# Sustainability and productivity in global livestock grazing
## Current challenges and future pathways

Johannes Piipponen

Aalto University

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A doctoral thesis completed for the degree of Doctor of Science (Technology) to be defended, with the permission of the Aalto University School of Engineering, at a public examination held at the lecture hall AS2 of the school on 14 March 2025 at noon.

Aalto University
School of Engineering
Department of Built Environment

**Supervising professor**
Professor Matti Kummu, Aalto University, Finland

**Thesis advisors**
Dr. Mika Jalava, Aalto University, Finland

**Preliminary examiners**
Dr. Adrian Müller, Research Institute of Organic Agriculture, FiBL, Switzerland
Assistant Professor Zia Mehrabi, University of Colorado Boulder, The United States

**Opponent**
Dr. Adrian Müller, Research Institute of Organic Agriculture, FiBL, Switzerland

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**TIIVISTELMÄ**

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**Väitöskirjan nimi** Laidunnuksen kestävyys ja tuottokyky globaalissa mittakaavassa: nykyiset haasteet ja tulevaisuuden mahdollisuudet

**Artikkeliväitöskirja**

**Sivumäärä** 114

**Avainsanat** laidunnus, maanpäällinen biomassa, maankäytön tehokkuus


Maailman väkiluvun kasvaessa, vaurastuessa ja enenevässä määrin kuluttaessa planeettamme luonnonvaroihin kohdistuu yhä suurempi paine. Ruoan tuottaminen kaikille ympäristön kannalta kestävästi on haastavaa, mutta mahdollista, mikäli nykyisiä tuotantorakenteita ja ajatusmalleja muutetaan. Lihantuotannon ja -kulutuksen vähentämisen on todettu olevan keskeisessä asemassa ympäristöhaasteiden ratkaisemisessa, sillä lihantuotanto kuluttaa huomattavasti luonnonvaroja. Globaali eläintuotanto on noin viisinkertaistunut 1960-luvun jälkeen väkiluvun 'vain' kolminkertaistuessa.

Samalla kun eläinperäiset ravinnonlähteet ovat ravitsemuksellisesti tärkeitä suuressa osassa maailman maita, monissa vauraissa maissa lihatuotteiden kulutus on karannut käsistä. Tämä uhkaa ihmisten terveyttä ja ympäristöä. Tähän asti on kuitenkin ollut epäselvää, millä alueilla eläintuotantoa olisi hyvä vähentää tai lisätä, ja missä nykyisten tuotantotapojen käyttö on edelleen perusteltua.
Tässä väitöskirjassa keskityttiin laidunmaihin ja tutkittiin asiaa tehokkuuden ja ympäristön kannalta: selvitettiin missä eläimet voivat laiduntaa, kuinka suuri on kunkin alueen laidunnuskapasiteetti, millä alueilla esiintyy ylilaidunnusta ja missä laitumet voisivat ylläpitää nykyistä suurempiakin eläinmääriä. Väitöskirjassa tutkittiin myös, missä eläintuotanto ja kasvintuotanto kilpailevat tai eivät kilpaile keskenään ja missä maankäytön muokkaukset lisäisivät ruoantuotantokapasiteettia, biodiversiteettiä ja hiilensidontaa.

Väitöskirja osoitti, että vajaa kolmannes maailman laidunalueista kärsii alentuneesta laidunnuskapasiteetista tai ylilaidunnuksesta. Ruokaa olisi mahdollista tuottaa nykyistä enemmän, mikäli kasvintuotantoon soveltuvat ja ympäristön kannalta vähemmän merkittävät laidunalueet käytettäisiin viljanviljelyyn. Biodiversiteettiystävällinen laidunnus edellyttäisi huomattavasti nykyistä pienempiä laidunpaineita sekä maidon- ja lihankulutustasojen alenemista. Mikäli osa laidunalueiksi muokatuista metsäalueista palautettaisiin luonnontilaan, hiilensidontaa olisi mahdollista lisätä merkittävästi (määrä ylittäisi vuosien 2021–2023 hiilidioksidipäästöt). Vastaavasti alkuperältään ei-metsäpohjaisilla laitumilla saavutetut hiilensidontahyödyt olisivat huomattavasti pienemmät, mikäli alue palautettaisiin luonnontilaan.

Maankäytön ja tuotantotapojen muutoksille on hyvät perusteet, ja tämä väitöskirja selventää, missä haluttuja muutoksia voitaisiin toteuttaa. Väitöskirjassa luotiin lisäksi lukuisia karttoja/aineistoja, jotka toimivat datalähteinä jatkotutkimuksille, joiden tulisi huomioida maankäyttösuunnittelussa ympäristönäkökulman lisäksi myös sosiaaliset, ekonomiset ja kulttuurilliset tekijät.

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**ABSTRACT**

**Author** Johannes Piipponen

**Name of the doctoral thesis** Sustainability and productivity in global livestock grazing: current challenges and future pathways

**Article-based thesis**

**Number of pages** 114

**Keywords** livestock grazing, aboveground biomass, land use efficiency

As the global population grows, becomes more affluent, and increasingly consumes planet's limited natural resources, the pressure on ecosystems intensifies. Producing food sustainably for everyone is challenging but possible if existing production structures and mindsets are changed. Reducing meat production has been reported to be one of the key solutions in addressing environmental challenges because it is highly resource-intensive, requiring significant amounts of land, water, and feed. Global livestock production has increased nearly fivefold since the 1960s, while the population has only tripled, thus amplifying the strain on ecosystems. Animal-source foods are vital for many diets, yet excessive meat consumption in affluent nations harms health and the environment. Grazing, in particular, is a major land user and influences ecosystems, but the exact locations where it could sustainably occur remain unclear.

This dissertation examines the opportunities and challenges associated with livestock grazing in terms of efficiency and environmental aspects. It assessed the distribution of biomass availability for livestock consumption, carrying capacity and its changes, as well as grazing intensities at a global scale. Concurrently, this work identified areas experiencing overgrazing and regions with potential for increased grazing. The research also analyzed the competition between livestock and crop production, exploring how shifts in land-use could increase food production capacity. Furthermore, the dissertation investigated the limits of biodiversity-friendly grazing and explored where removing grazers and allowing ecosystem restoration would enhance carbon sequestration.

The findings reveal significant sustainability issues in many grazing lands due to overgrazing, decreasing carrying capacity, inefficiency, or carbon emissions. Strategic land-use changes could significantly increase global food production while minimizing harmful environmental impacts. The research highlights regions where shifting grazing lands to croplands could most effectively benefit the food supply. It also underscores the complex trade-offs between production and biodiversity conservation, as achieving biodiversity goals requires reduced grazing pressure, impacting production levels of meat and milk. Reducing beef production on grazing lands that were formerly forests could lead to substantial carbon sequestration, while removing grazing in naturally non-forested areas would yield less significant environmental benefits, suggesting that targeted interventions are necessary for optimal outcomes.

While there is a strong rationale for reducing livestock production, this work clarifies where desirable changes could be most effectively implemented and where current grazing practices potentially remain important. This research also provides novel datasets and maps for future research, which should also consider social, economic, and cultural factors in land-use planning.

# Acknowledgements

Reaching this point has been rewarding, yet not trivial, since many (seemingly) well-planned things turned out quite differently than expected. Perhaps that is how it should be. Anyway, here we finally are after 2 kids, roughly 5 years, and over 10 research articles (published or in progress) later. Getting here would not have been possible without the substantial help and support I have received.

First, I extend my gratitude to my supervisor, Professor Matti Kummu. You encouraged me to always aim for excellence in every aspect of my research and to push hard, which I appreciate. Your dedication to all the work we do, including our joint articles and my academic progress, has been outstanding and has always led to better outcomes. But even more importantly, I am grateful for the flexibility and support you showed when the situation demanded it. Moreover, I enjoyed our casual conversations about our mutual interests in the environment and consumption. I also want to thank Mika Jalava, who turned out to be an ideal thesis advisor. You reminded me of the point of all this, which was important as I am far from a punctual scholar who enjoys playing with small details. You helped me to understand why those are sometimes necessary in this academic context. Besides, you have the remarkable capacity to talk about all other topics beyond work (try him!), which also helped me not sink too deeply into the PhD bubble.

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I have had the privilege of working with leading experts in the field and extend my gratitude to all my co-authors, most of whom I have yet to meet in person. Your valuable contributions have significantly enriched this work. I am particularly grateful to Jan de Leeuw, whose early guidance shaped my research trajectory. Thanks also to my former boss Kyösti Arovuori, who perhaps just wanted to get rid of me and pointed me toward this PhD position, and to Tapani Yrjölä for the ‘Kananhoito-ohjeet’ (Chicken Care Instructions).

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My siblings Kaarle, Emilia, Vilhelmiina, Hilkka and Jaakko; Thank you for the support, time, and activities that, luckily, took place away from the computer screen. It would have been a boring journey if everything had happened there over the past few years. I prefer to be more of a Chandler Bing than someone who constantly talks about work with you. Or well, many of our discussions were about animals anyway, which is quite close. I also want to express my sincere gratitude to my parents, Riitta-Miina and Aaro, who have supported me through my earlier studies, hobbies, and related decisions, while trusting I can always manage somehow. Special thanks for helping with the kids and for your willingness to spend sleepless nights with them as well as early mornings in the cowhouse.

Last, I do not even know what to say to my beloved wife Anna-Maria. Despite all the family struggles we have had recently, you have always understood, encouraged, loved and advised me, for which I am truly grateful. Also, thanks to my beautiful daughters Hilla and Hulda, who helped me maintain a healthy work-life balance and brought (still do!) additional meaning, laughter and great ideas to our lives.

Espoo, February 2025
Johannes Piipponen

# Contents

# List of Publications

This doctoral thesis consists of a summary and of the following open-access publications which are referred to in the text by their numerals.

**Publication I.** Piipponen, J., Jalava, M., de Leeuw, J., Rizayeva, A., Godde, C., Cramer, G., Herrero, M., Kummu, M., 2022. Global trends in grassland carrying capacity and relative stocking density of livestock. Global Change Biology 28, 3902–3919. https://doi.org/10.1111/gcb.16174

**Publication II.** Piipponen, J., Jalava, M., Resare Sahlin, K., Sandström, V., Cramer, G., Hayek, M.N., Zanten, H.V., Zabel, F., Kummu, M., 2024. Potential shifts between grazing and cropping to increase global food production. Manuscript under 2nd round of review in Nature Food.

**Publication III.** Resare Sahlin, K., Gordon, L.J., Lindborg, R., Piipponen, J., Van Rysselberge, P., Rouet-Leduc, J., Röös, E., 2024. An exploration of biodiversity limits to grazing ruminant milk and meat production. Nature Sustainability 7: 1160–1170. https://doi.org/10.1038/s41893-024-01398-4

**Publication IV.** Hayek, M.N., Piipponen, J., Kummu, M., Resare Sahlin, K., McClelland, S.C., Carlson, K., 2024. Opportunities for carbon sequestration from removing or intensifying pasture-based beef production. Proceedings of the National Academy of Sciences 121, e2405758121. https://doi.org/10.1073/pnas.2405758121

# Author's Contribution

**Publication I**: Global trends in grassland carrying capacity and relative stocking density of livestock.

JP, JdL, MK, JM and CG designed the study with support from all co-authors. JP collected the data, conducted the analysis, and produced the outputs shown in the study, with assistance from GC (simulating uncertainty) and AR (Google Earth Engine code). JP led the writing of the manuscript with contributions from all co-authors.

**Publication II:** Potential shifts between grazing and cropping to increase global food production.

JP, MK, and JM designed the study with consultation from all co-authors. JP gathered the data, conducted the analysis, and produced the outputs shown in the study, with assistance from VS and KRS (compiling feed conversion ratio data), HHEvZD (defining land use ratio), and FZ (providing data for priority conservation areas). JP wrote the manuscript, with contributions from all co-authors.

**Publication III:** An exploration of biodiversity limits to grazing ruminant milk and meat production.

KRS contributed to the conceptualization, methodology, data collection, analysis, led article writing, revisions, group coordination and acquisition of funding. LJG contributed to the conceptualization, methodology, article writing, revisions, and acquisition of funding. RL contributed to the conceptualization, methodology development and article revisions. JP contributed to grassland carrying capacity methods, additional data analysis, article writing and revisions. PVR contributed to methodology, data analysis and revisions. JR-L contributed to the conceptualization, methodology and revisions. ER contributed to the conceptualization, methodology, data collection, analysis, article writing and revisions, and acquisition of funding.

**Publication IV:** Opportunities for Carbon Sequestration from Removing or Intensifying Pasture-based Beef Production.

MNH, JP, and KC designed the research. MNH, JP, MK, and KRS conducted the research and contributed analytical tools. JP developed novel geospatial datasets on pasture productivity and performed additional data processing under MK's supervision. MNH aggregated and analyzed ecosystem carbon data, creating all figures and tables for the manuscript. SCM prepared soil carbon data for analysis, while KRS provided feed conversion ratios and national herd proportions for pasture utilization. MNH, JP, MK, KRS, SCM, and KC wrote the paper and contributed to its revision.

# Terminology

**AGB** Aboveground biomass: Estimated amount of biomass in dry matter that animals can sustainably consume from year to year.

**ASF** Animal-sourced food: Food derived from animals, such as meat and milk.

**CC** Carrying capacity: The number of animal units that an area can sustainably hold, based on the available AGB.

**COI** Carbon opportunity intensity: trade-off between carbon sequestration and pasture productivity; higher values suggest greater potential for sequestration relative to the food productivity loss.

**FCR** Feed conversion ratio: Efficiency of animals in converting AGB to food (e.g., 200 kg of AGB may be needed to produce 1 kg of protein).

**LUR** Land use ratio: Compares the land-use efficiency between different agricultural practices (e.g., crops vs. livestock).

**RQ** Research question: The main question or set of questions that guide the scope and focus of the study.

**RSD** Relative stocking density: Measures the proportion of AGB currently consumed, indicating overgrazed or undergrazed areas.

# 1 Introduction

## 1.1 Problem definition and rationale

Our world faces unprecedented environmental challenges, which are largely driven by a rapidly growing population that consumes finite resources at unsustainable rates (Ranganathan et al., 2016). The global food system must meet the nutritional demands of billions while respecting the carrying capacity of ecosystems (Springmann et al., 2018). In this context, livestock production plays a central and complex role, which is often oversimplified in public discourse.

While crops provide the majority of human-consumed proteins and kilocalories, animal-sourced foods (ASF) have steadily increased their contribution to global nutrition (FAO, 2022b). As of 2022, chicken, pork, and beef dominate global meat production, accounting for approximately 39%, 34%, and 21% of total meat output, respectively (FAO, 2022b). The majority of livestock production occurs in integrated crop-livestock systems or highly specialized operations, where animals often rely on feed sources that could otherwise be directly consumed by humans (Herrero et al., 2013). This is particularly evident in the poultry and pig sectors, but also in the high-performing cattle sector (FAO, 2022b, 2014). However, grazing-based livestock production, which contributes to approximately one-third of all ruminant protein production globally (Mottet et al., 2017), and which is the focus of this dissertation, will likely remain a crucial element of global food systems for reasons that will be explained and explored in this thesis.

Ruminants like cattle, sheep, and goats, as well as some monogastric animals such as horses, have the unique ability to convert inedible plant biomass (grass, leaves) into valuable nutrition (milk and meat) by utilizing resources that would otherwise go unused (Sandström et al., 2022; Van Zanten et al., 2018), as also summarized in appended Publications II-III. This capability is especially significant given the increasing demand for food, feed, fuel, and fiber, which places immense pressure on agricultural land (Smith et al., 2010), as also discussed in Publication I. Yet, public conversations and opinion pieces often oversimplify the issue, sometimes even suggesting that all ASF should be eliminated from our diets due to their inefficiency compared to crops and the environmental harm caused by domestic animals. While scholars broadly agree that reducing excessive meat consumption in affluent societies benefits both human health and the environment (Godfray et al., 2018; C. Li et al., 2024), the implications and potential locations of such a shift are not trivial, as discussed throughout Publications II-IV.

In theory, the principles of supply and demand suggest that strongly reduced meat consumption should eventually lead to decreased production volumes and a corresponding decline in livestock numbers. Although this is not that straightforward in practice, these considerations lead us to important questions: *How many animals should be allowed to exist, and where should the reduction of livestock populations begin?* Moreover, *how can it be ensured that any reductions in livestock numbers are implemented in a way that maximizes environmental benefits while minimizing negative impacts on food security and beyond?*

Balancing conflicting goals and identifying acceptable compromises is critical. Changing agricultural systems is complex and slow, as land use reflects multiple drivers and motivations and is far from random (van Vliet et al., 2015). Understanding where changes in production practices and land use could feasibly occur is vital. Given the high stakes, decisions on livestock reduction must be supported by research, grounded in local realities, and considerate of both environmental and socio-economic factors. While this dissertation examines challenges and future pathways in land-use change, it is important to remember that often local actors ultimately decide (and practically implement) how land is managed. Their economic, cultural, social, and other needs fundamentally shape whether and how changes are adopted (Sharma et al., 2015; Mehdi et al., 2018).

## 1.2 Knowledge gaps and research questions

Existing research has identified opportunities for low-opportunity cost animal-sourced foods (ASF) and sustainable livestock grazing (Van Hal et al., 2019). Diets with small amounts of grass-fed meat can potentially be more efficient than purely plant-based diets, as ruminants can convert inedible biomass outside croplands into nutritious food (Van Zanten et al., 2018). Studies have shown that, in certain settings, properly managed low-intensity grazing can support specific aspects of biodiversity and provide ecosystem services (Gao and Carmel, 2020; Herrero et al., 2009; Wang and Tang, 2019), while in subsistence farming, livestock remains crucial for food security and risk management (Baiphethi and Jacobs, 2009). Progress has been made in estimating the global extent of grazing lands, which cover a significantly larger share of world's land area compared to croplands (Klein Goldewijk et al., 2017).

Research has also recognized significant environmental concerns related to animal production, including biodiversity loss, climate change, water scarcity, and land degradation (Herrero et al., 2009; Nkonya et al., 2016). Studies have quantified livestock-related greenhouse gas emissions (Herrero et al., 2013; FAO, 2022a; Runting et al., 2024) and demonstrated how sustainable practices in the grazing stage can reduce these (Pelton et al., 2024). These issues have become particularly important given that global livestock production has increased nearly fivefold since 1961, while the world population has roughly tripled (FAO, 2022a). The large contribution of ASF to total greenhouse gas emissions of food, including both production- and consumption-based emissions, has also been evaluated (Xu et al., 2021). Research has also advanced our understanding of the potential for redirecting feed crops to direct human consumption (Cassidy et al., 2013) or otherwise optimizing crop distribution to increase global food production capacity and decrease feed-food competition (Dai et al., 2023; Wen and Chen., 2023)

Despite these contributions, significant knowledge gaps persist. Many existing studies focus primarily on cropland potential, often overlooking nuances in production practices, such as grazing intensity, yield potential, and local environmental conditions of grazing lands alongside croplands (Herrero et al., 2009; Mueller et al., 2012). For instance, advances have been made in assessing land suitability for plant production (Schneider et al., 2022) and quantifying potential protein and energy yields from plant-based agriculture (Davis et al., 2017), but precise quantification of forage availability on grazing lands remains elusive (though initial attempts have been made, e.g., by Fetzel et al. (2017) and Petz et al (2014)). In the context of grazing, global-scale research often relies on coarse assumptions and low-resolution data, limiting the ability to make spatially explicit comparisons between cropland, grazing land, and other land uses. Many valuable studies comparing production efficiency focus on local or regional scales, making it difficult to capture the broader global picture (Tichenor et al., 2017; Van Zanten et al., 2016). Additionally, policymakers and researchers lack a clear understanding of how transitioning to sustainable grazing practices would impact production volumes at a larger scale, or whether production losses in some regions could be offset by gains elsewhere. As a result, critical areas where changes in grazing land use would yield the greatest benefits or be most justified remain unidentified.

This dissertation addresses some of these gaps by estimating environmentally sustainable grass-based feed production levels globally (Publication I), forming the foundation for subsequent studies that evaluate the potential shifts between grazing and cropping to increase global food production (Publication II), explore biodiversity limits and sustainable production practices in grazing systems (Publication III), and assess opportunities for carbon sequestration from altering grazing-based beef production (Publication IV). The overarching goal is to identify regions where grazing practices can potentially be altered with maximum benefits (e.g., increased food production or carbon sequestration) and minimal adverse effects (such as decreases in production levels or harm to biodiversity). By improving the understanding of these areas, this thesis provides an atlas of options that can inform policies and practices aiming to enhance land use for a more sustainable future. More explicitly, the research questions that provide a comprehensive framework for evaluating the sustainability and efficiency of grazing systems on a global scale are:

**RQ1:** What is the current ecological status of global grazing lands, as measured by key environmental indicators?

**RQ2:** How do different grazing land management strategies impact global food supply and environmental sustainability, and where are these strategies most effectively applied?

**RQ3:** Where does grazing have a sustainable role in land use, and where might it be reasonable to reduce or abandon grazing in favor of alternative practices?

Figure 1 illustrates the interconnectedness of the individual studies within this dissertation, demonstrating how each publication contributes vital pieces to the complex puzzle of sustainable land use.

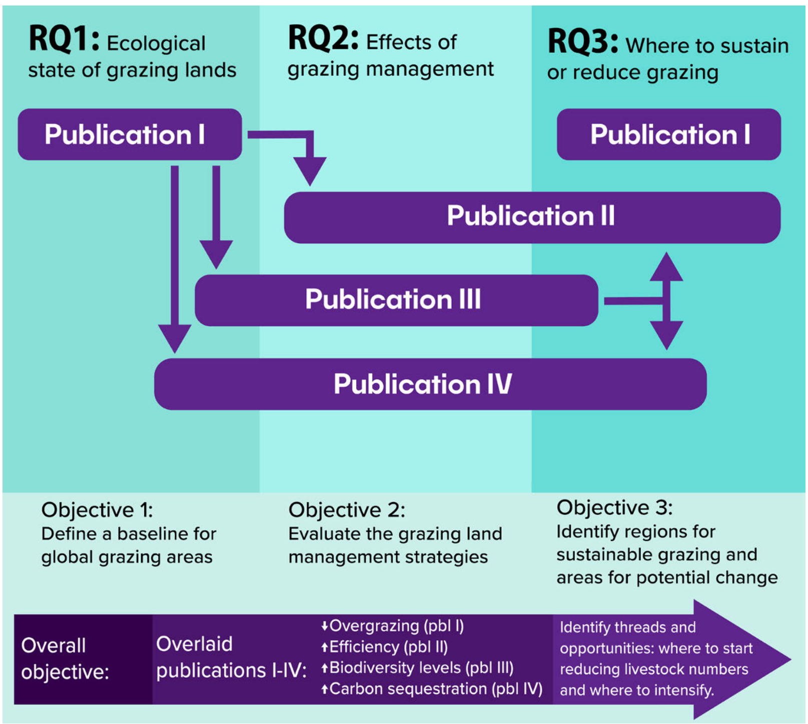



**Figure 1** Thematic placement and contributions of Publications I–IV in relation to research questions (RQs) 1–3, showing the research progression from baseline assessment through management evaluation to identifying sustainable grazing opportunities. The overarching aim, indicated by the large arrow, is to apply the findings from all publications to optimize grazing practices for both environmental and production benefits.

## 1.3 Primary objectives

This dissertation aims to shed light on sustainable grazing by examining opportunities and challenges from various perspectives. More specifically, the aim is to answer the research questions by:

1. <u>Defining a baseline for global grazing areas:</u>
   Provide a detailed understanding of global grazing lands, their resources, and current environmental conditions using relevant environmental indicators developed in this thesis. This includes estimating the annual aboveground biomass (AGB) available for grazing, evaluating livestock carrying capacity (CC) and its trends, detecting overgrazing through relative stocking density (RSD), and assessing carbon opportunity intensity (COI) to evaluate carbon sequestration potential. The thesis also evaluates how close different countries are to implementing biodiversity-friendly grazing practices. (Publications I, IV, III; research questions RQ1, RQ3).
2. <u>Evaluating the grazing land management strategies:</u>
   Examine how different land-use practices affect global food supply and environmental sustainability and identify where changes in grazing land usage are most effectively applied. This includes comparing the food production capacity of grazing lands and croplands and investigating where shifts from grazing lands to croplands (or vice versa) could most effectively increase the global food supply. Additionally, the thesis analyzes how adopting biodiversity-friendly grazing would impact meat and milk outputs. The thesis also explores how removing grazing livestock from certain areas could increase carbon sequestration and how the resulting production losses could be counterbalanced by intensifying production in areas with lower potential for mitigating carbon emissions. (Publications II–IV; RQ2, RQ3).
3. <u>Identifying regions for sustainable grazing and areas for potential change:</u>
   Create a map that synthesizes key findings from this thesis to pinpoint where grazing appears sustainable and where shifting to alternative land uses (cropland, forest, natural state) could provide significant environmental or food production benefits. This analysis directly addresses where it is sustainable to continue (current) grazing practices and where changes would be most justified (Publications I–IV; RQ3).

## 1.4 Definitions, scope, and shortcomings

In this dissertation, the term "grazing animals" encompasses all ruminants and other livestock whose diet is predominantly grass-, forage-, or leaf-based, regardless of whether they physically graze on pasture or receive cut-and-carry forages (e.g., harvested fresh grass or hay) in barns. Many systems, especially in temperate regions such as parts of Europe, combine both approaches: animals might graze outdoors during warmer seasons but rely on stored forage during winter. Due to data limitations, this dissertation treats any potentially usable aboveground biomass within a grid cell as available for local consumption by grazing animals, without distinguishing whether biomass is consumed directly on-site or transported elsewhere. Consequently, all grass- or forage-based production is referred to here as "grazing land" production, recognizing that some animals may not physically graze on pasture.

It is important to note that this dissertation focuses on sustainable grazing from an environmental perspective, and does not extensively address social, economic, or cultural factors. Additionally, other important aspects of sustainable food production, such as fisheries and aquaculture, are not covered in this study. The use of supplementary feed in grazing systems and the methane emissions from ruminants, while significant topics in livestock research, are also beyond the scope of this work. While these aspects are undoubtedly important in the broader context of sustainable agriculture, they are not the primary focus of this thesis.

The analyses rely heavily on optimization approaches that emphasize biophysical and environmental parameters; as such, they do not fully capture the socioeconomic realities faced by local communities and land managers. While these modeling frameworks offer insights into possible theoretical boundaries for more sustainable grazing, they may overlook important practical trade-offs related to livelihoods, cultural values, and local policy contexts (Herrero et al., 2009). This is particularly relevant for vulnerable populations, where generalized recommendations could inadvertently marginalize stakeholders or disrupt livelihoods (Sharma et al., 2015; Wang and Zhang, 2024). Consequently, any operational use of these results should be undertaken with caution, bearing in mind that implementing changes in real-world settings demands integrating socioeconomic factors and engaging diverse stakeholders, as emphasized in the Discussion section.

## 1.5 Significance and contribution

This dissertation provides a novel, spatially explicit global analysis of sustainable grazing practices, offering a starting point for identifying regions where land use changes could yield substantial benefits in both environmental sustainability and production efficiency. The findings offer valuable insights for policymakers, land managers, and stakeholders aiming to balance agricultural productivity with environmental conservation. By mapping the interplay between existing and potential grazing intensity, carbon sequestration as well as biodiversity-friendly grazing intensity, the dissertation highlights key areas where targeted interventions can yield the most significant impact (Figure 1).

# 2 Data and methods

To achieve the outlined objectives, this study employs a combination of spatial analysis, remote sensing, ecological and statistical modeling, data harmonization and literature review. All input datasets used are publicly available or accessible upon request. Additionally, this research produced several new datasets, which are also freely available for use by other researchers. The research integrates numerous global datasets and utilizes geographic information system (GIS) tools to perform spatially explicit analyses at a moderately high resolution. The key datasets related to land use, biomass productivity, livestock densities, carbon sequestration, and others are described below and also found in the articles attached to this dissertation.

## 2.1 Data

This research relies heavily on satellite-derived observations, which provide critical environmental measurements such as temperature, photosynthesis rates, and tree canopy cover. The remote-sensing data sources used offer freely accessible, frequently updated, and globally comprehensive insights essential for detailed ecological and environmental assessments. Most of the data utilized in this dissertation come from databases that provide global or regional information in rasterized or tabular formats. These datasets vary in spatial resolution—from 30 × 30 meters to 10 × 10 kilometers—and cover diverse time periods, reflecting the temporal dynamics of the studied phenomena.

A key dataset produced in this research is the aboveground biomass (AGB) data. This newly developed dataset, derived from existing open-access data sources, represents the annual accumulation of aboveground net primary productivity (NPP) that is accessible to grazing animals and serves as a foundational dataset for Publications II-IV. The AGB estimation method is first developed in Publication I, using temperature to partition NPP into above- and belowground components. While this original method is utilized in Publication III, it is later refined in Publication II by incorporating an expanded set of field samples and using both temperature and precipitation as predictors for NPP partitioning. This refined version, with minor adjustments in forest cover handling, is then applied in

Publication IV. In all versions, the aboveground NPP is converted to biomass and adjusted for dense forests and steep slopes.

Another crucial dataset is the Feed Conversion Ratio (FCR), which is compiled at the national level in Publication III and utilized in Publications II and IV. Table 1 lists the most relevant datasets used in the quantitative analyses, including their temporal spans and application across Publications I–IV. This table distinguishes between existing data sources and novel datasets produced in this research. Figure 2 illustrates the relationships between the data used in Publications I-IV and highlights the novel datasets produced in this research.

**Table 1** Key input datasets and produced data utilized in this dissertation, including their temporal spans and usage in Publications I–IV.

| **Datasets produced** | **Source** | **Publication I** | **Publication II** | **Publication III** | **Publication IV** |
|---|---|---|---|---|---|
| Aboveground biomass (AGB) | Publication I, II | 2001–2015 | 2001–2020 | 2001–2015 | 2001–2020 |
| Tree cover multiplier | Publication I | 2001–2015 | 2001–2020 | 2001–2015 | 2001–2020 |
| Carrying capacity (CC) | Publication I | 2001–2015 | | | |
| Relative stocking density (RSD) | Publication I | 2001–2015 | | | |
| Feed conversion ratio (FCR) | Publication III | | 2000 | 2000 | 2000 |
| Land use ratio (LUR) | Publication II | | 2020 | | |
| Land use shifts for increased food production | Publication IV | | 2020 | | |
| Carbon opportunity intensity (COI) | Publication IV | | | | NA |
| **Environmental and observational data sources** | | | | | |
| Temperature | TerraClim | 2001–2015 | 2001–2020 | 2001–2015 | 2001–2020 |
| Precipitation | TerraClim | | 2001–2020 | | 2001–2020 |
| Terrain slope | Amatulli et al. (2020) | Constant | Constant | Constant | Constant |
| Land cover type (IGBP classes) | MODIS | 2001–2015 | 2001–2020 | 2001–2015 | 2001–2020 |
| Net primary productivity (NPP) | MODIS | 2001–2015 | 2001–2020 | 2001–2015 | 2001–2020 |
| Tree canopy coverage | MODIS | 2001–2015 | 2001–2020 | 2001–2015 | 2001–2020 |
| **Modeled, literature and statistical data sources** | | | | | |
| Carbon conversion factor | Literature review | Constant | Constant | Constant | Constant |
| Proper use factor (PUF) | Literature review | Constant | Constant | | Constant |
| Grazing land extent | HYDE | | 2020 | 1700, 2017 | 2020 |
| Cropland yield and extent | SPAM | | 2020 | | |
| Livestock distribution | GLW | 2010 | | | |
| Crop suitability index | Zabel et al. (2022) | | 2010–2039 rcp8.5 | | |
| GAEZ v4 | Fischer et al. (2021) | | 2010 | | |
| FAOSTAT | FAO (2022b) | | 2020 | 2000 | |
| Carbon stocks, present | Erb et al. (2018) | | | | NA |
| Carbon stocks, potential | Searchinger et al. (2018) | | | | NA |

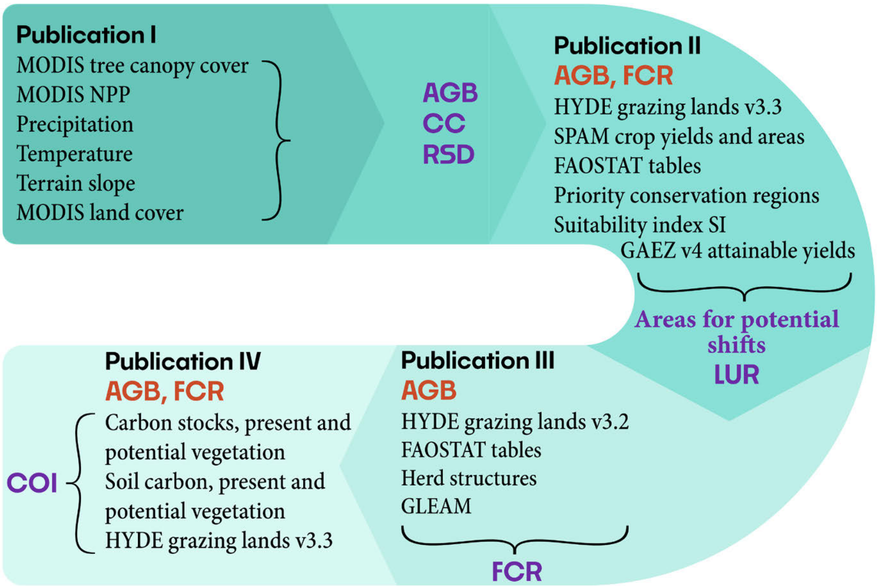



**Figure 2** Data flow and novel datasets (in purple) produced in appended Publications I–IV, with orange indicating instances where a dataset from one publication is used in another. Abbreviations: Aboveground biomass (AGB), carrying capacity (CC), relative stocking density (RSD), feed conversion ratio (FCR), land use ratio (LUR), carbon opportunity intensity (COI).

## 2.2 Methods

The methodology in this dissertation relies on extensive spatial data analysis, integrating multiple global datasets in various formats and resolutions. The research combines diverse data sources - from high-resolution satellite imagery to comprehensive agricultural statistics - to analyze relationships between climatic, agricultural, and environmental variables. Global datasets used for spatial analysis are typically large, with varying resolutions (e.g., cell sizes of 30 × 30 m or 10 × 10 km) and formats. The research process begins with extensive data collection from various sources, followed by data cleaning, processing, harmonization, and gap-filling to create compatible datasets for analysis. Table 2 presents the core methods used in Publications I–IV.

The basic principles of spatial data analysis used in this dissertation appear deceptively easy: harmonized rasters (grid-based spatial data) are frequently summed, subtracted, multiplied, divided, or analyzed using statistical methods. While the core analytical techniques may seem simple, the true complexity and challenge lie in the nuanced understanding and preparation of the data. Once datasets are compatible, the subsequent analysis can be relatively straightforward, and the outcomes can be plotted as global maps. However, achieving this compatibility is rarely a trivial task. The process of combining various datasets meaningfully requires a deep understanding of their underlying structures, characteristics, and potential correlations. Additionally, outcomes derived from combining different datasets must be scientifically sound.

**Table 2** Main analysis methods used in Publications I–IV, categorized by general, spatial, and statistical methods.

| General and spatial analysis methods | Publication I | Publication II | Publication III | Publication IV |
|---|---|---|---|---|
| Descriptive statistics | x | x | x | x |
| Data visualization | x | x | x | x |
| Exploring time series | x | x | x | x |
| Zonal analysis tools | x | x | x | x |
| Spatial interpolation | x | | | |
| **Statistical and modeling methods** | | | | |
| Data analysis | x | x | x | x |
| Monte Carlo simulations | x | x | x | x |
| Linear trends | x | | | |
| Correlations | x | x | x | x |
| Census statistics | | | x | |

Linking global agricultural data, such as modeled gridded livestock distribution and biomass production, is complex because the data often represent a single phenomenon within a grid cell. For example, it might be known that the estimated number of goats in a 100 km² (10 × 10 km grid cell) area is 200 and the biomass amount is 1,000 metric tons. However, it is unclear whether these goats are concentrated in a specific part of the grid cell (e.g., in a barn) or evenly distributed. Even with additional datasets (e.g., those revealing grazing land areas within the same pixel), the extent to which goats can access the estimated biomass or whether they are supplemented with other feeds cannot be definitively known. Despite the ongoing advancements in data quality and sources, it is not always possible to completely understand what happens on the ground or in individual grid cells. Fortunately, pixel-by-pixel understanding is not necessary for this dissertation; instead, gaining insight into the larger perspective is important.

In the context of this dissertation, exploratory data analysis and descriptive statistics are often sufficient to reveal the main characteristics and features of the data. In fact, this is a key principle in this dissertation: using simplified methods is often assumed to be more effective than letting complex analyses and hypotheses about the data lead the analysis. Besides, using straightforward models facilitates clearer interpretation. As spatial data modeling has become increasingly common and numerous datasets exist, it is common for one dataset to indirectly include information also present in another dataset. When utilizing such datasets that have been modeled using various data sources, along with advanced and complex methods, an outcome may be obtained (e.g., a new raster), but it can be difficult to interpret or determine its relevance.

However, more complex relationships (compared to basic correlations, linear regressions, or arithmetic operations) between different data sources must regularly be considered in high-quality science. For example, all input data contain inherent uncertainties that must be accounted for. In this work, Monte Carlo simulations were used to assess combined uncertainties, as implemented in Publications I–IV. Similarly, global analyses and datasets always contain assumptions whose sensitivity must be explored, as was done in the publications presented below. Together, uncertainty and sensitivity analysis allow for a more robust understanding of the reliability of the results.

Lastly, most analyses were conducted using R software (Publications I, II, and IV), with additional tools like Google Earth Engine (Publications I-II) and ArcGIS (Publication III) used for specific tasks. Most maps and figures were further refined using Adobe Illustrator.

# 3 Findings

This section presents the key findings from the appended publications, addressing the research questions outlined earlier. Each subsection corresponds to a specific research question and integrates results from relevant publications.

The foundation for this research is established through four interconnected publications. Publication I develops high-resolution estimates of aboveground biomass (AGB) and assesses the carrying capacity (CC) of grazing lands and relative stocking density (RSD) of grazing lands. Building on this, Publication II compares the food production efficiency of grazing livestock versus crop cultivation, identifying regions with significant potential for land-use reallocation. Publication III explores biodiversity-friendly grazing intensities and their implications for food production, while Publication IV examines the carbon sequestration opportunities linked to modifying pasture-based beef production. Figure 2 presents the created datasets and their relationships, while Figures 3-4 display the key results from individual publications. Figure 5 synthesizes all findings into a comprehensive Aggregated Grazing Indicators Map.

## 3.1 Ecological status of global grazing lands

*Addressing Research Question 1 (RQ1): What is the current ecological status of global grazing lands, as measured by key environmental indicators?*

Publications I, III, and IV provide a comprehensive assessment of grazing lands' ecological sustainability status through multiple environmental indicators. These indicators include aboveground biomass (AGB), carrying capacity (CC) and its temporal trends, relative stocking density (RSD), biodiversity-friendly grazing thresholds, and carbon opportunity intensity (COI).

Publication I lays the foundation by estimating the global availability of grass-based feed for livestock and assessing grazing possibilities across different regions, along with the status of forage utilization on the world's grazing lands. The study produces a novel, high-resolution (500 m), spatially explicit AGB dataset for potential grazing areas. This dataset represents the first global AGB estimation at this precision and lays the groundwork for calculating CC and RSD, as shown in Figure 3a-c. One significant contribution from Publication I is also the development of the tree cover multiplier function incorporated in the AGB calculations. This function estimates the amount of forage (grass, leaves, branches) available to animals in the understory, accounting for the effects of tree canopy cover on forage accessibility. While this function has limitations, it provides a valuable foundation for subsequent studies and has already been adopted in publications beyond this dissertation (e.g., T. Li et al., 2024; Wang et al., 2024).

Publication IV expands the ecological assessment by introducing the COI metric, which indicates the potential for ecosystem carbon sequestration relative to the amount of pasture productivity that would be foregone if grazing were to end. The study reveals substantial variations in COI values globally, with particularly high values in regions where pastures have replaced natural forests (Figure 3d). These findings underscore the ecological implications of current grazing practices on carbon sequestration potential in different locations.

Publication III complements this assessment by examining the ecological sustainability of grazing lands from a biodiversity perspective. By applying biodiversity-friendly grazing intensities—limiting biomass removal to 0–20%—the study evaluates how current grazing practices align with biodiversity conservation goals across different countries. The research provides insights into how close different countries are to achieving grazing practices that support biodiversity conservation.

Collectively, these publications offer a comprehensive assessment of the current ecological status of global grazing lands. **The key findings include:**

1. Aboveground biomass (AGB), carrying capacity (CC) and its temporal trends (Figure 3a-b). Estimated AGB levels might be cautious compared to previous comparable estimates. There are notable variations between years due to natural annual fluctuations and longer-term trends. Decreasing CC trends in Europe, Southeast Asia, southeastern Brazil, and the eastern United States suggest worsening grazing conditions, potentially due to land degradation, climate change, or poor management. Increasing CC trends in parts of South America and the Sudano-Sahel area in Africa indicate improving grazing possibilities.
2. Relative stocking density (RSD) (Figure 3c). Several regions show high RSD values, indicating potential overgrazing. These include South and Southeast Asia (particularly China, India, Pakistan, and Iran), northwestern Europe, and parts of Africa near Chad and Sudan. In these areas, grazing pressures exceed the local carrying capacity, which might cause ecological degradation. Understocked regions include Australia, southern Africa, Canada, and Russia, suggesting that grazing resources are underutilized and there may be potential for sustainable intensification.
3. Carbon opportunity intensity (COI) (Figure 3d). High potential for carbon sequestration (high COI) appears in South and Southeast Asia, northwestern Europe, and parts of Africa. Halting grazing in these areas could result in

substantial carbon sequestration benefits relative to the amount of beef production lost. Conversely, the Central United States, Australia, and Central Asia show low or negative COI values, suggesting limited carbon benefits from abandoning grazing activities compared to the production forgone. In some native grasslands, such as Northern China and Western Australia, removing livestock might reduce ecosystem carbon stocks due to expected soil carbon losses (negative COI).

4. <u>Biodiversity-friendly grazing limits.</u> Regions near sustainable biodiversity limits include Oceania, which could maintain 82% of current grazing-land-based beef production within biodiversity thresholds. Additionally, parts of sub-Saharan Africa could sustain about 45% of its current milk production. Regions significantly exceeding sustainable biodiversity limits include South Asia, where only about 1% of current meat production aligns with biodiversity limits. In general, a larger share of meat can be produced within biodiversity limits compared to milk.

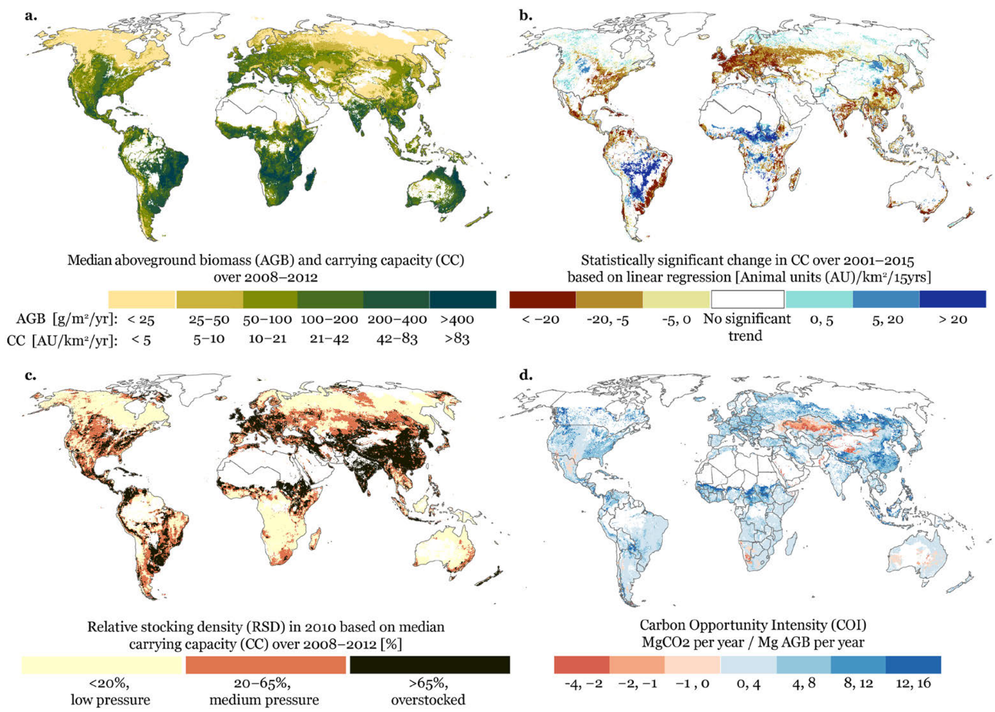



**Figure 3** Key environmental indicators describing the ecological status of global grazing lands: (a) Median aboveground biomass (AGB) and carrying capacity (CC) on grazing lands over 2008-2012 (Figure 2 from Publication I), (b) the statistically significant trend of CC over 2001–2015 based on linear regression (Figure 2 from Publication I), (c) relative stocking density (RSD) on grazing lands (Figure 4 from Publication I), and (d) carbon opportunity intensity (COI) of grazing lands including negative values (Figure S5 from Publication IV).

## 3.2 Efficiency: impact of management strategies on food supply

*Addressing Research Question 2 (RQ2): How do different grazing land management strategies impact global food supply and environmental sustainability, and where are these strategies most effectively applied?*

Publications II, III, and IV contribute to this research question by exploring how different grazing land management practices influence global food production and environmental outcomes. Publication II evaluates the potential for increasing global food production by altering land use between grazing lands and croplands. Using refined AGB estimations and national feed conversion ratio (FCR) data, the study evaluates how much food (specifically protein and energy per hectare) could be produced globally by grazing livestock. Publication II then compares these food outputs with those from crop production and assesses the land-use efficiency of these two primary agricultural systems. The findings reveal that in 2020, grazing lands contributed only a minor share of the total protein, with crops producing most of it (Figure 4a). Although grazing lands cover vast areas, their capacity for protein and energy production is often lower compared to crops. If the majority of protein within an area originates from grazing livestock, it generally indicates that crops are either not growing there or occupy such a small portion of the grid cell that their contribution to total production is minimal. However, grazing-reliant livestock plays a significant role in protein, energy, and micronutrient production in regions where climate or soil conditions limit crop cultivation, such as Central Asia, Australia, and the world's northernmost and southernmost areas (Figure 4a).

Publication II introduces the land use ratio (LUR) (Van Zanten et al., 2016) globally for the first time to compare land-use efficiency. The LUR quantifies the relative food production efficiency (in terms of protein or energy) between crops and grazing livestock per hectare. The analysis reveals significant regional variations in land-use efficiency: in many areas suitable for crop cultivation, crops can produce up to ten times more protein per hectare than grazing livestock (LUR > 10) (Figure 4b). Conversely, in regions where environmental constraints limit crop cultivation such as poor soil quality, steep terrain, or arid climates grazing remains the most efficient use of land for food production (LUR < 1) (Figure 4b). In these areas, grazing livestock serves a vital role in converting inedible biomass into valuable nutrients while supporting livelihoods and landscape functionality.

Finally, based on the foregoing analysis, the study maps areas where strategic land-use changes between grazing and cropping could most significantly boost protein and energy supplies with minimal negative impacts, and where existing land allocation remains unchanged. The results show that shifting from grazing to cropping or vice versa could boost global protein and energy supplies by up to 21%

and 19%, respectively, without compromising micronutrient supply or priority conservation areas (Figure 4d). This potential for land-use optimization is illustrated in Figure 4 c-d, which highlights areas with the greatest opportunities for producing more protein through strategic land-use shifts. It is important to note that implementation of the changes presented in Figure 4c-d naturally presents challenges, as grazing lands hold value beyond food production, such as supporting livelihoods and providing non-provisioning ecosystem services. Real-world transitions between grazing and cropping require careful consideration beyond net production benefits. Factors such as infrastructure demands, financial mechanisms, and market conditions can greatly influence the feasibility of such shifts. In many regions, switching between production systems may require substantial investments in supply chains, agricultural inputs, or extension services beyond what is assumed here. Therefore, local-scale considerations are necessary for more detailed analyses of potential impacts (Mehrabi et al., 2020), including social implications and sustainability considerations (see Discussion).

Publication III examines the impact of adopting biodiversity-friendly grazing intensities on meat and milk outputs. The findings suggest that restricting grazing to these limits would result in global production of meat and milk corresponding to 26–40% and 9–13% of current grassland-based outputs, respectively. Publication III also reveals that altered management practices and shifting from meat-specialized to meat-and-dairy systems could increase sustainable production while still remaining within these biodiversity limits. The research identified regions where grazing intensities could be reduced to protect vulnerable ecosystems, particularly in arid and semi-arid regions, and areas where grazing could be sustainably intensified (especially areas where grazing is a natural component of landscape dynamics). This article highlights the complex balance needed between livestock production and biodiversity conservation.

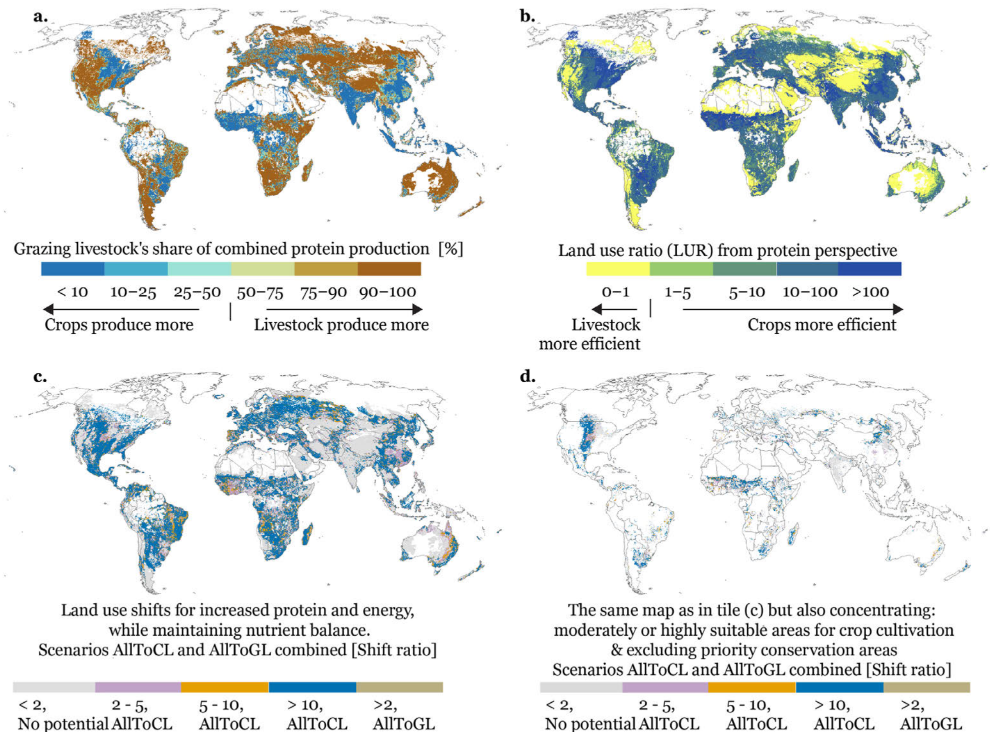



**Figure 4** Current patterns, land use efficiency and potential shifts for increased food production. (a) Proportion of the total protein (protein from crops and grazing livestock combined) contributed by grazing livestock (Figure 3 from Publication II), (b) land use ratio (LUR) calculated from a protein perspective (Figure 3 from Publication II), (c) potential land-use shifts for increased protein and energy production under the 'All to cropland' (AllToCL) and 'All to grazing land' (AllToGL) scenarios as presented in Publication II (Figure 4 from Publication II). In panel (d) this scenario is further allocated outside priority conservation and to areas where suitability for crop cultivation is moderate or high. The AllToGL category is nearly invisible due to the scarcity of such regions, reflecting that the AllToGL scenario yields only a minor fraction more protein and energy than the baseline scenario does, generally much less than twice as much as in the baseline scenario.

Publication IV reveals significant carbon sequestration opportunities through modifications of grazing land-based beef production. The research finds that removing beef-producing cattle from high-carbon intensity grazing lands (that used to be forests) could sequester 125 GtCO2 into ecosystems, which is an amount greater than global fossil CO2 emissions from 2021–2023. This removal would lead to a modest loss of approximately 13% of the global total beef production on pastures, predominantly within high– and upper-middle-income countries. The findings underscore the significant carbon opportunity cost associated with converting forests to grazing land. Furthermore, the study explores the possibility of intensifying grazing-based beef production in low-carbon-intensity pastures to compensate for potential production losses from removing cattle from high-carbon areas. The analysis shows that this approach could fully counterbalance the global loss of beef production if areas with low-carbon intensity pastures and less efficient beef production simultaneously intensified their beef production to 47% of OECD levels. This approach aims to balance the demand for beef production with the need to reduce the carbon footprint of the livestock sector. **Key findings from these publications include:**

1. Increasing food production efficiency. Shifting land use from grazing to cropping in suitable areas can significantly increase global protein and energy supplies, without compromising micronutrient supply. Nevertheless, grazing remains the most efficient land use across 1,728 million hectares (nearly double the global cropland area)
2. Biodiversity conservation. While biodiversity-friendly grazing intensities would significantly reduce current production levels, dual-purpose systems for meat and milk offer higher efficiency within these constraints.
3. Carbon management. Removing grazing from high-COI areas offers substantial carbon benefits while intensifying production in low-COI regions can offset production losses.

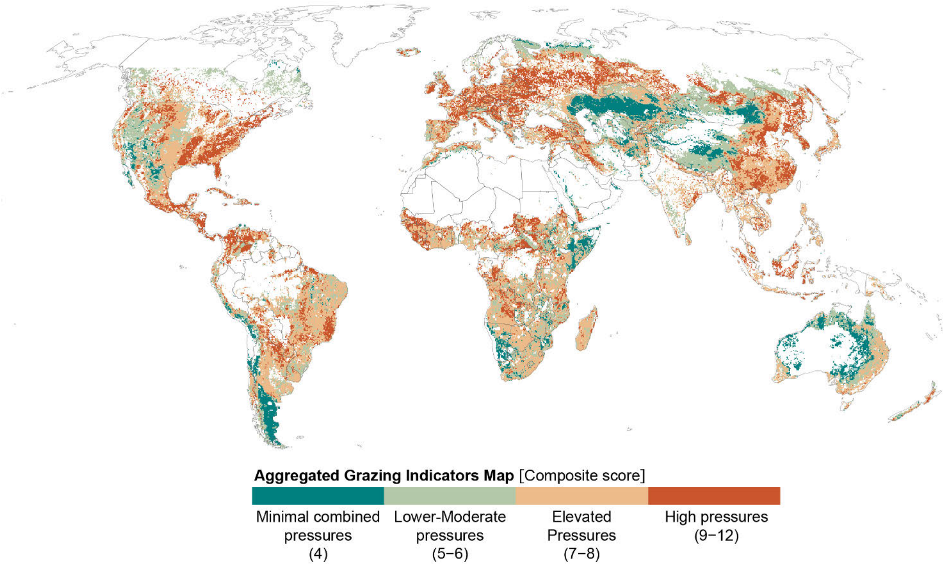
## 3.3 Summary of core findings

*Addressing Research Question 3 (RQ3): Where does grazing have a sustainable role in land use, and where might it be reasonable to reduce or abandon grazing in favor of alternative practices?*

To provide a convenient, high-level overview of where grazing may be more or less viable based on the biophysical indicators developed in this thesis, a simple composite index was constructed by aggregating four variables—relative stocking density (RSD), land use ratio (LUR), potential land-use shifts, and carbon opportunity intensity (COI). This single metric offers a practical way to visualize broader patterns and identify regions where multiple environmental pressures may coincide. However, because these metrics are simply summed, favorable results in one component can offset weaker performance in another. Consequently, while the composite map is a useful synthesis for the purposes of this dissertation, it cannot capture the full complexity of real-world systems and should not be used in isolation to guide policy or interventions. As discussed throughout this thesis, focusing on biophysical indicators alone inevitably omits socio-economic and cultural dimensions, and the global resolution may conceal important local variations. Any recommendations based on these results must therefore be verified by detailed, context-specific analyses in consultation with local stakeholders.

Figure 5 (hereafter referred to as the "Aggregated Grazing Indicators Map") integrates each of the four variables into three categories (1 indicating favorable conditions, 2 suggesting potential concerns, and 3 indicating higher risks). Under this classification, "favorable" refers to areas where maintaining grazing appears advisable, while "higher risk" points to regions where ongoing grazing may be problematic, such as in cases of overgrazing, inefficient land use, or missed carbon sequestration opportunities.

Composite scores range from 4 (indicating relatively favorable conditions across all indicators) to 12 (suggesting substantial pressures). While Figure 5 concisely visualizes these spatial patterns, additional insights from Publications I–IV provide a more complete picture of the environmental, productivity, and carbon-related challenges and opportunities associated with grazing in different parts of the world. Overall, the Aggregated Grazing Indicators Map highlights notable regional variations in grazing land viability. Some regions exhibit considerable overlapping pressures and elevated risk, while others appear to support grazing practices more readily under the indicators used here.




**Reclassification of indicators for Aggregated Grazing Indicators Map**

| Variable | Favorable Recoded as 1 | Potential concerns Recoded as 2 | Higher risk Recoded as 3 | Location in this dissertation |
|---|---|---|---|---|
| RSD | < 0.2 | 0.2 – 0.65 | > 0.65 | Figure 3c |
| LUR | < 1.0 | 1.0 – 10 | > 10 | Figure 4b |
| Land Use Shift | < 2 | 2 – 10 | > 10 | Figure 4c |
| COI | ≤ 3.3 | 3.3 – 6.5 | > 6.5 | Figure 3d |

**Figure 5** Aggregated Grazing Indicators Map. This composite figure reflects key indicators from Publications I, II, and IV (RSD, LUR, and COI) to show where biophysical pressures are higher (red, higher values) or lower (green, lower values). The classification thresholds in the accompanying table are based on biophysical considerations only and do not encompass socio-economic factors. As such, this map is intended strictly as a synthesis tool for this dissertation.

**Key insights from the aggregated biophysical indicator approach:**

1. Regions with higher biophysical risks (areas of concern):
   Eastern Asia, Europe, parts of sub-Saharan Africa, Southern Latin America, and Eastern North America show concerning patterns across multiple indicators. These regions typically exhibit high RSD (indicating overgrazing), high LUR (suggesting crops could be more efficient), and high COI (pointing to significant carbon sequestration potential if grazing were reduced). Many of these areas could produce more protein and energy if converted to croplands and show a decreasing trend in carrying capacity (CC; Publication I).
2. Regions with sustainable grazing potential (with some disagreements):
   Most of Australia shows relatively favorable conditions (low values) on the on the Aggregated Grazing Indicators Map, with generally low RSD, LUR, and COI. However, Eastern Australia is an exception, with high RSD and LUR, and suggesting potential for conversion to cropland. Notably, a significant portion of current production in Australia could still be maintained within biodiversity-friendly grazing pressures (Publication III), illustrating how different sustainability metrics can sometimes yield contrasting conclusions.

   Central Asia, including Kazakhstan and the Tibetan Plateau, showed low LUR, low or negative COI values, and no potential for land-use shifts from grazing to croplands. This suggests that current grazing practices may be suitable for these regions, even though some areas, particularly in Tibet, exhibit high RSD values, indicating potential overgrazing. Parts of sub-Saharan Africa (e.g., Somalia, Namibia), Eastern Argentina, and the Western United States also stand out as more sustainable according to the indicators used in this thesis.

# 4 Discussion

## 4.1 Key scientific advances

This dissertation advances understanding of sustainable land use and food production practices through the comprehensive analysis of grazing systems at a global scale. The research provides new insights into sustainable grazing, its opportunities and challenges, which has not been done at such a spatially explicit level before. Another important achievement of this work is the development of several novel datasets, including aboveground biomass (AGB), carrying capacity (CC), relative stocking density (RSD), tree cover multiplier, biodiversity limits of sustainable grazing, opportunities for land use shifts to increase food production, global land use ratio (LUR), and carbon opportunity intensity (COI). These datasets significantly advance the quantification of interactions between grazing intensity, ecosystem health, and carbon sequestration potential (Figure 2).

The findings from each article build upon one another to create a comprehensive framework for evaluating the environmental sustainability and efficiency related to grazing livestock. For instance, the areas where RSD, LUR, and COI values are low indicate regions where animal production could likely remain sustainable. Conversely, high RSD, LUR, and COI values, coupled with poor biodiversity outcomes, suggest regions where mitigation measures are necessary. This integrative approach enables the overlaying of multiple datasets to identify critical hotspots for sustainable interventions and conservation planning, offering practical insights for both policy and land management.

*Contributions of this research compared to existing studies:*

1. <u>Advanced biomass estimation methodology (Publications I- II):</u> Existing studies have estimated biomass availability globally, but with limitations that this research aimed to address. For instance, studies closest to the AGB estimations presented in Publication I, such as Petz et al. (2014) and Fetzel et al. (2017), provided global assessments using a single global factor to partition biomass into aboveground and belowground components (i.e., AGB = 0.60 * NPP). The approach used in this thesis refines this method by introducing a more nuanced partitioning technique, which uses temperature and precipitation as predictors to determine biomass allocation. Moreover, this research incorporated more

detailed considerations of terrain slope and tree cover, factors that were often bypassed or heavily simplified in other global studies.

2. Identifying shifts between grazing and cropping for increased food production (Publication II): Although the food production capacity of croplands has been evaluated in existing studies (Cassidy et al., 2013; Davis et al., 2017), the equivalent production capacity (in terms of protein, energy, and micronutrients) of grazing lands and particularly in comparison to those of crops has not been assessed in a spatially explicit manner before. The presented work fills this gap, offering a more complete picture of global food production potential. Furthermore, while Van Zanten et al. (2016) introduced the concept of LUR to compare the efficiency of crop versus livestock production, this study is the first to apply the LUR globally.
3. Quantifying environmental and production trade-offs in grazing management (Publications III-IV): Publications III and IV further contribute by exploring the trade-offs involved in transitioning towards more environmentally sustainable grazing practices. Publication III forms the basis for examining biodiversity-friendly production limits globally in a grazing-specific context and provides country-specific feed conversion ratios, extending existing regional-level estimates (Herrero et al., 2013; Mottet et al., 2017). While existing research by Hayek et al. (2021) quantified the carbon opportunity cost of grazing, it did not account for variations in pasture productivity or potential production intensification. Deepening this work, Publication IV develops the COI metric, which captures large differences in grazing land productivity for meat production, enabling targeted restoration that optimizes the trade-off between livestock removal and carbon sequestration.

## 4.2 Limitations in global analysis

Satellites provide regularly updated, regionally consistent, and cost-effective data, which allows continuous monitoring of vast areas. Global studies utilizing this remote sensing data provide an effective foundation for analyzing macro-level phenomena. This method also minimizes biases inherent in national statistics, where political agendas may influence the reported data (Koch-Weser, 2013).

However, these benefits come with several significant limitations. Global-scale studies necessitate simplifications and assumptions that can lead to inaccuracies (van Veen and Roland Ortt, 2024). While the analyses presented in this dissertation are reliable on a broader scale, they are unlikely completely accurate at the local level and may fail to capture local realities that are crucial for practical decision-making (Wyborn and Evans, 2021). The challenge of selecting an appropriate scale for research is widely recognized (Wilbanks and Kates, 1999; Wu and Li, 2009); global studies are often criticized for lacking nuance and being overly broad, whereas local studies, though rich in detail, may not address systemic implications. Although striking a balance between these scales is challenging, both are essential and complement each other in understanding complex global phenomena (Buřivalová et al., 2015; Mehrabi et al., 2020).

The increasing availability of data often creates a temptation to incorporate all possible new information into analyses. However, adding more variables or data sources does not necessarily guarantee a better outcome, especially when potential improvements in performance or result quality cannot be validated (Meyer and Pebesma, 2022).

## 4.3 Specific limitations of the dissertation's studies

Although powerful, the satellite-based methods used in Publications I-IV struggle to detect fine-scale environmental conditions such as feed quality or dead biomass. Current remote sensing technologies cannot accurately capture vegetation beneath forest canopies. Publication I develops a method to estimate understory forage, but it remains a rather coarse approach when applied globally, potentially leading to inaccuracies in biomass estimates. Similarly, the inability to differentiate between plant species and their palatability (i.e., feed quality) affects the precision of the estimates. Additionally, while the thesis examines interannual variability in forage availability, data limitations prevented the development of AGB estimates at finer temporal scales. Considering seasonality e.g. through monthly estimates would be valuable for practical grazing management planning (Fetzel et al., 2017).

The use of modeled datasets, like gridded livestock of the world (GLW), introduces another layer of uncertainty as they map data into grids using predictive models rather than direct observations. These models are valuable for identifying broad patterns, yet they can be unreliable at the individual grid cell level, underscoring the importance of ground-truthing and validation, as emphasized by Nagai et al. (2020). The uncertainty and sensitivity analyses conducted for Publications I-IV provide important insights, but it's crucial to recognize that these do not guarantee the accuracy of the results, especially at local scales. Similarly, the analyses heavily rely on AGB estimates which, as discussed earlier, are likely at least partially incorrect and lack independent ground-truthing. While uncertainty analyses and some comparisons to other results have been conducted, the study does not quantitatively compare the calculated AGB results to observed ground measurements, nor does it assess the extent of improvement over previous datasets using standardized validation methods. Although this affects the precision of the findings and subsequent research building on the data, even imperfect global analyses provide valuable insights and a foundation for future work as research progresses iteratively.

The focus on biophysical factors, while providing valuable insights, overlooks critical socio-economic and political dimensions of food systems. Land tenure, economic viability, and local livelihoods play crucial roles in land use decisions (Adams et al., 1999) but are not captured within this thesis. This limitation reflects a broader challenge in food systems research, as highlighted by (Chrisendo et al., 2024), who calls for more integrated approaches that consider both biophysical and socio-economic factors.

Furthermore, in Publication III, the assumption of subtracting 10–20% from AGB (based on aridity) to determine the biodiversity benefits of grazing is likely oversimplified. Although these figures are grounded in literature, biodiversity is an exceedingly complex concept. It encompasses aboveground and belowground components, including plants, microbes, and various organisms (Wang and Tang, 2019). This complexity makes it challenging to determine, based on a single metric, where grazing positively impacts overall biodiversity on a global scale. Another challenge is that some of the data used in this research cover different time periods. The FCRs data is from 2000, while most of the other data is more recent, from around 2010 or 2020. On one hand, the fundamental relationship between feed input and animal output has not changed drastically since 2000, so using this older dataset does not invalidate the broad, global-level conclusions presented here. On the other hand, relying on older FCR data introduces extra uncertainty, as different studies (e.g., Herrero et al., 2013; Mottet et al., 2017; Mekonnen and Hoekstra, 2012) present varying FCR estimates based on different assumptions and methodologies. These variations can affect outcomes, particularly total protein or calorie estimates of grazing livestock. To assess the extent of this effect, we conducted sensitivity analyses (see supplementary material of Publication II), which confirmed that although the main patterns remain consistent, newer FCR data could refine the precision of our estimates. Additionally, the assumptions made in Publication IV regarding the improvement of FCRs towards OECD levels are arguably optimistic. Setting ambitious targets can drive progress, but it remains challenging to envisage how such levels could be realistically attained.

Moreover, a limitation in the assessment of COI is the inherent uncertainty concerning how much carbon can actually be sequestered in natural ecosystems. Publication IV shows notable regional variation in COI, but broader literature suggests that these sequestration outcomes are highly context-dependent and may be limited by ecological saturation, land-use history, and practical constraints (Lewis et al., 2019; Mo et al., 2023). For instance, even in optimistic restoration scenarios (such as those presented in Publication IV), carbon sequestration is projected to offset only a limited fraction of current fossil-fuel emissions, typically equivalent to a few years' worth, underscoring that land-based approaches alone are insufficient in addressing the climate crisis. Within this context, our findings—though indicating potentially meaningful carbon benefits in specific high-COI regions—should be viewed as illustrating relative opportunities rather than an all-encompassing solution. Therefore, the theoretical carbon gains from discontinuing grazing could be overestimated, particularly in long-established grasslands where soil carbon may already be near saturation.

## 4.4 Way forward

The path towards implementing research findings into practical actions requires a strong consensus among stakeholders. This raises important questions about the appropriate level of governance (see Mehrabi et al., 2020): Is national-level action sufficient, or is supranational coordination needed to address these global challenges effectively? Based on the results presented here, it remains difficult to determine conclusively which level of governance would be most effective, because this dissertation did not explore political or economic mechanisms in detail. However, the environmental costs of grazing are not limited to the local area, while the benefits typically remain more local. Consequently, supranational organizations may be in a better position to guide or incentivize environmentally responsible policies, especially where grazing systems cross national borders.

This thesis emphasizes the importance of overlaying reliable analyses, as demonstrated in Figure 5, but future studies should also consider factors beyond this research. The findings of this dissertation, however, provide an initial foundation for identifying high-risk areas and suggesting targeted interventions. For instance, regions where multiple indicators constantly show overgrazing could benefit from policy measures such as controlled grazing schedules or livestock density restrictions. As remote sensing technologies advance and scholars improve the methodologies presented in this dissertation, an increasingly accurate picture of both problem areas and regions with untapped potential can be expected (although newer methods and datasets do not automatically translate to improved accuracy, see Kerner et al. (2024)). Yet, continuing refinement of remote sensing technologies and modeling approaches may strengthen these preliminary insights. Moreover, integrating socio-economic factors into these analyses will provide a more holistic understanding of the complex dynamics at play.

Continuous efforts are being made to enhance the reliability of datasets, such as ongoing projects aiming to estimate more accurate feed conversion ratios (FCRs). Although future advancements might yield useful studies like identifying individual animals from aerial photographs (Ocholla et al., 2024; de Lima Weber et al., 2023) and may be useful for certain precision-management applications but might not lead to direct policy changes. On the other hand, that approach could reduce the necessity of combining different datasets in the same way as in the articles of this dissertation. Nevertheless, it can be even more important to provide actionable information to decision-makers in a way that promotes real change.

Several promising avenues for future research emerge from this work. First, there is a need to explore the potential of silvopastoral systems, which remain poorly understood globally (Öllerer et al., 2019). Second, investigating the complex impacts of grazing on biodiversity requires further attention, as the effects of different grazing intensities affect plants, organisms, and above- and below-ground biodiversity in ways that are not fully understood (Wang and Tang, 2019). Third, it's still unclear whether grazing animals should be considered primarily for food production, or if other aspects such as landscape aesthetics and cultural traditions are more significant in low-intensity grazing systems. Fourth, developing methods for global monitoring of woody encroachment and land degradation is important. For example, increasing livestock density might boost protein production but heightens the risk of land degradation, underlining the importance of trade-off analyses. Moreover, clustering grazing lands into low- and high-risk categories using archetype analysis (e.g. following the approach used for groundwater systems by Huggins et al. (2024)) could enhance the identification of regions where changes in grazing land use are particularly beneficial or problematic.

At a minimum, this dissertation identifies upper and lower boundaries for sustainable grazing, illustrating what might be feasible under different grazing regimes and providing a foundation for discussing potential trade-offs associated with changes in grazing land use. Although social, economic, and cultural dimensions lie outside this research, the biophysical evidence presented here indicates where livestock production may be reaching ecological limits, where moderate intensification might still be possible, and which regions offer potential for more sustainable management practices. Such insights help policymakers avoid overlooking the fundamental biophysical limits and opportunities of grazing systems. Future work could employ participatory methods that bring local communities, government agencies, and researchers into the same process. This approach ensures that more sustainable grazing and land-use solutions are not simply imposed from above but are rooted in community needs and experiences.

Finally, uncertainties raise important questions about the future of grazing lands. If animals are removed, will these areas remain as pastures, be reforested, or undergo other rewilding measures? As global analyses are refined and the gap between macro-level trends and local realities hopefully becomes smaller, the scientific community moves closer to developing sustainable land management strategies that are both globally informed and locally relevant. The challenge lies in translating this growing body of knowledge into actionable policies, requiring continued collaboration between researchers, policymakers, and local communities. This dissertation shows that even partial data and indicative results can guide preliminary, practical steps (e.g., prioritizing at-risk regions or restricting stocking densities). Further socio-economic research may refine these interventions, but clear biophysical insights already exist to direct at least some immediate policy decisions.

# 5 Conclusion

Global livestock numbers and current production practices exceed sustainable levels. However, complete elimination of production animals is neither realistic nor necessarily beneficial, particularly as certain production methods, such as livestock grazing, can be environmentally sustainable if practiced correctly. The findings of this dissertation highlight both opportunities and threats related to sustainable livestock grazing and demonstrate the complex nature of sustainable land management decisions. Moving from research to reality demands integrating environmental analyses with social and economic perspectives, ensuring that research-based solutions can be effectively implemented in real-world contexts. This requires keeping farmers, pastoralists, Indigenous peoples, and local communities involved throughout the process, as their insights are crucial for balancing environmental sustainability with fairness and local realities.

*Three key insights from this dissertation:*

1. <u>Possibilities for alternative land uses exist.</u>
   In many regions, reducing or discontinuing grazing would significantly enhance environmental sustainability and land-use efficiency. However, lowering livestock densities on overgrazed lands does not necessarily mean large-scale cropland expansion; instead, it may involve retaining grazing at lower intensities. Where neither cultivation nor grazing is suitable, allowing the land to revert to a more natural state can be an option worth considering. Recognizing these alternatives and biophysical boundaries helps identify where transitioning away from grazing would provide the greatest net benefit.
2. <u>Many grazing lands are still best used for grazing.</u>
   A large portion of the global land area is unsuitable for crop production but can support animal husbandry, contributing to local food security even if not greatly increasing the global food supply. Sustainable grazing involves maintaining relatively low grazing pressure and concentrating activities in areas that have historically served as grazing land, where flora and fauna have adapted to grazing over time. The value of grazing extends to maintaining cultural landscapes, preserving traditional practices and livelihoods, and even supporting biodiversity and conservation efforts in some settings. Although overall meat consumption levels should decline due to the high global volumes,

which contribute to environmental strain and health risks, removing livestock entirely from well-suited grazing areas can disrupt local economies and habitats. It might be necessary to reconsider the role of grazing beyond simple food production.

3. Better data alone will not drive change—socio-economic contexts matter. Remote sensing and modeling continue to advance, but actual shifts in land use require implementing what is already known. Yet, local-scale verification of results and the integration of socio-economic indicators are needed to identify where changes in land use—be it reduced grazing or alternative land use—are most likely to yield significant benefits while minimizing harm.

# References


Abatzoglou, J.T., Dobrowski, S.Z., Parks, S.A., Hegewisch, K.C., 2018. TerraClimate, a high-resolution global dataset of monthly climate and climatic water balance from 1958–2015. Scientific Data 5, 170191. https://doi.org/10.1038/sdata.2017.191

Adams, M., Cousins, B., Manona, S., 1999. Land tenure and economic development in rural South Africa: Constraints and opportunities. Overseas Development Institute London.

Amatulli, G., McInerney, D., Sethi, T., Strobl, P., Domisch, S., 2020. Geomorpho90m, empirical evaluation and accuracy assessment of global high-resolution geomorphometric layers. Scientific Data 7, 162. https://doi.org/10.1038/s41597-020-0479-6

Baiphethi, M.N., Jacobs, P.T., 2009. The contribution of subsistence farming to food security in South Africa. Agrekon 48, 459–482.

Buřivalová, Z., Bauert, M., Hassold, S., Fatroandrianjafinonjasolomiovazo, N., Koh, L.P., 2015. Relevance of Global Forest Change Data Set to Local Conservation: Case Study of Forest Degradation in Masoala National Park, Madagascar. Biotropica. https://doi.org/10.1111/btp.12194

Cassidy, E.S., West, P.C., Gerber, J.S., Foley, J.A., 2013. Redefining agricultural yields: from tonnes to people nourished per hectare. Environ. Res. Lett. 8, 034015. https://doi.org/10.1088/1748-9326/8/3/034015

Chrisendo, D., Heikonen, S., Piipponen, J., Banafa, T., Deryng, D., El-Wali, M., Heino, M., Irz, X., Jalava, M., Láng-Ritter, J., Mazac, R., Niva, V., Pihlajamäki, M., Roitto, M., Tuomisto, H., Kummu, M., 2024. Socioeconomic pathways toward sustainable food systems. Preprint at: https://doi.org/10.21203/rs.3.rs-4304589/v1

Dai, G., Hou, Y., Fang, Q., Zhang, X., Wang, H., Wang, S., Zhu, X., Zhang, F., Oenema, O., 2023. Boosting domestic feed production with less environmental cost through optimized crop distribution. Resources, Conservation and Recycling 194, 106996. https://doi.org/10.1016/j.resconrec.2023.106996

Davis, K.F., Rulli, M.C., Seveso, A., D'Odorico, P., 2017. Increased food production and reduced water use through optimized crop distribution. Nature Geosci 10, 919–924. https://doi.org/10.1038/s41561-017-0004-5 de Lima Weber, F., de Moraes Weber, V.A., de Moraes, P.H., Matsubara, E.T., Paiva, D.M.B., de Nadai Bonin Gomes, M., de Oliveira, L.O.F., de Medeiros, S.R., Cagnin, M.I., 2023. Counting cattle in UAV images using convolutional neural network. Remote Sensing Applications: Society and Environment 29, 100900. https://doi.org/10.1016/j.rsase.2022.100900

DiMiceli, C.M., Carroll, M.L., Sohlberg, R.A., Huang, C., Hansen, M.C., Townshend, J.R., 2017. Annual global automated MODIS vegetation continuous fields (MOD44B) at 250 m spatial resolution for data years beginning day 65, 2000–2010.

Erb, K.-H., Kastner, T., Plutzar, C., Bais, A.L.S., Carvalhais, N., Fetzel, T., Gingrich, S., Haberl, H., Lauk, C., Niedertscheider, M., 2018. Unexpectedly large impact of forest management and grazing on global vegetation biomass. Nature 553, 73–76.https://doi.org/10.1038/nature25138

FAO, 2022a. GLEAM (Global Livestock Environmental Assessment Model Version 3.0).

FAO, 2022b. Food and Agriculture Data Statistics (FAOSTAT).

FAO, 2014. World mapping of animal feeding systems in the dairy sector. FAO, IDF and IFCN.

Fetzel, T., Havlik, P., Herrero, M., Erb, K.-H., 2017. Seasonality constraints to livestock grazing intensity. Global Change Biology 23, 1636–1647. https://doi.org/10.1111/gcb.13591

Fischer, G., Nachtergaele, F.O., Van Velthuizen, H., Chiozza, F., Francheschini, G., Henry, M., Muchoney, D., Tramberend, S., 2021. Global agro-ecological zones (gaez v4)-model documentation.

Gao, J., Carmel, Y., 2020. A global meta-analysis of grazing effects on plant richness. Agriculture, Ecosystems & Environment 302, 107072. https://doi.org/10.1016/j.agee.2020.107072

Gilbert, M., Nicolas, G., Cinardi, G., Van Boeckel, T.P., Vanwambeke, S.O., Wint, G.R.W., Robinson, T.P., 2018. Global distribution data for cattle, buffaloes, horses, sheep, goats, pigs, chickens and ducks in 2010. Scientific Data 5, 180227. https://doi.org/10.1038/sdata.2018.227

Godfray, H.C.J., Aveyard, P., Garnett, T., Hall, J.W., Key, T.J., Lorimer, J., Pierrehumbert, R.T., Scarborough, P., Springmann, M., Jebb, S.A., 2018. Meat consumption, health, and the environment. Science 361, eaam5324. https://doi.org/10.1126/science.aam5324

Hayek, M.N., Harwatt, H., Ripple, W.J., Mueller, N.D., 2021. The carbon opportunity cost of animal-sourced food production on land. Nature Sustainability 4, 21–24.https://doi.org/10.1038/s41893-020-00603-4

Herrero, M., Havlik, P., Valin, H., Notenbaert, A., Rufino, M.C., Thornton, P.K., Blummel, M., Weiss, F., Grace, D., Obersteiner, M., 2013. Biomass use, production, feed efficiencies, and greenhouse gas emissions from global livestock systems.

Proceedings of the National Academy of Sciences 110, 20888–20893. https://doi.org/10.1073/pnas.1308149110

Herrero, M., Thornton, P.K., Gerber, P., Reid, R.S., 2009. Livestock, livelihoods and the environment: understanding the trade-offs. Current Opinion in Environmental Sustainability 1, 111–120. https://doi.org/10.1016/j.cosust.2009.10.003

Huggins, X., Gleeson, T., Villholth, K.G., Rocha, J.C., Famiglietti, J.S., 2024. Groundwaterscapes: A Global Classification and Mapping of Groundwater's Large-Scale Socioeconomic, Ecological, and Earth System Functions. Water Resources Research 60, e2023WR036287. https://doi.org/10.1029/2023WR036287

Kerner, H., Nakalembe, C., Yang, A., Zvonkov, I., McWeeny, R., Tseng, G., Becker-Reshef, I., 2024. How accurate are existing land cover maps for agriculture in Sub-Saharan Africa? Sci Data 11, 486. https://doi.org/10.1038/s41597-024-03306-z

Klein Goldewijk, K., Beusen, A., Doelman, J., Stehfest, E., 2017. Anthropogenic land use estimates for the Holocene – HYDE 3.2. Earth System Science Data 9, 927–953. https://doi.org/10.5194/essd-9-927-2017

Koch-Weser, I., 2013. The reliability of China's economic data: An analysis of national output.

Lewis, S.L., Mitchard, E.T.A., Prentice, C., Maslin, M., Poulter, B., 2019. Comment on "The global tree restoration potential." Science 366, eaaz0388. https://doi.org/10.1126/science.aaz0388

Li, C., Bishop, T.R., Imamura, F., Sharp, S.J., Pearce, M., Brage, S., Ong, K.K., Ahsan, H., Bes-Rastrollo, M., Beulens, J.W., 2024. Meat consumption and incident type 2 diabetes: an individual-participant federated meta-analysis of 1 97 million adults with 100 000 incident cases from 31 cohorts in 20 countries. The Lancet Diabetes & Endocrinology 12, 619–630. https://doi.org/10.1016/S2213-8587(24)00179-7

Li, T., Feng, W., Lü, Y., Ma, L., Liu, Y., Luo, Y., Liang, H., 2024. Quantifying impacts of livestock production on ecosystem services: Insights into grazing management under vegetation restoration. Journal of Cleaner Production 470, 143359. https://doi.org/10.1016/j.jclepro.2024.143359

Mehdi, B., Lehner, B., Ludwig, R., 2018. Modelling crop land use change derived from influencing factors selected and ranked by farmers in North temperate agricultural regions. Science of The Total Environment 631–632, 407–420. https://doi.org/10.1016/j.scitotenv.2018.03.014

Mehrabi, Z., Gill, M., Wijk, M. van, Herrero, M., Ramankutty, N., 2020. Livestock policy for sustainable development. Nat Food 1, 160–165. https://doi.org/10.1038/s43016-020-0042-9

Mekonnen, M.M., Hoekstra, A.Y., 2012. A Global Assessment of the Water Footprint of Farm Animal Products. Ecosystems 15, 401–415. https://doi.org/10.1007/s10021-011-9517-8

Meyer, H., Pebesma, E., 2022. Machine learning-based global maps of ecological variables and the challenge of assessing them. Nat Commun 13, 2208. https://doi.org/10.1038/s41467-022-29838-9

Mo, L., Zohner, C.M., Reich, P.B., et al. 2023. Integrated global assessment of the natural forest carbon potential. Nature 624, 92–101. https://doi.org/10.1038/s41586-023-06723-z

Mottet, A., de Haan, C., Falcucci, A., Tempio, G., Opio, C., Gerber, P., 2017. Livestock: On our plates or eating at our table? A new analysis of the feed/food debate. Global Food Security, Food Security Governance in Latin America 14, 1–8. https://doi.org/10.1016/j.gfs.2017.01.001

Mueller, N.D., Gerber, J.S., Johnston, M., Ray, D.K., Ramankutty, N., Foley, J.A., 2012. Closing yield gaps through nutrient and water management. Nature 490, 254–257. https://doi.org/10.1038/nature11420

Nagai, S., Nasahara, K.N., Akitsu, T.K., Saitoh, T.M., Muraoka, H., 2020. Importance of the collection of abundant ground-truth data for accurate detection of spatial and temporal variability of vegetation by satellite remote sensing. Biogeochemical cycles: Ecological drivers and environmental impact 223–244. https://doi.org/10.1002/9781119413332.ch11

Nkonya, E., Mirzabaev, A., Von Braun, J., 2016. Economics of land degradation and improvement-a global assessment for sustainable development. Springer Nature. https://doi.org/10.1007/978-3-319-19168-3

Ocholla, I.A., Pellikka, P., Karanja, F.N., Vuorinne, I., Odipo, V., Heiskanen, J., 2024. Livestock detection in African rangelands: Potential of high-resolution remote sensing data. Remote Sensing Applications: Society and Environment 33, 101139. https://doi.org/10.1016/j.rsase.2024.101139

Öllerer, K., Varga, A., Kirby, K., Demeter, L., Biró, M., Bölöni, J., Molnár, Z., 2019. Beyond the obvious impact of domestic livestock grazing on temperate forest vegetation – A global review. Biological Conservation 237, 209–219. https://doi.org/10.1016/j.biocon.2019.07.007

Pelton, R.E.O., Kazanski, C.E., Keerthi, S., Racette, K.A., Gennet, S., Springer, N., Yacobson, E., Wironen, M., Ray, D., Johnson, K., Schmitt, J., 2024. Greenhouse gas emissions in US beef production can be reduced by up to 30% with the adoption of selected mitigation measures. Nat Food 5, 787–797. https://doi.org/10.1038/s43016-024-01031-9

Petz, K., Alkemade, R., Bakkenes, M., Schulp, C.J.E., van der Velde, M., Leemans, R., 2014. Mapping and modelling trade-offs and synergies between grazing intensity and ecosystem services in rangelands using global-scale datasets and models. Global Environmental Change 29, 223–234. https://doi.org/10.1016/j.gloenvcha.2014.08.007

Ranganathan, J., Vennard, D., Waite, R., Dumas, P., Lipinski, B., Searchinger, T.I.M., GLOBAGRI-WRR, M.A., 2016. Shifting diets for a sustainable food future, Installment 11 of Creating a Sustainable Food Future. World Resources Institute Washington, DC.

Runting, R.K., King, D., Nolan, M., Navarro, J., Marcos-Martinez, R., Rhodes, J.R., Gao, L., Watson, I., Ash, A., Reside, A.E., Álvarez-Romero, J.G., Wells, J.A., Ritchie, E.G., Hadjikakou, M., Driscoll, D.A., Connor, J.D., Garber, J., Bryan, B.A., 2024. Balancing livestock production and environmental outcomes in northern Australia's tropical savanna under global change. Environ. Res. Lett. 19, 104014. https://doi.org/10.1088/1748-9326/ad6f2d

Running, S.W., Zhao, M., 2019. MOD17A3HGF MODIS/Terra Net Primary Production Gap-Filled Yearly L4 Global 500 m SIN Grid V006. 2019, distributed by NASA EOSDIS Land Processes DAAC 35. https://doi.org/10.5067/MODIS/MOD17A3HGF.006

Sandström, V., Chrysafi, A., Lamminen, M., Troell, M., Jalava, M., Piipponen, J., Siebert, S., van Hal, O., Virkki, V., Kummu, M., 2022. Food system by-products upcycled in livestock and aquaculture feeds can increase global food supply. Nat Food 3, 729–740. https://doi.org/10.1038/s43016-022-00589-6

Schneider, J.M., Zabel, F., Mauser, W., 2022. Global inventory of suitable, cultivable and available cropland under different scenarios and policies. Sci Data 9, 527. https://doi.org/10.1038/s41597-022-01632-8

Searchinger, T.D., Wirsenius, S., Beringer, T., Dumas, P., 2018. Assessing the efficiency of changes in land use for mitigating climate change. Nature 564, 249–253. https://doi.org/10.1038/s41586-018-0757-z

Sharma, D., Vergara-Asenjo, G., Cunampio, Mitzy, Cunampio, R., Cunampio, Mara, Potvin, C., 2015. Genesis of an indigenous social-ecological landscape in eastern Panama. Ecology and Society 20. https://doi.org/10.5751/ES-07897-200437

Smith, P., Gregory, P.J., van Vuuren, D., Obersteiner, M., Havlík, P., Rounsevell, M., Woods, J., Stehfest, E., Bellarby, J., 2010. Competition for land. Philosophical Transactions of the Royal Society B: Biological Sciences 365, 2941–2957. https://doi.org/10.1098/rstb.2010.0127

Springmann, M., Clark, M., Mason-D'Croz, D., Wiebe, K., Bodirsky, B.L., Lassaletta, L., de Vries, W., Vermeulen, S.J., Herrero, M., Carlson, K.M., Jonell, M., Troell, M., DeClerck, F., Gordon, L.J., Zurayk, R., Scarborough, P., Rayner, M., Loken, B., Fanzo, J., Godfray, H.C.J., Tilman, D., Rockström, J., Willett, W., 2018. Options for keeping the food system within environmental limits. Nature 562, 519–525. https://doi.org/10.1038/s41586-018-0594-0

Sulla-Menashe, D., Friedl, M.A., 2018. User guide to collection 6 MODIS land cover (MCD12Q1 and MCD12C1) product. USGS: Reston, VA, USA 1–18. https://doi.org/10.5067/MODIS/MCD12Q1.006

Tichenor, N.E., van Zanten, H.H., de Boer, I.J., Peters, C.J., McCarthy, A.C., Griffin, T.S., 2017. Land use efficiency of beef systems in the Northeastern USA from a food supply perspective. Agricultural Systems 156, 34–42. https://doi.org/10.1016/j.agsy.2017.05.011

van Hal, O., de Boer, I.J.M., Muller, A., de Vries, S., Erb, K.-H., Schader, C., Gerrits, W.J.J., van Zanten, H.H.E., 2019. Upcycling food leftovers and grass resources through livestock: Impact of livestock system and productivity. Journal of Cleaner Production 219, 485–496. https://doi.org/10.1016/j.jclepro.2019.01.329

van Veen, B.L., Roland Ortt, J., 2024. Simplification errors in predictive models. FUTURES & FORESIGHT SCIENCE 6, e184. https://doi.org/10.1002/ffo2.184

van Vliet, J., de Groot, H.L.F., Rietveld, P., Verburg, P.H., 2015. Manifestations and underlying drivers of agricultural land use change in Europe. Landscape and Urban Planning 133, 24–36. https://doi.org/10.1016/j.landurbplan.2014.09.001

Van Zanten, H.H.E., Herrero, M., Hal, O.V., Röös, E., Muller, A., Garnett, T., Gerber, P.J., Schader, C., Boer, I.J.M.D., 2018. Defining a land boundary for sustainable livestock consumption. Global Change Biology 24, 4185–4194. https://doi.org/10.1111/gcb.14321

Van Zanten, H.H.E., Mollenhorst, H., Klootwijk, C.W., van Middelaar, C.E., de Boer, I.J.M., 2016. Global food supply: land use efficiency of livestock systems. Int J Life Cycle Assess 21, 747–758. https://doi.org/10.1007/s11367-015-0944-1

Wang, C., Tang, Y., 2019. A global meta-analyses of the response of multi-taxa diversity to grazing intensity in grasslands. Environ. Res. Lett. 14, 114003. https://doi.org/10.1088/1748-9326/ab4932

Wang, Q., Okadera, T., Nakayama, T., Batkhishig, O., Bayarsaikhan, U., 2024. Estimation of the Carrying Capacity and Relative Stocking Density of Mongolian grasslands under various adaptation scenarios. Science of The Total Environment 913, 169772. https://doi.org/10.1016/j.scitotenv.2023.169772

Wang, Y., Zhang, J., 2024. Research on cultural diversity and sustainable land-use management assessment model. Front. Environ. Sci. 12. https://doi.org/10.3389/fenvs.2024.1359521

Wen, M., Chen, L., 2023. Global food crop redistribution reduces water footprint without compromising species diversity. Journal of Cleaner Production 383, 135437. https://doi.org/10.1016/j.jclepro.2022.135437

Wilbanks, T.J., Kates, R.W., 1999. Global change in local places: how scale matters. Climatic Change 43, 601–628. https://doi.org/10.1023/A:1005418924748

Wu, H., Li, Z.-L., 2009. Scale Issues in Remote Sensing: A Review on Analysis, Processing and Modeling. Sensors 9, 1768–1793. https://doi.org/10.3390/s90301768

Wyborn, C., Evans, M.C., 2021. Conservation needs to break free from global priority mapping. Nat Ecol Evol 5, 1322–1324. https://doi.org/10.1038/s41559-021-01540-x

Xu, X., Sharma, P., Shu, S., Lin, T.-S., Ciais, P., Tubiello, F.N., Smith, P., Campbell, N., Jain, A.K., 2021. Global greenhouse gas emissions from animal-based foods are twice those of plant-based foods. Nat Food 2, 724–732. https://doi.org/10.1038/s43016-021-00358-x

Yu, Q., You, L., Wood-Sichra, U., Ru, Y., Joglekar, A.K.B., Fritz, S., Xiong, W., Lu, M., Wu, W., Yang, P., 2020. A cultivated planet in 2010 – Part 2: The global gridded agricultural-production maps. Earth System Science Data 12, 3545–3572. https://doi.org/10.5194/essd-12-3545-2020

Zabel, F., 2022. Global Agricultural Land Resources – A High Resolution Suitability Evaluation and Its Perspectives until 2100 under Climate Change Conditions (v3.0). https://doi.org/10.5281/zenodo.5982577

Business, Economy

Art, Design, Architecture

Science, Technology

Crossover

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