of the cases is high. In addition, dairy farms based on pasture with low concentrate supplementation were rare (estimated to be less than 1% of all dairy farms) in Denmark at the time of the study.

The farms were followed over the course of more than three years, starting in May (Farm A) and August (Farm B) 2021 and ending by the end of 2024. The study approach included collection and generation of both qualitative and quantitative data. Data and methods frequently used in animal science (analysis of data on production and BCS) were integrated with qualitative data from interviews, conversations with both farmers and biodiversity experts, as well as observations at repeated visits to the farms (i.e., 24 and 26 farm visits to farms A and B, respectively). The body condition of cow is an indicator of access to nutritional resources but can also reflect other factors such as disease and has been termed an 'iceberg' indicator for the overall welfare of the animal (Fisher et al., 2020). Thus, the BCS measure was chosen to indicate the overall system-cow compatibility at the farms. This was complimented by the qualitative data to provide better understanding of the underlying contexts of the BCS measures and to unfold the complexity of balancing different factors in the daily farm management (Ritter et al., 2023).

We worked with two overlapping time periods in the study. First, the approximately 3.5-year overall study period, and second, the BCS observation period, during which the BCS of all cows were observed and recorded up to eight times per cow. Although these study periods overlapped chronologically, they represent different methodological approaches to the fieldwork, and yet the methods were linked to address the research questions. For example, interviews were conducted to reflect on and discuss the BCS and production data with the farmers. Figure 5.1 provides an overview of the study design and the chronology of the data generation, which will be described in more detail following the case farm descriptions in section 5.3.1.

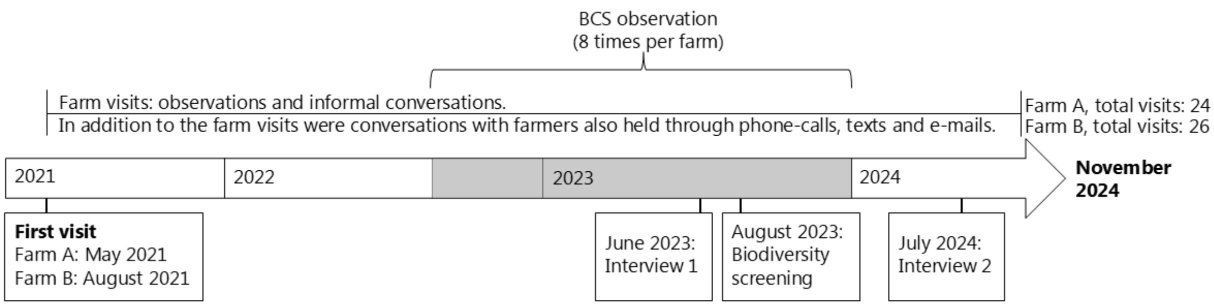

Figure 5.1 Overview of the study design and fieldwork timeline for data generation.

5.2.1 Case farm descriptions

Farms A and B both included around forty lactating cows during the study, which is considered small-scale in a Danish context where the average herd size in 2023 was 246 (Denmark's Statistics, n.d.). While the management and landscapes of the two farms differed substantially, they both operated with an average yearly milk yield per cow that amounts to approximately half of the Danish national average of 11,310 kg energy corrected milk (ECM) per cow per year in 2022-23 (Viking Data- & Ydelsesservice, 2024). The general characteristics of the two farms are summarised in Table 5.1. A rough overview of the feeding can be found in Table 5.2. In the following, the background and pro-duction practices are described for each farm.

Table 5.1 Farmers and farm characteristics. Values separated with a slash indicate values for 2022 and 2023, respectively

	Farm A	Farm B
Farmer pseudonym in citations	F.A.	F.B.
Age of managing farmer	71-74	29-32
Nr. of employers	0	1-2
Started the dairy prod., year	1990	2019
Avg. number of dairy cows per year	40.1 / 39.1	30.1 / 40.7
Breeds[1]	RDM, JER, FAY	MIX, RDM, JER
Stable characteristics[2]	Loose, deep litter	Loose, deep litter
Pasture access	All year[3]	April-November
Milking system	Tandem milking parlour with 6 spots	Tandem mobile milking wagon with 4 spots
Calf management	Nurse cows / dam-calf	Nurse cows / dam-calf
Calving period	March-July	Bi-seasonal (with irregularities)
Replacement heifers	Housed with cows when >1 year. Separation and weaning at 3-5 months.	Housed separate from cows after separation and weaning at 3-5 months.
Milk yield/cow/year, kg ECM[4]	5,250/5,927	4,546/5,107
Milk yield/cow/day, kg ECM[4]	14.4/16.2	12.5/14.0

[1]RDM = Red Danish Milking breed; JER = Jersey (Danish); FAY = Finnish Ayrshire; MIX = Mixed breed.
[2]At Farm B, included access to an outdoor concrete area, the barn was only used during the housing season
[3]Only in rotation in growth period. Pastures adjacent to the stable used during the winter at the leisure of the cows.
[4]ECM = Energy-corrected milk

5.2.1.1 Farm A

The feed consisted of grazed pasture forage and wrap silage for all animals. Lactating cows were additionally supplemented with a concentrate-mix at milking (see Table 2). The farmer practised a low-input feeding approach, feeding relatively low amounts of dry matter (DM) per day without attention to precise optimisation or the chemical composition of the feed. This practise was developed through experience, the characteristics of the local land and a graph from a handbook for cattle husbandry from 1997 showing the highest feed efficiency (kg ECM per Scandinavian feed unit) up to a production of approximately 18-20 kg ECM per day. A study (Butler et al., 2008) showing improved milk quality from low-input grazing-based dairy systems, had further in-spired Farmer A to use the low-input, grass-based design. His goal for the production was that it should, as he phrased it, "*rest in itself*", aiming for a simple and balanced production that did not rely on too many inputs or constant problem-solving.

Lactating cows, dry cows and heifers >1 year were housed together in the same herd in a deep-litter loose-housed system and had access to both the pastures and the stable all year round. Nurse cows and calves were housed in pens located by the end of the deep litter area. Nurse cows were separated from the calves in the morning and grazed with the herd until they were milked by the farmer in the afternoon. The farmer had always practiced this nurse cow system. However, in 2023 the farmer decided to let the cows care for their own calves until sale or separation and weaning. The farmer delivered the milk to an organic dairy cooperative, and the bull and other surplus calves to an organic beef producer. There were no employees at Farm A.

5.2.1.2 Farm B

Farm B was not yet fully established in terms of farm infrastructure and cow numbers by the start of the study. He was driven by the idea of regenerating soils with permanent pastures and grazing cattle while turning sunlight into high quality food. This was inspired by the 'Holistic Management' farming and grazing method (Savory and Butterfield, 2016), which will be specified later. During the study period, the management of this farm changed considerably through experience and experimentation. In August 2021, all cattle were 100% grass-fed, and the farmer used late (~4 months post-partum) dam-calf separation, natural mating, and horned cattle. In 2022, the farmer started supplementing lactating cows with a small amount of rolled barley, and in 2023 he started using artificial insemination. Gradually, over the study period, the dam-calf system was replaced with a nursing-cow system, separating dam and calf 2-3 weeks post-partum.

The animals were housed 100% at pasture throughout the growth season (April-November), where the pastures, at times supplemented with silage, formed the core of the feeding. During the off-growth season, they were housed in a barn with access to an outdoor concrete area. Heifers, and during the grazing season, also nursing and dry cows, were housed separate from the lactating cows. The cows were milked in a mobile milking parlour, which up until 2023 were moved between the pastures in the grazing season. In 2023, Farmer B established a more permanent milking location for the grazing season. During the winter the milking parlour was parked on a concrete plat-form next to the stable. All milk was processed and sold through their own farm dairy at a premium price. During the study period, the farmer had 1-2 employees helping with milking, feeding, and grazing management.

Table 5.2 Feeding characteristics based on data on the winter feeding and yearly use of concentrate. Values separated with a slash indicate values for 2022 and 2023, respectively

	Farm A	**Farm B**
Feed substrates	Pasture, silage, concentrate mix	Pasture, silage, rolled barley
Winter feeding composition for lactating cows[1]		
Total Dry matter intake (DMI)/day, kg	13.3/14.4	12.4/16.3
Roughage share of DMI, %	77%	83%/71%
Concentrate share of DMI, %	23%	17/29%
Conc. fed, avg. kg DM/cow/year[2]	1,096/1,218	365/942
Conc. fed, kg DM/cow/day[3]	1.4-4.8	1.0-4.8

[1]It was assumed that no pasture forage of consideration was consumed during the winter, although the cows at Farm A had access to pasture. DMI for the winter period were estimated from the average use of roughage and concentrate during this period.

[2]Estimated from the total purchase of concentrate. The amount for 2022 at Farm B were used from August-December. Thus, if the amount used during those months had been used for the entire year, the amount would have been 876 kg DM/cow/year.

[3]Where the variation at Farm A depended on the dosage to the specific cow (according to her milk yield), the variation at Farm B were primarily adjusted according to season and time (e.g. the cows were fed more concentrate in winter compared to spring, but also more the winter 23/24 compared to the winter 22/23).

5.2.2 Quantitative data

The quantitative data included a longitudinal study of cow body condition as well as production data, including calving and dry-off dates, milk yields, and medical treatment events, from September 2022 until December 2023. The milk yield data were extracted from the test-day milk recordings performed 11 times a year. At Farm A, nursing cows were milked once a day. The same was true for cows with calves during the 22/23 winter at Farm B, whereas later, missing milk yield data in Farm B meant the cow was nursing calves and not milked. The supplementary figures, Figure 5A1 and 5A2, illustrating the milk yield data for the individual cows, are thus difficult to interpret, as we could not specify the exact time periods where each of the cows were both nursing and being milked.

During the 16-month BCS observation period, all cows (lactating, nursing and dry cows) at each farm, were scored approximately every second month (8 times in total). All recordings were performed by the same observer (first author, Eriksson). BC scoring was trained together with experienced herd health veterinarian, (co-author, Bay Lastein) before the observation period was initiated. This included testing the BCS method at pasture. As it was not possible to restrain animals at these farms to allow for palpation, the BCS were performed at pasture or in a loose housed setting (winter). Thus, all scorings were done with a distance to the animals between 1 and 15 m using a five-point scoring system (1 = emaciated, 5 = severely over-conditioned) with quarter point increments (Edmonson et al., 1989). Autofocusing binoculars were used when needed to read the ear tags and/or to get a closer look for BCS determination. The cows were inspected from behind and from the side. Intra-observer (test-retest) reliability was tested both before and during the BCS observation period, with good to excellent agreement beyond chance (see Appendix 5A).

The final BCS dataset from Farms A and B included 312 and 306 scorings of 46 and 47 cows, respectively, each scored at least once in the observation period. Of these, 35 cows from each farm had at least seven scoring events covering a full year, which we consider sufficient to represent the individual cows' BCS fluctuations over time, and refer to as a full BCS course for the cow.

5.2.3 Qualitative data

The qualitative data consisted of interviews and fieldnotes from personal observations at the farms and informal conversations with the farmers, and one of the employees at Farm B. Farms A and B were each visited 24 and 26 times, respectively, by Eriksson.

The informal conversations were purposely shaped by the conditions and events at the time of the visit. The longitudinal study of body conditions ensured a regular visiting schedule (at least every second month) with observations of pastures and farm conditions, giving insights into the everyday dynamics of cow-pasture management over the changing seasons.

Two semi-structured interviews were conducted at each farm. The first was con-ducted on June 14, 2023, by the researchers Eriksson and Overstreet and was themed around the farmers' observations of the cows on pasture and how the farmers navigated pasture-feeding as a central part of their production. The second interview was conducted on July 29, 2024, by Eriksson. This was themed around the idea of 'the good cow' and challenges related to feeding strategy, breeds and production. The BCS data, including BCS patterns for the herd and individual cows were used actively during this interview. Interviews 1 and 2 from both farms lasted 20-30 and 45-60 minutes, respectively, and were recorded and fully transcribed. Fieldnotes from farm visits were digitised and pictures and video materials were used to supplement fieldnotes.

In addition, both farms underwent a qualitative biodiversity screening on August 17, 2023, conducted by two biologists (Biologists A and B) from a private company specialising in working with farmers and other landowners to improve biodiversity. The date was deliberately selected by the biologists as the optimal time of the year to evaluate biodiversity value and potentials. The visits were intended to contribute material to the discussion on how or whether dairy farming can play a role in nature conservation – more specifically by mitigating genetic biodiversity loss through managing pastures that support species associated with open, meadow-like habitats, a landscape type increasingly scarce in Denmark (Levin and Normander, 2008). The visits lasted around three hours at each farm, and the farmers and Eriksson accompanied the biologists during their evaluations and engaged in informal conversations about their observations during the assessments. These visits resulted in reports made by the biologists, evaluating the nature value and potentials at the farms and providing data for this paper.

While the first semi-structured interview at the farms was conducted in English (because native English-speaking author Overstreet participated in those interviews), all other quotes used in the present paper, were translated from Danish to English by the first author, using a University of Copenhagen-licenced version of the AI tool Microsoft Copilot as support to consider and choose between alternative suggestions to the translations. This process helped facilitate and improve the translations of meanings. In addition, the informants (farmers and biologists) were presented with the translated quotes for approval.

5.2.4 Data analysis and research ethics

The questions this paper set out to explore, and the presented results, were identified through iterative analytical movements between the field of study, the heterogeneous data material, interpretations, and analysis. Framing the analysis was a drive to understand how interests of achieving good conditions and outcomes for the cow-pasture relation on the two case farms unfolded. This included a special attention to the risks and potentials associated with aims of multifunctionality in dairy farming, as framed in the introduction. Working with only two farms enabled this novel approach of integrating different sources of data, considering multiple aspects and the relations between the farmers' practices, aims, and ideas, and the outcomes of the cow-pasture relation.

This work was part of the transdisciplinary research project 'Cattle Crossroads. Researching Danish livestock production for the future', which was approved by The Research Ethics Committee at the Faculty of Humanities and the Faculty of Law, University of Copenhagen. A signed declaration of consent to use quantitative and qualitative data from interviews, conversations, and farm records was obtained from both farmers. All material was stored in a secure drive. Additionally, both farmers and bi-ologists were presented with these writings, to avoid misconceptions, as is standard procedure in ethnographic research (Iphofen, 2021).

5.3 Results

To structure the empirical data and results, this section is divided into the following four topics, each relating to the four research questions: 1) reviewing the body condition scoring and milk yield development in relations to risks of prolonged nutritional stress, 2) the farmers' attention and responses to system-cow compatibility indicators, 3) the pasture and grazing management, and finally 4) the biologists evaluations of the grassland conditions and nature value, with emphasis on potentials for biodiversity loss mitigation.

5.3.1 Patterns in body condition and milk yield, with focus on risks of nutritional stress

The average herd BCSs across all observations over the 16 months were 2.8 and 3.1 for Farms A and B, respectively. Figures 5.2 and 5.3 show the development of a) the average daily milk yield over time and b) the average BCS over time, including the distribution of individual cows, throughout the observation period, for Farms A and B, respectively. The average BCSs over time at Farm A were relatively stable, with small fluctuations around the overall mean of 2.8 (ranging from 2.7 to 3.0). The lowest average seemed to appear during the growth season where most cows were in the first part of their lactation, and where the average daily milk yields were highest (between ~20-25 kg ECM/day/cow). At Farm B the average herd BCSs showed an increasing trend from the beginning (3.1 and 2.9 at the two first observation events) to the end of the observation period (3.2 and 3.4 at the two last observation events). This was also found in the average daily yields, which were higher by the end of the grazing season in 2023 (~22 kg ECM/cow) compared to 2022 (~17 kg ECM/cow). The drop in daily milk yield during the high summer of 2023 was likely connected to the bi-seasonal calving design, where more cows were in late lactation at that time.

Average BCS and variation only inform on population-level. To analyse the dataset for risks of excessive nutritional stress affecting the individual cow, the data from the very thin cows (BCS < 2.5) were extracted for deeper analysis. During the observation period, there were nine observations of BCS 2.25 at each farm (2.9% of all scores). These involved five cows (11% of all scored cows) at Farm A and seven cows (15% of all scored cows) at Farm B with at least one BCS of 2.25. The BCS trajectories of these cows are depicted in Figures 5.2b and 5.3b for Farms A and B, respectively, to show the context of the incidences of very low BCS. The BCS profiles can also be found in the individual cow plots together with milk yield data in the appendix Figures 5A1 and 5A2, respectively.

The five cows at Farm A were Cow A1, A4, A10, A28 and A31, who all had a full course of BCSs. Apart from Cow A1, who was a Finnish Ayrshire, they were categorised as RDM breed, although with high shares of Finnish Ayrshire genetics. This was the breed Farmer A had preferred before it was included into the RDM breeding program under the name VikingRed (VikingDanmark, 2020). Both Cow A1 and Cow A4 were old cows (15 and 12 years at first BCS observation, and on 10th and 9th lactation, respectively). Where Cow A1 continuously had a low BCS, the low BCS for Cow A4 coincided with a drop in her daily milk yield (see Figure 5A1) shortly after she was treated for ruminal bloat and dried off. The remaining three cows had BCS of 2.25 observed 1-2 times during the autumn of 2022 and had BCS 2.5-2.75 throughout the rest of the observation period (see Figure 5.2b). They all yielded above the farm average during the same period (Figure 5.2a). Only one, Cow A1, stayed at that very low BCS-level, and overall, the cows that produced the most milk appeared to also be the ones that remained relatively thin over time at Farm A.

The seven cows at Farm B were Cow B7, B8, B16, B20, B21, B45 and B47. All had full courses of BCS observations, except Cow B45 that was culled after the first observation and therefore has no trajectories in Figure 5.3. Three were Jerseys, two RDM breed, and two mixed breeds (50% Holstein). The observations of BCS 2.25 for five of these cows occurred during the 22/23 winter. All five cows had calved in November and December 2022 and were therefore in early lactation during that winter. Reviewing their daily milk yield in Figure 5.3a, it appears that the low BCSs were not due to the expected high milk yield in early lactation but rather associated with other factors related to the winter housing period, as all cows increased in milk yield and BCS once they were back on pasture again. Over the 2023 growth season at Farm B, no animals had very low BCS, and the number of thin cows decreased, as is evident in Figure 5.3b.

To contextualise and nuance these results, they were brought to the farmers in the interviews in July 2024, motivated by the idea that a low BCS can mean different things depending on the context, and not necessarily be a product of the feeding design. In the next section, we present the farmers' thoughts and perspectives on cow management and thin cows, based on data from interviews and farm visits from the entire study period (described in section 5.2.3).

5.3.2 Farmers' cow and feeding management: broad attention to milk yield, manure, and cow behaviour

What does it mean — and what does it do to the cow — to be thin? Farmer A was asked this question in the interview in July 2024, during a discussion of the preliminary results from the BCS observations. "*I mean.. they don't seem different*" he answered and said that he had never dried off a cow because of body condition or experienced any health issues specifically related to thin cows. The farmer summarised his feeding approach as follows:

F.A.: "*I have something and then it's the cows that have to adjust. They have to figure out what they want to do with it… and if it's lousy quality, well then they don't give as much milk and that's it*."

In other words, the farmer expected the cows to adjust to variability in feed quali-ties and amounts. However, he did manage the concentrate allocation by differentiating the amount according to the individual cow's production level – assessed in the milking parlour on a daily basis – which differed considerably among the cows:

Eriksson: "*Then there are some cows to which you give more concentrate feed than others?*"

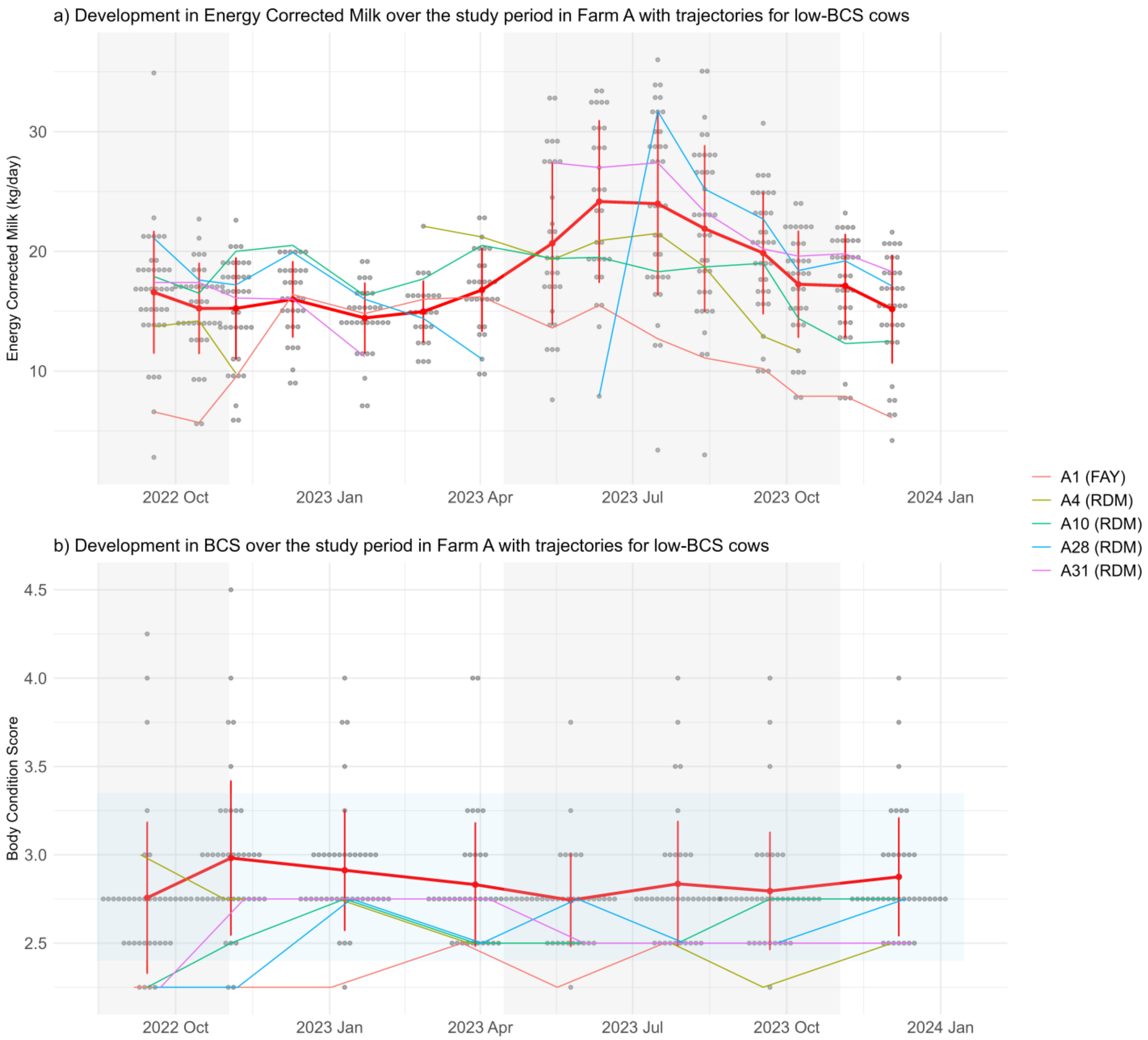

Figure 5.2 Farm A a) Daily milk yield and b) Body Condition Scores (BCS) in the study period from 2022-09-01 to 2023-12-31. The blue shadings in b) mark the optimal BCS range for dairy cows in production (Roche et al., 2009). Grey points represent individual cows and the grey shaded area mark the grazing (growth) season. BCS and milk yield trajectories for cows with at least 1 BCS of 2.25 are shown. Red line-connected points and vertical bars mark mean and standard deviations for the herd average, respectively.

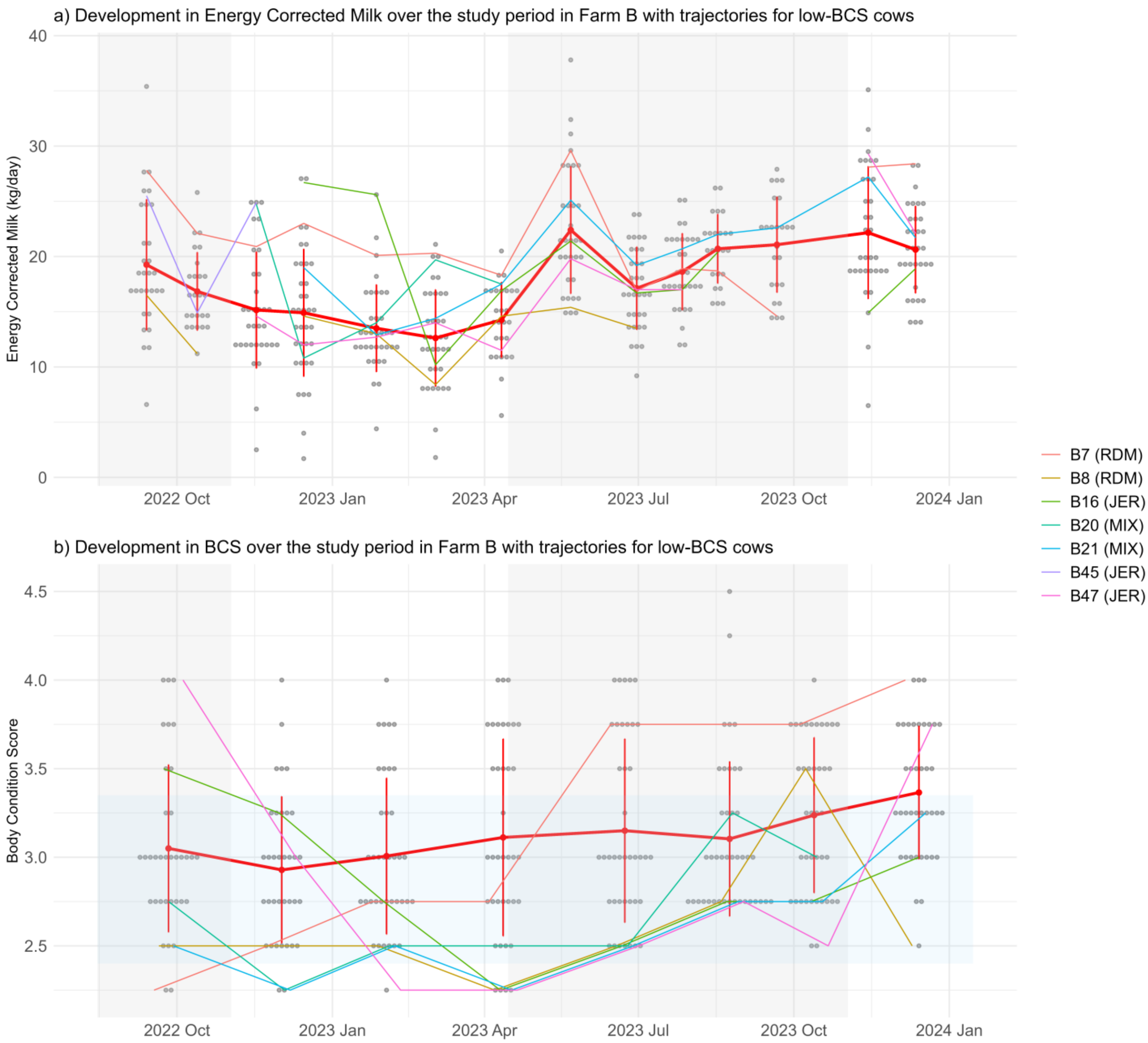

Figure 5.3 Farm B a) Daily milk yield and b) Body Condition Scores (BCS) in the study period from 2022-09-01 to 2023-12-31. The blue shadings in b) mark the optimal BCS range for dairy cows in production (Roche et al., 2009). Grey points represent individual cows, and the grey shaded area mark the grazing (growth) season. BCS and milk yield trajectories for cows with at least 1 BCS of 2.25 are shown. Red line-connected points and vertical bars mark mean and standard deviations for the herd average, respectively. Cow B45 was culled shortly after the first BCS observation and therefore do not have a BCS trajectory.

F.A.: ”*Yes. That's if they are very high-yielding, it takes a toll on them. There are some that produce significantly more than the average. […] Some produce around 8000 kg of milk per year and some around 3[000]*”.

While the farmer had at one point indicated that he sometimes would increase the concentrate supplementation, if a cow was very thin, he also commented:

F.A: "*…but you also have to be careful with that because then they just give more milk, and then you are in the same position as before*".

When asked about the '2.25 BCS'-cows mentioned in the previous section, Farmer A talked about the cows' milk yield level (in relation to Cow A10, A28 and A31) and age (in relation to Cow A1 and A4) as causative reasons for the low BCS.

About Cow A1, Farmer A said: "*Yes, she is old*". He had said already at the beginning of the BCS observation period that he was not sure she would be able to handle another calf, indicating that she was getting too old to continue for much longer. To Cow A10, when asked if she was 'good' and thrived in the system, Farmer A answered:

F.A.: "*Yes, she milks a lot" and "I actually think she does… because she is one that pushes her way forward… when she goes in for milking, she stands there and then the others just have to get out of the way*".

Cow A10 was on her 6th lactation during the entire observation period. At the time of the final BCS scoring, she had reached 617 Days in Milk (DIM) and almost 10 years of age. She lactated until April the following year (dry off at 753 DIM) and had her 7th calf in June 2024. Extended lactations such as this were a common phenomenon at Farm A. Farmer A had explained that he would often let the older cows 'skip a calving', demonstrating a management approach that considered the individual condition of each cow and adapted farm operations accordingly.

The attention to the general condition, drawing on information on both behaviour, milk production and appearance of the cows, appeared as the primary input Farmer A used to assess health and well-being. In that sense, a cow could be thin (e.g. BCS 2.25) for a period, as long as she behaves and produces normally.

Such attention and perspective were also found at Farm B. About Cow B45, the one that was culled after one (2.25) BCS observation, Farmer B explained that she had lived in a tie stall system for many years and had not adapted well to the loose-housing and pasture-based system and thus ended up being culled. Further, on the BCS observation day in April 2023, where four cows had a BCS of 2.25, Farmer B said in a conversation about them, that he found that as long as they were milking, eating, and were up and walking, then it should be ok. However, he was not completely happy with that winter, as evident from the following statement from the interview in July 2024, when asked to comment on the Jersey cows that were thin during the barn housing period:

F.B.: "*…now I think it's hard to say whether it has been the system and feeding and such, or if it has been a combination of many things. But among other things, there has been a hierarchy and some horns that maybe have kept them from just being able to eat…*"

He believed the challenge with hierarchy was the primary cause of the low BCS of the Jersey cows B16 and B47, but also generally for the low scores that winter. After that winter, the farmer started using artificial insemination instead of natural mating, primarily to breed for polled genetics to avoid both horns and dehorning, which he considered negative for animal welfare.

The quality, i.e. digestibility and energy content, of the silage fed during that winter had varied. Early in the season, Farmer B mentioned that he regretted purchasing some of it, referring to an autumn seed grass cutting, and saying that he could see on the cows' milk yield whether the feed was good or not. During the 22/23 winter, the barley supplementation for the lactating cows had been around 2.4 kg DM/day/cow. This amount, although it was lower during some parts of the 2023 growing season, was doubled during the following winter, increasing the concentrate supplementation significantly. When discussing the overall increasing trend in BCS over the observation period Farmer B added:

F.B.: "*I also know that we have become better and better at cutting silage, and we have gotten better and better winter feed. […] But… of course, the biggest factor is that the energy al-location has been higher… but I also think it can be due to so many things*".

Indeed, it seemed as if the 22/23 winter period had been challenging in terms of providing good enough conditions for the cows, partly because of the issues with horns combined with feed bunk space, and partly because of low forage quality in combination with cows being in early lactation. Farmer A, who had all calvings during the spring and early summer, said that he would usually start feeding with the first cut silage and successively feed with the subsequent cuttings, following the later lactation stages with lower quality forage. However, as Farm B had calvings late in the year, such a strategy is less suitable, as some of the cows will be in early lactation during the winter and therefore have a higher energy demand. Having seasonal calvings is by far most common in low-input, pasture-based farming, and most practical, as it synchronises the availability of the amount and quality of the main resource input (pasture forage) and the peak requirements of the animals (Roche et al., 2018; Delaby et al., 2020). The late calvings at Farm B were due to the need for a year-round and relatively stable supply of milk to their farm dairy, as Farmer B pointed out:

F.B.: "*It's clearly easiest for the stable [the cow production part] to gather them together [the calvings], but for the dairy, it's difficult to handle*".

While both farmers would supplement the pasture forage when needed with silage bales, the practice was most frequent at Farm A, who had more animals per grazing area compared to Farm B (see Table 5.3). At Farm B this was allocated on the ground in the paddock where the cows were grazing, where at Farm A, silage was allocated at the feed table in the milking barn or in a feeding ring at the pasture just outside the stable entrance. The adjustment between grazed and stored forage at Farm A was based on a daily evaluation of the amount of milk in the tank, but also gut feeling:

F.A.: "*It's day by day, looking at the amount of milk in the vat [the milk tank], when it's decreasing as… yeah. […] And sometimes you have to be ahead*".

Thus, if the milk yield seemed to go down or the farmer felt like it was needed, the supplementation with silage was increased.

Farm A and Farm B also had different practices around concentrate allocation. In contrast to the cow-adapted allocation at Farm A described in the beginning of this section, concentrate allocation was primarily adjusted according to the season and grassland conditions at Farm B, with no or only occasional differentiation between the cows. This was likely driving the large proportion of cows with very high BCS that we observed especially during the last half of the observation period (see Figure 5.2b). This connection was also made by Farmer B, who explained in July 2024 that they had not (yet) established a cow-adaptive concentrate allocation system for the employees, who from April 2024 had taken over all the daily work with milking and feed allocation.

While neither farmer controlled the specific composition of the feed, they each had different production contexts, i.e. seasonal vs. bi-seasonal calvings, milk sold to cooperative vs. processing all milk at a farm dairy, and one-person farm vs. farmer with employees. Moreover, the level of experience in managing the farms appeared as a central factor in the challenges faced, where Farmer A had had much more time to explore and experiment, to find what worked well within his local context. At Farm B, both the animal data and the communications with Farmer B indicated the ongoing process of learning and improving farming skills such as making good silage. The conditions at Farm A appeared in contrast very stable. So, although the overall average BCS at Farm B was higher than what was found at Farm A, the observations and conversations at the farms indicated that Farmer A and the cows experienced fewer challenges over the study period, which in part also seemed related to the simpler operation, with no employees or dairy processing capacity to balance, and many years of experience.

Another factor both farmers paid attention to, was the functioning of the cows' rumens by observing the manure as an indicator of production and cow wellbeing. In the interview during the summer of 2023, Farmer B was asked if he ever looked at the manure to get a feel for the state of the cows and the feed quality:

F.B.: "*All the time. Every time you go for milking and get the cows in. It's [the manure consistency] an indication of how much milk there will be in the tank. […] I mean, you can definitely read everything you need to know"*.

Both farmers told the same story about the springtime and good alfalfa forage, that it would boost the milk yield, but also give very liquid manure. In such cases they both trusted the cows to regulate their feed intake to balance the rumen, by providing straw or hay for the cows to eat at their leisure:

F.A.: "*…they can eat the straw then. […] they can manage that very well themselves. […] I think they're experts in being cows*".

This section has unfolded how the context of specific cows, i.e. old age, disease, or not being able to adjust from previous tie-stall conditions, to specific challenges concerning the winter housing with horns, hierarchy and feed access issues, varying silage quality in combination with start lactation, and not yet having established a system for differentiating the concentrate supplementation had created challenges for balancing BCS for some cows. It also showed how the farmers tended to such issues by observing the cows and their production and responding by improving practices to enhance conditions or deciding to cull specific cows. As such, excessive body fat mobilization specifically caused by the feeding approach and production design did not seem to be perceived as a problem to these farmers, although some cows were continuously relatively thin.

As indicated by the interview excerpts on manure and alfalfa, both farmers pay attention to how specific forage types and pastures affect milk yield and the rumen function. Thus, based on the qualitative data (fieldnotes and interviews), we will move on to investigating the grassland practices and how the interests and goals of the farmers guided or changed the pasture management.

5.3.3 Farmers' pasture and grazing management: balancing multifunctional goals

Farms A and B were both designed as grassland farms, with no cultivation of annual crops. However, as we will see later, Farm B did reestablish 12 ha of grassland in 2022, sowing it with yellow peas for whole crop harvest with a pasture seed mix underneath. Both farmers operated under a 'reduced nitrogen application'-scheme, meaning that their average nutrient application to the fields at highest could be 65 kg N ha-1. In addition, while both farmers imported silage, straw and concentrate feed, they also exported nutrients via the deep litter bedding from the stable to local organic vegetable and grain producing farms with no animals.

At Farm A, because of the decision to let the pastures remain unploughed, all grazed pastures were categorised as permanent grassland during the study period. The pasture swards had developed in plant species composition without any reseeding. The farmer said that after two years in a row with summer drought (2018-2019), "*all the grasses disappeared*", changing the species composition of the pastures.

During the time the farmer was operating the farm, some of the fields were by local community officials designated for nature protection by law (so-called §3), as they developed into a nature type that should be protected. This status was in place from the beginning of the present study.

Farmer A said that the total daily milk yield fluctuated from day to day (by up to 100 L, approximately 12-14%) during the summer period, depending on which pasture the herd was grazing. The fields with nature protection 'gave' the lowest amount of milk. He added that he could smell on the milk, when the cows had been eating herbs such as yarrow, because of the content of essential oils. Even though these more bio-diverse fields yielded a lower amount of milk, he talked about them fondly. Some of the grasslands at Farm A – particularly those used for silage cutting (~18 ha) and the most intensively grazed pastures – would usually receive slurry from the milking barn in spring. However, Farmer A explained that the farm's annual milk yield was primarily determined by the amount of precipitation during the growing season, which he considered the most limiting factor for pasture productivity. As such, pasture management was generally characterised by a low degree of productivity optimisation and many of the grazed pastures were unfertilised, apart from the nutrients naturally deposited by the cattle.

Table 5.3 Farm and grazing area. Grazing intensity viewed as area per grazing animal or kg animal per grazed area. Values separated with a slash indicate values for 2022 and 2023, respectively.

	Farm A	**Farm B**
Total farm area, ha	47	57
Main grazing area[1], ha	28	33 / 43
Share of area ≤ 5 years since tilled, %	0	83 / 87
Area with meadow-like pastures[2], ha	11.5	3.9
Additional grazing area (heifers)[3], ha	0	10
Stocking intensity[4], kg animal/ha	924 / 864	505 / 522
Soil type	Sandy	Sandy clay

[1]Where the herd with the lactating cows were grazing

[2]At Farm A this area was a part of the main grazing area, whereas the area at Farm B was separate from the main grazing area and grazed by either heifers or dry cows.

[3]Farm B had a grazing area (permanent grass) 5 km from the farm, only used for heifers and not considered in this paper. At farm A heifers below 1 year were kept at stable, and all others were part of the main cow herd.

[4]Applicable for main grazing area, which at Farm A included grazing heifers, but at Farm B only included cows. Cow weights were assumed to be 550 kg on average and the weight of the grazing heifers at Farm A were assumed to average 250 kg.

Starting out 30 years earlier, Farmer A had looked to grazing-based dairy systems in New Zealand, Ireland and the UK for grazing management inspiration and had practiced a dynamic rotational grazing system, with 14 paddocks in daily rotation. The farmer said at the first farm visit in 2021 that he aimed for "*short and leafy*" pastures. However, already at this visit, he said that he had skipped the sectioning of the largest pasture but noted that "*they actually graze it pretty evenly*". Some pastures were primarily used as night and winter pastures. These were the ones connected to the milking and barn building. Others, primarily the ones where the herd had to cross the public road, were grazed less frequently. According to the farmer, the cows rarely went to the farthest end of one of these pastures, indicating an uneven grazing pressure also within this pasture. Hence, while the average stocking rate depicted in Table 3, with around 864-924 kg animal ha-1, indicates an even pressure at all pastures, this was not the case in practise.

Within the study period, new ideas on grazing management started to take root in Farmer A. In May 2023 he said:

F.A.: "*Here in the autumn of my career, I want to focus on adjusting the number of cows to the land area*".

A year after, he had decided to start retiring and in the interview in July 2024, he reflected on his grazing approach:

F.A.: "*I actually think I have done it wrong… I think I should have just let them [the cows] out and let them take care of themselves*".

Over the study period, and especially during 2023-24, Farmer A had gradually downscaled the number of cows from approximately 50 to 30 and experimented with less controlled grazing management. The farmer was aware of his pivotal shift in perspective, evident from the following interview excerpt:

F.A.: "*Yes… it's the complete opposite… In those [referring to his books on grazing-based dairy production], they [the cows] are just lawnmowers. They shouldn't be… they should be the ones who decide*".

Eriksson: "*Does it also come with the idea of creating a more natural system?*"

F.A.: "*Yes… and I can see that there are many more butterflies and insects and bees…*"

From this, it appears as if Farmer A is concerned with the natural functioning of cattle, wanting to allow the cows to do what cows prefer to do, seeing how it also supports the pasture ecosystem. Thus, the ideas Farmer A had shifted towards were characterised by an act of 'stepping back' and giving (even) more agency to both animals and land.

At Farm B, the link between pastures and cows was central to why and how the dairy production started. However, this played out in a substantially different way compared to Farm A. Consistently throughout the study period, Farmer B and his employees stuck to the holistically managed grazing system, where the cow herd was moved at least twice a day, operating through the idea of balancing pasture rest-time according to sward growth rate, rather than the typical stocking density balancing efforts, and where some of the pasture sward is meant to be trampled down to decompose (feed the soil). While some of the pastures at Farm B had been permanent for many years, most were seeded by the farmer in 2018 and 2019, when the production was initiated, after taking over the management of the land from the previous agricultural cultivation of the fields. The fields that were reestablished in 2022, were by Farmer B named "boring grassland" inherited from the previous farming operation. Farmer B explained why they were reestablished:

F.B: "*They were just not producing, the fields. They were simply too poor*".

Thus, most of the fields grazed by the lactating cows were relatively young (see Table 5.3). The used seed-mixes had contained 20+ species, mixed by the farmer himself, to achieve high plant species diversity in the fields. Farmer B's aim was to let the pastures be permanent and ensure high fertility and feed quality through 'animal impact' (defoliation, trampling and excreting) achieved through holistic grazing. However, this proved to be a challenge. During a visit at the end of June 2022, Farmer B and the employee involved in milking and cow management discussed this:

F.B.: "*It's clear that what's missing is animal impact. High animal impact kickstarts growth and nutrient cycling. There's a spot where we had the gathering area at 11.1 [a specific pasture], where the grass is younger and looks the way I want it. But I can't move the cows eight times a day… This is the hardest period right now, from now until the end of August… There just needs to be more trampling*".

In May 2023, the farmer explained how he had adapted his pasture management:

F.B.: "*I have borrowed a tractor and a flail mower, so I'm following the cows with it. It should also stimulate growth. I would prefer that they [the cows] trampled it down, but it's just difficult with dairy cows… I could easily do it with beef cattle. But with dairy cattle, where their enormous energy needs have to be met at the same time as having them to trample. Damn, that's difficult*".

Later the same year he clarified how he was using and thinking about this management practise to maintain the regenerative idea of feeding the soil:

F.B.: "*Topping off the pastures is a tool that must be used correctly. I top-off once a year and leave the plant material, which is what the cows haven't eaten. I always do the top-off right after the cows have been there*".

In the interview with Farmer B in June 2023 he, however, expressed unsatisfaction with the pastures, but great fondness towards alfalfa, and regrets about seeding orchard grass, demonstrating his pasture observations and learning process:

F.B.: "*[…] I really have poor soils I see, but you can have alfalfa that are this tall…*"

Eriksson: "*Why do you think you have poor soils?*"

F.B.: "*Aaah… They're just not producing anything [laughing]. Maybe it's my management… Well.. I think it's a mix between many things. […] I've learned so many things the past 5-6 years. […] But I think I've listened a bit too much to like one person in the beginning […]. He loved orchard grass. It is everywhere and it is growing very well in the spring. But quite quickly, it just gets really rough and not super nice. […] So, I wanna plough it all… You know, get rid of it and just seed alfalfa [laughing, joking]".*

It was clear, when observing the cattle at Farm B, that they also shared this fondness for alfalfa, seeking out these plants over others when grazing. And, as Farmer A, Farmer B generally trusted the animals to eat what they needed:

F.B.: "*I am a generalist. I have chaos that needs to be orchestrated. I also, at the core of it, don't care what the cow eats; she knows best what she needs*".

Throughout the study period, the fertilising practises at Farm B also evolved. In 2021 Farmer B had been hesitant to apply the slurry collected from the winter stable to the fields, because he wanted to interfere as little as possible with the natural nutrient dynamics of the pasture. However, one of the fields had slurry in July 2022 and in the spring 2023 the farmer applied slurry as soon as the soils were dry enough for the tractor and slurry spreader. He also took the first cutting of pasture forage for silage at some of the youngest pasture fields in the spring 2023. Altogether, the development in the pasture management was visible from the observations over the three summers of the study period. Especially the silage cutting and top-off practice of 2023 appeared to in-crease the uniformity of the pastures and decrease the number of blooms and seed heads in the high/late summer. It also made the pastures look greener.

Overall, the pasture management development at Farm B was characterised by an increased degree of human control, all aimed at increasing the feed value of the forage and productivity of the fields (to better sustain a sufficient milk production). However, Farmer B maintained an attention and awareness towards the grassland processes and his interference with them.

In summary, while the two farms, A and B, were relatively similar in terms of size and production design, the dynamics and development of the pasture management in many ways contrasted each other. Farmer A developed towards less control, accepting the pasture productivity as it was, balanced cow nutrition with supplementation of silage and considering ideas of adjusting animal numbers to the land capacities. Farmer B on the other hand, worked hard to increase and improve the output from the pastures to better sustain the dairy production, increasing control and interference, although within the framework of 'orchestrating natural processes'. Notably, the contrasting career stages and the farmers different goals for the pastures likely played a role in their respective focus and ambition regarding pasture productivity optimisation.

5.3.4 Biologists' evaluation of pasture conditions: varying potentials for (genetic) biodiversity

On the 17th of August 2023 both farms were visited by two biologists (Biologists A and B) as described in section 5.2.3. The biologists inspected all the grazed pastures together with the farmers and Eriksson.

The tour around the pastures at Farm B started with two of the permanent pastures, which turned out to be in good alignment with what the two biologists were looking for in terms of nature value or area development. These comprised 3.9 ha in total, a 3-ha nature protected meadow area bordering the shore of a lake known for its rich bird life, and an adjacent permanent grass area of 0.9 ha. Both areas had been grazed by dry cows or heifers and had not been included in the holistic grazing management plan. Farmer B said: "*These areas kind of serve as a parking lot for the dry cows*", indicating that pasture management was not a priority here and that the pastures were used as needed within the farm's logistics.

Entering the smaller permanent area, where a handful of dry cows were grazing, Biologist A remarked that it was very good that there were so many flowers. Farmer B said that he did not have the heart to top it off, but he probably lost a lot of feed units because of that. Biologist B also remarked on the many anthills and said that it indicated low grazing pressure. Biologist A asked the farmer if he was deworming the cows to which he answered: "*I would never do that*". This is something the farmer also had mentioned the previous year, saying that the worst thing he could imagine would be having to administer deworming medication because, as he said, "*I know how bad it is for the environment*".

In the biodiversity report the biologists wrote the following about this area:

"*There is a good variety with both open areas, scattered trees and bushes, as well as willow thickets. The field contains many different nectar plants, including hemp-agrimony, greater knapweed, and common bird's-foot-trefoil. The field is not registered as a §3 meadow but is developing into protected nature [nature worth protecting]*".

About the meadow area by the lake shore, they wrote:

"*[It] appeared very species-rich at the time of inspection, with many fine plant species. The fact that the meadow is so flower-rich contributes to high biodiversity in itself, but it is also very positive for the local insect fauna, which can find food and breeding sites here. The plants on the meadow benefit from extensive grazing, which keeps the meadow open*".

At Farm A the biologists saw great potentials for the entire area. At the time of the visit, they found a large part of the grazing areas to contain fine nature value. These comprised 11.5 ha out of the 28-ha grazing land and were part of the main grazing area. About these areas the biologists wrote:

"*The fact that the dry meadows appear so rich in flowers during the peak summer period is very positive for the local insect fauna. […] The grazing of the dry meadows is in many ways good, and the flower bloom was fine and varied at the time of the visit (August)*".

The pastures the biologist found to be relevant in terms of nature value for biodiversity loss mitigation, coincided with the areas where the cows had to cross the roads to enter. These pastures also included very steep slopes or were otherwise difficult to access for large machinery. At one of these, a small cluster of oak trees were growing, however, clearly kept down by the cows, as they were showing signs of being topped off. Walking across the fields, the two biologists remarked on species they saw, which were species typical for dry meadows. "*This is what the common bird's-foot-trefoil really looks like*" said one of them, while pointing to the familiar yellow flowered plant, which however appeared much smaller and lower in growth, compared to the ones also found in the main grazing land of Farm B. Other species they emphasised as species typical for the dry meadow nature type, e.g. the grassland mushroom, Blackening waxcap (Hygrocybe conica), and the Pantaloon bee (Dasypoda hirtipes).

Walking across some of the more distant pastures which were not covered by nature conservation, Biologist B remarked that she found that they ought to be protected, as they were in good development. She expressed surprise when Farmer A said they had been Christmas tree plantations just 17 years earlier. When he started leasing the fields in 2006, the trees had been cut down, the area ploughed and sown with barley with a pasture grass mix underneath.

However, at both farms there were areas, where the biologists remarked on the negative effects of the production practises or where they evaluated that there was little biodiversity. For Farm A, they wrote the following about the pastures closest to the stable (constituting 8.7 ha):

"…the areas where the animals gather in winter showed signs of overgrazing and nutrient loading, which is negative for biodiversity. The potential for development towards dry meadow grassland is considered to be

high if fertilization stops and extensive year-round grazing without supplementary feeding is carried out. […] The field shows great potential for developing rich biodiversity and would be ideal to consider in the establishment of a large, interconnected natural area with extensive grazing"

The main grazing area at Farm B, which comprised 42.9 ha in 2023 (see Table 5.3), where the lactating cows were grazed using holistic management principles, were deemed 'too productive to matter', despite the relatively high species richness com-pared to typical pasture swards for dairy cows. Biologist B remarked, when we walked across one of these: "*Well, you can probably tell that our enthusiasm has significantly de-creased since we got out here*".

When asked if such fields did not have any benefits at all, she said: "*Well yes, it helps the generalists [insects that do not depend on specific plant species or environments], but they don't really need help as such*".

At the time of the visit, most of these fields were 1-5 years old and the practise of top-ping off the pastures around June-July was initiated. In the reports the biologists wrote:

"*The rotational grasslands, under the current management regime, do not have the potential to support biodiversity of any significance. This is mainly due to the application of nutrients, which results in dense, grass-dominated vegetation*".

Overall, there were no statements in the reports actively supporting the ideas of multifunctionality. Discussing the potentials for extensive, small-scale dairy farming, such as Farm A, to create and maintain open nature areas and to contribute to biodiversity loss mitigation, Biologist A said: "*Well, it is very difficult to promote something [extensive dairy farming for biodiversity], when there aren't so many examples*". However, alternative perspectives emerged in the periphery. At Farm B, a long barrow was situated next to one of the permanent pastures which was included in the main grazing area. As the biologists wrote, such a burial mound can create a 'historical window' into the species richness that had been in the landscape back in time. Along the edge of the fence at the adjacent field, which was part of the main grazing area, a population of oxlip (Primula elatior) was found. About this they wrote:

"*Oxlip is common in Denmark, but it is not usual to see it bordering cultivated fields*".

After this observation, Farmer B talked about his farming practises: "*I see the soil surface as a mirror. What is above the soil surface reflects how much there is below. The cows are our tool to feed the soil*".

Biologist A who, besides from her education in biology, had attended agricultural school and worked as a farmer, said: "*Imagine if everyone who managed our land had your approach, things would look completely different here [in Denmark]*".

While she was likely not suggesting that all should do just that, the comment emphasises the seemingly obvious connection between farming practices and the effects of various approaches to production on the surrounding areas.

In summary, both farms contained pastures that aligned well with the biologists' perspectives on biodiversity-promoting development and nature value, specifically in terms of their qualities as meadow-like landscapes. At both farms, these pastures had been permanent for many years and were difficult to access for large machinery. They had therefore been spared from ploughing and most likely not been subjected to slurry fertilizing for many years. At Farm A, these areas were an active part of the daily grazing management of the mixed herd and covered a large share (41%) of the total grazing area. However, at Farm B they formed a smaller share (8.3-10.5%) and were used for heifer or dry cows, when the grazing logistics demanded it. The more productive or intensely grazed and fertilized pastures, the biologists found less or not at all valuable for biodiversity loss mitigation in the given states.

5.4 Discussion

This study investigated the potentials of low-input pasture-based dairy farming to create conditions that both accommodate dairy cow nutrition and create value for biodiversity loss mitigation with special attention to the dynamics in farmers' cow and pasture management.

In the following we will discuss the results in three sections, encircling 1) system-cow compatibility, 2) the nuances of biodiversity, practices, and other ecosystem functions and 3) the ongoing negotiations of the cow-pasture relations made by the farmers.

5.4.1 Situated accounts of system-cow compatibility using longitudinal mixed-method case studies

Using the longitudinal and mixed-methods approach enables us to infer that the few instances of very low BCS were likely attributed to factors other than the feeding schemes. This included age, and challenges with hierarchy issues combined with some animals having horns which led to some cows not getting sufficient feed access in the winter stable at one of the farms. The long study period with regular farm visits allowed us to see how such factors were noticed and responded to in different ways in the farmers' management, e.g. improving skills, breeding for polled genetics, culling cows, or adjusting concentrate allocation. We find that this type of information is essential to include in such assessments, together with information on BCS developments over the seasons. In addition, data on daily milk yield complemented this by giving further context to the metabolic turnover at the different BCS observation events. As such, only the old and retirement-ready Cow A1 (17 years old at last BCS observation) showed a persistently very low BCS, whereas all others increased in BCS after a temporary period of very low BCS, or were culled.

The average BCS over the 16 months found at Farms A and B (2.8 and 3.1, respectively) were generally similar to what has been found in other studies researching pasture-based dairy production under no, low or moderate concentrate supplementation levels (0-1,830 kg DM/cow/lactation of standard length (~305 days), which equals 0-6 kg DM/cow/day), ranging from around 2.5-3.1 for the average herd BCS on a 5-point BCS scale (Matthews et al., 2012; Ferris et al., 2014; Coffey et al., 2018; Crossley et al., 2021; Schori and Münger, 2021). Other studies reporting on BCS in indoor-based yield-optimised dairy farms found both lower and higher averages (2.5 and 3.5) (Aeberhard et al., 2001; Green et al., 2014). Average BCS, however, do not say much about the extreme low BCS cases and thereby the potential risks for malnutrition.

The number of BCS observations < 2.5 were all at 2.25 in the present study, and they constituted 2.9% of all scorings at both farms and involved 11% and 15% of the measured cows, at Farms A and B, respectively. Few other studies have stated the BCS spectrum and distribution. However, Green et al. (2014) found that approximately 45% of their 15,150 scores were < 2.5 on a 1-5 BCS-scale with 0.5 increments, suggesting a much higher percentage of very thin cows. However, an Irish study on 82 spring-calving, pasture-based farms found that on average only 2.2% (but ranging between 0-14.9%) of cows during the grazing season (one single observation per cow) had a BCS ≤ 2.5, suggesting a general higher body condition than what we found in our study (Crossley et al., 2021). Furthermore, the Irish study referred to BCS ranges adapted to the seasonal production system, recommending target scores of 2.75–3.25 during the grazing period and 3.00–3.50 during housing – targets 0.25 higher than what was recommended by Roche et al. (2009). However, the Irish study results also implied that there were large differences among the analysed farms in relation to the distribution of BCS in the herds. As such, there does not appear to be consistency in the literature regarding the relationship between average feeding schemes and BCS findings. Nevertheless, comparisons across studies should be interpreted with caution, as score allocations – despite a similar BCS-scale ranges – are likely to vary between observers (Kristensen et al., 2006). Furthermore, while scientific literature generally agrees that BCS is a good measure for the animals’ energy reserves, the correlation between low BCS and potential negative emotional states, such as hunger, is debated (Roche et al., 2009; Fisher et al., 2020). A study from New Zealand investigated the possibilities that thin cows experienced physiological hunger, using time spent foraging under conditions of generous pasture allowances (and daily concentrate supplementation of 0, 3, and 6 kg DM/cow) as a proxy for hunger. The cows in their study had BCS ranging from 2.0 to approximately 4.25 when translated into a 5-point BCS scale. Although the study found that cows with lower BCS spent more time foraging, the time spent on the different recorded behaviours (grazing, ruminating, lying, standing) was found to be within normal ranges for all cows. Thus, the study concluded that low BCS cows were able to balance their milk production with an increased feed intake, without compromising limits for normal behaviour (Matthews et al., 2012). To complement physiological and behavioural time-budget measures, qualitative behavioural assessment – where the animal's body language is interpreted to also capture emotional or affective states – is increasingly used in animal welfare assessment (Fleming et al., 2016). This closely resembles the daily assessments made by the farmers in the present study and illustrates how such observations can be just as valuable for assessing and ensuring animal well-being. However, it also highlights the need for a high level of skill and attentiveness from the caretakers.

Using the BCS both as an indicator for system-cow compatibility as well as a tool to guide the interview process helped to qualify how ensuring sufficient conditions for dairy cows cannot be reduced to a specific feeding scheme. Rather we have shown how it is a product of the context of the individual cows and the farmers' (and their employees') skills, experiences, experimentations and attentions to both pasture conditions and animals. Although at lower levels than would be the case in a yield-optimised dairy production, supplementation with both stored roughage and concentrate turned out to be an important tool to ensure adequate energy allocation to the lactating cows in our study farms. Thus, while some of the cows – especially at Farm A – consistently had relatively low BCS (2.5-2.75), the management of the farmers ensured that body fat was not mobilized to unacceptable levels. A surprising observation at Farm A was that several cows had no or only 0.25 BCS-fluctuation over the entire observation period, contrary to the larger fluctuations typically seen across a lactation. Of the 35 cows with a full course of BCSs, 13 (37%) cows had a stable body condition across both season and lactation stage, a pattern found in cows with different milk yield levels (see Figure 5.A1).

It should be noted that none of the study farmers had purebred Holstein cattle, which is otherwise the most common dairy breed in Denmark (Kristensen et al., 2015; Strudsholm, 2025). This is not a coincidence, as the Holstein breed is known for its high-volume yields, and likely not suited for low-input systems (Davis et al., 2020). A Danish feeding trial compared the growth rate of heifers from respectively Danish Holstein (HOL), RDM (called VikingRed by VikingGenetics), and HOL x RDM on either a standard optimised ration or a low energy ration. They found that the RDM heifers had the same growth rate on both rations, whereas especially the growth of the pure-bred HOL heifers was lower (VikingGenetics, 2021). Further, both RDM and the cross-bred heifers showed higher average BCS than the HOL heifers on the low energy ration. Although this was an experiment with heifers and not lactating cows, it supports – like the studies referred to in the introduction – that some breeds are better fitted to low(er)-input feeding schemes. In the present study, we did not find that the cows of RDM and Jersey breeds in the study should be incompatible with the pasture-based production design. However, breeds and breeding strategies directed toward grazing systems would likely be beneficial, as also suggested by others (Roche et al., 2018; Davis et al., 2020), and this topic was also a conversation topic at the visits to Farms A and B.

5.4.2 Nuances in aims and potentials for biodiversity and other ecosystem functions

Through the evaluation and statements of the biologist, the value for biodiversity loss mitigation corresponded negatively with an increasing degree of pasture productivity, farmer interference (fertilisation and top off practices), as well as grazing intensity. Both farms included pastures seen as valuable, although these were most central at Farm A.

Viewing the observations and evaluation by the biologists together with information on the pasture management, they appeared to correspond with what is known as the "humped-back model theory". This model for grassland diversity describes how highest species richness is found under moderate biomass production levels and lowest under very low (e.g. desert) and high biomass production (e.g. intensive agriculture) (Fraser et al., 2015). It is also in line with findings on other grassland studies, where high productivity and forage quality have been found to negatively affect species richness (Van Vooren et al., 2018; Le Clec'h et al., 2019).

The stocking intensity recommended for nature conservation (mimicking natural densities) is 70-250 kg ha-1 and maximum 400 kg ha-1 (Ejrnæs et al., 2023). These guide-lines refer to recommended year-round grazing intensities for herbivores that roam freely in an area. Dairy production typically involves a much larger degree of animal handling compared to beef production, because the dairy herd is brought to the milking parlour at least once, often twice, a day and where animals potentially are grouped in different ways over the seasons (e.g. as was the case for heifers, dry cows, and nursing cows during the grazing period at Farm B). Thus, the average stocking densities at approximately 864-924 and 505-522 kg ha-1 for the main grazing areas at Farms A and B, respectively (see Table 3), did not reflect the actual grazing pressure for all pastures.

We have no record of the grazing intensity of the two nature-like pastures at Farm B, besides that the areas were used for less-controlled grazing management practices. However, the statements from Biologist B, about the correlation between the number of anthills and a low grazing pressure, indicated a low pressure. At Farm A we observed a much higher average stocking density than the recommendation for nature conservation, although lower than the typical intensive grazing systems found in Ireland, which in a study on stocking density ranged from 1,200-1,600 kg ha-1 (Coffey et al., 2018). Nevertheless, the grazing at some of the more biodiverse pastures were evaluated as "in many ways good", indicating a differentiated grazing pressure between the different pastures and within some of the less heavily grazed pastures. This was the case with the more distant pastures at Farm A, where the herd had to cross a road. The days when these were grazed, the herd did likely not always return after the afternoon milking, as the herd never stayed at them over night.

Another point often emphasised as important for nature conservation is that the animals are not given feed supplements in any way, so as not to import nutrients to the grasslands. This was also one of the suggestions the biologists made for some of the areas at Farm A, where they saw great potentials "*if fertilization stops and extensive year-round grazing without supplementary feeding is carried out*". Yet, the effects of feed supplementation are likely to differ, depending on the practices around it. At Farm B, the animals were kept 100% at pasture and also received any potential feed supplementation there during the grazing season, much like would be the practice with beef cattle. However, as described in section 3.2, the supplementation at Farm A always occurred in or just outside the stable and thus away from the distant and most biodiverse pastures. Moreover, manure and slurry were collected from the deep litter and milking barn stable and distributed to cut-fields (slurry) or exported to a local vegetable producer (deep litter). Thus, there can be practices specifically related to dairy farming, which make it possible to provide feed supplements to cattle grazing biodiverse pas-tures, with low risk of importing excessive amounts of nutrients to those specific pastures. This was likely the case for the Farm A pastures evaluated in positive terms, which constituted 41% of the grazing area. However, such nuances were not considered in the statements by the biologists.

The EU target of 30% of land areas protected by 2030 specifies that 20% can include extensive production, making space for efforts of multifunctionality. It is within this category that low-input pasture-based dairy farming could play an important role. Moreover, in a country like Denmark, where the majority of the land mass (~60%) is in arable rotation (The World Bank Group, 2024), it is also highly relevant to evaluate the effect of land-use practices on the surrounding landscape. The omnipresence of available nutrients in the Danish landscapes has indeed been listed as a likely cause for persistently low species richness in wetland conservation attempts (Baumane et al., 2021). As demonstrated by the oxlip growth at the perimeter of one of the main grazing areas at Farm B, the focus of increasing pasture productivity through orchestration of natural processes as opposed to high nutrient input, might provide an indirect value, though low impacts on the surrounding landscape. Furthermore, multispecies pastures create functional diversity which can support soil life and functions, nitrogen supply and in-crease production resilience under varying weather conditions (Erisman et al., 2016; Reed and Morrissey, 2022). Thus, although these productive pastures may not directly provide habitat for rare or specialist species and thus mitigate biodiversity loss, they can hold significant value within a holistic sustainability framework by supporting other ecosystem functions and buffering more sensitive habitats.

5.4.3 Cow-pasture dynamics: Farmers' negotiations of control, care, and rhythms

While UK farmers and other key stakeholders seem reluctant to say that grazing is fundamental for both animal welfare and environmental mitigation (Shortall, 2019; 2024), we saw that both of the farmers in this study regarded grazing as both a funda-mental part of a fulfilling life for cattle, environmental stewardship and their own en-joyment as farmers. Even though the UK farmers were reluctant to make such claims, they also communicated a clear sentiment of 'the joy of grazing' (Shortall, 2024), which can be interpreted as a reflection of a sense of 'rightness'. A similar statement was made by a stakeholder from the Irish industry, quoted in Shortall (2019, p. 48), who said that, to them, cattle belong outside, grazing pastures. Indeed, Shortall (2019) found that the dominant belief among Irish dairy stakeholders was that grazing dairy cows is essential and promotes both animal welfare, environmental mitigation, and profit maximisation. As such, the farmers in the present study aligned with this way of regarding sustainability. However, Shortall (2022) found that among Irish dairy farmers producing within grass-based frameworks, there was an intensive focus on high field-productivity goals, which was generally obtained through external fertilizer input to pastures of perennial rye grass – a practice thought off as a 'good farming practice'. Such methods were specified in an experimental study of breed performance in intensive pasture-based dairy farming in Ireland, where the pastures were established with 1-2 species and received 250 kg inorganic N/ha/year (McClearn et al., 2020).

This contrasts the attention both Farmers A and B showed to the living world of the pastures, expressed through a low degree of human interference (e.g. applying <65 kg organic N/ha/year) and letting the pastures 'rest in themselves' (Farm A), and an aim to orchestrate natural processes and establishing multispecies pastures to improve soil fertility and pasture productivity (Farm B). While only Farmer B actively framed his production approach as aiming to regenerate soil health, both farmers operated within a more-than-human ethics of care mindset. This is characteristic for what is known as regenerative agriculture, where the farmers relate and understand their dairy farm as situated in biological and social webs of relations (Seymour and Connelly, 2023; Overstreet, 2025). Cattle farmers from the regenerative agriculture-movement equally aim to orchestrate animal movements on pasture to build soil carbon, resituating cattle as a part of the biogenic carbon cycle through grass-eating and specific grazing practices (Cusworth et al., 2022 2024). However, such aims do not live in a vacuum, but are – as we have shown in this paper – situated within specific contexts that imply specific constraints, challenges and potentials.

From ethnographic studies at farms in Finland, Norway and Italy, Kallio and LaFleur (2023) identified three kinds of dynamics within more-than-human relations in regenerative farming: 1) balancing between control and cohabitation, 2) caring for and taking care of, and 3) attending to rhythms of (re)production. At the case farms, these dynamics centred around the pasture and grazing management, although in different ways.

Farmer B was clearly affected by being in a phase of establishing practises, infra-structures, skills and the cow-herd, while balancing milk production and the on-farm dairy capacity and output demand rhythms. To some extent this forced him to make compromises to his initial goals. His wish to minimise human disturbance of the cow-pasture system was also challenged by pastures he described as "*being too poor*" and "*not producing anything*", resulting in reestablishment of pastures, or the desire to do so.

Aims of caring for both soils and energy demands of lactating dairy cows was seen through how Farmer B narrates the top-off (mowing) practises as something that should be used with caution, how he only reluctantly and in relatively small doses applied slurry to the pastures, how he left the plant material when topping off under the logic that the cows did not eat it and therefore it was better left to feed the soil (decompose) and how rather than imposing specific control measures, he aims to 'orchestrate a chaos', recognising the complex relations in the system he manages.

Farmer A, in these last years of his farming career, increasingly shaped his production around principles of cohabitation. We interpret this as the farmer making increasingly more space for land and animal agency (Blattner et al., 2020). He had for many years left the pastures to develop dynamically, even when it entailed lower biomass production and digestibility. He also actively embraced wide variation in cow productivity, kept all animals from the age of one year together in one stable group, letting many cows become much older than the average 4-5 years typical for Danish dairy cows (Arla Foods, 2025), and aimed to let the cattle graze relatively freely all year round, not wanting the cows to be "just lawn mowers", but instead giving them the opportunity to co-determine movements, rhythms, relations, and outcomes.

Throughout, the relationship between cows and pastures has been central to negotiating multiple interests. It serves as a balance point between the cows' dual role as milk producers and ecological agents, and the pastures' function as feed, habitat, and ecosystem.

5.5 Conclusions

This study explored the risks and potentials of pasture-based, low-input dairy farming through a mixed-methods approach, integrating animal data, farmer perspectives, and biodiversity screenings conducted by visiting biologists. The longitudinal analysis of BCS and milk yield data did not indicate malnutrition related to the feeding scheme, which – it is worth noting – included a considerable amount of supplementary feeding. This method-integrating approach opened up nuanced perspectives, moving beyond the study of system categories and isolated indicator measures. We showed through detailed accounts of the two case farms and farmers how good conditions for and of dairy cows are a highly situated matter. Through dynamics of supplementary feeding, daily observations, cultivating skills and adjusting balances in accordance with farm-specific constraints, both farmers demonstrated attentive care toward both cows and pastures. In fact, the cow-pasture relations were found to be at the centre of ongoing negotiations of control, care, and contrasting rhythms, balancing system-cow compatibility, ecosystem interferences, animal agency, and production output. The degree of farmer-led orchestration in grazing and pasture management – through fertilisation, controlling cow movements, and managing plant-species composition – appeared decisive in how the nature value of pastures was evaluated by the visiting biologists. They found that pastures with high productivity, nutrient loading or overgrazing offered limited biodiversity benefits, which was the case for approximately 59% and 90% of the grazed pastures at the two farms, respectively. This is not to dismiss the value of productive pastures with high functional diversity, which can contribute to other ecosystem functions, such as carbon storage, water regulation and nutrient cycling – essential for cultivating long-term healthy and resilient agricultural systems. However, permanent pastures used less intensely – unfertilised and more extensive grazing – aligned more closely with criteria for increasing species richness and thus to mitigate biodiversity loss. The rhythms associated with traditional dairy farming practices – such as daily cow movements away from pastures for milking and supplementary feeding, as well as seasonal regroupings – seemed to create unique opportunities for incorporating biodiversity-rich pastures that are sensitive to nutrient loading and overgrazing, while still meeting the relatively high energy demands of lactating dairy cows.

This study highlighted how cow–pasture relations and grazing management offer a compelling case for studying and engaging with holistic perspectives on sustainability and green transitions in dairy farming. Grazing practices intersect with concerns for animal welfare, environmental health, and production economy, forming a junction point for balancing multiple interests simultaneously. While pasture-based dairy farming is becoming increasingly rare in Denmark and across Europe, we argue with this study that such systems should not be overlooked. Their design offers a meaningful entry point for engaging with the complexity of green transitions in agriculture. By integrating the needs of humans, animals, and landscapes, pasture-based systems highlight the interconnected challenges of sustainability. To support this, more interdisciplinary research is needed – bringing together social and natural sciences and combining both quantitative and qualitative methods – to deepen our understanding of how these systems navigate and balance diverse, situated interests.

Supplementary Materials: Included in Appendix 5A and 5B.

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Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: Anonymised body condition score data and R-code used for visualisation are available upon request from the first author.

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5.6 Appendix 5A

Before initiating the longitudinal BC data collection at the case farms, an in-tra-observer reliability of the scoring method on pasture were tested at a dairy farm with Holstein cows – a breed selected solely for reasons of convenience, as it was not used at the case farms included in the study. This was part of the training of the observer who performed all recordings throughout the present study. Forty Holstein dairy cows were scored on pasture. Of these, 36 were rescored in the stable a few hours later. The cows were still loose, and most were scored with an up-close inspection, but no palpation. Intraobserver reliability between pasture and stable observations was tested using Cohen's weighted kappa (Cohen, 1968) and resulted in a kappa-value at 0.63 or 0.84 with linear and quadratic weights, respectively. Depending on the weight used, this gives a "fair to good agreement beyond chance" or "excellent agreement beyond chance" (DataNovia, 2018). A similar test was performed during the study period, where all cows (n = 42) at Farm B were scored at pasture twice the same day, once in the morning and once in the afternoon, with kappa-values at 0.79 and 0.91 for the two different weighing options, both indicating "excellent agreement beyond chance". The methodology was therefore evaluated as reliable in terms of development over time.

5.7 Appendix 5B

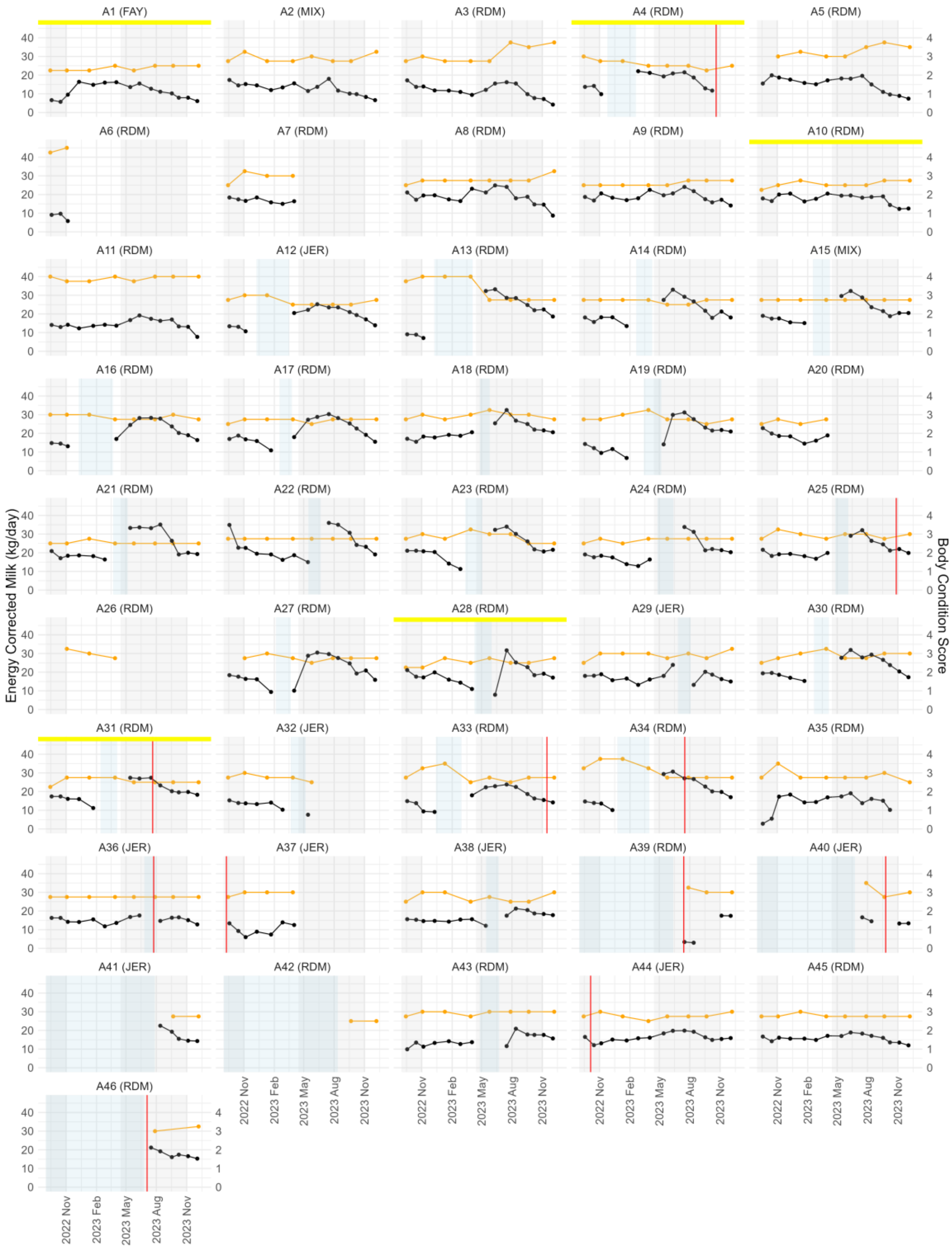

Figure 5.A1 Farm A Body Condition Scores (orange) and milk yield (black) plotted in the study period from 2022-09-01 to 2023-12-31 for individual cows in farm A. Grey shadings mark the grazing period. Light blue shadings mark dry periods. Red vertical lines mark treatment events. Yellow horizontal bars mark cows with at least 1 BCS of 2.25.

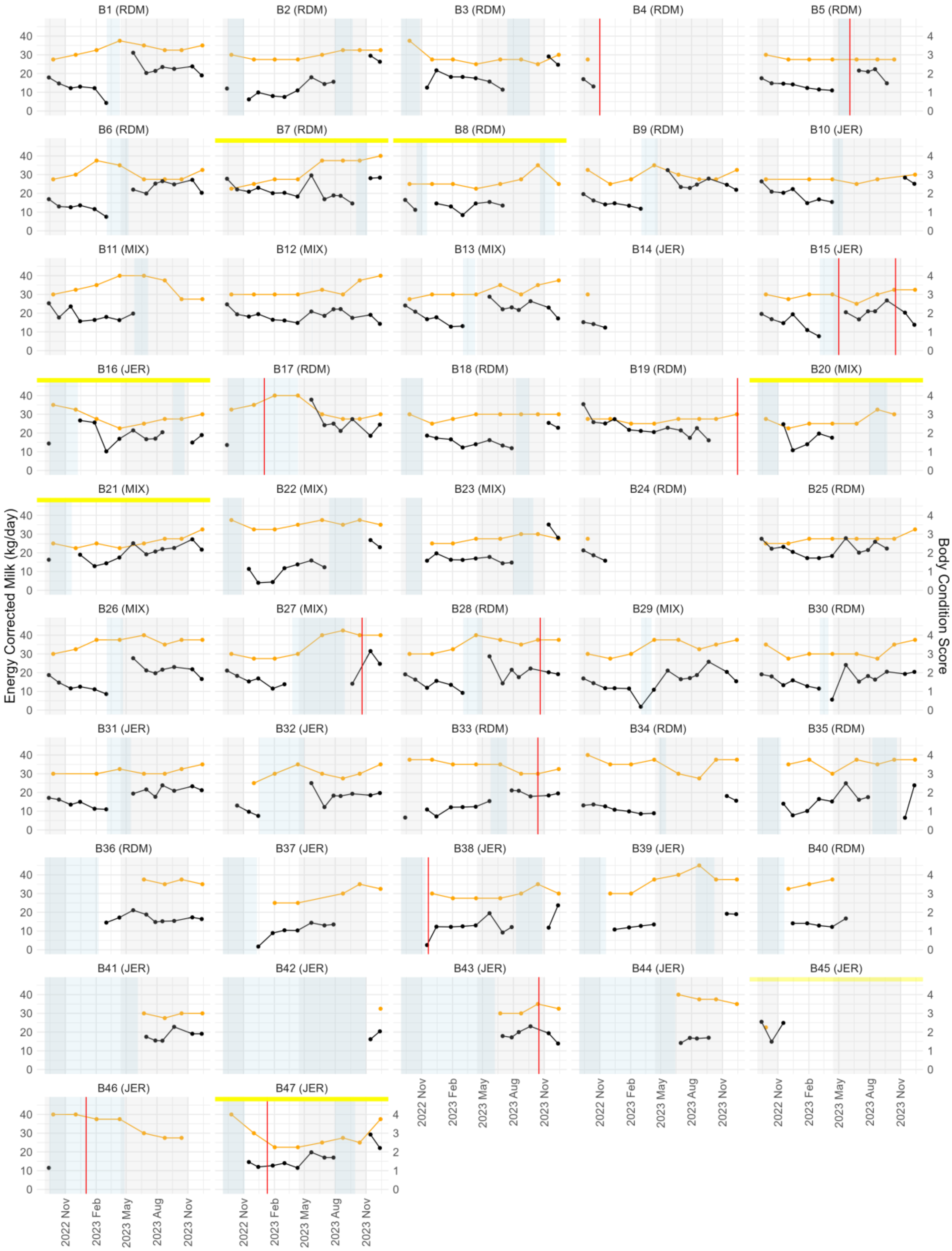

Figure 5.A2 Farm B. Body Condition Scores (orange) and milk yield (black) plotted in the study period from 2022-09-01 to 2023-12-31 for individual cows in farm A. Grey shadings mark the grazing period. Light blue shadings mark dry periods. Red vertical lines mark treatment events. Yellow horizontal bars mark cows with at least 1 BCS of 2.25.

6 Manuscript III: Doughnut Agronomy. Dairy farming and Well-being in 21st century Denmark

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Abstract

For decades, agriculture in Denmark has been shaped by a productivity-oriented livestock agronomy. However, national and international climate and ecological crises pose a scientific as well as practical challenge to the dominant and seemingly limitless productivist farming model. Currently, Denmark pursues net-zero climate targets mainly through technological optimisation, a narrow approach with potential socio-ecological consequences that occludes alternative sustainability pathways. This paper presents reflections based on interdisciplinary research by anthropologists and animal and veterinary scientists on Danish dairy farms with low-input, grass-based and regenerative practices. More specifically, the paper shows how mainstream agronomy has largely failed to attend to extensive dairy systems that do not target maximised yields but instead prioritize ecological limits and meaningful human-animal-nature relationships. Building on economist Kate Raworth's Doughnut Economics-framework and its holistic approach to sustainability, the paper argues for making visible these alternative dairy farming systems as practices worthy of agronomic attention. Extensive dairy systems can work as a productive challenge to mainstream agronomy, urging it to become a science for the 21st century by expanding its knowledge base to include farming that integrates cattle into local landscapes and sustainable food systems, while nurturing both human and animal well-being.

Keywords: agricultural development, dairy production, Doughnut Economics, interdisciplinary research, 21st century agronomy

6.1 Introduction: Climate-efficient food production and Livestock Agronomy

In 2020, something remarkable happened in Denmark: The country's first dedicated climate act was signed by the parliament. "The world's most ambitious climate act", as it was framed by the press and politicians, promises to reduce greenhouse gas (GHG) emissions with 70 percent by 2030 compared to the 1990 level. By 2050, the act targets a net-zero society, and some years later to store carbon amounting to 10% of 1990 levels (Tvarnø, 2022). Within days of passing the act, Denmark's ambitious step to reduce GHG emissions made it into public media across the globe (Timperley, 2020). The Minister of the Environment was invited to speak at international fora, and Denmark was staged as a pioneer country to follow. After the honeymoon period was over, harsh reality set in. Especially for the agricultural sector that is accountable for around one third of Danish emissions, with the livestock sector being responsible for the majority of these (Nielsen et al., 2023). As political attention towards bringing down national emissions increased, the livestock sector responded by emphasising a counternarrative in which mainstream animal production is portrayed as supremely efficient and optimised and thus already one of the most sustainable animal productions in the world (Hastrup et al. 2022). As such, the Danish livestock sector, including the authorities and researchers, are often asked to advise similar sectors abroad and, in this way, encouraged to work as a role model for other countries with regard to food production. In this perspective, Denmark is seen by the industry and political allies as a frontrunner in sustainability, implying that the global climate as a whole would be worse off if Denmark reduced its efficient animal production, as it would risk shifting animal-based food production to other less efficient and productive countries (Dalgaard et al., 2011; Olesen et al., 2021).

The prevalent narrative of a climate-friendly Danish animal production rests on relative sustainability measures of efficiency per unit of product, e.g. litre of milk or kilogram of meat. What it does not do is to take comprehensive stock of the multiple environmental effects of animal production that could challenge this view of mainstream intensified livestock farming as a sustainable means to food (Bøgh Sørensen, 2025). Repeatedly, it is said that cows with their ruminant character can turn 'useless' grasslands, indigestible for monogastric species such as poultry, pigs and humans, into healthy and rich food products. However, cows in Denmark are most often not fed on useless grasslands, but on grain and forage grown on valuable arable land (Brieghel et al., 2022; Kristensen et al., 2015), hence competing with areas needed to produce food crops for a growing global population (Eriksson et al., 2025; van Zanten et al., 2016). In other words, the focus on isolated animal productivity and efficiency measures both builds on and fosters a narrow knowledge base to underpin science-based agriculture, just as it renders sustainability as largely a technical feat.

Looking back, the systematic knowledge on animal productivity was an important driver in Denmark's shift from grain to animal-based agriculture in the early 20th century (Henriksen and O'Rourke, 2005). Further, studies from elsewhere show how knowledge, education, and norms can both be drivers and barriers for system transformation in agriculture (Cusworth et al., 2021; Vermunt et al., 2022). Agrarian knowledge paradigms and work are therefore important leverage points (Meadows, 1999) for green transition and key for building the social capital needed for agricultural transformation. As Denmark pursues net-zero climate targets mainly through technological optimisation, both the potential socio-ecological consequences of this approach and any alternative pathways to sustainable livestock systems are consequently occluded from view. Socio-ecological benefits have for instance been discussed by Vaarst (2015), applying ideas of eco-functional intensification through diversification and attention to the value of and care for animals of the farm systems, including both the domesticated livestock, earthworms, pollinators, wild birds and mammals. However, despite this pioneering work, farms that develop through encompassing eco-functional measures rarely become objects of professional agronomic attention in Denmark, which tends to focus on specialised intensive systems – even though studies from many other countries document multiple beneficial effects of diversified agriculture (Rasmussen et al., 2024). Not necessarily due to lack of interest, but simply because education, teaching, research, regulations, subsidies and the infrastructure are all geared towards an intensive, yield-optimised production. However, given the increasingly critical situation of environmental degradation and planetary pressure, the time is ripe for paying attention to alternative pathways, and by implication alternative ways of knowing and researching dairy farming.

Hence, zooming in on alternative dairy farms as a case in point, this paper draws from fieldwork observations from relatively small-scale (40-140 cattle), pasture-based and low-input dairy farms in Denmark to argue that livestock agronomy as a discipline, specifically what is known as animal science, needs to rethink its perspectives and repurpose its knowledge base, to be able to analyse, understand and facilitate the socio-ecological benefits such farms have to offer. During our fieldwork, farmers at alternative dairy farms have repeatedly told us that they have problems getting relevant support from their advisors; locally attuned expertise about running a dairy farm without aiming for growth through animal numbers and maximised productivity is scarce. Accordingly, the aim of this paper is to address the knowledge gap detected through our fieldwork: the need for a different approach to farm evaluation and optimisation. Specifically, we seek to explore and make visible how an alternative livestock agronomy might pay attention to overlooked practices that take us beyond relative sustainability, i.e. beyond the view of cattle as single units of efficient feed conversion.

To do this, we mobilise the work of economist Kate Raworth from her book “Doughnut Economics. Seven Ways to Think Like a 21st-Century Economist” (2017). Working from a circular image of a doughnut made up by an ecological ceiling and a social foundation, Raworth analyses the balancing acts needed to attend to socio-economic and ecological processes at the same time. She criticises mainstream economics, and employs the planetary boundaries framework (Richardson et al., 2023) to argue that the focus on economic growth is no longer a valid position in the 21st century, given the on-going and multiple ecological crises we are facing. Inspired by the visual force, clarity, and encompassing perspective and not least her call to think an academic discipline differently, we use Raworth’s seven ‘steps’ for our analysis. Thus, we adopt

Raworth's critique of 20th century economics to argue that mainstream livestock agronomy in Denmark – the scientific discipline that has enabled and driven optimisation of livestock production in Denmark – is equally stuck with growth as an outdated criterion, and that an agronomy appropriate for our times needs to attend to a broad range of production parameters.

This paper is organised into four sections. In the first section we briefly outline and unfold the seven 'steps' and the doughnut economy as a theoretical framework. The second section specifies the origin and context of the empirical material. The third section presents our findings in three subsections, each covering 2 or 3 of Raworth's seven (related) 'steps' as applied to the context of alternative dairy farming, including a table summarising our findings at the end of the section (Table 3). The fourth and final section discusses the importance of considering the narratives and context of knowledge work and access for driving transformative change of the agricultural sector and how our work contributes to this.

6.2 Theoretical Framework: Doughnut Economics and Ontological Politics

The ideas of doughnut economics build on the realisation that, instead of development through incremental changes, a systems change is necessary (Meyer and Newman, 2020). This aligns with what Raskin et al. (2008) – scholars of sustainability and global development – termed the 'Great Transition', a developmental scenario shaped by the interplay of market forces, policy reforms, and lifestyle changes.

Raworth argues that we need a new developmental paradigm, as no nation has yet succeeded in improving social conditions without simultaneously increasing environmental degradation. She critiques her own field – economics – by highlighting how mainstream models tend to ignore ecological boundaries, overlook social inequalities, marginalise unpaid and care work, and promote a narrow, market-centred worldview. In response, she proposes seven ways to think differently, aiming to transform outdated 20th-century economic thinking and retool the discipline for the 21st century (outlined in Table 6.1).

Table 6.1: Seven ways to think like a 21st century economist (Raworth, 2017, pp. 26–27)

	From 20th to 21st century economics	
	from	*to*
1 Change the Goal	GDP	the Doughnut
2 See the Big Picture	self-contained market	embedded economy
3 Nurture Human Nature	rational economic man	social adaptable economy
4 Get Savvy with Systems	mechanical equilibrium	dynamic complexity
5 Design to Distribute	'growth will even it up again'	distributive by design
6 Create to Regenerate	'growth will clean it up again'	regenerative by design
7 Be Agnostic about Growth	from growth addicted	growth agnostic

Thus, her work urges us to change the ways in which we work with development. Instead of staying within separated fields of knowledge, we should revise the ways we think, design, measure, and develop to acknowledge interrelations within complex social-ecological systems (Raworth, 2017; Reyers et al., 2018). To do this, she draws on the insights from, among others, systems thinker Donella Meadows and her work on leverage points (Meadows, 1999), emphasising how small changes can produce big transformations. Meadows identified the paradigms, goals, rules and power structures that shape complex systems (living and societal) as the most effective points of intervention for achieving systemic transformations.

Raworth's 'steps' towards a more timely economics provide a productive background for figuring and understanding dairy farming otherwise. Materials from our fieldwork presented in the following work to "agronomise" Raworth's ideas and critiques of last century economics. In doing so, we also engage in what philosopher and anthropologist Annemarie Mol has called, "ontological politics" (Mol, 1999). The notion implies that making some things and practices visible and other things and practices invisible is a political act. In other words, what a scientific discipline chooses to foreground and background has a bearing on what that discipline can 'know'. In an analysis of a foot and mouth disease outbreak in the UK, Mol and her colleague John Law argue that this disease outbreak enacts different 'veterinary realities', and that researchers need to pay attention to how facts are established within each of these versions of foot and mouth disease (Law and Mol, 2011). Their point in highlighting ontological politics is to say that each fact about foot and mouth disease outbreak comes with a distinct repertoire that makes this fact knowable, possibly excluding other facts. This resonates clearly with our findings, as we have observed in our project how alternative dairy productions have continuously been disregarded in mainstream Danish livestock agronomy, as they do not rest on productivism. The 'doughnut agronomy' that we pursue here is thus an attempt to form a more comprehensive basis for agronomy in Denmark and beyond, so that extensive dairy farms can become scientifically knowable in countries where livestock expertise otherwise revolves around feed intensification and yield-optimisation.

6.3 Methods and Materials

The data material used in this paper was generated through an interdisciplinary research project addressing green transition within Danish dairy cattle production by exploring alternatives to the intensified and yield-focused production. Our research project was funded shortly after the Danish climate act was passed, and since 2021 we have studied how different notions of sustainability have been defined, used, contested, negotiated and at times rejected altogether within a varied dairy sector, and how these discussions have been approached by farmers, universities and policymakers. As indicated, a central gist of our project has been to investigate the daily practices of dairy cattle farmers who do not fit into the mainstream intensified production, and to explore how sustainability is differently at play at these farms. Therefore, we set out to find farmers whose dairy production was not in competition with food crop production, primarily sustained from marginal soils not suitable for cultivation. In Denmark, such farms are incredibly difficult to find, so in our project we broadened up to also let other ecological considerations play a part. Biodiversity concerns, integrated diversification of plant production with dairy cows, and soil health became other factors by which to produce data for our study. Throughout, we have also engaged with intensive dairy farms in Denmark, which has helped deepen our understanding of how different types of knowledge are used and the practical goals and outcomes of different optimisation strategies.

Accordingly, from 2021 to 2024, we (especially Eriksson, first author) conducted extensive fieldwork at two low-input, pasture-based dairy farms, both with approximately 40 dairy cows. This involved recurring visits to each site (24 and 26 visits, respectively), allowing for in-depth insights into their production systems. Data collection included production records, informal conversations, and two semi-structured interviews at each farm – the first lasted 20 and 30 minutes, and the second 45 and 60 minutes. In addition, we draw on informal conversations during sit down meetings and/or field (and stable) walks, observations, as well as spontaneous meetings from shared field trips to 19 other farms and sites, each visited 1-3 times between 2021-24. Two of these were selected for in-depth analysis through a semi-structured interview (1.5 and 2.5 h of length) and review of production data. Table 6.2 provides an overview of the farms, their location, and the total number of visits. While some alternative dairy farms were found through searches at web pages, e.g. homepages of Danish dairy cooperatives, most of the visited farms were included via networks and encounters throughout the project exploration.

Table 6.2 Overview of farms/sites visited during fieldwork.

Production type	No. of farms	No. of organic[1]/ conventional farms	Location in Denmark, Islands/Peninsula	Accumulated no. of visits
Low-input dairy[2]	8	7/1	4/4	60
Intensive dairy	8	5/3	3/5	12
Low-input beef	2	2/0	1/1	2
Grain/vegetable[3]	2	2/0	2/0	3
Rewilding park	1	NA	0/1	1

[1] or biodynamic, applicable for one farm

[2] One of these was a mixed 100% grass-based dairy-food crop production, which therefore also belongs in the grain/vegetable production. However, it is only counted under low-input dairy.

[3] One with a cattle herd for nutrients and soil health and one relied on imported cattle (and other livestock) manure.

Further, the fieldwork included interviews with people involved in the Danish dairy sector, attending meetings and conferences with researchers, advisors and the industry in general, and reading various media content and publicly available documents. Together, these materials and experiences were used by the author group to discuss and reflect on the knowledge used – and not used – in dairy farming today and potentials for changed practices in a future sustainable food production system. Rather than being a product of a pre-structured data collection, the materials for this paper have been selected from the whole research group's body of fieldwork. This implies engaging and combining both semi-structured interviews and review of quantitative production data with iterative fieldwork resulting in a broad exploration of green transition of alternative cattle production in Denmark. The field-examples engaged with in the result section were not chosen in order to form a representative picture of 'alternative dairy farmers' or 'alternative dairy farming practices', and our aim is not to map particular farms or practices. Rather, it is to explore and revitalise the knowledge basis of livestock agronomy otherwise stuck in 20th century ideals of technological intensification. The observations from the farms are thus used to challenge a scientific lock-in. The analysis presented in the following section was constructed from continuous iterations of the empirical material guided by the ideas presented by Raworth (2017).

6.4 Results: Landscapes, complexity and distribution

The empirical data is discussed through the following three subsections: 1) Integrating dairy cows in landscapes and food system, 2) Working with social and complex systems, and 3) Knowledge distribution and developmental paradigms. Each section rests on 2-3 of Raworth's 'steps', as will be emphasised along the way.

6.4.1 Integrating dairy cows in landscapes and food system

The examples from alternative farmers presented in this section reference the first, second and sixth of Raworth's 'steps': 'Changing the goal', 'Seeing the big picture', and 'Create to regenerate'. They all point to changes of broadening perspectives, with attention to designs that make both planet and people prosper.

6.4.1.1 Situating production goals in local contexts

Hans had been operating his small dairy farm in Zealand since 1990, where he had taken over the management of 47 dairy cows and youngstock, at the time in a tie-stall system, and around 50 ha of land. In 1992, Hans converted to organic production and later rebuilt the stable to a loose-housed system, allowing the animals to move around freely. Grazing had been a central part of the production from the very beginning. When asked about his perception of a 'good' farm and production strategy, he said: "*If it* [the production] *can rest in itself, then it's fine.*" According to Hans, the total milk yield from his farm was typically around 5000 kg of energy corrected milk (ECM) per cow per year, i.e. less than half of the national average milk yield of 11,496 kg ECM per cow per year in Denmark today (Viking Data- & Ydelsesservice, 2024), which he said was "*good enough for him*". Whereas milk yield on most Danish dairy farms is the overarching goal of production and thus the primary yardstick for assessing the value of each cow, farmer Hans notably places milk yield "way down on the list", as he put it, of the qualities he values in his animals and in his life with them. As such, Hans has had cows with a large variation in their productivity, ranging from 3,000-8,000 kg ECM per year.

Such an approach to animal productivity, radically different from the norm, merits the question of what other aspects then set the direction for the production. In other words, how does Hans know how to manage his farm when he deviates from prioritising milk yield above all else? The idea of resource efficiency had been an important factor in shaping Hans' farm management. As increases in milk yield per cow beyond a certain point follow the law of diminishing marginal returns (Bach et al., 2020) or, as Hans puts it, "*you get less milk per feed unit at a higher feed level*", Hans found that the optimal production level would be around peak feed efficiency rather than at the maximised yield. The idea of 'resting in itself' has likewise, and perhaps in synergy with this, also played an important part. When we asked Hans when he felt like he had an established system, he answered: "*It was when I stopped ploughing. Then there came a sort of calm. Decisions were easier to make*". Hans made this decision to stop ploughing approximately six years after buying the farm, after finding that most of the soils – despite a history of conventional cultivation – were unsuited for crop production by organic methods. Leaving the pastures as permanent grass, he let go of the ambition to control the surrounding fields with an aim of optimising production according to standardised and detached goals.

While the first years of Hans' farming had been characterised by a mainstream industrial approach of feed optimisation and field cultivation, he gradually adapted his farm design and operation to the specific qualities of the land and his herd, and thus the system became much simpler to navigate. In place of cultivated fields with maize, which had been the standard before Hans bought the place, the hilly landscape around the farm was now constituted by permanent pastures, a large share resembling dry meadow grasslands, creating value for both cows, insects and the human residents of the area. Specifically, Hans changed his approach from one of narrowly optimising on the management of fields and animals to one of gradually figuring out the potentials, limits and balances of the land and production. Instead of asking how much milk his cows could yield, he started responding to the inherent possibilities and limitations of both land and animals. This is in line with the shift Raworth put out for the 21st century economist; a transition from a one-sided focus on growth in GDP as a measure of well-being to use the illustrative doughnut model as guiding goal, with its upper and lower limits for operation and multiple indicators. Such goals cannot simply be put into simplistic numbers or equations but carries a much higher complexity and depth.

Hans' example illustrates that a livestock agronomist working to implement a doughnut economics approach to dairy farming would have to be able to understand the concrete and internal dynamics of the farmer's herd and abilities of the land and strike place-bound balances accordingly. This implies viewing the value of cows for dairy farmers and the farm environment in a much broader way than what is currently common, and to heed the specific landscape features instead of trying to 'implement' a non-local ideal of milk yield.

6.4.1.2 Changing optimisation metrics

Another farmer from our fieldwork, whom we call Eric, operated a larger farm with around 266 ha of land in arable rotation and 89 ha grazed permanent grassland. Eric said that he saw himself as a plant producer, who also had dairy cows. The farm production was designed as a mixed feed-no-food crop-livestock system. Thus, he grew crops for human consumption from the cultivated fields and sustained around 130 dairy cows and their youngstock from the grass areas of the farm. Eric told us that he had balanced the number of cows with how many he could feed from the grassland that he needed for a healthy organic crop-rotation. He explained:

”*We live off making products for people from plant production, and then we have this grass, in our meadows and we also have some grass on our arable areas, and that is to make the organic crop rotation work, and then the grass, we cannot use it for food production, but we can through the cows. So instead of putting it in a biogas plant or just leaving it fallow, as was done before – these seven-year crop rotations that were used before, because it was known that the field needed a year's break or two, otherwise nothing could be produced… but we manage to make a product through the cows*.”

The point here is that the number of dairy cattle on Eric's farm corresponds to the available area of clover-grass leys that fixate nitrogen and improve soil structure and health on his arable lands. In other words, the cows live off the grass crops made available through Eric's organic production of potatoes, legumes and grain foods, essentially making dairy a byproduct of plant production as opposed to the other way around.

The production on Eric's farm had not always been designed this way. When he took over farm operation from his father in 1997, it was a specialised milk production with around 160 high-yielding Holstein cows. However, based on an idea of optimising food production, instead of the isolated milk production, Eric calculated how many people he could feed in different systems. He compared a simulated system with the maximum number of high-yielding dairy cows that he could feed from the entire farm-area – which was 250 – with a simulated mixed feed-no-food crop-livestock system with crop production for direct human consumption. The latter system turned out to enable feeding thrice as many people. Such a calculation is rare to even consider in much productivity and specialisation-oriented agronomy, even though a concern for feeding a growing global population is often an explicit concern. Thus, in 2017 Eric transitioned away from specialised dairy production, changed the feeding and breeding strategy to fit the feed-no-food production frame, adjusted the number of cows to the grassland capacity and targeted the crop production for human consumption.

In this shift, Eric – just like Hans from before – shifted away from a goal of maximising milk yields, but also embodied a novel paradigm for dairy farming, from being a specialised agricultural sector optimised independently to becoming part of a larger food system, where the motive is food and human nutrition.

Raworth urges us to "see the big picture" when considering the aptitude of economic models to describe economic activity. Raworth points to Paul Samuelson's foundational 'Circular flows diagram' of monetary flows published in 1948 as exemplary of a particular kind of epistemological myopia that has come to characterize 20th century macroeconomics: even though economic activity necessarily implies flows of energy, natural resources and waste, mainstream economic models systematically leave these out of the equation. As such, the trouble with economic models is not so much in the models themselves, but what they leave out. Raworth argues:

"*In the words of system's thinker John Sternman, 'The most important assumptions of a model are not in the equations, but what's not in them [...]'. The Circular Flow diagram certainly needs to be introduced with this caveat. It makes no mention of the energy and materials on which economic activity depends, nor of the society within which those activities take place: they are simply missing from its cast of characters.*" (Raworth, 2017, p. 66).

Eric's calculation, as rare as it is, foreground the question of feeding a growing population while taking the (local and situated) carrying capacity into consideration, accomplished through a change of the metrics used to evaluate the production design. Hereby, he extended and reordered the model's cast of participants. It is this attention to the greater role of dairy cows as embedded in food systems and societal context that we consider important for a timely agronomy.

6.4.1.3 Participation in the cyclical processes of life

A young farmer, whom we call Niels, was running a newly established small-scale dairy farm with approximately 40 dairy cows. The farm had operated since 2019, and it was born from the regenerative movement. Niels was driven by the idea of building soil carbon and fertility through grazing and grass-based cattle farming and had designed the dairy farm accordingly. The previously cultivated fields were established as multispecies pastures and grazed by the cattle using holistic grazing – a rotational grazing system with relatively small paddocks and movement of the herd multiple times a day, especially in high growth periods. Thus, it was based on the idea of designing and orchestrating cattle systems in concert with the natural flows and processes. In our fieldwork we have repeatedly observed that intrinsic for all the farms we have called alternative, is a focus on grass-fed cattle and their ability to enhance agro-ecosystem health through recycling of nutrients, ensuring long-term fertile and productive soils and crops, while avoiding dependencies on external inputs in the form of artificial fertilisers, pesticides, and feed imported from distant places. In Raworth's sixth step, 'Create to regenerate', she points to a necessary shift for human economies and businesses away from the linear, degenerative, industrial designs, to a regenerative one, characterised by recycling and generosity. She writes:

"*This ubiquitous industrial model has delivered strong profits to many businesses and has financially enriched many nations in this process. But its design is fundamentally flawed because it runs counter to the living world, which thrives by continually recycling life's building blocks such as carbon, oxygen, water, nitrogen and phosphorus.*" (Raworth, 2017, p. 212)

In this, grazing livestock can play a keystone actor in recycling nutrients to cultivated fields. Importantly, heeding the big picture of feeding a growing population through maximisation of food production, this recycling value of livestock should be distributed to food crop and not feed production. We saw this connection established at Eric's farm. However, this was also a feature we observed at Hans' and Niels' farms. Both being small-scale specialised and grass-based dairy productions, who only managed grasslands intended to stay permanent, they exported nutrients, primarily in the form of deep litter bedding from the stable, to organic vegetable and grain producing farmers, which no longer had animals of their own. When we visited Clara from the vegetable production, who had received deep litter from both Hans and Niels, she remarked on the value and necessity of this connection between organic food crops and livestock:

"*Vegetables need something to live off – this comes as a surprise to many.* […] *There aren't enough organic livestock farms for organic crop farming to manage without conventional manure. Then you have to have the animals yourself…*"

Clara also told us that they use the deep litter bedding as a long-term investment for good soil health, providing organic matter to the fields, stimulating the life and structure of the soil. Thus, while Hans and Niels had specialised dairy productions, they supported the recycling of nutrients and matter, while also focusing on working with the natural abilities of ruminant for positively engaging with the processes and rhythms of permanent grasslands, making space for multifunctionality, and regeneration of soils and landscapes. This division of labour between livestock farmers and farmers producing high value vegetables for human consumption, is a result of increased specialisation. With that, vital circular relations between livestock and fertile soils have been made invisible, reinforced by the introduction and use of artificial fertilisers, representing the industrial production design.

In a regenerative economy, Raworth suggest, will economists not only measure value as the monetary throughput, but employ what she calls 'living metrics' for measuring and guiding economic activities, considering and counting measures for both ecological integrity and social well-being. Likewise – we argue – a broader cast of practices and metrics must be included in 21st century agronomy and other knowledge bases to allow and support the re-design of agricultural systems and the roles of livestock in these – also if it entails smaller, multicrop and multispecies farms, where diverse pools of biogeochemical matter are being recirculated and distributed, or as put by Raworth, "*using nature as a model, mimicking life's cyclical* *processes of take and give, death and renewal, in which one creature's waste becomes another's food*". (Raworth, 2017, p. 219).

6.4.2 Working with social and complex systems

Moving on from the attention to the overall value and role of dairy cows for landscapes and food systems, this section addresses the ideas from Raworth's third and fourth step; 'Nurture human nature' and 'Get savvy with systems'. Both present ideas on how to engage and work with(in) complex systems and sociality, as we will unfold through the continuation of the examples of Hans and Eric from the previous section.

6.4.2.1 Factoring in interspecies sociality

Danish agriculture is, as noted in the introduction, often highlighted for being knowledge intense, high-tech and rational – epitomised by the agronomist of the 20th century. With numbers and calculations of feed plans, feed conversion ratios and economic simulations in hand, the mainstream agronomist has long been busy translating farm data into economical gains, thereby supporting the Danish farmer as an exporter of agricultural products to a competitive global market. Meticulously selected crops have been converted into protein and energy, that again have been converted into milk yield booked separately for each cow before being measured as Energy Corrected Milk (ECM) in the bulk tank. These conversions have been subsumed into a national annual report presenting the total yield for the Danish dairy herd and eventually summarised to a number celebrating the increase in the average daily milk yield from around 6 kg per cow at the beginning of the 1900s (Kristensen et al., 2015) to almost 30 litres per cow in 2024 (Viking Data- & Ydelsesservice, 2024). Similarly, the offspring from meticulously selected cows have been bred primarily according to their ability to produce large amounts of milk. In such rational calculations, other factors which are not easily measured appear as 'waste' or 'irrational'. In this perspective, the figure of the rational economic man has been a driver of agricultural development – and indeed the agronomy of the 20th century. Raworth describes this as the picture of human nature in mainstream economics: the "*solitary, calculating, competing and insatiable*" human. Raworth suggests a shift "*from rational economic man to social adaptable humans*". She writes:

"*First, rather than narrowly self-interested we are social and reciprocal. Second, in place of fixed preferences, we have fluid values. Third, instead of isolated we are interdependent. Fourth, rather than calculate, we usually approximate. And fifth, far from having domination over nature, we are deeply embedded in the web of life.*" (Raworth, 2017, p. 102)

Let us be clear – when Raworth writes that 'we are social' we explicitly include more-than-human forms of life in this sociality. Anthropological studies have almost by definition been narrowly focusing on anthropos i.e. the human, but a recent turn towards understanding how human beings are thoroughly embedded, and thus dependent, on other species (big and small) has revitalised and expanded the field of socio-cultural life

(Swanson et al., 2018; Tsing et al., 2024; Tsing, 2015). Liveability is no longer to be understood as a question of surviving singularities (for example one individual, one species, one nation), but a much more entangled affair and often with unforeseen feral effects (Tsing et al. 2024). In our fieldwork among alternative farmers, we saw a host of multidirectional relations between farmer and cattle that took us far beyond singular relations centred on maximising yield. Put differently, the alternative farmers did not perform as rational economic men.

Consider Hans, for instance. With around 45 cows he knew all of them well, especially on the appearance of their udder. He said that he found milking to be one of the most enjoyable parts of his work because this was a practice that involved close-up interaction with the cows. To him, this close-up interaction demanded that he attuned carefully to the cows. When asked at the brink of retirement after 40 years in dairy farming what he had enjoyed the most, Hans replied:

"*I think it has been this, where you walk among a herd of cows, where they are calm… some might lick you, some might try to butt you* [laughing]. *It's the relationship of trust. I think that's been the best part.*"

More concretely, he never rushed the cows in but let them come at their own pace which differed greatly from day to day and cow to cow: "*Sometimes it* [milking the cows] *takes one hour and other times two and a half"*. Hans used a tandem milking parlour with three individual stalls on either side of the milking pit – the ground-level area where the farmer is placed. The stalls were placed so that the cows were standing sideways to the farmer. Hans expressed great delight in this system because it allows for close contact with the animals: "*…then suddenly someone is nuzzling my neck – it's quite cozy*". Enthusiastically, we asked if we could see him milk? Preferably not, he responded and qualified that the cows would not want to come in, because they were not used to other people being around.

In most Danish dairy farms, a cow gives birth to a calf every year to keep the milk production active, and the calf is separated from the dam after a minimum of 12 h (24 h in organic production) to enable harvesting the milk for human consumption. In Hans' case, under the notion that a cow can do a much better job of taking care of calves than he could himself, all calves stayed with either the dam or a nursing-cow until weaning (and separation) at 3-5 month of age. Thus, the nursing system enabled 'full-time' milking of more cows, while nursing-cows were milked in the milking parlour only once a day. The relation between cow and calf is often backgrounded in modern dairy production. However, Hans' thoughts and practices highlight finely attuned and vulnerable interspecies relations in place when the cow's milk is not given directly to the calf but to the farmer. This reciprocity that is at stake in dairy production where the action of giving and taking milk for Hans is not just anybody's business, but an interaction that demands trust and affection. It is a relation cultivated over years, with all the particularities and historicity that comes from long term relations. A kind of relation that the logic of the rational man or an economy of scale would not be sensitive to. Even though calculations might suggest scaling up or the introduction of a robot milker, this would not be in the interest of this farmer – who is much more interested in the unpredictable interspecies relations. We find this emphasis on more-than-human sociality and trust to be an important aspect of dairy farming, and one that should be kept at the forefront of discussions around sustainability too, as dairy farming essentially entails human interference with intimate bodily functions and social relationships between cow and calf.

6.4.2.1 The skill of listening to the land

According to Raworth, 20th economics was unduly influenced by mechanical physics. Tellingly, the science of economics established 'market mechanisms' as the central feature, responding to the pushes and pulls of supply and demand. What if, Raworth asks, we were to speak of 'market organisms' instead? This would defuse the fiction that Newtonian laws direct life. As Raworth puts it:

"*Craving the authority of science, economist then mimicked Newton´s laws of motion in their theories, describing the economy as if it were a stable, mechanical system. But we now know it is far better understood as a complex adaptive system, made up of interdependent humans in a dynamic living world*" (Raworth, 2017, pp. 129–130).

Any system is more than the sum of its components. The feedback loops and delays, which form the interplay between the system's core elements, the stocks and the flows, make for emergent behaviour, too complex to be predicted and controlled. Therefore, it takes a good listener to get savvy with systems – and to adjust, or redesign, along the way.

Eric and his farm operation provide an interesting case for Raworth's focus on system savviness, given his attention to the balances of his farm system: The flows, the shock absorbers, the timings, and the rhythms. The meadows at Eric's farm had previously been drained and cultivated by his grandfather. However, they were now once again permanent grass and formed an essential part of the flows of animals and nutrient on the farm. Eric explained:

"*It's not necessarily the calculation in feed units, but it's about having feed at critical times during a drought period, where the meadows become essential for survival. I don't know if that's what is meant by 'the meadow is the mother of the field'* [an old Danish proverb (da.: 'Eng er agers moder')] *…At least, that is what I always argue.*"

This old Danish saying is usually taken to point to the essential capacity of meadows for provision of fertilization for cultivated fields. Through the seasonal flooding by a stream, the meadows are supplied with nutrients from the water. When grazed by cattle or harvested for hay or silage production, the meadows provide feed for cattle who in turn recycle nutrients as manure, which can then be applied to the cultivated fields. However, as Eric pointed out, the point is not only the meadows' nutritional value, but the ways in which they fit into the flows of the farm, also enabling him to cultivate the arable fields with food crops instead of feed and making the farm system more resilient.

Eric is in many ways personally in touch with the farm system as a whole – redesigning it along the way, we might say. He relies on his generational knowledge of the land combined with a daily morning walk to get a 'feel for the place' as he once expressed it. In most years, he is completely self-sufficient with feed for the animals and only imports straw and some of the sowing seeds for the food crop cultivation. As such, he himself can oversee the effects of his operation on the land that his whole production relies on, in contrast to farming systems that are sustained by spatially distant supply chains of e.g. soy-based feed. To Eric, this proximity to the whole operation was vital, enabling a 'feel for the place'. Other ways in which Eric has designed the farm with attention to rhythms, flows and shock absorbers appear in the seasonal calving system, where the high energy needs of the lactating cows coincide with the grass availability early in the growth season. As Eric said during a visit in 2024: "*The way we have chosen to run our farm is what is optimal specifically for our place*", emphasising that optimal designs are likely to be context dependent and thus not the same for all places. It is therefore not necessarily the details of the design per se, but the ways in which Eric attends to the workings and flows of the place, basing his design on a daily practice of listening to the land. We believe that such listening to the land should feature more prominently in the 21st century agronomy. More than ever, we need to enable specific and localised sensitivities to our ecosystems and their carrying capacities. While the polycrisis is certainly planetary, it is not only that and has to be studied in local patches (Tsing et al., 2024, p. 24). And while agricultural regulations are designed through calculating and mechanistic thinking, the living, self-organising and dynamic farm systems of the real world are by no means fixed but must be followed in – as Raworth describes it – the dance of complexity – or a morning walk on the farm.

6.4.3 Knowledge and developmental paradigms

We have touched on the goals, the connections to food systems and long-term liveable landscapes, as well as on how sensitivity towards the capacities, flows and rhythms of land and human-animal relations are features important to take into account in various ways through the data and metrics used to design, operate and optimise farm systems. In this section we move into ideas presented in Raworth's fifth and seventh step: 'Design to distribute' and 'Be agnostic about growth'. As we will see in the following, our fieldwork has also presented insight into the challenges of acting differently in a country where the mindset of the 20th century agronomy as we have framed it, is dominant.

6.4.3.1 Access to networks of diverse knowledge

In June 2023, we were invited by a Danish organic agricultural advisory company to present our research project during a collegial inspiration excursion they hosted for a group of organic plant and cattle advisers. When we introduced ourselves, we showed the planetary boundary framework and the practices and potentials that we were seeing through our fieldwork at the alternative dairy farms included in our project. This gave rise to some discussions in the group, the majority of whom were agronomists and trained to think sustainability from a relative approach. A few weeks later, Eriksson met with one of the agronomist-advisers. He mentioned that he had thought the discussions at the previous event had been very interesting, especially the topic of feed-food competition and the question on whether it makes sense to feed human edible crops to cattle from a resource efficiency perspective. He further remarked that this question was not usually brought up among his advisor colleagues. This exemplifies what our conversations with farm advisers throughout our fieldwork have shown, that the overarching production paradigm adopted by cattle advisers is clearly founded by the path of the 20th century agronomy, as outlined throughout this paper. This was also emphasised by Eric, the farmer from before, who during a long interview touched upon the general focus of cattle advisers:

"*…it represents a, what do you call it… a sector-segregated optimisation way of thinking. I mean, those who are advisers for cows try by all means to maximise milk production. None of them think in terms of whole systems… but that's just how it is.*"

When Raworth says that we should 'Design to distribute' she refers to the distribution of not only monetary wealth, but also other sources of wealth. She emphasises that distributive designs are concerned with power relations and access to resources such as land, technology and knowledge. Zooming in on the characteristics of the available knowledge in the dairy industry, we found, as we introduced in the beginning of this paper and showed in the above excerpts from our fieldwork, that the alternative approaches to dairy farming at large are left unsupported by knowledge production, and that the prevailing knowledge paradigms generally point towards more cows and more milk.

This was similarly apparent on several occasions at Niels' farm, the young regenerative farm from before. In a conversation during a hot summer period, he expressed that he found it hard to practice holistic grazing with dairy cows, their high energy needs demanding substantial time for foraging and ruminating and thus leaving little time for many paddock moves a day. He expressed that he wished he could follow a course in the area to expand his knowledge on the practice. However, he had not come across such grazing management course and did not believe it existed in Denmark, "*at least not in the way I want to do it*", he said. Later that same year however, the adviser firm Niels used for making the farm subsidies application hosted a network event at Niels' farm named "*Milk production in another way*" – showing curiosity and willingness to develop their knowledge capacity and communication on these alternative farms. Knowing that we shared similar interest, Niels invited us to join. One of the things on the agenda prepared specifically for the event, was an analysis of the production economy at Niels' farm. Niels and his team were selling the milk through their own farm dairy and charged a premium price, at least double of what organic farmers delivering to the large Danish dairy cooperations were paid. Still, coloured by the start-up phase including building infrastructures and many hard-earned learning experiences, the bottom line had not been positive. The economic adviser presented an analysis based on an exploration of the effects of doubling the number of cows, going from 40 to 80 cows, which then would – assuming similar profit margins after the upscale – improve the economic result. Seemingly, the only response to little or no economic gain, the adviser gave, was to produce his way out of the situation – without considering the specific land capacities, Niels' aims and ideals, nor the environmental impacts. A different kind of redistribution of the resources that make up Niels' farm – the grass, cows, the farm dairy and soil health – could not readily be factored in by the adviser who was relying on the market to improve the bottom line. 'Let's grow out of bad economy' simply appeared as the go-to response.

It is overdue for 21st century livestock agronomy and its active advisors, who carry great power in the shaping and development of agricultural systems, to incorporate a practice of professional reflection on the models and data they include and exclude from their calculations. Like Raworth asks for a new distributive economy, we also need a science of agronomy which creates distributive networks of diverse forms of knowledge through broad and interdisciplinary engagement in the major challenges of our time. This includes a welcoming of embedded and nature-inspired practices for dairy and other livestock production forms and an exploration of new metrics with larger perspectives in their ways of measuring, optimising and developing farm systems and economies.

6.4.3.2 Reframing progress and development

At the 2023 Cattle Congress — an annual event hosted by the Danish Agriculture & Food Council — around 2,000 researchers, farmers, students, and industry experts gathered to hear the latest research and discuss the state and future of cattle production in Denmark. At the congress dinner, seated at long tables beside a group of dairy farmers, we reflected on the day's presentations and the likely need for a decrease in the number of cattle in Denmark considering the environmental crises. The farmer next to us felt provoked by our conversation on downscaling and objected "*But we should also be allowed to develop our businesses*". He was a dairy farmer with 300 cows in indoor production, cultivating maize, grass and – with the new EU subsidy requirements about diversifying crop rotations – now also barley and rapeseeds. He was a conventional farmer, because, as he phrased it "*I want to have an efficient production*". His dairy farm and thoughts on development follow the pathway that most Danish dairy productions have trailed in the past 100 years, where specialisation and increasing herd sizes have brought economy of scale benefits and made expensive infrastructures feasible, where the use of pesticides and artificial fertilisers enabled larger crop yields in the fields and where year-round indoor housing made for more streamlined production systems, allowing for maximum human control of feed intake and animal activities (Kristensen et al., 2015).

In Raworth's last step, she highlights the importance of reviewing and rethinking structures and designs in society which make us financially, politically and socially addicted to the growth paradigm and asks how to become agnostic about growth. In our fieldwork we have encountered radically different views on economic growth that guide us toward the agnosticism that Raworth calls for. One such was at the farm of Jens who started a dairy production with Jersey cows following typical conventional farming practices back in 2011, investing in machinery and two new trench silos needed for the indoor dairy production. However, after years of consideration and inspiration from farmers in the US and Ireland, he changed to organic and pasture-based production. He sold the large machinery, put the cows on pasture, changed to seasonal calving design and almost 100% grass feeding. When we visited the farm in September 2023, they had downscaled the number of cows from the original 170 to around 140, to strike a better balance between the cows and the amount of feed the 200 hectares of grassland could produce. The cows each yielded around 3800 kg ECM per year. Jens made the following comment to his production:

"*I do it like this because I believe it is the right way to keep cows. (...) If I had just started out like this, the economy would have been no issue. Now, I still have the loan in the bank I made to buy machinery and build the two trench silos that I don't even need now*".

Further during our conversation, he explained how the starlings went from "*being a pest to just being a part of the landscape and system*" and how hoof trimming, which had been a needed regular practice in the indoor production, had at large become redundant after the cows were housed almost exclusively on pasture. As such, he pointed to several positive effects derived from the pivotal production transition. However, emphasising our previous point, he also told us that "*you are completely alone in it*", referring to the lack of accessible advisory expertise.

We argue that this example from Jens points to two important aspects of development and dairy farming design. Firstly, development, or growth in Raworth's terminology, is what you make it. Contrary to what the conventional farmer at the Cattle Congress seminar dinner table indicated, business development can be much more than an increase in animal numbers or productivity. In the case of Jens, it included a shift in production design which afforded daily joy, a better work environment, and significantly decreased the need for large machinery, buildings, and material use. Secondly, through this example we contextualise and nuance the otherwise empty word 'development' by showing how, for Jens, an awareness of limits and balancing elements, such as the carrying capacity of the grasslands, present development on other terms than the prevailing growth paradigm. Such agnosticism demands that progress and economic gain are separated, and it is only right for the science of agriculture to factor in such more diverse and interconnected ways of designing paths ahead. Working through all of Raworth's seven 'steps' has provided a way to conceptualise how the evaluation, development, and progress of livestock farms can be framed in more diverse and holistic ways. Following the schematics of Raworth, we suggest seven shifts in the knowledge and thinking which underpins livestock agronomy, which are summarised in Table 6.3.

Table 6.3 Seven ways to think for transforming a 20th century livestock agronomy to one fit and relevant for considering the encompassing the socio-ecological challenges of the 21st century.

	From 20th to 21st century livestock agronomy	
	from	*to*
1 Change the Goal	non-local productivity goals	goals adjusted to local landscapes
2 See the Big Picture	specialised production optimisation	system-embedded optimisation
3 Nurture Human Nature	backgrounding human-animal relationship	making interspecies sociality fundamental
4 Get Savvy with Systems	quantitative, standardised production metrics	attending to place-based landscape and production dynamics
5 Design to Distribute	only farms in growth will survive	creating networks of diverse forms of knowledge
6 Create to Regenerate	linear, technological solutions	integrated farm designs using the living world as a model
7 Be Agnostic about Growth	expansion addicted	factoring in diverse and interconnected developmental pathways

6.5 Discussion and conclusion: Practicing Doughnut Agronomy

The previous sections cover a broad range of topics and practices, from ecological integrity, food system dynamics, interspecies relationships and care, knowledge narratives and developmental theory. While each area forms entire fields of research, the main argument we bring forth in this paper is to show how such broad perspectives require a broader knowledge basis in livestock agronomy than the mainstream science presents; indeed, our farmer collaborators kept pointing to instances where they had to try out things for themselves or look to sources of inspiration outside formal agronomic channels of knowledge transfer. Exploring the radically different ways to understand and practice a green transition is important due to the wider implications such epistemological work has in shaping what development should be – and which ontological politics should be foregrounded. To emphasise the overarching aim of practicing a livestock agronomy that actively engages with both social and ecological limits, we have reformulated the seven focal points outlined in Table 6.3 and presented them in Figure 6.1. This visual representation illustrates the concept of doughnut agronomy, framing the practices we consider central for guiding the development of livestock farming within broader goals of safe and just operation. This includes working with situated goal sets informed by local capacities and sensitivities and a focus on food output maximisation, deploying embedded metrics, quantitative as well as qualitative. Without doubt, it will require a shift in perspectives on knowledge boundaries, moving from modes of specialisation, standardisation, fixed models and best-practices to modes of relational knowledge, including broader ecologies and landscape specificities, whole system optimisation and interdisciplinarity.

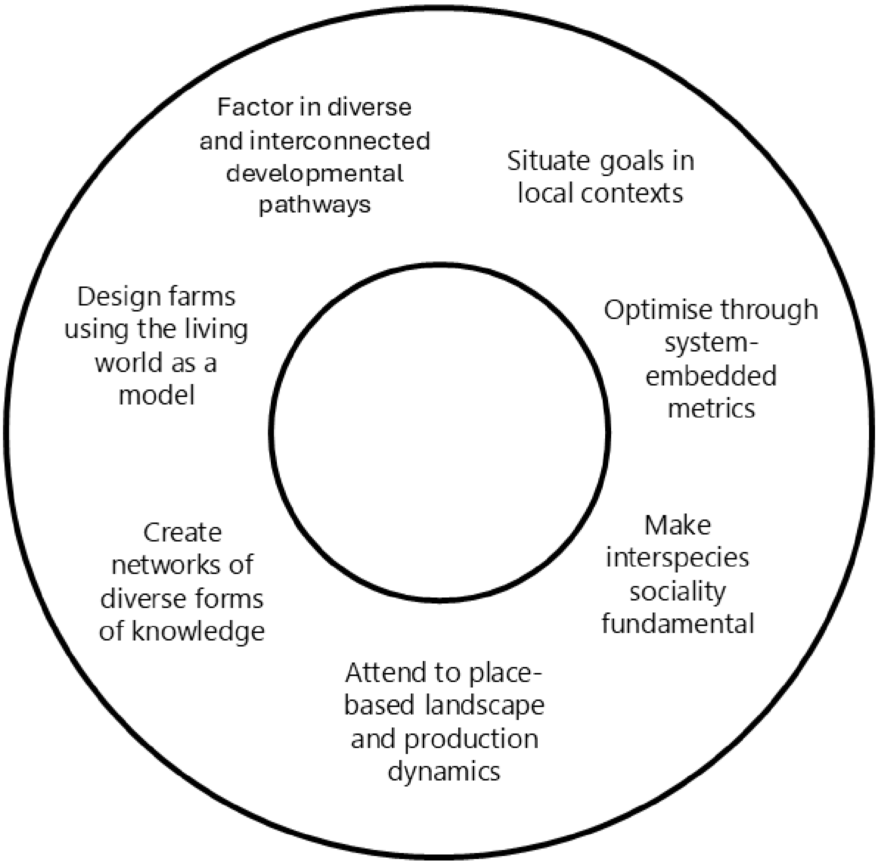

Figure 6.1: Practicing doughnut agronomy: A conglomerate of the knowledge practices supporting development of farms with livestock which balance health and well-being for people, animals and planet.

This broad attention was similarly suggested by human geographer George Cusworth (2023), who emphasised the importance of attending to farm metabolics, more specifically the inputs, outputs and transformations so that *"...care can flourish, and violence can be minimised across a broader geographic range*". Further, more than 30 years ago, the Dutch rural sociologist Jan Douwe van der Ploeg advocated for an increased focus on endogenous development patterns in agriculture, which is a developmental pathway generally motivated by and fitted to local needs and capacities, as opposed to exogenous development, which is more externally driven, market orientated and input dependent (Van der Ploeg, 1994). He called for a revitalisation of what he termed the ‘classical agronomy’ as opposed to the ‘technology-oriented agrarian science’. He wrote:

“*Whilst the former* [classical agronomy] *was based on an extensive knowledge of empirical diversity, on implied 'logics' and specific sets of social relations of production, the latter stand for a far reaching 'adieu' to the empirical reality of farming, since they are mainly oriented to technological transformations*” (Van der Ploeg, 1994, p. 27)

Yet, the Danish dairy industry and the agronomy supporting it have – as we have shown and experienced throughout four years of study – largely not heeded such suggestions. As such, it is our hope that situating the argument in empirical stories analysed through Raworth’s framework for changing what now seems like an outdated knowledge paradigm can add new entry points and dimensions to the discussion.

By way of ending, the focus on the knowledge underpinnings of mainstream dairy farming has emphasised first, that the goals for the dairy industry are narrowly defined as production optimisation, which again hampers comprehensive environmental mitigation efforts and changes towards more balance food/feed ratios. Secondly, the study has highlighted alternatives to further intensification and technological dependency—alternatives that are often scientifically marginalised. These pathways focus on holistic balancing efforts rather than regulating isolated components. They include approaches where land-based capacities and broader food system indicators determine animal numbers; where attention is given to the flows of nitrogen, phosphorus, and organic matter within circular and distributive networks; and where human-animal relationships are shaped by respect and reciprocity. Pursuing these modes of cultivating situated relations rather than isolated achievements is an invitation to agronomists to approach their valuable expertise in a new light.

However, cattle and livestock systems are influenced by many stakeholders and structures. With the extensive challenges we face today, an awareness of making space for such perspectives is certainly not only relevant for agronomists, but a much wider crowd of people, including the decision-makers who are obliged to implement the Climate Act that we mentioned in the opening of the paper, while ensuring landscape transformations in consideration to biodiversity, flows on nutrients, and soil health. As such, our argument is not solely directed at agronomy, but rather encourages a shared responsibility for retooling and combining different areas of expertise for generating a sustainable farm, food and consumption system that – locally – heeds the planet as a finite and circular ecosystem.

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Research Ethics

All farmers have read and commented on paper drafts, and any data and interpretation corrections have been incorporated. This includes the citations, which have been translated from Danish to English. All names used for the farmers in this study are pseudonyms. Data, including field notes, interview recordings and their transcriptions, pictures and farm documents were stored in digital form on a secure university drive. The research project was approved by the Research Ethics Committee at the Faculty of Humanities and the Faculty of Law, University of Copenhagen.

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7 Discussion

The aim of this PhD has been to contribute new qualitative and mixed-method insights to sustainability research within the field of animal science. It has engaged with ongoing discussions about the future of Danish dairy cows and the agricultural systems they are part of and depend on, while exploring how animal science as a discipline can broaden and adapt its approaches to absolute sustainability. More specifically, the project examined the operations, potentials, and challenges of farms practicing low-input, pasture-based dairy farming. It also combined qualitative and quantitative data and metrics to assess sustainability and provided reflections on how transdisciplinary research can strengthen animal science and support the green transition of livestock farming.

Although a specific definition of what constitutes a low-input dairy production has not been established earlier in the thesis, this question is relevant across the three papers and will therefore be discussed here. A group of European agronomists used – for pragmatic reasons – the (economic) value of external input costs per grazing livestock unit to differentiate between low- and high-input dairy farms, analysing data from 20 important milk-producing countries in the EU, extracted from the Farm Accountancy Data Network (Bijttebier et al., 2017). They noticed considerable variation in the characteristics of dairy systems between the different countries, as the median external input costs per grazing livestock unit differed from €176.04 (Romania) to €964.58 (Finland). Followingly, they decided to define country specific low-input and high-input limits, using the upper and lower quartile within each country to categorise high-input and low-input dairy farms, respectively. They found substantial difference in what qualified as a low-input dairy farm across the EU countries. The Danish farms were ranked number 17 out of 20 in terms of the median external input costs per grazing livestock unit (€738.22) with the cut-off value for high-input and low-input being €647.33 and €858.91, respectively. Similar values for e.g. Ireland (ranking 3) and Germany (ranking 11) were €367.29 (low-input: €303.29; high-input: €460.91) and €640.26 (low-input: €498.59; high-input: €818.30), respectively. In Denmark and Ireland, the difference between the low-input and high-input cut-offs was smaller (Denmark: €211.58, Ireland: €157.62) and larger in Germany (€319.71). This suggests that Danish and Irish dairy systems are more uniform in their economic input use – although they are at opposite ends of the input intensity spectrum, meaning that a low-input system in Denmark would qualify as a high-input system within the Irish context. The wider spread in Germany may reflect a broader spectrum of farm types, ranging from low-input extensive systems to highly intensive operations.

This emphasises the large differences in how dairy farming can be practiced (Shortall, 2019). The question remains whether it makes sense from an environmental point of view to define low-input and high-input in such relative and economic terms. Other studies have made the distinctions based on feeding characteristics. For example, Butler et al. (2008) studied 25 UK farms and used the feed components fresh forage, conserved forage, and concentrate, as well as pasture and pasture management characteristics to differentiate between high-input, and organic and non-organic low-input. They did, however, not suggest any cut-off value but presented the average share of the different diet components allocated in the three production system categories. For example, during the outdoor period, the proportions of fresh forage were 37, 84, and 95%, and the proportions of concentrate were 35, 8, and 5% of the DMI in the three systems, respectively. Similar values for the indoor period for high-input and organic low-input dairy farms (missing for non-organic low-input) were 0% and 24% (fresh forage) and 44% and 23% (concentrate). Total DMI was estimated to 19.5, 17.6, and 16.9 kg DM/day for the three systems. In a comprehensive meta-analysis of carbon footprint of different dairy systems, agronomists from Germany defined 'pasture-based (low-input)' as a production where a minimum 50% of the DMI came from pasture and not more than 25% from concentrate (Lorenz et al., 2019). Relating these approaches to the farms investigated in this thesis, it is reasonable from these definitions to call the production at Farm A, B and C (Described in Manuscript I and II) low-input, although the concentrate allocations during the winter at Farm A and B were close – or just over – the cut-off value of 25% concentrate share (Table 2, Manuscript II). Also conserved forage played a larger role during winter and – at Farm A operating on marginal lands – also at times during the grazing period. As we described and discussed in Manuscript II, there are many interests and thus dynamics in place, when running a pasture-based dairy farm where environmental and ecosystem health is also part of the goals set by the farmer. As such, there can be situations where the concentrate allocation must be higher to sustain the energy needs of lactating cows or where conserved forage is needed to supplement pasture forages to avoid intensifying management of permanent pastures. In that sense, low-input can be more than an aim for a specific share of forage – although that certainly is a part of it. It can be a mindset, an idea of cultivating more circular systems or – as Farmer A (Hans) puts it – 'to rest in itself'. The American soil scientist and agricultural researcher J. F. Parr and his colleagues suggested in a publication in 1990 the following definition of low-input farming:

> "*…low-input farming systems seek to optimize the management and use of internal production inputs (i.e., on-farm resources) in ways that provide acceptable levels of sustainable crop yields and livestock production and that result in economically profitable returns. This approach emphasizes such cultural and management practices as crop rotations, recycling of animal manures, and conservation tillage to control soil erosion and nutrient losses, and to maintain or enhance soil productivity. Low-input farming systems seek to minimize the use of external production inputs (i.e., off-farm resources), such as purchased fertilizers and pesticides, wherever and whenever feasible and practicable, to lower production costs, to avoid pollution of surface and groundwater, to reduce pesticide residues in food, to reduce a farmer's overall risk, and to increase both short- and long-term farm profitability*" (Parr et al., 1990, p. 52).

It has been remarked that such a definition could be applied for many different farming 'categories' and lacks quantified limits for inputs (cut-off values) (Poux, 2007). Indeed, it is not likely that any farmer would say that they use more external inputs than what they find necessary, practical or feasible – regardless of their use or choice of system. However, Parr et al.'s definition – which encompasses agricultural systems as a whole and not specialised dairy systems as such – emphasises practices of crop rotation, recycling of animal manure, conservation tillage practices for supporting soil health and fertility and limit degradation, as well as an emphasis on avoiding environmental pollution, improving the working environment, and thinking in both short and long-term perspectives. The input limits and practices to uphold such holistic aims are likely to be informed by local contexts and thus, it might not be productive to figure out and state exact limits useful for governance. Instead, as we emphasised in Manuscript III, such practices and outcomes arise from how farmers, researchers, advisors, and other stakeholders choose and are trained to think about, relate to, and optimise the agricultural systems, which – maybe to a larger degree than specific numbers for input limits – are fundamental for the low-input way of farming.

Continuing from Parr et al.'s definition, I will in this chapter discuss how the research in this thesis, has addressed the three research questions in three following sections:

- First, the potentials and challenges found in relation to green transition through alternative (low-input, pasture-based) ways of farming with dairy cows in a discussion framed by the PBF and the doughnut model.
- Second, how the research paradigm and metrics used in evaluating and researching possible pathways for green transition determine what is found and foregrounded as well as ignored and backgrounded.
- Third, my research approach and what inviting new and transdisciplinary perspectives into the field of animal science has challenged and offered.

7.1 Potentials and challenges in low-input, pasture-based dairy farming

In this section, I synthesise and discuss the findings related to the first research question of this PhD. I begin by exploring the potential of low-input, pasture-based dairy farming, focusing on the PBF processes most relevant to Denmark's green transition. Second, I discuss the need and potential for integrating dairy production into food system optimisation, aimed at achieving both a safe and just transformation (as defined in Section 2.3). Finally, I examine the challenges associated with operating and transitioning to such alternative paradigms for dairy production within the Danish context.

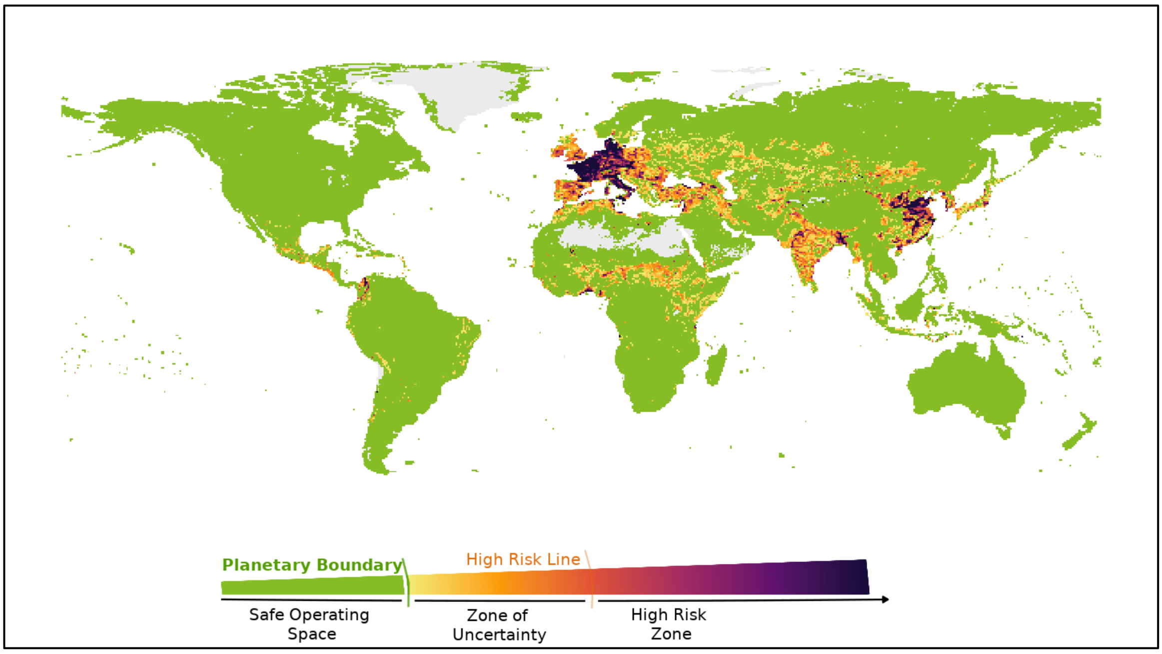
7.1.1 Attending to ecosystem health and biosphere integrity

Through the three manuscripts, I – together with the co-authors – have shown how changing the way dairy cows are fed, opens up multiple potentials for supporting biosphere integrity, reducing nutrient use and producing within a production paradigm which limit the number of animals a farm can have.

As a result of the grass-based feeding design, we found in Manuscript I, that Farms A-C's dairy and meat production was supported by 78-100% temporary or permanent grasslands. Sustaining dairy cows primarily through perennial crops that maintain living roots in the soil year-round can enhance net primary production and energy input (via maximised photosynthesis) to the soil, thereby supporting soil biota (Martin et al., 2020). Especially Farmer B – motivated by ideas of holistic management (Savory and Butterfield, 2016) – put explicit attention to soil functions and soil care in his management, incorporating measures of 'feeding the soil' through trampling from cattle and leaving topped-off pasture forage rather than harvesting it (see Manuscript II), as would be the usual practice. The ecological benefits of such approaches has been suggested to support soil formation, water and nutrient cycling abilities, and biodiversity (Teague and Kreuter, 2020). However, literature shows considerable variation in the potentials for building soil carbon through holistic (rotational) grazing. Results showing large and fast increases in soil organic carbon have been heavily disputed and other studies suggests that it is unlikely that pasture carbon storage can mitigate the climate impacts from the enteric fermentation (Nordborg, 2016; Ren et al., 2024). Yet, the method represents essential attentions to ecosystem functions and a paradigm shift for cattle farming (Gosnell et al., 2020). Thus, the grass-fed and pasture-based farm design for dairy cows enables incorporation of practices which support (agro)ecosystem health and reduce pollution without decreasing productivity – also known as eco-functional intensification (Vaarst, 2015). For example, multispecies pastures – as was seen in all the alternative farms – show great potentials for maintaining high biomass productivity levels under low or reduced levels of fertilisation, are highly suitable (and appreciated by the cows) as forage for dairy cows, and can provide functional diversity and drought resilience of the pastures (Finn et al., 2013; Hopkins and Elgersma, 2022; Jezequel et al., 2024; Loges et al., 2020). The incorporation of deep-rooted forage species such as red clover and alfalfa was highlighted by both Farmer B (see Manuscript II) and Farmer C as particularly valuable during the dry months of May and June in 2023, which saw very little precipitation. All the alternative farms studied operated with reduced nutrient input, applying no or less than 65 kg of nitrogen per hectare per year on land directly supporting dairy production. This is a critical finding. Globally, nutrient use has exceeded planetary boundaries – by over 200% for nitrogen and 100% for phosphorus (Richardson et al., 2023). Especially driven by the high proportion of land under cultivation (see section 2.2) and year-round precipitation patterns, nutrient pollution is a large problem in the Danish ecosystems.

Hence, eco-functional intensification focus on creating more resilient and low-impact systems through a higher functional integrity (Erisman et al., 2016). Such measures has been emphasised as an important path for mitigating pressures on biosphere functionality and pursuing a net-zero food system (Rockström et al., 2025). A recent publication, assessing the global and spatial transgression of the functional integrity since the 1600, found that the boundary for this process is now transgressed on 60% of the global land area. A total of 38% was found in the high-risk area. This is caused by land-use change and biomass harvest by human activities, which accelerated in the 19th and 20th century. By changing natural year-round vegetation and increasing human appropriation of the net primary (biomass) production through harvest, the energy available to the biosphere and its processes is significantly decreased (Stenzel et al., 2025). Maps generated from the models used in this publication showed how Denmark already in the 1600 transgressed the boundary for safe levels of land conversion and harvest (see Figure 7.1). In other words, we have for (very) long transformed natural ecosystems and harvested a much larger share of the resources and natural production for ourselves, leaving little to sustain the functioning of ecosystems. Thus, besides eco-functional intensification, we showed in Manuscript I also showed how it is possible to have a dairy production, using large shares of permanent, semi-natural, meadow-like pastures, decreasing the need for cultivated areas. In Manuscript II, we proposed that such permanent pastures can act as a buffer zone between intensively cultivated land and nature conservation areas, due to the minimal risk of nutrient leaching from permanent pastures (Smit et al., 2021). Further, it has been pointed out, that semi-natural habitats interspersed with cultivated farmland are important to ensure essential functions for crop production (e.g. pollinations by wild insects) as well as migration paths for non-farmland species in-between larger conservation areas (Herzog and Schüepp, 2013). However, we also argued that these more extensive dairy farming systems to some extent can contribute directly to biodiversity loss mitigation through incorporation of semi-natural pastures – characterised by lower productivity but higher ecological value.

However, the suggestion to involve dairy cattle in such aims remains a contested issue. Through meetings, email correspondence, and shared field trips with biologists working on genetic biodiversity in Denmark, my Cattle Crossroad colleagues and I repeatedly encountered the view that combining dairy production with nature conservation would be ineffective – or even counterproductive – due to the high risks of overgrazing and nutrient pollution. It was said that farmers should focus on producing intensively with high yields, so that we can make space for larger nature areas without any form of production, as production interests will inevitably compromise biodiversity potentials, as was also concluded in a study of 'biodiversity promoting beef production' (Ejrnæs et al., 2023). The argument about maximising yields on production land so that more land can be allocated to high-quality nature has a simple logic to it and represent what is often called the land sparing strategy (Grau et al., 2013). However, historically, the intensification and yield-optimisation of Danish agriculture have not led to an increase in areas with open nature types, which have instead suffered a steady decline (see section 2.13). Rather, it has led to increased production specialisation and cultivation-based land-use practices, alongside rising animal productivity. At the same time, grazing has ceased on many permanent grasslands, which have since been abandoned and subjected to encroachment (Finderup Nielsen et al., 2021). Further, the decrease in the total agricultural area in Denmark since the 1960s has not benefitted nature and biodiversity. Instead, the "spared" areas have to a large extent, been converted into (production)forests, buildings, and infrastructure (Levin and Normander, 2008).



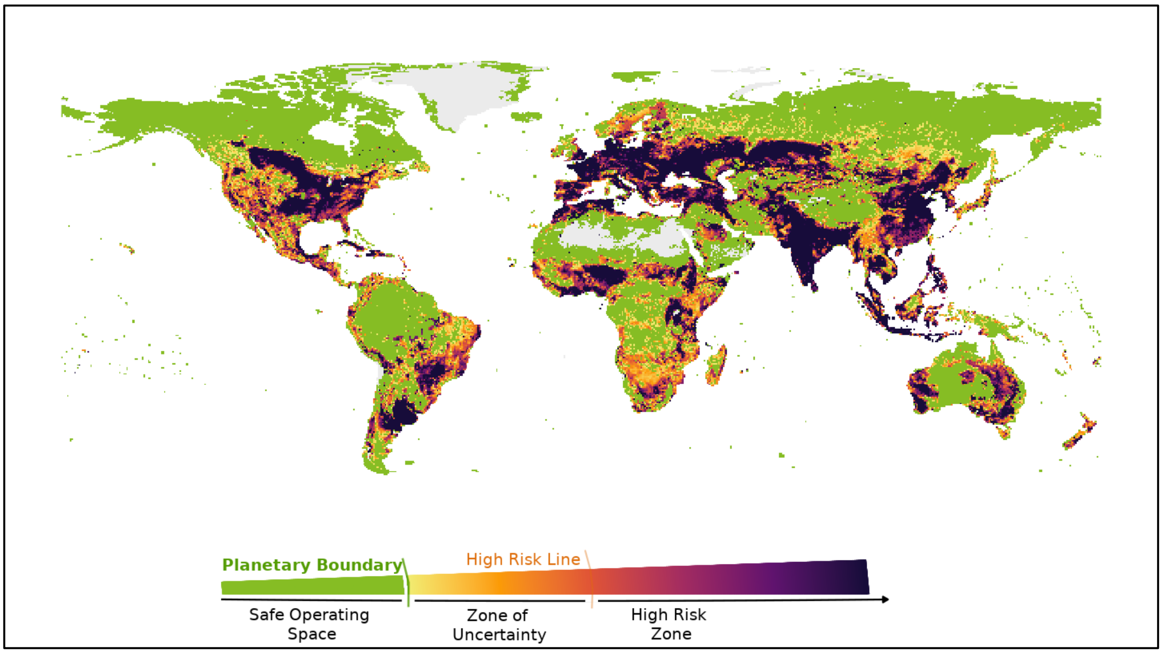


Figure 7.1 Human appropriation of net primary production as planetary boundary in year 1600 (above) and 2014 (below). (Credit: Potsdam Institute for Climate Impact Research (2025), based on Stenzel et al. (2025)).

For the land sparing strategy to be effective in practice, it requires coordinated planning and regulation by governments. While such initiatives are underway in Denmark, they are far from sufficient for Denmark to meet the EU's biodiversity targets of protecting 30% of land – 10% of which must be strictly protected and 20% allowing for extensive production (Biodiversitetsrådet, 2024; Europarc Federation, 2024). Given the current extent and ecological quality of permanent nature in Danish landscapes, it may not be advisable to dismiss the potential for improving or maintaining meadow-like habitats – such as those found at Farms A and C, and to some extent B and D (see Manuscripts I and II) – even if, in theory, these areas could achieve higher conservation value if converted to 'wild nature' without any production.

Besides potentials of permanent pastures and eco-functional intensification, the organic and extensive concepts indicated important potentials for eliminating or reducing the use of novel entities – more specifically pesticides and antimicrobials (Rockström et al., 2025). While medical treatment was not explicitly studied, my colleagues and I repeatedly encountered statements about low need for and use of veterinarians and treatments with antimicrobials. Likely, this was a product of keeping animals with a lower metabolic turnover, and thus less physiologically pressured, in combination with the low herd sizes and spacious outdoor housing at pastures a large proportion of the year. However, this would need further investigation to be confirmed.

Finally, discussion of methane emission has been given little attention throughout this PhD, where the focus on land use and land-use practices has been at the forefront. However, throughout my fieldwork, I did encounter expressions of naturalisation of enteric methane emissions amongst some 'alternative' farmers. They argued against the prevailing climate impact assessment methods of cattle farming, thinking that the ruminant digestive process is a natural, and thus not problematic, phenomenon. However, as pointed out by Cusworth et al. (2022), naturalness provide a 'slippery' ground for comparison, as natures are multiple. The number of ruminants on a global scale are heavily manipulated by humans, not to mention the unnatural amount and characteristics of the feed many of these ruminants eat (discussed later). Yet, in Manuscript III we shared examples on how farmers had transitioned their farm designs and practises based on ideas of grass-feeding, grazing and how to live well with cows, which had caused a down-scale of animal numbers (Eric and Jens) to better balance the number of animals with the capacities of the land. Similarly did Farmer A (Hans in Manuscript III) – as explained in Manuscript II – downscale the number of cows in the later years of his career and said, that if he had been 50 years now, then he would have continued with just 30 cows to see how it could develop. Thus, navigating and developing through attention to land-specific capacities incorporated a natural limit to cow numbers, which resulted in a decrease in the number of animals – a simple, low-tech, and effective way of reducing the total farm emissions of GHGs. As a consequence, such downscales most often lead to a lower milk output. Within the relative way of thinking about sustainability and through the dominating – yet associated with considerable scientific uncertainty – argument of production leakage (Hastrup et al., 2022), such downscaling efforts are seen as fruitless. However, considering that almost 200 countries have signed the Paris Agreement, a high leakage percentage might be less likely, despite the opportunity in regards to market opportunities. In addition, as stated in chapter 1, the potentials found in alternative dairy farming practices rest on the premiss that local and global food consumption patterns must shift towards a higher share of plant-sourced production.

7.1.2 Optimising food systems instead of dairy cows and farms in isolation

Extensive dairy farming is not appropriate anywhere. At least not when aiming to maximise the efficiency of land use for food output. Soils suited for cultivation yield the highest food output if used for a diverse food crop production, as became clear from our estimations of feed-food competition in Manuscript I. Especially Farm B, where a large share of the land use was evaluated suitable for cultivation, showed a high level of land-based feed-food competition with eLUR and pLUR values of 3.6-4.0 and 1.5-1.7, respectively, under organic growing conditions (where a ratio > 1 means that a pure food crop production would yield more nutrients compared to the current production from the same area). Thus, while Farm B operated through important considerations to the living world – as discussed in the previous section – the use of soils suitable for cultivation as pastures for dairy production, involved a food provision opportunity cost. Instead, low-input pasture-based dairy farming contribute most efficiently to the food system by utilising land unsuitable or unavailable for cultivating food crops (either for feasible, topography, environmental, or fertility building reasons). Hence, either as Farm A in a landscape of marginal soils or as Farm C, as a mixed dairy-food crop production, where the integration of temporary multispecies pastures grazed by cattle show potentials to sustain soil health and fertility in the cultivated soils (Cooledge et al., 2022).

The mixed system design was practiced at both Farms C and D – only the difference was that while the cultivated areas at Farm C were used for food crops, the majority at Farm D were used for feed. As we showed in Manuscript I, this distinction ensured that the extensification of the dairy operation did not entail a decrease in land-use efficiency for food production, even when animal productivity is more than halved compared to intensive dairy production. On the contrary. Farm C used on average 424 m^2 land area per GJ HDE and thus produced food more efficiently in terms of land use compared to the intensive and more specialised Farm D, which on average used 526 m^2 per GJ HDE. This was achieved with a higher share of permanent pastures (23.5% vs. 12%), no use of soy-based feed vs. import of a high energy and protein feed mix containing soy, fewer (42%) dairy cows, high degree of self-sufficiency of land-use 96-97%, and on sandy soils, which generally gives lower crop-yields than the clay soils which dominated at Farm D. The catch (or added benefit – depending on the perspective) was a much larger share of plant-sourced food from the farm output (77% vs. 9-34% of the total HDE output). It can be argued that a transition of the Danish agricultural system is needed, not only in relation to environmental concerns, but also to increase the self-sufficiency degree of especially fruit and vegetables in Denmark, which currently is at 27% (Fødevarealliancen, 2025).

A new role for dairy cows emerges through these food system and nature integrated practices – specifically the mixed production and use of permanent pastures. Instead of providing large quantities of milk (and meat), they provide resilience (diversity and functionality in landscapes), maintain semi-natural, meadow-like grasslands, create economic and food outputs from fertility building perennial crops (discussed in Manuscript I) and recycle nutrients to cultivated fields and thus supporting the food crop production. Similar ideas were presented in a report from nine NGOs in Denmark titled 'From feed to food 2' (it was the second of its kind and thus the number '2'), which suggested a total transformation of the Danish agricultural sector and food production. It included a transition toward 100% organic production primarily targeted direct human consumption and a conversion of about one fourth of the agricultural area (680.000 ha) to nature and forest. In this vision, livestock were integrated – much like the farmers studied in this PhD aimed for – in landscapes and food systems, sustained by grass from permanent pastures, residual products from the food crop production and grass protein from biorefinery. Thus, this was estimated to entail a radical decrease in the numbers of all livestock in Denmark, where dairy cows would constitute 160.000 individuals (a 70% reduction to current dairy cow population), and the total cattle population would be at 610.000 individuals. Accordingly, dairy cows would only comprise 26% of the total population in this vision based on local goals and limits. Poultry and pig would be reduced by 75 and 95%, respectively (Danmarks Naturfredningsforening et al., 2023). The report estimated that such a transition would reach the national goals for reductions in GHG emissions, significantly increase nature and forest areas and mitigate the negative impacts of nutrient leaching to water environment, while increasing the net-protein supply from the Danish agricultural sector, as no soy or other feed proteins would be imported.

Such a vision and comprehensive simulation show how it is possible to achieve encompassing goals for both food supply, land-use practices, climate mitigation, and nature, but likewise, that it requires massive transformation of the wiring of the Danish agricultural landscape as it is today. Negotiating new balances between animal- and plant-sourced food is essential for increasing land-use efficiency of the global food production (Foley et al., 2011). Results from a programming study using the Netherlands as a case, suggested that the highest land-use efficiency is found at 12% animal-sourced protein in human diets, although pointing out that this number would be influenced both by population size and land characteristics. With higher populations and/or higher shares of land unsuitable for food crop cultivation, more animals would be needed, to recycle waste from the food crop production or produce a food output from the unsuitable lands (Van Kernebeek et al., 2016).

7.1.3 Challenges for alternative production paradigms for dairy farming

As shown in Manuscript III, farmers navigating through food system and landscape-integrated production optimisation have currently little support from knowledge institutions, advisory services and the dairy industry. In addition, segregated and linear production optimisation is dominating the discourses of sustainability and green transition (Brieghel et al., 2022; Hastrup et al., 2022). As Eric – Farmer C – in Manuscript III said, the advisory services represent "*a sector-segregated optimisation way of thinking*" and "*…try by all means to maximise milk production*". Jens said that he felt he was completely alone in the transition toward low-input pasture-based farming. He wrote to me a year after our visit to ask if I had contact to farmers he could get, as he were missing people to spar and share experiences with. Hans – Farmer A – had produced alternatively for many years and was part of the group of pioneering farmers producing organically and had in the beginning been part of farmer discussion groups (ERFA groups). However, slowly, as other producers either closed or intensified, he dropped it. There simply was nothing for him there anymore. As one of the biologists in Manuscript II noted, there are very few examples of dairy producers which manage to incorporate permanent pastures in the manner which Farmer A did, which makes it hard to consider such pathways. This creates a negative cycle, where limited knowledge and experience make it harder to support the production system, and the lack of engagement and belief in it persists – partly because there are so few examples to learn from and study. Thus, there is need for more knowledge on how rhythms of production and nature can co-exist, as has been emphasised by others (Bengtsson et al., 2019). For example, as we did in Manuscript II, where we explored if the shift in feed characteristics increased risks of undernutrition in the relatively low-input, pasture-based Farms A and B. While not finding that the cows of RDM, Jersey and mixed breeds suffered from excessive mobilisation of body fat, the study emphasised how relations between feeding schemes and body conditions of cows are entangled in dynamic factors of pasture characteristics, reproduction rhythms as well as the skills and experience of the caretakers. However, as other literature also suggest, breeds and breeding programs specifically aimed towards this type of production would support the success of such production forms (Davis et al., 2020; Roche et al., 2018). However, a Dutch study found that knowledge on breeds and breeding is generally geared towards intensive dairy production and that organic farmers aiming for more resilient animals are left to experiment on their own (Nauta et al., 2009). VikingGenetics, the genetic provider in Denmark (and elsewhere), also operates within the intensive narrative that sustainable production requires high-yielding dairy cows (VikingGenetics, 2025). Another Dutch study found that five mechanisms were preventing the transition to what they termed 'nature-inclusive' agriculture, where one was regime resistance – a barrier that was connected to the other four barriers which addressed lack of incentives, perspectives, knowledge and concrete and shared vision for nature-inclusive farming (Vermunt et al., 2022).

Economic subsidy systems are also to a large degree prioritising and favouring large-scale, intensive production models (Kortleve et al., 2024). In the Netherlands, policy reforms for sustainability have been targeted conventional operations, overlooking the potentials of pioneering farmers that have developed their practices through eco-functional initiatives (Hoes and Aramyan, 2022). Some of these policy initiatives can inadvertently create adverse environmental and social effects. For example, as part of the EU's Common Agricultural Policy (CAP) reform for 2023–2027, several eco-schemes to support biodiversity and sustainable land use was introduced in Denmark. One such scheme is flower fallow (*blomsterbrak*), where farmers can sow flower-rich mixtures on land that is taken out of production – thus established on arable land, but also potentially on former permanent grassland, provided that the area is ploughed and reseeded. Further, such flower fallow needs to be reseeded every second year to fulfil the subsidy criteria. As such, what Farmer A experienced in 2024 was that the land-owner of some of the pastures he had leased since 2006 (and kept permanent since then) wanted to increase the rental fee, because – as they said – they could always just plough it and establish a flower fallow and get a higher economic income that way. Ironically, the hectare-based subsidy possible to obtain from ploughing and sowing a flower mix exceeded what was possible to receive by continuing the organic management of the permanent pastures.

Over the course of the four-year project, we frequently encountered a high level of ridicule from dairy industry stakeholders toward these alternative approaches to dairy farming. They were often dismissed as economically unrealistic, labelled as 'old-fashioned', and criticised for not being innovative. Many described them as a romanticised return to the past – nostalgic but inefficient – representing regression rather than progress. Seemingly, such narratives have lived for a while and also in other parts of the world, as it was similarly articulated by the low-input advocate and soil and agricultural scientist Parr et al., (1990) – referred to earlier – who wrote about common misconceptions about low-input farming systems:

> "*Low-input/sustainable farming systems represent a return to agriculture that was practiced in the 1930s. This is simply not true. These farmers use modern equipment, certified or hybrid seed, soil and water conservation practices, conservation tillage, and the latest innovations in livestock feeding and handling. They minimize the use, and need for, off-farm purchased inputs of fertilizers and pesticides through sod-based crop rotations, integrated crop/livestock management, and recycling crop residues and animal manures to maintain soil productivity*" (Parr et al., 1990, p. 52).

Indeed, low-input, pasture-based farming is a knowledge-intensive way of farming – although in a different way than an intensive dairy farm – requiring high levels of skill and attention across a broad field. Further, it is not opposed to the use of technology. For example, all the alternative farmers used (or started using) sexed semen and beef semen to control the production of replacement heifers and improving the meat potentials of 'surplus calves' as well as the possibility to select for polled genetics.

7.2 Mixed methods, food metrics, and contextual analysis

This section discusses how the different ways of researching sustainability in dairy production were able to foreground overlooked or discarded potentials for alternative dairy practices.

7.2.1 Measures of food supply and land use

When aiming to design food production with livestock, the metrics used – I argue – should be rooted in the basic need of humanity (food and nutrition) and the planetary crises, thus operating actively with both the social foundation and the ecological ceiling drawn in Doughnut Economics (Raworth, 2017). As evident from the PBF and the review of the Danish condition in chapter 2, the use of land is a central element to most of the PB processes and is a finite resource. As such, using units of land serve as a fitting basic unit for exploring environmental carrying capacities.

In Manuscript I (chapter 4), we used HDE (human digestible energy) and QP (quality adjusted protein output) as the measure for farm output, abandoning the sector segregated production metrics of kg crop, milk and meat. Given that animal sourced food is not nutritionally necessary for humans, the societal need is not found as milk and meat, but in food and nutrition. This way of measuring (and optimising) production systems works actively to balance activities towards a joint aim of 'doughnut agronomy'.

Analyses of farm outputs as HDE and/or protein and land use have been made in several publications (Hennessy et al., 2021; Ineichen et al., 2023; van Zanten et al., 2016), however always with dairy farms in isolation from other production forms – even when analysing mixed livestock-crop farms. The study on low-input farming in the EU referred to in the beginning of the discussion similarly attempted to exclude any farm where dairy was not the main activity (Bijttebier et al., 2017). The tendency to evaluate dairy farming in isolation is likely rooted in how agricultural knowledge, practice, and organisation have been divided into sectors for specialised optimisation. Efforts to generalise and quantify the impacts of dairy, pig, poultry, and crop production separately enable researchers to identify targeted solutions for existing systems and to better predict outcomes and risks. To combine dairy and food crop production in the same measure can be provoking, as it does not give a specific measure for the dairy cows, but simply for a specific farm within specific contexts and thus not producing 'scalable results'. However, I argue that it is unlikely that green transition of the agricultural sector and food system transformation can happen through scalable initiatives.

A study analysing 56 Swiss alpine dairy farms (based on data extraction from the Swiss Farm Accountancy Data Network) through life-cycle-assessment (LCA) found a negative relationship between global and local environmental performance measures (Jan et al., 2019). The researchers found that higher production intensity at the dairy farms (digestible energy output per land-use area) was associated with better environmental performance at a global level, but linked to poorer local environmental outcomes both when measured through farm area (direct land use) and cradle-to-farm gate land use (total land use). Thus, this implied that targeting and navigating environmental sustainability at the global scale risk causing local environmental degradation, highlighting a tension between local and global perspectives. This points to a seemingly impossible situation. However, what database-driven and LCA-based studies often fail to capture is the diversity and complexity of the farms behind the data. For instance, no information was provided about the characteristics of the 56 dairy farms included in the study. While the findings are valuable, such studies are limited in their ability to explore food system dynamics, consider alternative ways of thinking and developing, engage with overlooked pathways (e.g. benefits of mixed productions), and account for the situated complexities at the local scale. Thus, reflexivity on the abilities and limitations of different research methods are crucial to keep in the forefront of discussions on green transition. Employing different evaluation methods and metrics in research on recommended dietary shift to reduce environmental impacts has been found to either conclude a shift toward pork and poultry derived food (and reducing beef) or toward 'low-opportunity cost' dairy and beef, meaning forms that does not entail feed-food competition (and a reduction of monogastrics). These two paths were found in research either using fixed impact methods (e.g. LCA) or system orientated methods, respectively (Frehner et al., 2020; Van Zanten et al., 2022). Along the same line, as discussed in Manuscript I, I found that conclusions on efficiency were highly affected by the assumptions behind the estimates.

Moreover, research on socio-ecological systems (i.e. systems deeply embedded in both society and biosphere in a complex web of relations) suggests that the 'pillared' view on sustainability development – the division into economic, environmental and social sustainability and their respective indicators – is *"inadequate in its separation of social and ecological systems into sectors and policy targets with underlying assumptions of reducibility, linear trade-offs or synergies, and separability*." (Reyers et al., 2018, p. 270). Therefore, we need new ways of researching, evaluating, and developing farm systems. Raworth (2017) and her 'seven ways to think' suggests a way to work and rework the underlying rationales, designs, and considerations in the knowledge disciplines. Another method to engage in the complexity of social and ecological systems is to make situated analyses.

7.2.2 Situated analysis and integrated efficiency

The current conditions of the Danish landscape and ecosystems discussed in chapter 2, suggests that there are non-scalable elements (Tsing, 2012) of the living world which has been subjected to the scaling mechanisms of the agricultural development in Denmark. Drainage and the use of external inputs have in many ways allowed equalisation of farm operations across large landscape diversities, with little consideration to the inherent qualities and functions of local places and sensitivities.

Approaching farm evaluation through the situated analysis developed as a way to consider the variability in the Danish landscapes and places, was an attempt to qualify the non-scalability of dairy farming practises across diverse spaces. This allowed for a place-specific efficiency evaluation, where the same type of farm and farming output can be evaluated differently, depending on the local specificities. This attention was formed through a distinction between 'types' of land (cultivated, temporary ley, permanent pasture, fallow), as they serve different functions and availabilities for cultivating a food crop. The LUR (land-use ratio) measure, also employed in Manuscript I, which was used to estimate the potential feed-food competition of a certain operation at a certain place, consider this variation through the suitability assessment.

This assessment proved an important entry point for discussing landscape functions and the acceptable extent of human equalisation to landscape diversities. One could call it a discussion on the acceptability of human appropriation of land system functions – linking to the measuring unit of the functional integrity of the biosphere found in the PBF (Haberl, 2015). The typical implication of a suitability assessment includes an analysis of the practical and economical potentials of cultivating a crop based on quantitative measures of climate, soil and other topography characteristics (Ineichen et al., 2023; Rabia et al., 2013). In Manuscript I, we instead made a qualitative assessment based on conversations with the farmers, personal observations as well as soil and nature conservation maps. In addition, we adopted a broader understanding of suitability – one that includes the opportunity cost of cultivating land that could otherwise serve other landscape functions. This approach allowed us to incorporate diverse landscape interests, which is a crucial consideration for safeguarding biosphere integrity in optimisation efforts. Thus, our suitability assessment asked – what are these soils good for and what use can they and the surrounding landscape carry? However, a limitation to the method used was that we were not able to consider that some of the land in cultivation, might not be considered suitable under those terms. This was for example the case of an area with organic soils that were under cultivation at Farm D, which in relation to climate interests should be left unploughed and rewetted to reduce the large CO_2 fluxes from such soils (Günther et al., 2020).

By differentiating the types of land-use practices among the four farms discussed in Manuscript I, the analysis highlights the potential of pasture-based farms to operate in more ecologically sensitive landscapes with minimal use of cultivated land. This nuance would have been entirely overlooked if land use were treated as a uniform category – for instance, Farm A used around twice as much total land area compared to Farms C and D per unit of food output. These distinctions are also the reason why milk or even food nutrient outputs cannot always be compared directly across time and space to determine inferiority or superiority of dairy productions. Cows in other parts of the world, especially in places where the milk productivity per cow is low, often serve a much larger variety of functions compared to the typical Danish dairy cows. Followingly, they are not only a low input source of milk (and meat) and fertiliser for food crops, but are also serving as social insurance and a source of livelihood in areas where few options are available (Douphrate et al., 2013). In Manuscript II we used situated analysis in another way. We used BCS as an indicator for system-cow compatibility, but also in combination with qualitative observations, and as a tool to engage with the farmers' situated accounts of cow and pasture management, feeding, and well-being. This way we were able to provide depth and complexity to data that normally is removed from its context.

Even the term efficiency – so frequently used – is mouldable in its understandings. Usually, it is discussed in terms of how little of a resource is needed to produce a certain outcome, e.g. when we estimated the use of arable land per HDE farm output in Manuscript I. It narrows the attention to one goal. I will call this 'efficiency in singular', or isolated efficiency. However, what was also included in Manuscript I, was the context and discussion of the potential multiple values of dairy cows, e.g. nutrient recycling, generating food output and income for the farmer of fertility building ley, and/or grazing of permanent grasslands for potentially improving biodiversity (as was addressed in Manuscript II). Dairy cows in such systems, integrating with its context can be termed 'efficiency in plural' or integrated efficiency. From that perspective, it is the cow's integrated value, working towards many interests at once across socio-ecological scales, which makes it an efficient cow.

The well-established "eco-efficiency" assessment, which is a quantitative assessment of the balance between the value (including products *and* service) and the environmental impacts of a production, does to some degree catch the diverse value of the plural cow. A study assessing 44 multifunctional dairy farms found that the mean eco-efficiency of the organic farms in the assessment was higher than that of the conventional farms (Grassauer et al., 2022). However, the study also reported great variability in the farming approaches and the pathways they could follow for improving their eco-efficiency. Thus, the study concluded that there are multiple ways of achieving higher eco-efficiency, which depended on the individual farm-context and choices of the farmer. This, however, was not unfolded further. Typically, quantitative research from animal and agricultural institutions do not leave much space for such information. Instead, it is the study of 'things', the outcomes and achievements, which are in the forefront. The eco-efficiency, the production, the emissions, the achievements. Rarely is the information that comes before and drive for these events included. However, to capture knowledge of higher socio-ecological value, I find that the study of 'things' should, to a much higher degree, be framed by a more relational based research, as we did in both Manuscript I and II.

7.2.3 The case of enteric methane emission

Despite the overwhelming focus on reducing enteric methane emission from dairy cows in research and governmental regulation in Denmark (see chapter 2), this was deliberately not a direct focus in this PhD work, which calls for further clarification and discussion.

Research on reducing CH_4 emission from the enteric fermentation is currently high on the political and scientific agenda in Denmark. The metrics or 'functional unit' used in research studies are typically total CH_4 production per cow per day (g/d), CH_4 yield (g/kg DMI), or CH_4 intensity (g/kg ECM) (e.g. see Hansen et al. (2022)). Such measures can indeed be useful to understand the effects of different feeding schemes on the emission profiles and efficiencies. However, total emissions can increase, despite potential animal efficiency improvements, if the total DMI, total milk production or number of cows increases. As such, it is an isolated efficiency measure, decoupled from the rest of the farm system, and in that sense, I argue, unfit to be used as a guiding measure for the future of dairy production. It risks achieving little because of the rebound effect, where gains in efficiency are offset by increased production and consumption levels (Giampietro and Mayumi, 2018; Hauschild et al., 2020). This was illustrated by a study researching the GHG efficiency and total emission of the Irish dairy industry around the time of the abolishment of the EU milk quotas. From a study of representative Irish dairy farms from 2000-2017 the GHG emission intensity from the farm systems (kg CO_2eq/kg milk) were found to decrease by 13.1%, hence achieving a lower emission per kg milk. However, in the same period, the number of cows per farm increased by 95.6%, concentrates fed per cows increased by 31.4%, milk yield per cow by 15.3%, stocking rates increased by 15% and thus *total* farm emissions increased by 85.5% (Läpple et al., 2022). Accordingly, despite the increase in productivity and decrease of emission intensity, the development resulted in a net increase in GHG emissions from the dairy farms.

This is not to say that efficiency does not matter. It does. However, when used to guide farm development, it should at least be based on total farm and not isolated animal measures. A study estimating the GHG emission intensity of dairy productions with increasing milk production productivity (measured as kg ECM/cow/year) found that on a cradle to farm gate level (including emissions from feed production, animals and manure) CO_2eq-emissions per produced kg ECM decreased drastically up to a production level of 2,000 kg ECM/cow/year, and continued to decrease, although at a slower pace, until a production level around 5-6,000 kg ECM/cow/year. After this, the emission levels were observed to stabilise, regardless of increasing milk productivity (Gerber et al., 2011). Reviewing the farm system emissions of CO_2 and CH_4 measured per cow in this study, it found that emissions increased with rising productivity. Where the increase from CO_2 was linear, coupled to an increased use of inputs and fossil energy, the increase in CH_4 emission was diminishing, at least up to a production level of around 7,000 kg ECM/cow/year. At this point the increasing rate appeared to accelerate again. The authors suggested that an explanation to this might be "*that the effect of feed quality improvements on digestibility and thus emission intensity is less pronounced at the high end of the productivity scale*". This trend is also reflected in the estimates of per-cow methane emissions in 1990 and 2023, during which the average national milk yield increased from approximately 8,000 to 11,300 kg ECM/cow/year (Viking Data- & Ydelsesservice, 2024), and enteric methane production rose from 128 to 162 kg CH_4 per dairy cow per year (see Section 2.2.1).

Feed efficiency follows the law of diminishing returns (Bach et al., 2020). This means that the feed needed to increase the milk yield per cow increases with increasing production levels due to a higher DMI and thus feed passage rate through the rumen, which decreases the digestibility per DM (Volden, 2011). This was also the underlying rationale for why Farmer A operated with lower feeding and production levels compared to the national norm in Denmark, as described in Manuscript II. Interestingly, the productivity level of Farm A was at the level (between 5 and 6,000 kg ECM/cow/year) which the previously mentioned study found to be the threshold for achieving the highest level of emission intensity efficiency. These measures are off course

based on considerable uncertainty and affected by the decisions and assumptions made by the researchers of the study.
Altogether, it serves as a good picture for how it is important to work from a whole system evaluation and regulate in accordance to absolute numbers, rather than animal-based efficiency estimates, e.g. CH_4 intensity (g/kg ECM). Yet, it is precisely such measures mitigation efforts the Danish dairy industry and government are aiming at currently. The potentials of using feed additives or changes in the chemical composition of the feed through the use of fat, nitrate or 3-NOP was briefly presented in chapter 2. However, they have been found not to be additive in their effects (Maigaard et al., 2024a) and thus not adequate to yield the needed reductions in total GHG emission. In addition, the use of 3-NOP would require high precision feeding conditions, as too high dosage has been found to affect cow eating behaviour and production levels (Maigaard et al., 2024b) and thus potentially create a strong lock-in in terms of the ways cows can be housed and fed. In addition, the long-term effect of 3-NOP is generally unknown (van Gastelen et al., 2024) and potentially risks shifting the burden of GHG emissions from the animals to the manure application on soil (Weber et al., 2021). A study has further pointed to negative effects on other environmental parameters, especially related to the use of nitrate (Dorca-Preda et al., 2024).

Thus, we are still to a large degree in the dark when it comes to long-term effects, potential negative side effects and the effect such a mitigation strategy will have on the development trajectory of dairy farming. That being said, the largest problem with seeing feed additives as the central ingredient for green transition of dairy production – and the reason why the topic has not been central in this project – is that it obscures the need for a much large encompassing transition, which put attention to local carrying capacities, relations across landscapes and the current health and welfare challenges of the intensive dairy farm system. As quoted from Rockström et al. (2009) in the introduction of this thesis, we do not have the luxury of focusing at one problem at the time. Thus, we need a more fundamental rethinking of the production backbone of the Danish agriculture, where dairy cows, other livestock and crop production to a much larger degree, are optimised through how they relate to each other, synergise and can be dimensioned in new balances, informed by capacities. Feed additive might play an important role, however, they should not prevent or replace the needed fundamental changes, as was also discussed by Brichet et al. (2023).

7.3 Repurposing animal science research

Working in a transdisciplinary project and collaborating closely with colleagues from a radically different discipline – anthropology and ethnography – with distinct research approaches, and within a project framework unlike my previous experiences, was both challenging and at times frustrating. However, it ultimately proved to be eye-opening and deeply rewarding.

7.3.1 Inviting new perspectives through transdisciplinary collaborations

The open way in which I approached research during this PhD work contrasts how I had been working previously in animal science related issues, and to normal practise within the field. I come from a science which mostly do experimental research or modelling of selected (quantitative) production data, where objectivity (perceived as free from specific personal values), sharp definitions, and hypothesis-testing are seen as good scientific work, as mentioned in chapter 3. Working closely together with anthropologists, engaging in research approaches typical for their scientific field, has to a large degree changed the way I regard scientific research and knowledge. I have gained an awareness of how answers and results – regardless of being qualitative or quantitative, are shaped by the perspectives within which they are being formulated and questioned. It was new to me to ask questions like; how do the questions I choose or are schooled to ask, and my potential definitions and system limits shape the answers that I can get? What world view, values, ethics, and assumptions lie underneath those questions? And how does the present shape the past, e.g., what are we looking for and comparing to in the past, because of what is happening and forefronted – focused on – in the present? These question are born from working with the – to me in the beginning equally astounding and bewildering – ideas of embodied, situated knowledge and political ontologies (which precisely asks such questions about the premisses of research) from the previously presented Donna Haraway and Annemarie Mol (Haraway, 1988; Haraway and Tsing, 2019; Mol, 1999). It challenged and has shaken the ideas of objective scientific results and knowledge I had obtained from my animal science studies. The notion and effects of aspiring for 'value-free' research has also been discussed by two Danish agronomists in their paper on systemic research in agriculture, who emphasised the inherent limitation in such research approaches:

> "*Society's demand for more wholeness-orientation in (for instance) agricultural research implies a critique of traditional disciplinary research that is not well suited to handle cross-disciplinary problems. And it implies a critique of the sciences that have difficulties with handling the criteria of relevance because they aspire to the scientific ideal of being value-free and independent of social interests*." (Alroe and Steen, 2002, p. 17).

Green transition in dairy farming is indeed deeply rooted in diverse societal interests and requires cross-disciplinary perspectives. Along the way in this PhD, there has been a lot to be inspired by and a lot to grasp. I have spent much time on understanding words as ontology, epistemology, material semiotics and actor-network theory at the same time as delving into soil structure, mineral associated organic matter, root exudates from plants, microbial life, GHG fluxes, biodiversity and rewilding as well as more cultivation based agronomy such as nutrient uses, crop varieties and cultivation risks and juggled questions of human nutrition such as how to measure food security and whether protein really is a useful indicator for food security or merely convenient for researchers wanting to find potentials for livestock farming. Embracing

this wide range of expert areas through cross-disciplinary engagement and conducting mixed-method studies was equally rewarding and challenging.
Besides the space for knowledge exchanges across science and society, such processes of disciplinary exchanges are an fundamental part of working within a transdisciplinary research project, where – as highlighted by German scholars experienced in socio-ecological research and sustainability – the difficult intellectual task is to bring knowledge, methods, and perspectives from different disciplines together, although not as a replacement for established practices within a discipline (Jahn et al., 2012).

Encountering this wide range of perspectives on agriculture and research shed new light on animal production science. In addition to my initial scepticism toward animal welfare improvement studies, I started seeing its typically narrow scopes – and underdeveloped reflections on the motivation behind the studies – as inadequate to engage with the complexity of development and green transition. I began seeing the rigidity of research investigating certain outcomes of specific interventions for solving isolated problems within herds as an obstacle (instead of a good method for establishing knowledge on causative relations between certain factors as taught during education). However, it leaves little room (or attention) to important information and relations, which are simply overlooked in typical experimental and pure quantitative studies.

The iterative study approach of this PhD project was challenging, because of the loss of control in the outcomes it entailed, but at the same time fundamental, as it enabled space for developing and adjusting the driving questions along the way to engage in complexity of the field. It also dismantled the notion of scientific ivory towers and challenged the traditional role of researchers as authoritative experts whose task is to reveal objective 'truths' from the field. Through such reflexive processes and exchanges, I was inspired to explore what situated knowledge (Haraway, 1988) would look like in animal science research, how to balance necessary reductions of the living world for producing quantitative estimates of outcomes and potentials with the situated entanglements, yielding new research practices, metrics and data use in animal science, as discussed in section 7.2. As such, in the words of the German transdisciplinary scholars, "*cross-disciplinary collaboration may function as a driver for disciplinary innovation by questioning and eventually reshaping internal borders*" (Jahn et al., 2012, p. 3).

7.3.2 Underexplored potentials in animal science research

I wrote in chapter 3 that the use of case farms is an established practise in animal science, where farm visits, conversations with farmers and followingly the conduction of experimental research over a longer period of time is typical. In this way, animal science research already has the practice of open farm visits. However, when the experimental study is initiated and data collection started, the conversations and observations from the fieldwork, which can be very extensive (e.g. I went to the same pig farm 2-3 times a week in 7 months for my MSc thesis), change in function. In our science, we are aware that it is important to note down

contextual elements and events at the case farms, because they can be important for explaining the findings from the experimental data. However – contrary to ethnographic fieldwork and analysis – these observations and conversations are not part of the research questions and rarely get to be a main or equal source of attention. Yet, the reoccurring farm visits provide a perfect opportunity and backbone for longitudinal qualitative fieldwork, where informal conversations and observations can situate quantitative findings within contexts and – if used actively in the analyses – provide a reflexive strength to animal science research.
I experienced this during this PhD, when I was doing BCS observations at my two main case farms. It proved to be a valuable tool to get insights and observations on the daily turnings at the farms, as I described in Manuscript II. All it took, was a mere shift in perspective of the relevance and role of different sources of data. In my PhD, the casual conversations with farmers and employees have been of central attention and contributed actively to shape the analyses and findings. For comparison, the conversations with the employees at the pig farm of my MSc-thesis were in most cases just that. Relaxed casual conversations and not subject to any scientific curiosity per se, besides when it was specifically related to my data collection. As such, it is not so much a shift in practise that I have experienced in this PhD, but rather a shift in perspective and attention to a wider spectrum of what knowledge and data can be and inform. I find one of the descriptions of fieldwork made by anthropologists Annemarie Mol and Jessica Mesman in their paper 'Neonatal Food and the Politics of Theory: Some Questions of Method' to encompass the weight such conversations have come to have throughout this PhD work, just with farms and farmers instead of hospital and nurses:

> *"To do fieldwork is to do something. So you get up early in the morning and ride your bicycle to the hospital. Attend this meeting or the other. Drink coffee with the nurses - who take drinking coffee as their break, but for the observer all the chatting is hard work."* (Mol and Mesman, 1996)

In this way, animal (and veterinary) sciences can become fitting disciplines for bridging knowledge fields and socio-ecological scales, as it provides excellent frames for conducting mixed-method studies, where different data sources and epistemological paradigms work together on addressing the same research questions. Where quantitative research by far is the most prevalent research approach within this field, there has – as also discussed in chapter 1 – been a notable increase in amount of studies using qualitative methods within dairy science over the past 12 years, although ethnographic approaches and subjects of green transition are mostly found in scientific communities outside of dairy science (Ritter et al., 2023; Vaarst et al., 2024). As also suggested by Vaarst et al. (2024), integrating animal sciences with social sciences and humanities opens up new ways of questioning and researching dairy farming, leading to nuanced and impactful outcomes. For instance, the human geographers Cusworth et al. (2024) showed how regenerative farmers engage with ecosystem health through spatio-temporal thinking – expressed in field management, ruminant feeding, and soil-building practices. Combining such a conceptual model for agro-ethical responsibilities with the outcome-oriented focus of animal science and agroecology – such as the estimations made in Manuscript I – could enable a deeper understanding of both the potentials and nuances in such models. Together, the combined perspective can help identify where and how livestock can most effectively contribute to food supply and (agro)ecosystem health, by drawing lines between farming and societal discourses and the optimisation of farms and productions. In other words, in order for animal science to produce research with nuanced and situated results, the foundational thinking behind the guiding assumptions, metrics and indicators needs to be strengthened through conceptual models and theory.

To support such aims, Raworth's framework for transforming human economies into safe and just space of operation served as a fitting backbone for showing how the ways of thinking in livestock agronomy can broaden to consider the integrated nature and potentials of livestock farming.

I see unexplored potentials for animal science to take a step out of its typical role as a science which 'finds solutions for the industry' through narrow research aims and specific results. To engage in transdisciplinary research projects and to a much larger extent enter the whelm of difficult questions about the role of domesticated animals in food systems, landscapes, and societies. This could, for example, involve broadening the scope of attention to include farms beyond the typical selection criteria of 'representative farms'. To this end, I have proposed conducting situated analyses of farms that are grounded in the overarching challenge of producing sufficient food without compromising local and global planetary health and stability. I believe this approach could significantly enrich the quality and reflexivity of findings in animal science research and transdisciplinary work, potentially opening up alternative solutions and pathways for the future of livestock farming in Denmark and beyond.

8 Conclusion

This PhD was part of a transdisciplinary research project where veterinarians, animal scientists, and anthropologists collaborated on exploring knowledge barriers for a green transition in Danish dairy production. It builds on the concept of absolute sustainability, emphasising the need to work with absolute limits both on a local scale respecting carrying capacities of a particular land and on a planetary scale working with limits as understood in the PBF.

It was found that low-input and pasture-based dairy farming presents potentials for green transition by foregrounding ecological functions through changed feeding and land-use practices. The three studies included in this thesis unfolded the potentials of integrating dairy cows into both semi-natural landscapes and organic food crop cultivation. This would help transform Danish agriculture and food production towards practices that attend to long-term ecosystem health and resilience while maximising total food outputs to feed a growing world population. Such a transition would inevitably require a transition towards a higher percentage of plant-based food consumption.

Through an in-depth mixed methods study of four organic pasture-based, low-input dairy farms, a situated land-use analysis method was developed. This approach incorporates a food systems perspective accounting for landscape variability to assess land-use efficiency at the farm level. Findings indicate that among the analysed farms, feed-no-food mixed systems and dairy and meat production from land unsuitable for food crop cultivation required the least amount of arable and cultivated land per MJ of human-digestible energy produced. Importantly, the qualitative farm data contextualised these estimates, adding depth to the analysis and strengthening its validity.

Further, cow-pasture management in low-input, pasture-based dairy systems was examined through 3.5 years of qualitative fieldwork, combined with a longitudinal study of cow body conditions over 16 months, and biodiversity screening of the case-farm pastures. Findings suggest that these nature-inspired farming practices can – despite low availability to knowledge and advisory services for this production form – support both functional and to some extent genetic biodiversity, without leading to excessive body fat mobilisation due to the more extensive feeding scheme. However, potentials for genetic biodiversity were only found on the most extensively use permanent pastures, and prospects of maintaining good conditions of dairy cows cannot be reduced to feed characteristics alone but is a product of many factors. Further research is needed to quantify their potential for biodiversity conservation and nutrient leaching mitigation.

Finally, this PhD thesis highlights the need for a more diverse understanding of agricultural development and a corresponding shift in the knowledge paradigm which underpin livestock agronomy in Denmark. By using Kate Raworth's Doughnut Economics framework on how to think differently, and analytical examples from alternative dairy farmers, seven ways to think like a 21st century agronomist were suggested. Among other things, this includes working with goals adjusted to local landscapes, using (food)system-embedded metrics for farm optimisation and making interspecies sociality fundamental.

Overall, these alternative dairy farming approaches offer promising pathways for re-thinking dairy farming approaches to address the planetary polycrisis and challenges of producing enough food for a growing population. They typically have fewer animals per land area, can easily integrate with plant-based food production and can use permanent semi-natural pasture for grazing. This opens up a different paradigm of efficiency for dairy cows, enabling rather than restricting opportunities for improving the lives of cattle.

9 Perspectives

This thesis was, as mentioned, not aimed at providing general solutions for the dairy sector. Instead, the content of this PhD offers material and entry points for important discussions within the subject of agriculture, livestock and approaches to green transition, based on the study of alternative dairy farming practises.

By illustrating the interactions of deep structures that condition the possible futures for dairy and livestock (Manuscript III), it was shown that green transition occurs as much in the narratives, scientific methods and metrics used by scientists and other stakeholders. The conclusions thus spur a call for food production integrated across different sectors and more transdisciplinarity in research. This includes

- adopting a systems perspective fostering food supply optimisation on whole-system level based on dietary energy, protein and potentially other crucial dietary factors and abandoning production targets based on consumer demand projections
- focusing on balancing production in line with what can be considered healthy for both people and the planet and fair to the animals. This includes having local measures for balancing production systems to align with local capacities for achieving and maintaining healthy agro-ecosystems, supporting soil functions and protecting nature areas against negative impacts
- embracing a wider perspective on what efficiency is and use and combine different sources of data and metrics allowing for assessment against finite limits to available resources and pollution effects. As climate and environments are dynamic entities, it is of utmost importance to develop skill and put attention to the weight of situated observation and assessment of local agro-ecosystem health as well as the effect on the surrounding environments by farmers and farm advisors. In this way, I point to a shift from 'best practices' to 'situated practices'
- that all cattle and other livestock should – in line with the idea of situated practises – be kept in locally, where they are needed (for multiple purposes) and not treated as scalable objects to be moved around.
- that technical solutions can provide advantages and potentials, however, only as long as they do not substitute or hinder a deeper structural transformation or create rebound effects
- continuous discussions of societal structures, narratives, paradigms and assumption should be kept, to make visible how such societal entities come together and condition future modes of production.

It is my hope that the contents of this thesis bring inspiration to future inter- and transdisciplinary projects for rewiring balances across the Danish agricultural landscapes in a recognition of planetary boundaries and local carrying capacities.

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11 Appendix

Table 11.1. Overview of studies summarising the quantification of the planetary boundaries and the estimation of the current use.

Process	(Rockström et al., 2009)	(Steffen et al., 2015)	(Richardson et al., 2023)
Climate change	**Transgressed** Atmospheric CO2 conc., ppm (boundary: 350 CO2 conc. Current: 387)	**Transgressed (zone of uncertainty)** Atmospheric CO2 conc., ppm Boundary: 350 Zone of uncertainty 350-450 Current: 398.5	**Transgressed (zone of increasing risk)** Atmospheric CO2 conc., ppm Boundary: 350 Zone of uncertainty (350-450) Current: 417
		Transgressed Energy imbalance at top-of-atmosphere, W m^{-2} Boundary: +1.0 Zone of uncertainty +1.0-1.5 Current: +2.3 (1.1-3.3)	**Transgressed** Total anthropogenic radiative forcing at top-of-atmosphere, W m^{-2} Boundary: +1.0 Zone of uncertainty +1.0-1.5 Current: +2.91
Biosphere integrity (rate of biodiversity loss)	**Transgressed** Extrinction rate (no. of species /Mio. species per year) (boundary: 10 Current: >100	**Transgressed** Genetic diversity: (extrinction rate, E/MSY) Boundary: <10 (goal ~1 E/MSY) Zone of uncertainty: 10-100 Current: >100	**Transgressed** Genetic diversity: (extrinction rate, E/MSY) Boundary: <10 (goal ~1 E/MSY) Zone of uncertainty: 10-100 Current: >100
		Not yet quantified Functional diversity: (biodiversity, intactness index (BII) – stress need for more appropriate variables) Boundary: BII at 90% Zone of uncertainty: 90-30% Current: 84% (applied to southern Africa only)	**Transgressed** Functional diversity: Measured as energy available to ecosystems (NPP) (% HANPP, Human Appropriation of the biosphere's NPP) Boundary: <10% HANPP of preindustrial Holocene NPP (i.e., >90% remaining for supporting biosphere function) Zone of uncertainty: 10-20% HANPP Current: 30% HANPP

Biogeo-chemical flows (2009: N cycle P cycle)	N-cycle: **Transgressed** Amount N_2 removed from the atmosphere for human use (Mio. tons/year) Boundary: 35, Current: 121	N Global: **Transgressed** Industrial and intentional biological fixation of N (Tg N yr^{-1}) Boundary: 62 Zone of uncertainty: 62-82 Current: 150	N Global: **Transgressed** Boundary is a global average. Anthropogenic biological N fixation on agriculture areas highly uncertain but estimates in range of ~30 to 70 Tg of N year−1. Boundary acts as a global "valve" limiting introduction of new reactive N to Earth system, but regional distribution of fertilizer N is critical for impacts. (Tg N yr^{-1}) Boundary: 62 Zone of uncertainty: 62-82 Current: 190
	P-cycle: **Not transgressed** Quantity of P flow into the oceans (Mio. tons/year) Boundary: 11, Current: 8.5-9.5	**Transgressed (zone of uncertainty)** P Global: P flow from freshwater systems into the ocean (Tg P yr^{-1}) Boundary: 11 Zone of uncertainty: 11-100 Current: ~22	**Transgressed (zone of increasing risk)** P Global: P flow from freshwater systems into the ocean (Tg P yr^{-1}) Boundary: 11 Zone of uncertainty: 11-100 Current: 22.6 Tg P yr^{-1}
		Transgressed P Regional: P flow from fertilizers to erodible soils, Tg P yr^{-1} mined and applied to erodible soils Boundary: 6.2 Zone of uncertainty: 6.2-11.2 Current: ~14	**Transgressed** P Regional: P flow from fertilizers to erodible soils, Tg P yr^{-1} mined and applied to erodible soils Boundary: 6.2 Zone of uncertainty: 6.2-11.2 Current: 17.5
Stratospheric ozone depletion	**Not transgressed** Conc. Of ozon (O_3), Dobson unit (DU) Boundary: 276, Current: 283	**Not transgressed** Boundary: < 5% reduction from pre-industrial level of 290 DU, assessed by latitude Zone of uncertainty: 5-10% Current: Only transgressed over Antarctica in Austral spring (~200 DU)	**Not transgressed** Boundary: < 5% reduction from pre-industrial level of 290 DU (~276 DU), assessed by latitude Zone of uncertainty: 261-276 DU Current: 284.6 DU
Ocean acidification	**Not transgressed** Global mean saturation state of aragonite in	**Not transgressed** Boundary: ≥80% of pre-industrial aragonite saturations state of mean surface ocean	**Not transgressed** Boundary: ≥80% of mean pre-industrial aragonite saturation state of surface ocean Upper end of zone of increasing risk: 2.75 Ω_{arag}

	surface sea water Boundary: 2.75 Current: 2.90	Zone of uncertainty: ≥80-≥70% Current: ~84% of the pre-industrial aragonite sat. state.	Current: 2.8 Ω_{arag}
Freshwater use (2009: Global freshwater use)	**Not transgressed** Consumption of freshwater by humans (km3/yers) Boundary: 4,000 Current: 2,600	**Not transgressed** Global: Max. amount of consumptive blue water (km^3yr^{-1}) Boundary: 4,000 Zone of uncertainty: 4000-6000 Current: 2,600	**Transgressed (zone of increasing risk)** Blue water: human induced disturbance of blue water flow Boundary: Upper limit (95th percentile) of global land area with deviations greater than during preindustrial, Blue water: 10.2% Upper end of zone of increasing risk: 50% (provisional) Current: 18.2%
		Basin: blue water withdrawal as % of mean monthly river flow Low/intermediate/high-flow months: Boundary: 25% / 30% / 55% Zone of uncertainty: 25–55% / 30–60% / 55–85% Current: NA	**Transgressed (zone of increasing risk)** Green water: human induced disturbance of water available to plants (% land area with deviations from preindustrial variability) Boundary: Green water: 11.1% Upper end of zone of increasing risk: 50% (provisional) Current: 15.8%
Land system change	**Not transgressed** % of global land cover converted to cropland Boundary: 15, Current: 11.7	**Transgressed (zone of uncertainty)** Global: Area of forested land as % of original forest cover Boundary: 75% Zone of uncertainty: 75–54% Current: 62%	**Transgressed (zone of increasing risk)** Global: area of forested land as the percentage of original forest cover Boundary: Global: 75%, values are a weighted average of the three individual biome boundaries Upper end of zone of increasing risk: Global: 54% Current: Global: 60%
		Biome: Area of forested land as % of potential forest Boundary (tropical/tempereate/boreal): 85% / 50% / 85% Zone of uncertainty: 85–60% / 50–30% / 85–60% Current: NA	**Transgressed (zone of increasing risk)** / **Transgressed** Biome: area of forested land as the percentage of potential forest (% area remaining) Boundary: *tropical*, 85%; *temperate*, 50%; *boreal*: 85%

			Upper end of zone of increasing risk: *tropical*, 60%; *temperate*, 30%; *boreal*: 60% Current: *tropical*: Americas, 83.9%; Africa, 54.3%; Asia, 37.5%; *temperate*: Americas, 51.2%; Europe, 34.2%; Asia, 37.9%; *boreal*: Americas, 56.6%; Eurasia: 70.3%
Atmospheric aerosol loading	**Not yet quantified**	**Not yet quantified** Global: Aerosol Optical Depth (AOD), but much regional variation	**Not transgressed** Interhemispheric difference in AOD Boundary: 0.1 (mean annual interhemispheric difference) Upper end of zone of increasing risk: 0.25 Current: 0.076
Novel entities (2009: Chemical pollution)	**Not yet quantified**	**Not yet quantified**	**Transgressed** Percentage of synthetic chemicals released to the environment without adequate safety testing Boundary: 0 Upper end of zone of increasing risk: NA Current: Transgressed