

Economic and Environmental Impact Analysis of Pasture-Based Agriculture: A Review of Economic Modelling Approaches

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Abstract Microsimulation is widely used in economics to analyse the distributional effects of policy and the behavioural responses of heterogeneous agents. In agricultural economics literature, farm-level simulation and bioeconomic models have developed in parallel with farm level microsimulation. These models operate at different scales but combine biological processes with economic and policy factors. The modelling literature provides little systematic assessment of how these approaches address economic and environmental outcomes in pasture-based agricultural systems. This paper addresses the gap through a systematic review of 173 peer-reviewed modelling studies published between 2000 and 2024. The analysis traces temporal and geographical trends in the literature, reviews methodological choices, and assesses how economic and environmental outcomes are modelled. The results show that farm-level simulation approaches account for the largest share of the literature, followed by optimisation models, while microsimulation and macro-scale approaches are less common. Most of the studies were at the farm-level and focus mainly on environmental outcomes, particularly land use and greenhouse gas emissions. Policy modelling concentrated on conventional production systems, while organic and low-input systems are underrepresented. Approximately half of the reviewed studies originate from Europe, and macro-level approaches account for less than 10% in literature. The literature exhibits a persistent pattern: models that handle farm-level heterogeneity seldom connect to sectoral outcomes, while those designed for aggregation are seldom applied to pasture-based systems. This limits the evidence base for policies that require both micro-level behavioural responses and macro-level assessment. Closing this gap will require integrated frameworks that couple farm-scale representation with sectoral or economy-wide models.

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1. Introduction

1.1. Background

Microsimulation is widely used in economics to evaluate distributional and behavioural responses to policy change (Creedy et al., 2011; Bargain, 2017; Emmenegger and Obersneider, 2024; Bardazzi et al., 2024). The applications extend beyond households to other economic units, including firms and farms (Vidyattama and Tanton, 2020; Axtell and Farmer, 2025; O'Donoghue, 2017). Agricultural production is shaped by public policy through subsidy regimes, regulatory frameworks, and environmental constraints. As a result, modelling approaches that capture behavioural response at the unit level are relevant in this sector. Farm-level simulation, and bioeconomic models have been

evolving parallel to microsimulation models. Although they originate from different methodological traditions, they share a common focus on simulating farm-level outcomes using unit-level data that combine biological production processes with financial and policy parameters (*Richardson et al., 2014; Tanton, 2014*).

A growing number of studies explicitly apply microsimulation to agricultural contexts. These include models of forestry planting decisions in Ireland (*Ryan and O'Donoghue, 2019*), the agricultural land rental market (*Loughrey and Hennessy, 2022*), farm irrigation decisions (*Dinh et al., 2019*), and the Australian farmpredict platform, which has been recently extended with machine-learning estimators (*Hughes et al., 2019; Hughes et al., 2022*). *Vidyattama and Tanton (2020)* extend this to a spatial farm microsimulation for Australia, showing how shocks to farmer incomes can be analysed at small-area level. In Brazil, microsimulation is used to assess the adoption of low-carbon systems under preferential credit (*Carauta et al., 2018*). *Montaud et al. (2017)* applied a dynamic CGE-microsimulation framework to evaluate the socio-economic consequences of climate variability. Attitudinal heterogeneity is also examined in literature, showing farmer attitudes influence openness to land transactions in Ireland (*Geoghegan et al., 2021*). These examples show the adaptability of microsimulation across production systems, although applications remain fragmented across the agriculture modelling literature.

Micro-level modelling approaches used in pasture-based agriculture share features with microsimulation. These include farm-level simulation and bioeconomic models, as well as agent-based models. Several of these approaches operate at micro level and are used to simulate counterfactual responses to policy and market constraints. This creates a point of comparison with the microsimulation literature, which similarly analyses heterogeneous units under policy constraints. Within production economics and systems analysis, micro-modelling has evolved alongside periods of emphasis on macro-scale approaches and has been used to examine firm-level behavioural and distributive responses (*Lee, 2019*). The expansion of environmental and climate policy has further increased the need for models that capture production responses and their environmental and economic outcomes across scales (*Eynde et al., 2024*).

Pasture-based agriculture is a highly regulated sector that is subject to environmental regulations and policy interventions aimed to reducing its environmental footprint. This regulatory and sustainability context creates a need for modelling approaches that examine ex-ante policy impacts across alternative scenarios (*Mercure et al., 2016*). These are the key strengths of microsimulation and farm-level bioeconomic models. While these approaches share common features, they differ in scale and in the way behavioural responses are represented. It is within this context that this review examines how the modelling approaches have been applied to assess economic and environmental impacts of pasture-based systems.

Earlier reviews have examined farm-level modelling in agriculture (*O'Donoghue, 2017; Richardson et al., 2014*). Building on this work, the present review compares modelling approaches used to analyse pasture-based ruminant systems. Pasture systems combine biological production processes with significant policy and regulatory exposure, therefore provides a useful setting for examining differences in modelling types, scale, and scope (*Vannier et al., 2022; Vogeler et al., 2014*). Pasture-based livestock systems also occupy an important place in global food economy and contribute substantially to global protein supply and rural livelihood and development (*Alders et al., 2021; Resare Sahlin et al., 2024*). At the same time, the livestock sector and ruminant production systems in particular are associated with greenhouse gas emissions, land use change and biodiversity loss, and land degradation pressure (*Kowalska and Bieniek, 2022; Mehrabi et al., 2020*). These characteristics have made pasture-based systems a focus of sustainability and policy debates, emphasizing the need for modelling approaches that can account for their complexity and inform evidence-based policy design.

Economic models provide a structured means of analysing the complexities of pasture-based agricultural systems including trade-offs between production, environment, and policy. They include farm level microsimulation (*Hynes et al., 2009*), as well as farm level optimisation and simulation models (*Kamilaris et al., 2020; Moraes et al., 2012*) and, more recently, machine learning (*Benavides et al., 2023; McVey et al., 2023*). Microsimulation in the pasture-based agriculture modelling literature has the capacity to simulate heterogeneity in farm structures, behavioural responses, and the distributional impacts of policy (*Haydarov et al., 2024; O'Donoghue, 2017*) and is therefore of great

potential to support the design of public policy in this policy intensive sector. However, microsimulation remains underutilised modelling pasture-based systems than established approaches such as simulation, optimisation, or econometrics (*Hughes et al., 2022*). Recent innovations show the use of machine learning within microsimulation frameworks to improve predictive performance (*Hughes et al., 2022*). *Rahman (2019)* proposed intelligent system design with bootstrapping to strengthen validation.

Farm-level simulation and bioeconomic models have traditionally been treated as a separate from microsimulation. The approaches nevertheless share several core features. Both operate at the level of units and represent heterogeneity across production systems. They are also used to examine responses to policy or environmental change under alternative scenarios. However, while microsimulation has developed a distinct identity in economics and social sciences, (*Figari and Paulus, 2015; O'Donoghue, 2017*) agricultural simulation models are more commonly associated with production economics, biological processes, and systems analysis. This siloed development has at times limited cross-fertilisation between the two literatures which have evolved largely in parallel. In this review, they are coded and reported as distinct categories in the descriptive analysis and examined comparatively in the discussion but compared conceptually to clarify their relationship. One contribution of this review is therefore to highlight the conceptual and methodological overlaps between these traditions, positioning farm-level simulation models as de facto microsimulation tools within the agricultural field. As such this review can be seen to build upon previous review article which applied a similar perspective (*O'Donoghue, 2014*).

The previous studies have examined modelling approaches used in pasture-based agricultural systems. *Richardson et al. (2014)* reviewed farm-level microsimulation models from a policy perspective. The review shows regional differences in modelling choices, with programming models prevalent in the EU and simulation models in the US. It emphasised the need for future research to strengthen environmental linkages, heterogeneity, and connections with rural economy. *Reidsma et al. (2018)* reviewed European applications, assessing farm models for policy evaluation in the EU and finds limited use of models for policy evaluation. Their review also points to the need for improved data, better model integration, and links between science and policy. *van der Linden et al. (2020)* assessed sustainability in farm models and showed models were limited to Europe and had limited coverage of social aspects. They recommend adapting and extending existing models toward integrated approach. The reviews do not adopt a global perspective and give little attention to agroecological farming practices farming practices that are increasingly emphasised in policy debates. They also do not examine the role of microsimulation in pasture-based agriculture. This study provides a global synthesis of economic modelling approaches for sustainability in pasture-based systems, considers farm-level simulation within the microsimulation tradition.

To address this gap, we conduct a systematic literature review of 173 peer reviewed studies published between 2000-2024 that model pasture based ruminant production systems with explicit economic and/or environmental outcomes. The review examines three dimensions (a) temporal and geographical trends (b) methodological choices regarding model type, applications, drivers, scales, data, and validation, and (c) the treatment of economic, environmental, and social sustainability. The paper proceeds as follows. Section 2 describes the methodology. Section 3 presents the results. Section 4 discusses the findings, and Section 5 concludes.

2. The theoretical framework

This review treats pasture-based agriculture (*Figure 1*) as a socio-economic and biophysical system in which external drivers influence farm decisions, resource use, and production. The framework identifies the main variables discussed in the literature and provides a basis for classifying and comparing modelling approaches. Time, geography, and population are treated as contextual conditions that shape system responses (*Agarwal et al., 2002*).

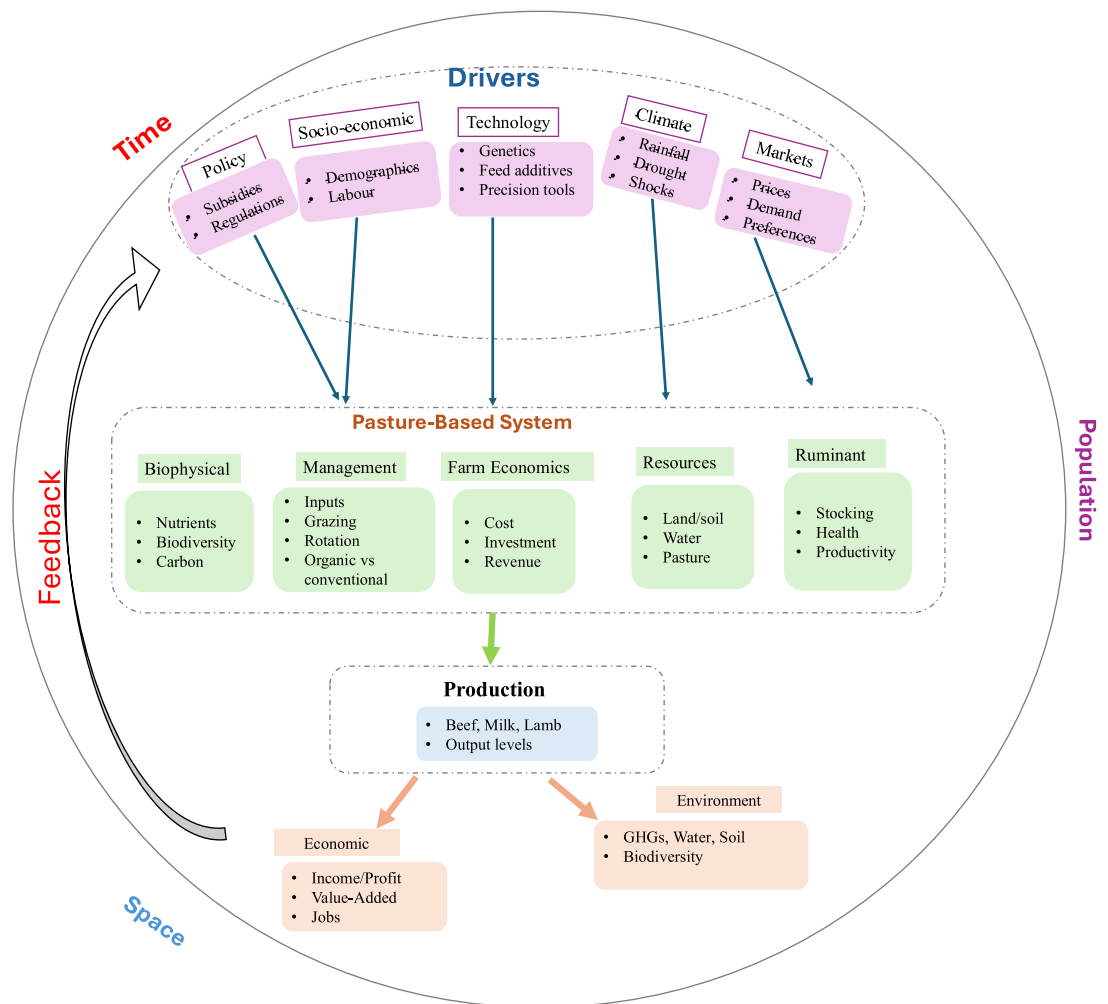


Figure 1 Conceptual framework of pasture-based agriculture.

2.1. External drivers of modelling sustainability in pasture-based systems

The external drivers were conceptualised as exogenous parameters that shape the conditions under which farms operate in pasture-based systems. Five categories of these external influences were distinguished as a way to show their connection to the system. To begin with, policy instruments shift farm system constraints through subsidies, agri-environmental measures, or regulations (*Bernini and Galli, 2024; Cillero and Reaños, 2023; Macgregor and Warren, 2006; Mooney et al., 2024*). This influences the system and feeds into outcome of farm system. Most importantly, market conditions determine price signals, as well as demand shifts, thereby influencing the intensity and type of production within pasture-based system (*Ayvaz Çavdaroğlu et al., 2021; Bonroy and Constantatos, 2015*). Environmental and climatic factors are viewed to act as stochastic shocks to yields that produce nonlinear fluctuations in output (*Deschênes and Greenstone, 2007; Emediegwu and Ubabukoh, 2023*). These changes are more often negative, difficult for economic agents to model and forecast accurately and strongly determine pasture growth, soil quality, and water availability (*Olesen and Bindi, 2002*). Technological change alters productivity parameters and the relationship between inputs and outputs within the production process (*Just et al., 1979; Huang and Wang, 2024*). In this context technology is defined to include genetic improvements and precision systems that alter productivity and farm cost structures (*Connor, 2015; Sonea et al., 2023*). Finally, socio-demographic structures, such as labour supply and succession influence farm management capacity (*Corsi et al., 2021; Ji et al., 2018*). These are key drivers of farm level and sectoral decision making.

2.2. Farm system Boundary

In this review, the farm system is defined as the micro-level production unit capturing the set of endogenous variables that determine farm-level production, management, and economic outcome. Household decision-making is embedded within this unit, while interactions with other economic actors are represented at higher levels of aggregation. Within the boundary, we define interrelated components which form the systems. The most clear one in our context is resources such as land, soil, water, pasture biomass (Lal, 2023), which contributes to production or inputs. Then we also conceptualize ruminants to represent the biological component, defined by herd size, animal physiological status (including morbidity and mortality risk), and productivity (Hutchins et al., 2024). The third variable we conceptualise was biophysical processes within the pasture-based farm system boundary. These include nutrient cycles, biodiversity, and carbon flows, often measured at field level (Schreefel et al., 2022). The fourth variable within the boundary we identify is management practices which in our context include input use intensity, strategy of grazing, and system type classified as conventional, low input, or organic (Moscovici Joubran et al., 2021; Samuel and Dines, 2023; Steinmetz et al., 2021). Then finally, farm economics which cover revenues farmers receive, farm costs, investment and importantly financial resilience (Spicka et al., 2019).

These components constitute the endogenous variables of farm-level analysis and together form the state vector of the farm at a particular point in time (Manners et al., 2025; van Mourik et al., 2021). Different modelling traditions conceptualise them in distinct ways for instance, optimisation models treat them as inputs to a profit maximising production function (Addis et al., 2021); while bioeconomic models incorporate biological dynamics and economics (Schmidtman et al., 2021); and microsimulation focuses on heterogeneity of the farm, and distributional incidence and recently environmental aspects.

2.3. Production

In this review production was conceptualised as the mapping of inputs and management choices into outputs of pasture-based production systems. It is seen as a connection between the farm system and sustainability outcomes. This segment describes how land, forage, labour, and capital can be converted into marketable outputs such as meat for beef systems. Production can be specified biologically, through feed-growth-yield functions, or economically, as the outcome of constrained optimisation (Patton et al., 2012). Heterogeneity in resources and farm practices also leads to variation in production across farms. Policy instruments and market prices as external drivers can rotate or shift production possibilities, while technological innovation shifts this outward. At aggregated levels, pasture-based agricultural production is treated as sectoral supply, linked to upstream inputs and downstream accounts, and can be extended environmentally to account for emissions or other externalities (O'Donoghue et al., 2019).

2.4. Sustainability outcomes

Sustainability broadly aims at balancing economic growth, environmental integrity and social well-being as the principle pillars (Keeble, 1988; Mensah, 2019). In the context of pasture-based system, the sustainability outcomes of production can be grouped into economic, environmental and social categories. Economic outcomes in our context include farm income, value added to the economy, and employment to the rural community. While environmental outcomes include greenhouse gas emissions, nutrient balance, water quality, biodiversity, and soil health (Tahat et al., 2020). These outcomes relate both to welfare objectives and to production externalities with the system. The outcomes also generate feed back into external drivers and the farm system. Economic outcomes affect investment, labour allocation, and intergenerational succession. Environmental outcomes may shape policy responses and consumer demand (Giller et al., 2006; Hayden et al., 2021). For example, poor environmental performance may lead to regulatory change, while favourable economic outcomes may encourage further investment in farms.

This theoretical framework provides a structured pathway for identifying how different modelling approaches represent variables, simulate responses, and evaluate outcomes. Micro-level approaches, including farm-level simulation, microsimulation, and agent-based models, operate at unit level and represent heterogeneity in resources, management, and behavioural responses to policy, market, and

biophysical drivers. Sectoral and economy-wide approaches, including input-output and computable general equilibrium models, operate at higher levels of aggregation and model inter-sectoral and environmental linkages. These approaches differ in scale and system boundary and are treated in this review as distinct modelling categories applied to pasture-based ruminant systems.

Finally, contextual variables such as time, geography, and population characteristics add complexity of the system and condition elasticities of response determining whether models operate at the micro level or macro-level spillovers.

In our study we review, the applications, modelling choices and technical characteristics made in relation to the variables defined in the theoretical framework.

3. Methodology

The review employs a hybrid scoping systematic approach to review literature of microsimulation and other modelling approaches for economic and environmental sustainability of pasture-based systems. Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines were partially applied as the reference framework for identification, selection, and synthesis of studies (Liberati et al., 2009; Page et al., 2021). The PRISMA checklist and flow diagram were used to document the search and screening stages and to ensure replicability of the review. PRISMA is ideally suited for narrow reviews where the scope is specific, and the literature is relatively limited. However, in the case of broad heterogenous modelling literature with different goals and different methodologies, we have had to adapt the framework.

Our hybrid approach falls between the stylised systematic approach of PRISMA, with the more qualitative approach of literature review or survey article. In our approach, we use the PRISMA structure as our sampling frame. Search results were supplemented through forward citation tracking of highly cited papers to identify additional relevant studies. Inclusion criteria are based on relevance to pasture-based agriculture rather than citation frequency. In addition to keyword-based screening, parameters not identifiable from titles and abstracts were extracted through structured full-text review.

3.1. Search strategy of literature

In the review, a full search was conducted across three databases, Scopus, Web of Science, and Google Scholar. Scopus and Web of Science were chosen as an established bibliographic databases that provide wide coverage of peer-reviewed economic literature (Pranckutė, 2021). Google Scholar was included to search for studies published in interdisciplinary and applied journals, that may not appear in Scopus and Web of Science (Haddaway et al., 2015). The search was restricted to peer-reviewed journal articles published in English between 2000 and 2024. Additionally, a backward and forth citation snowballing search was performed to identify further relevant studies not captured in the initial strategy.

All the retrieved studies were exported into a referencing tool Mendeley before screening in Microsoft Excel. Duplicates in excel were removed using manual screening. Titles and abstracts were then screened against eligibility criteria that the authors set. Then full-text reviews were later conducted by authors for the remaining studies to avoid errors. **Table 1** below documents the search strings used across the three databases.

Table 1. Search strategy of the review showing databases, strings and exclusion criteria.

Database	Search Field(s)	Search String	Filters Applied
Scopus	TITLE-ABS-KEY	("livestock production systems" OR "pasture-based agriculture" OR "grass-based livestock" OR "ruminant farming") AND ("model*" OR "microsimulation" OR "bio-economic model*" OR "input-output model*" OR "CGE model*" OR "system dynamics model*" OR "stochastic model*" OR "simulation") AND ("economic impact*" OR "profitability" OR "economic sustainability" OR "farm income") AND ("environmental impact*" OR "GHG emissions" OR "biodiversity" OR "land use change")	Exclude: Conference papers, Subject areas: Agri, Econ, Env Sci

Database	Search Field(s)	Search String	Filters Applied
Web of Science	TS (Topic: Title, Abstract, Keywords)	TS=("livestock production systems" OR "pasture-based agriculture" OR "grass-based livestock" OR "ruminant farming") AND TS=("model*" OR "microsimulation" OR "bio-economic model*" OR "input-output model*" OR "CGE model*" OR "system dynamics model*" OR "stochastic model*" OR "simulation") AND TS=("economic impact*" OR "profitability" OR "economic sustainability" OR "farm income") AND TS=("environmental impact*" OR "GHG emissions" OR "biodiversity" OR "land use change")	Document types: Articles, Review; Subject areas: Agri, Econ, Env
Google Scholar	Full text (title, abstract)	("livestock production systems" OR "pasture-based agriculture" OR "grass-based livestock" OR "ruminant farming") AND ("model*" OR "microsimulation" OR "bio-economic model*" OR "input-output model*" OR "CGE model*" OR "system dynamics model*" OR "stochastic model*" OR "simulation") AND ("economic impact*" OR "profitability" OR "economic sustainability" OR "farm income") AND ("environmental impact*" OR "GHG emissions" OR "biodiversity" OR "land use change")	Manual screening; Sort by relevance; Year range; Exclude patents & citations

3.2. Inclusion and exclusion criteria

The authors established a set of criteria to ensure consistency in the selection process. Studies were included if they met the following conditions: i) focus on pasture-based agriculture, with beef or other ruminant production systems as the main subject, ii) Applied clear modelling framework, ii) Report at least one economic and/or environmental impact.

Reviews, dissertations, theses, conference proceedings, and non-English publications were excluded. Dissertations and theses were excluded because the review was limited to peer-reviewed journal articles to ensure comparability in methodological reporting. Studies that lacked sufficient methodological detail were also omitted. When multiple publications relied on the same model, only the original methodological contribution was retained unless later studies introduced methodological extensions.

3.3. Data extraction and coding

After selecting studies for review, a structured coding framework was used to extract key descriptors which in our case include bibliographic details, Production systems modelled (ranging from conventional, organic, and low input), modelling approach, unit of analysis, sustainability dimension (including economic, environmental, and social), and policy among others. Note that, when a study applied multiple approaches, scales, variables or data sources, all were recorded to reflect the diversity of methodological practice. As a result, some studies appear multiple times across categories; however, results were normalised by the total number of included studies. Model type was determined through full-text assessment of each study. Author-reported terminology, such as microsimulation, bioeconomic models, and input-output models, was recorded. Classification relied on the modelling framework described in each study rather than on keywords alone.

3.4. Analytical approach

The review uses descriptive methods to present distribution of studies by modelling approach, application domain, external drivers, unit of analysis, sector, production system, data type, and software. Charts and heatmaps are plotted from the data, with percentages used to show the share within each modelling approach. This strategy enabled systematic identification of patterns and gaps in the literature, including the representation of different production systems, livestock sectors, and the balance between economic and environmental indicators.

Table 2 presents a conceptual typology of modelling approaches to support comparison across models. For each category, the table summarises applications, strengths, limitations, and representative studies. Farm-level simulation and microsimulation are presented together in this comparison

Table 2. Conceptual classification of economic and environmental modelling approaches applied to pasture-based agriculture.

Model Type	Distinctive Applications	Strengths	Weaknesses or Limitations of the approach	Key References and Examples
1. Farm-level simulation and microsimulation	<ul style="list-style-type: none"> Farm management, environmental impacts, profitability/resource allocation, policy evaluation 	<ul style="list-style-type: none"> Captures heterogeneity Flexible scenario testing Links micro and macro Can model distributional outcomes 	<ul style="list-style-type: none"> Data intensive Often siloed in different literatures (agricultural vs social policy) Many static applications without dynamic extensions 	<ul style="list-style-type: none"> Taylor et al. (2020); Vogeler et al. (2017); Hynes et al. (2009); O'Donoghue, 2017; Haydarov et al. (2024); Richardson et al. (2014); Reidsma et al. (2018)
2. Optimisation or Programming Models	<ul style="list-style-type: none"> Resource allocation, efficiency analysis, profitability 	<ul style="list-style-type: none"> Strength in trade-off analysis Identifies efficient solutions under constraints 	<ul style="list-style-type: none"> Typically assumes rational behaviour Often static; limited uncertainty 	<ul style="list-style-type: none"> Moraes et al., 2012; Addis et al. (2021); Finneran et al. (2012); Kamilaris et al. (2020)
3. Econometric or Statistical Models	<ul style="list-style-type: none"> Drivers of profitability, adoption, efficiency, policy evaluation 	<ul style="list-style-type: none"> Empirically grounded Flexible with data Good for causal inference 	<ul style="list-style-type: none"> Dependent on data availability Limited system feedback Weak predictive power outside sample 	<ul style="list-style-type: none"> Hanrahan et al. (2018); de Oliveira Silva et al. (2017); Cillero and Reaños (2023); Haydarov et al. (2024); Mehrabi et al. (2020)
4. Agent-Based Models	<ul style="list-style-type: none"> Farmer behaviour Technology adoption Collective dynamics 	<ul style="list-style-type: none"> Capture individual adaptation Learning, and social networks Explicitly represent behavioural decision processes 	<ul style="list-style-type: none"> Few applications Requires rich behavioural data Validation is difficult 	<ul style="list-style-type: none"> Ryan et al. (2018); Bolte et al. (2007); Mooney et al. (2024)
5. Input-Output or Bioeconomic IO (BIO)	<ul style="list-style-type: none"> Sectoral and economy-wide spillovers Trade Leakage 	<ul style="list-style-type: none"> Captures indirect effects and economy-environment linkages Transparent 	<ul style="list-style-type: none"> Assumes linearity Static multipliers Poor/hot representation 	<ul style="list-style-type: none"> behavioural Jin (2023); Zehetmeier et al. (2014); Breure et al. (2024)
6. Computable General Equilibrium	<ul style="list-style-type: none"> Trade, policy shocks, macroeconomic impacts 	<ul style="list-style-type: none"> Economy-wide perspective Consistent with national accounts 	<ul style="list-style-type: none"> Assumes equilibrium and rationality High data demands Less detail at farm level 	<ul style="list-style-type: none"> Cillero and Reaños (2023); Li and O'Donoghue (2012); van der Linden et al. (2020)
7. System Dynamics	<ul style="list-style-type: none"> Long-term trajectories, climate and sustainability policy 	<ul style="list-style-type: none"> Captures feedback loops, cross-domain integration Dynamic 	<ul style="list-style-type: none"> Oversimplification risk Calibration challenges; less detail at micro level 	<ul style="list-style-type: none"> Lieffering et al. (2016); Benavides et al. (2023); Stürck et al. (2018)
8. Integrated Assessment Models	<ul style="list-style-type: none"> Predictive analytics Pattern recognition Linking models 	<ul style="list-style-type: none"> Handles large datasets Flexible integration Emerging use in farm contexts 	<ul style="list-style-type: none"> Often 'black box' Weak interpretability for policy design 	<ul style="list-style-type: none"> McVey et al. (2023); Maseko et al. (2024); Sonea et al. (2023)

because both operate at unit level and simulate heterogeneous responses under alternative scenarios. For descriptive reporting however, the two approaches remain distinct in the results presented in Section 4 of this paper.

A deliberate choice was made to treat farm-level simulation and microsimulation as a unified category. While these traditions emerged in separate literatures of agri-environmental sciences, economics, and social policy, respectively they share a common pattern; explicit simulation of unit-level heterogeneity and the capacity to trace distributional outcomes under policy or environmental change. Identifying this overlap explains their importance as a benchmark against which other modelling traditions can be evaluated.

The classification is structured around five comparative criteria: (i) resolution, which distinguishes unit-level from aggregate modelling; ii) Treatment of behaviour including optimisation, empirical inference, or behavioural simulation; iii) dynamics for instance temporal and feedback mechanism; iv) System boundary, defined spatially as farm, sectoral, economy-wide, or coupled economy-environment, and v) Policy relevance showing the interpretability for ex-ante policy analysis, and distributional analysis.

The framework enables comparison across modelling approaches. Farm-level models and microsimulation operate at the level of units and do not have an economy-wide emphasis. Input-output and computable general equilibrium models ensure macro consistency but abstract from farm-level heterogeneity. The framework therefore provides a descriptive basis for mapping modelling approaches and interpreting the results reported in Section 4.

3.5. Databases and search results

The results of database and search are shown in the following PRISMA (Figure 1). The initial literature search identified 483 articles across the three databases and any additional snowballing searches from key references. These were distributed as Google Scholar (n = 168), Scopus (n = 60), Web of Science (n = 78), and by snowballing, (n=177). The highest share was from Google scholar and snowballing searches of references and citations. After removal of 71 duplicates, 412 article records remained for title and abstract screening. Nine non-peer-reviewed items were excluded. These included conference papers, theses and dissertations, and reports. This resulted in 403 full text articles available for eligibility assessment. From these an additional 197 articles were excluded, including: conceptual articles without modelling (n = 29); studies focusing on non-ruminant livestock production systems (=42); papers outside pasture-based agriculture scope (n = 148), crop only systems without a pasture component (n = 18); and two residual duplicates. This resulted in a final sample of 173 peer review studies that met the inclusion criteria which were retained for full text review (Figure 2).

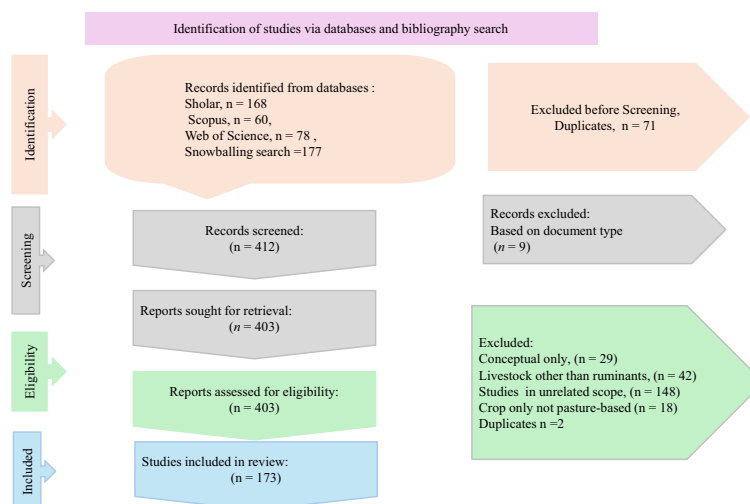


Figure 2 PRISMA Flow Diagram.

4. Results

4.1. Trends and geographical distribution of modelling studies

The first objective was to map the temporal and geographical evolution of economic and environmental modelling microsimulation studies in pasture-based agriculture between 2000 and 2024. Results are organised around three themes; temporal trends, geographical distribution and sectoral coverage, and production systems modelled.

4.1.1. Temporal distribution of studies

The temporal distribution of studies provide insight into how the field has evolved. Over the past two decades, modelling priorities have shifted from a narrow productivity focus towards addresses global sustainability challenges in ruminant systems. **Figure 3** presents the temporal distribution of studies over the review period. There is a clear publication trend showing expansion of the modelling literature since 2000. In the early 2000s, the field was small, with only three studies recorded between 2000-2004 and 10 studies in 2005-2009. A turning point emerged in 2010-2014, when the trend of publications rose sharply to 42 studies. This was followed by further increases in the period 2015-2019 ($n = 52$) and in 2020-2024 ($n = 66$ studies). More than two-thirds of studies were published after 2010, coinciding with major global policy shifts on sustainability, including the Kyoto Protocol (**UNFCCC, 1997**), the adoption of the Paris Agreement (**UNFCCC, 2015b**), and later the European Green Deal (**European Commission, 2019**).

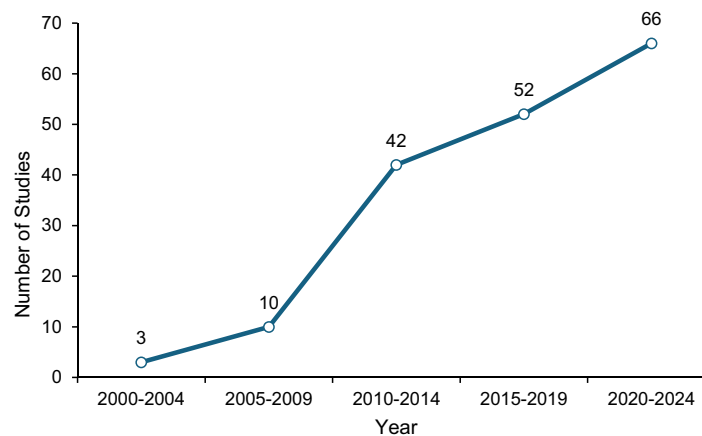


Figure 3 Temporal distribution of modelling studies published Annually between 2000 - 2024.

4.1.2. Geographical distribution and sectoral coverage

The geographical distribution of studies provide insight into where modelling capacity has been focused. **Figure 4**, Panel A, presents the geographical distribution of studies revealing strong regional disparities. Europe accounted for half the total of all models ($n = 86$; 50%), followed by Oceania ($n = 26$; 15%), North America ($n = 17$; 10%), Asia ($n = 15$), Africa ($n = 10$), and South America ($n = 10$). An additional nine studies adopted a global scope. Within Europe, Ireland, the United Kingdom, France, and the Netherlands were the most frequent in the published models of pasture-based systems.

Sectoral coverage in the review also varied by region (**Figure 4**, Panel B). Pasture systems were the most frequently modelled sector in Oceania and South America each accounting for 35% share. These were followed by North America (32%) and Europe (31%). Within the ruminants, beef sector modelling was most frequently represented in South America (35%) and North America (32%) suggesting the economic weight of the sector in these regions. Dairy production received greater representation in Oceania (26%) and Europe (21%), with 19% of African studies addressing dairy systems. Crop-livestock integration was most visible in Asia (23%) and Africa (17%). Studies that focus on sheep were frequent in Oceania (13%). The geographical and sectoral distribution of studies varied across region in the world, with beef sectors and pasture systems accounting for the largest shares of modelling applications during the review period.

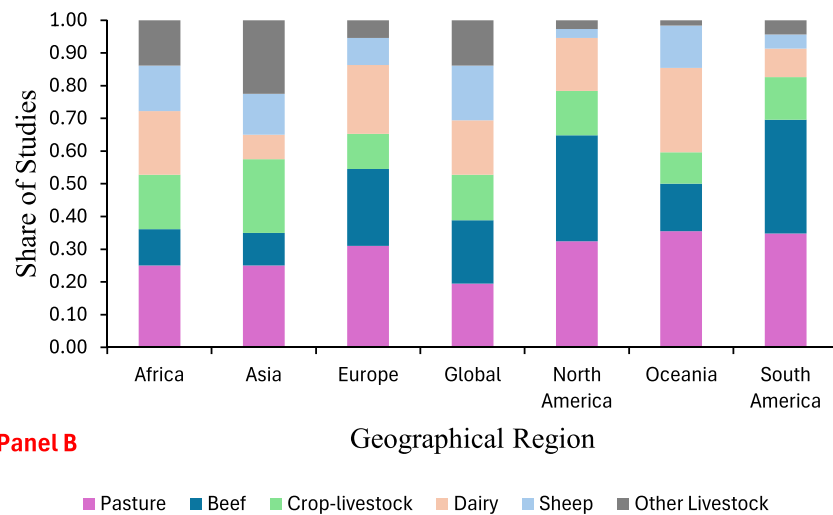
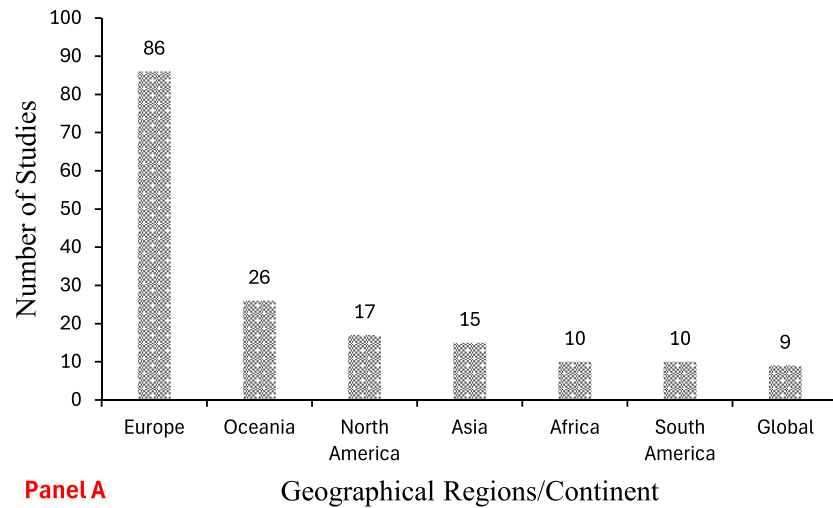


Figure 4 Geographical distribution of modelling studies (Panel A) and production system coverage by region (Panel B).

4.1.3. Geographical distribution of production systems

There are different approaches to agricultural production, often with varying production and environmental trade-offs. As shown in *Figure 5*, over the last two decades modelling efforts in pasture-based agriculture has most frequently addressed conventional production systems (61%), followed by low-input systems (25%). Organic production systems (6%) and other production systems (8%) account for smaller shares in modelling studies of pasture-based agriculture.

Disaggregated by region, Conventional systems were most frequently observed in North America (71%) and Oceania (70%), followed by Europe (61%) and Africa (25%) pointing to more intensive production systems in advanced economies. In contrast, low-input production systems were frequently modelled in Africa (58%) and South America (17%). Organic systems accounted for less than 9% of studies in all regions, with Europe showing the highest share. These results explain the global dependence on conventional systems for production the minor focus on low input an alternative production approaches across all regions.

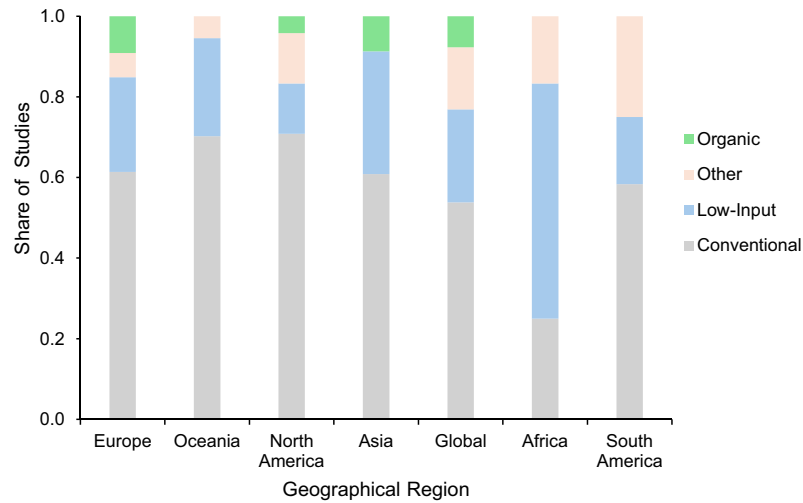


Figure 5 Distribution of production system by geographical region.

4.1.4. Drivers of the study

Figure 6 presents the distribution of reported drivers across the reviewed studies. Multiple drivers were coded for some studies with shares reported relative to the total number of included studies. Environmental factors were the most frequently cited in this period (95%), followed by bio-physical conditions (87%) and livestock (84%). Farm management (75%) and spatial drivers (71%) were also frequently reported, indicating the role of production practices and landscape context in farm system modelling. There are increased interests in technology (64%), policy and regulations (62%), and economic and market factors (57%). This indicates increasing attention to institutional and economic contexts in model design. Climate change (53%) and ecosystem services (46%) are less common drivers, despite their growing weight in sustainability debates. Water management (40%), institutional and social drivers (37%), and genetics and breeding (23%) were reported in a smaller share of studies. The result highlight how modelling and simulation literature in the last two decades has focussed on environmental, production, and management factors, with comparatively less attention drawn to institutional, social, or genetic dimensions in pasture-based agriculture.

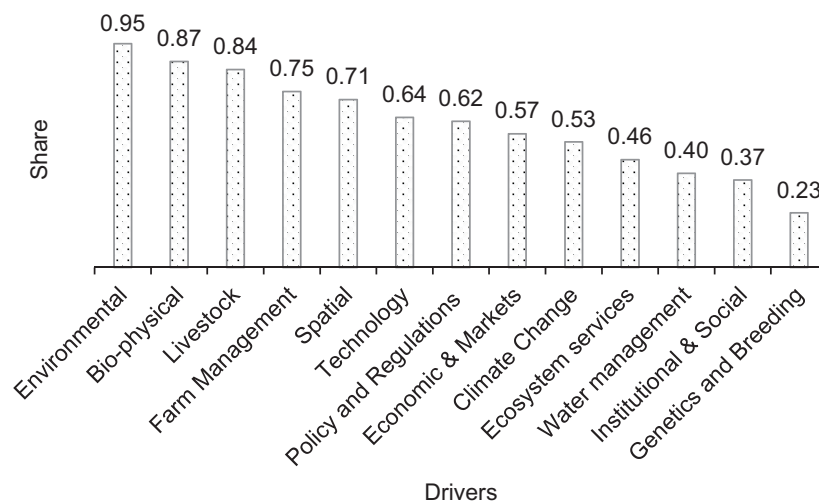


Figure 6 The drivers in modelling literature for economic and environmental impact analysis of pasture-based agriculture.

4.1.5. Drivers of modelling studies by method of analysis

This section presents the factors in the literature that motivated modelling choices. **Figure 7** summarises the distribution of drivers reported across modelling approaches.

Environmental, biophysical, livestock, and farm-management factors were among the most frequently cited drivers in the reviewed studies. In simulation models, the leading drivers were environment (12%), biophysical and livestock (11% each), and farm management (10%). Hybrid and integrated models showed a similar distribution with environment and biophysical drivers (11% each), livestock (10%), and farm management (10%).

Optimisation studies report environmental and biophysical factors with similar shares (11% each), followed by policy, economic, livestock, and farm management drivers (10% each). Econometric and statistical models were driven by livestock, biophysical drivers, alongside environmental factors (12% each). Policy, economic and farm management factors were among major factors (8% each). Earth system and GIS models were driven by environmental factors (13%) and livestock (12%). While System dynamics studies reported environment, biophysical, livestock, water management, and farm management (11% each) as central drivers.

Microsimulation studies reported policy and livestock drivers (14% each). Agent-based models showed a balance across policy, socio-economic, and livestock drivers (11% each). Among macro-scale approaches, input-output models reported economic, policy, socioeconomic drivers, while CGE models were driven by policy, socioeconomic biophysical, and livestock (14%). Integrated assessment models reported drivers distributed at 8% each. Machine learning studies reported environmental and spatial factors (18%).

The next section examines how these approaches were operationalised including scale of analysis, data sources, and validation strategies.

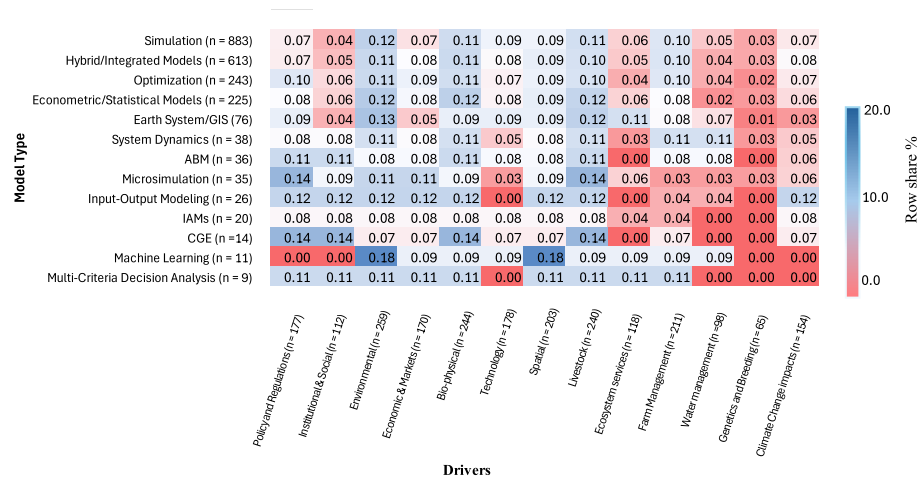


Figure 7 Drivers that motivated modelling choice.

4.2. Methodological choices

4.2.1. Modelling approaches

Methodological choices in economic and environmental impact analysis determine both the scope of applications and the nature of inferences drawn from the studies. Different approaches are employed depending on the objectives and analytical scope of the study. **Figure 8** reports the distribution of modelling approaches in the reviewed studies. Farm-level simulation models accounted for 70% of applications, followed by hybrid or integrated approaches (49%). This reflects the complexity of pasture-based systems, where models often adopt integrated frameworks rather than relying on a single method. Econometric or statistical methods accounted for 18% of studies and optimisation models 16%. Other approaches were infrequently applied (each ≤ 3%). This shows reliance on simulation-based frameworks within the literature, with relatively limited use of approaches that capture heterogeneity or distributional effects, such as microsimulation.

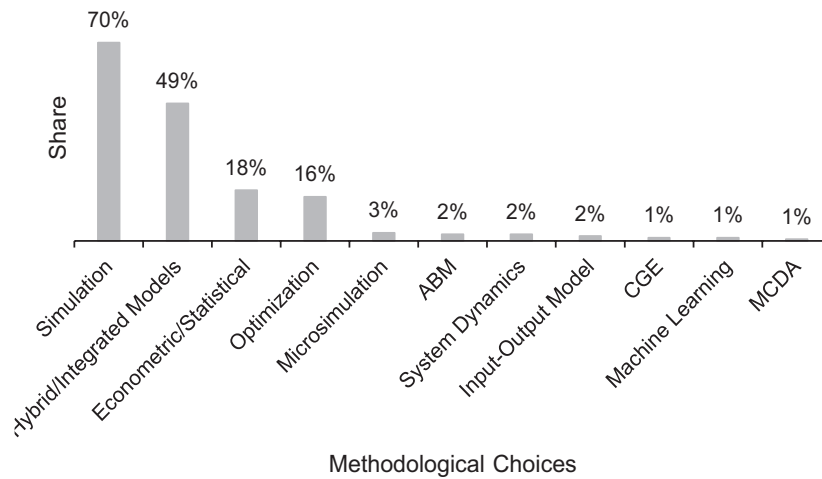


Figure 8 The frequency of modelling approaches used in economic and environmental impact analysis of pasture-based agriculture.

4.2.2. Modelling approaches and geographical distribution

Geographical differences in the distribution of modelling studies are evident (*Figure 4*). In *Figure 9*, European studies account for 57 simulation models (52% of global applications), 41 hybrid or integrated frameworks (40%), and 16 optimisation studies (41%). Econometric and statistical models also originate largely from Europe, with 18 studies (39%). North America contributed nine simulation and nine hybrid applications (each 8%), while Oceania contributed 20 simulation studies (18%) but had fewer contributions in other categories. Africa, Asia, and South America contributed three or four studies per approach.

Five studies (3%) in the sample described their approach as microsimulation. Three were conducted at farm level and two at regional scale. Half of the microsimulation studies were in Europe, while the remainder were distributed across Asia, Africa, and global-scale analyses. Microsimulation is data intensive, its concentration in Europe points to the availability of disaggregated farm and household datasets, which limits external validity in regions lacking comparable data.

Similar patterns were observed in other approaches. Earth system modelling was mainly conducted in Europe (16 of 25 studies), as were agent-based models ($n = 7$). Macro focused models such as input-output and system dynamics models were applied less frequently outside Europe. Overall, approximately two-thirds of the reviewed studies originated in Europe, revealing regional priority for methodological development.

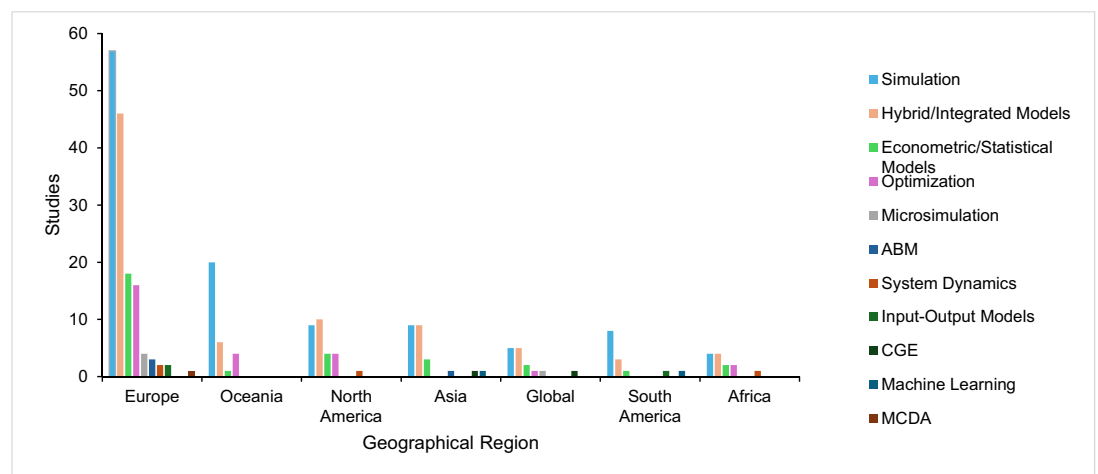


Figure 9 Shows the distribution of modelling approaches across geographical regions.

4.2.3. Applications across sustainability domains

Figure 10 presents the distribution of thematic domains across modelling approaches in pasture-based systems over the past two decades. Simulation models were applied across environmental (15%), farm management (15%), resource use (14%), and pasture-related (12%) domains, with smaller shares in climate change (10%), risk and uncertainty (10%), economic outcomes (9%), and policy (8%). Hybrid and integrated models showed a similar pattern, with 14% of applications in environmental, farm management, and resource use domains, 13% to pasture, while economic outcomes (10%) and policy and climate change (11% each) themes were fewer.

Econometric and statistical models allocated 16% of applications to environmental themes and 15% to resource use, with economic and pasture domains each accounting for 12%, and policy and farm management for 8% each. Optimisation models exhibited a similar distribution with environmental and farm management domains (13% each), resource use and pasture (12% each), and smaller shares in climate change (9%) and policy (11%).

Microsimulation models, though few in number, were applied to economic, policy, farmer behaviour domains (each 17%), as well as environment and farm management themes (each 13%). Agent-based models were distributed across farm management, resource use, pasture, policy, and economic outcomes (13% each). Among macro-level methods, CGE models allocated 17% each to economic, policy, and farmer behaviour modelling, with smaller shares in environmental and farm management domains (8% each). Input-output models were applied to environmental, resource use, and policy domains (16% each). System dynamic models were distributed across environmental, farm management, resource use, and pasture themes (13% each). Earth system models were directed mainly towards environment (17%), farm management (15%), and pasture (15%). Integrated assessment models showed a balanced distribution across environment, resource use, pasture, and policy domains (13% each). Machine learning studies a new approach were frequent on environmental, farm management, resource use, and pasture domains (18% each).

Across approaches, environmental, farm management, resource use, economic domains accounted for the largest shares of applications. Policy, and farmer behaviour were less modelled, while animal health and welfare was rarely considered.

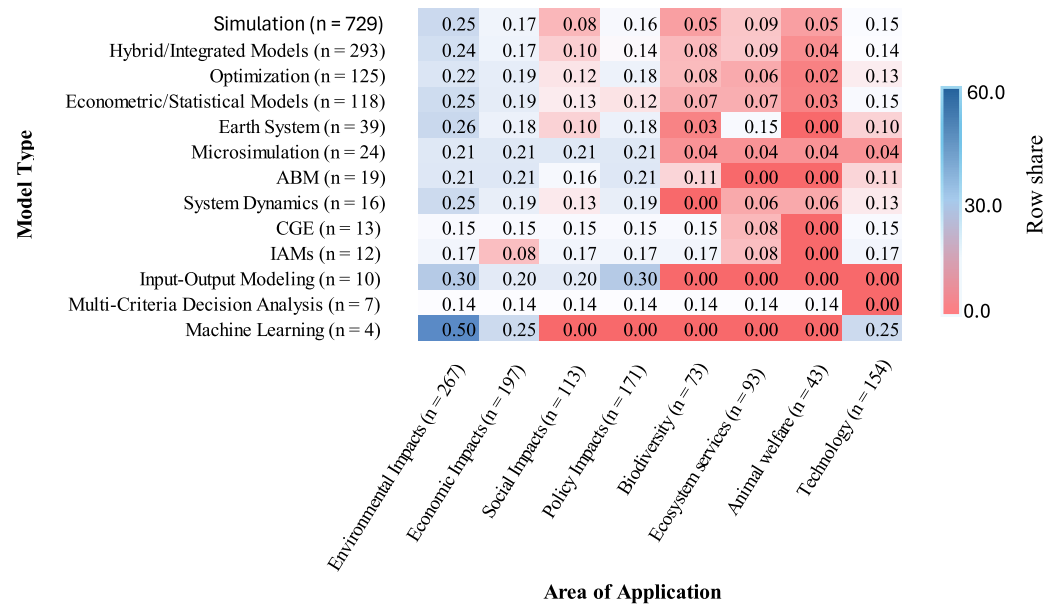


Figure 10 Applications of modelling approaches across sustainability domains.

4.2.4. Unit of analysis in modelling studies

Across modelling approaches in the literature of pasture-based agriculture, the farm level (n = 64 model studies) was the most frequently reported unit of analysis. Simulation models (39%) and

optimisation models (8%) were applied at farm scale. Simulations studies also extend to field (55%) and animal/group levels (46%). Econometric and statistical models were distributed across farm (12%), field/plot (10%), and regional (11%) scales. Hybrid and integrated models were likewise applied at farm-level (30%), with smaller shares at national (21%) and regional (20%) scales.

Macro-scale models were applied at higher levels of aggregation. Input-output models were applied at national level (4%) with limited application at farm levels. A similar pattern was observed for CGE and IAMs in pasture-based systems.

Five studies described their approach as microsimulation. Three were conducted at farm level and two at regional scale. Agent-based models were mainly applied at regional and animal/group scales, while earth system models were implemented at field and regional levels.

The review showed that applications were most frequently conducted at farm and animal/group units of analysis. Regional and national analyses were less frequent and were largely associated with macro-economic or environmental modelling frameworks (Figure 11).

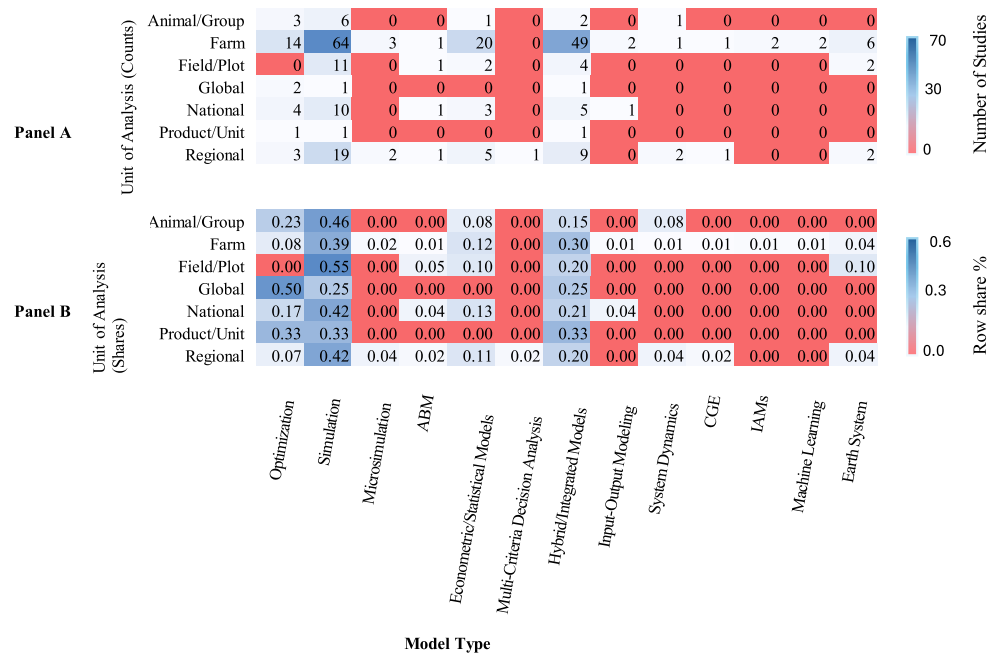


Figure 11 Show the distribution of modelling approaches by unit of analysis.

4.2.5. Data sources across approaches and production systems

Figure 12 reports data sources across modelling approaches. Microsimulation models relied on farm survey data (63%), supplemented by published studies (13%) and national statistics (13%). ABM which also operate at the micro level showed a similar distribution, with 60% using survey data and 20% drawing on published sources. Econometric, statistical, and optimisation models used a broader mix of data sources, including surveys (33%), published studies (24-28%), and market data (9 -13%). Input-Output and Computable General Equilibrium studies relied on secondary data sources, including national statistics and market data.

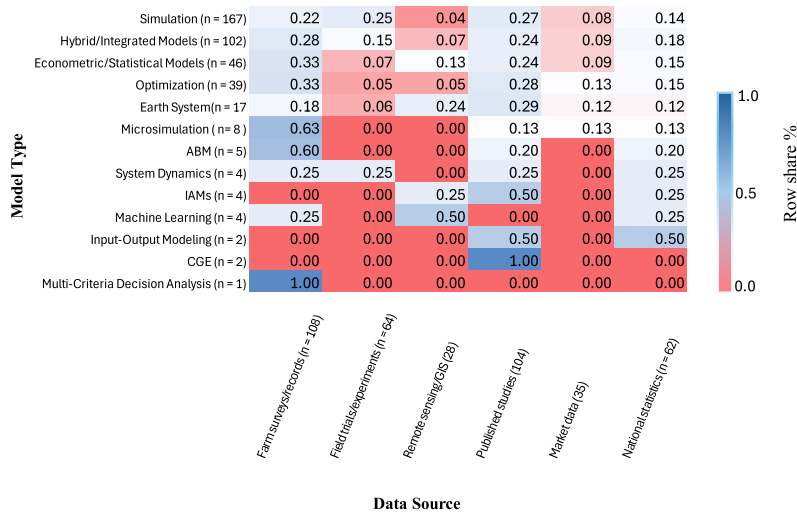


Figure 12 Data sources by modelling approach in sustainability assessments of pasture-based agriculture.

4.2.6. Software across modelling approaches

Figure 13 reports the software platforms used across modelling approaches. Simulation studies most frequently used Microsoft Excel (33%), R (24%), and SAS (14%), with smaller shares using Stata (6%) for modelling. Hybrid and integrated models followed a similar pattern, with Microsoft Excel (40%) and R (25%) most commonly reported. Econometric and statistical models most frequently used R (35%), GAMS (15%), and Stata (15%). Optimisation studies reported Microsoft Excel (36%), R (27%), and GAMS (27%).

Microsimulation studies used Stata (40%), R (20%), ArcGIS (20%), and Java (20%) for analysis. Some of the approaches show distinctive software traditions. System dynamics models were implemented in Vensim (40%) and STELLA (40%), while earth system models used R (33%) and GAMS (33%). CGE studies were frequently implemented in GAMS (67%). ABMs were split between MATLAB (50%) and Stata (50%). For MCDA, input-output, and machine-learning studies, software was not generally reported. Spreadsheet tools (Excel) and statistical packages (R and Stata) were frequently reported in farm-level and econometric studies, whereas specialised platforms (GAMS, Vensim, and STELLA) were more common in optimisation and systems-based approaches.

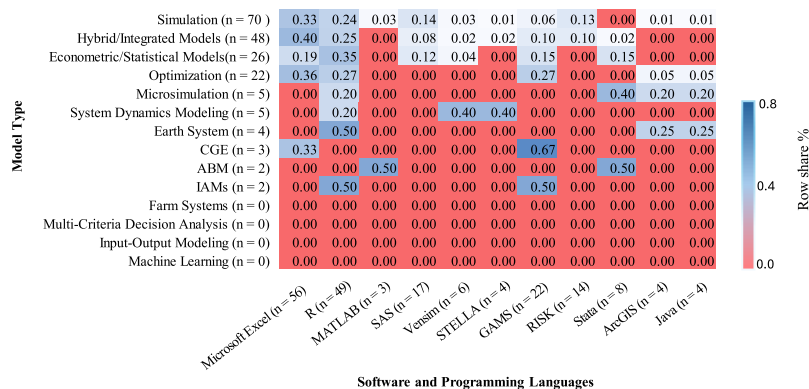
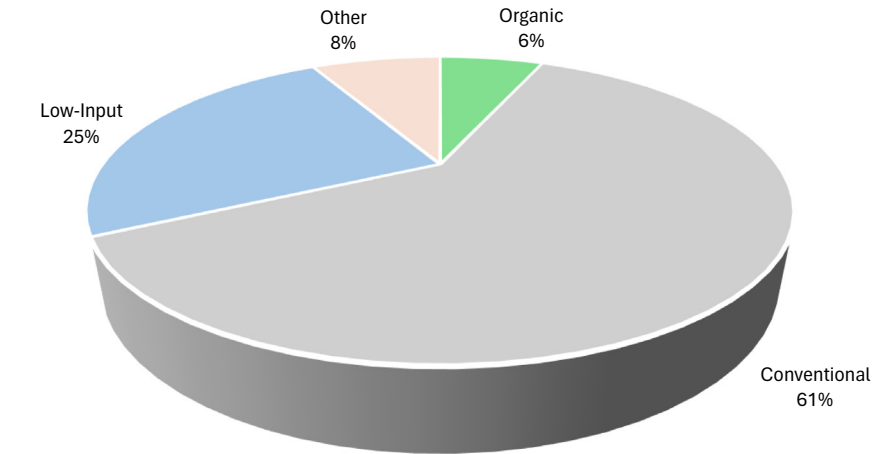


Figure 13 Software by modelling approach.

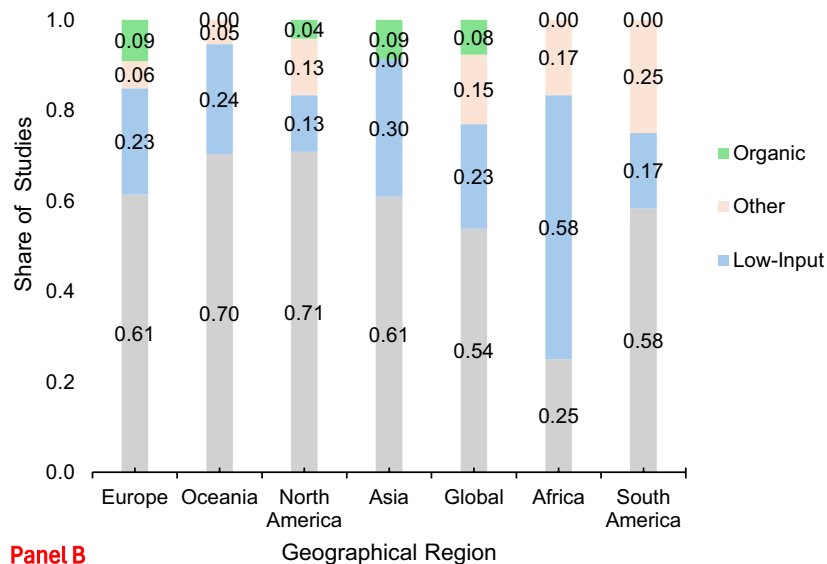
4.2.7. Model behaviour and validation

Model behaviour refers to the structural specification of models in terms of dynamics and the treatment of uncertainty. Deterministic models accounted for 40% of the sample, followed by dynamic (24%), static (20%), and stochastic (16%) designs (**Figure 14A**). Deterministic approaches were most frequent at the farm and global scales, while stochastic methods, relevant for representing risk and uncertainty, were comparatively rare. Dynamic models were frequently applied at national and regional levels, while static designs showed equal distribution across all scales.

Figure 15 presents the validation strategies reported in the reviewed studies. Sensitivity analysis (47%) and calibration against farm level data (39%) were the most frequent approaches. Benchmarking against other models (22%) and expert judgment (18%) were less frequent. Few studies combined multiple validation strategies. The reliance on internal rather than external validation indicates concern over external generalisability, where studies inform policy debates.



Panel A



Panel B

Figure 14 Modelling behaviour by scale of application: Panel A reports share of behaviour types across all studies; Panel B shows their distribution across spatial scales applied.

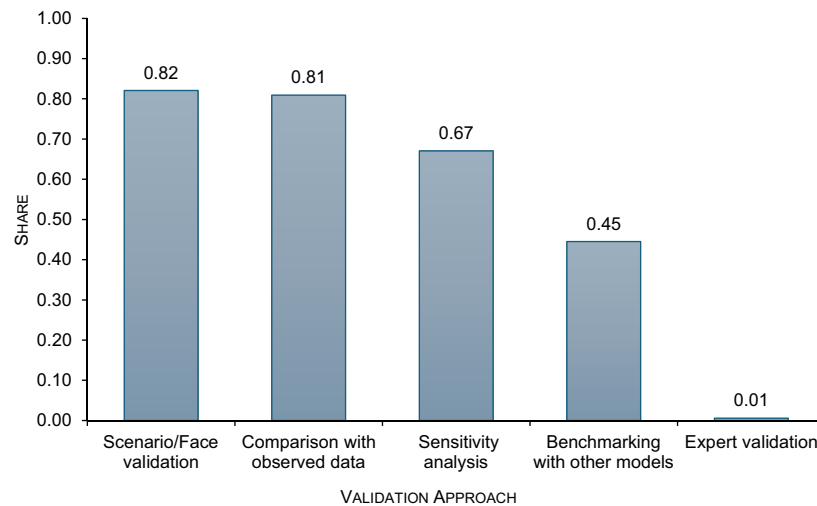


Figure 15 Validation strategies adopted in the reviewed studies (share of studies, %).

4.3. Sustainability modelling

4.3.1. Impacts addressed by modelling approaches

Figure 16 presents the distribution of sustainability impacts examined across modelling approaches. Economic and environmental impacts accounted for the largest shares across model types. Simulation and hybrid models allocated one quarter of applications to economic impacts (25% and 24% respectively) and 17% each to environmental impacts. Econometric (19%), optimisation (19%), and input-output (20%) models were more frequently applied to economic and policy outcomes. CGE models show a more balanced distribution allocating similar shares to economic, environmental, policy and social impacts (15% each). In contrast, system-based approaches exhibit greater thematic diversity. Earth system models focus primarily on biodiversity (17%) and ecosystem services (15%), while microsimulation allocates equal shares to economic and environmental impacts (21% each). Of the two machine-learning studies identified (n=2), one examined environmental outcomes (50%). Across literature, social outcomes and ecological dimensions such as biodiversity and ecosystem services were less frequently represented compared to economic and environmental outcomes.

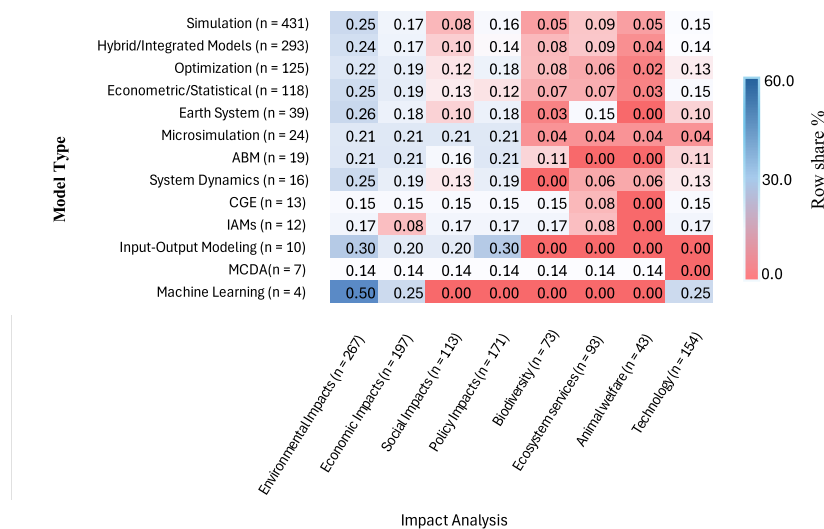


Figure 16 Distribution of impact domains across modelling approaches (row-normalised shares).

4.3.2. Economic and environmental indicators modelled

Figure 17 presents the distribution of sustainability themes in the reviewed modelling studies. Environmental indicators were classified as resource-use and impact measures and constituted the most frequently reported outcome category over the review period 2000-2024. Among resource use indicators, land use (76.9%) was the most frequent modelled indicator, followed by agrochemical use (57.8%) and nitrogen input (56.6%). Among impact parameters, greenhouse gas emissions were more frequently reported, including methane (51.4%), CO₂ (50.3%), and N₂O (49.1%). Soil quality (38.2%), water (23.1%), carbon sequestration (20.2%), and biodiversity (19.7%) were less frequently reported.

The most frequently modelled economic indicators were productivity (69.4%), farm cost (48.6%), and profitability (45.1%). Trade (10.4%), GDP contribution (4.6%), and fiscal impacts (4.0%) were considered far less frequently over the last two decades. Social dimensions of pasture-based system were least frequently covered. Limited attention was given to indicators such as labour (35.3%), livelihoods (18.5%), equity (15.0%), food security (13.9%), employment (12.1%), and animal health (11.6%). Overall, the literature emphasises environmental and farm-level economic outcomes, with only partial integration of macroeconomic and social dimensions. This affirms the need for modelling approaches that capture broader sustainability objectives and distributional consequences.

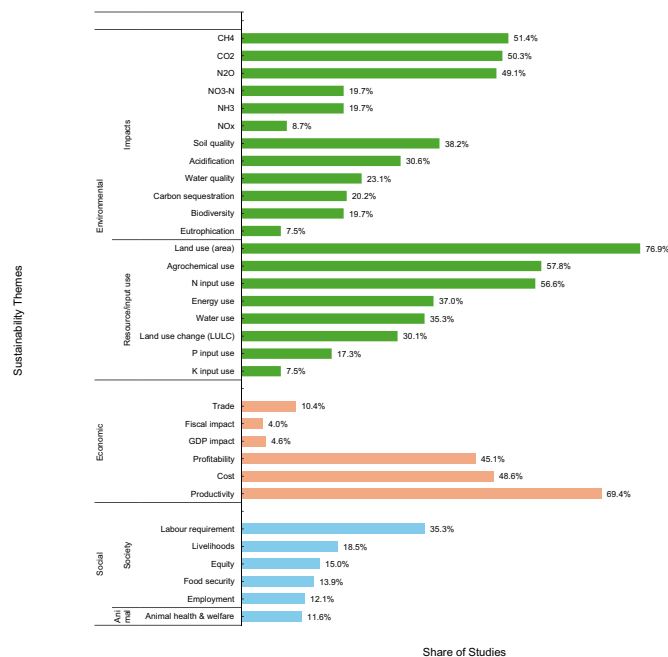


Figure 17 The distribution of sustainability impacts assessed across reviewed studies.

4.3.3. Policy instrument drivers by production system

Figure 18 presents the distribution of policy instruments modelled across production systems. The results show a clear focus of policy drivers in conventional agriculture systems. Regulations account for 61% of application in conventional systems, followed by subsidies (57%) and other policy instruments (56%). Taxes and levies demonstrated an even strong focus with 71% of applications directed at conventional systems.

Organic systems had a more balanced representation across policy in the last two decades. The most frequently modelled policy instruments modelled were subsidies (24%) and other instruments (23%), followed by regulations (22%), while taxes were only examined in 12% of applications. Low-input systems were rarely examined in policy orientated modelling. The share of studies ranged from 9% for regulations to 15% for other instruments.

Policy simulation focuses more on conventional production. Historically, regulations and fiscal instruments have been designed to target input intensive systems. In contrast, organic agriculture

is more commonly linked to incentive-based schemes aimed at encouraging transition. Low input systems remain absent from policy orientated modelling.

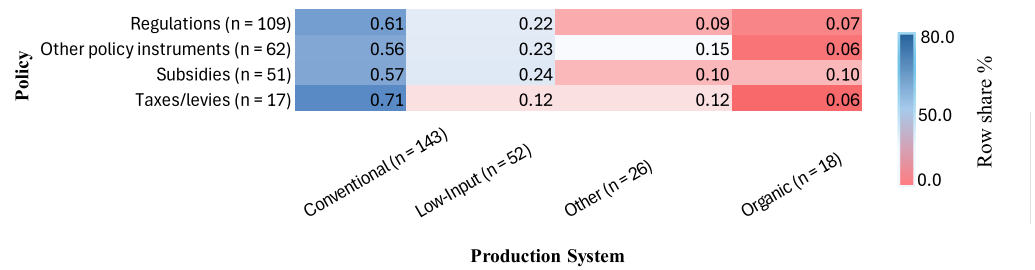


Figure 18 Shows the distribution of policy instruments modelled across production.

5. Discussion

5.1. Temporal and geographic distribution

The review of 173 studies shows a growing trend in the modelling literature for pasture-based agriculture in the last two decades, with the number of publications increasing markedly after 2010. This trend coincides with major international sustainability agreements, including the UN Sustainable Development Goals (Jones et al., 2017), the Paris agreement, and subsequent European policy initiative such as the EU Green Deal (European Commission, 2019; UNFCCC, 2015a). The growth in modelling studies therefore appears to reflect increasing policy and societal demands for sustainable food production.

The geographical distribution in the literature however was heterogeneous. More than half of the reviewed studies originate from Europe, followed by Oceania. Latin America, Africa, and Asia are less represented, despite the relative economic importance of pasture-based systems particularly in Latin American where countries such as Brazil and Argentina have large ruminant based sectors that contribute substantially to national exports and land-use change (Fleck, 2024). This pattern supports the findings of previous regional reviews that reported modelling research is focused in regions with better institutional capacity and data infrastructures (Reidsma et al., 2018; van der Linden et al., 2020). These differences in regional coverage may affect the transferability of model results across production systems and institutional environments. For example, model outputs from European agricultural production systems may not be generalised to emerging economies where production structures, data environments, and institutional contexts differ.

Sectoral coverage follows a similar pattern. Conventional pasture, dairy, and beef systems account for the majority of studies, while mixed crop-livestock and sheep systems are less frequently examined.

5.2. Methodological Choices

5.2.1. Application Across Modelling Approaches

Modelling approaches reviewed in pasture-based agriculture show a clear methodological hierarchy. Simulation and hybrid bioeconomic models show the largest share and are more frequently applied at the farm level. These models integrate biological processes and management decisions under environmental constraints (Taylor et al., 2020; Vogeler et al., 2017).

In Table 2, farm-level simulation and microsimulation are grouped together conceptually based on their unit-level modelling characteristics. These models both operate at the farm or household level, integrate heterogeneity, and also evaluate counterfactual scenarios. In the descriptive statistics (Figure 8), however, they are reported separately to reflect how the two distinct streams of literature typically classify them. Although they originate in different research traditions, they share several structural features. Agricultural simulation has traditionally emphasised production and biophysical processes (Jones et al., 2017), whereas microsimulation has focused on distributional and policy outcomes (Mertens et al., 2022). Recognising their shared foundations allows for a more integrated perspective, where advances in one tradition such as behavioural specification and validation methods

in microsimulation can inform the other, and vice versa. This framing is important for broadening the scope of microsimulation applications in agriculture and situates farm-level models more firmly within the microsimulation research community.

Optimisation models focus on resource allocation and profitability analysis, and framed sustainability as an efficiency problem under dynamic conditions (*Addis et al., 2021; Moraes et al., 2012*). In comparison, approaches designed to capture distributional effects and economy-wide outcomes, such as microsimulation, CGE, and input-output models, appear less frequent. This limits the capacity of existing modelling frameworks to assess policy trade-offs and sector-wide or economy-wide effects within the same framework, a gap repeatedly identified in literature (*Jin, 2023; O'Donoghue, 2017*).

Another limitation concerns behavioural assumptions embedded in several modelling approaches. Optimisation models often assume fully rational decision-making and perfect foresight, assumption that may not reflect the bounded rationality and risk aversion observed in farm-level behaviour (*Hayden et al., 2021*). Input-output models, rely on linear production relationships that fail to capture substitution or technological change over time (*Breure et al., 2024*). Deterministic models also tend to neglect uncertainty and stochastic variation, limiting their ability to represent risk and resilience, inherent features of pasture-based systems (*Bewley et al., 2010*). While these assumptions simplify modelling structure, they may abstract from behavioural diversity and technological change over time. Incorporating behavioural heterogeneity, non-linearity therefore represents an important area for future modelling development, where microsimulation and hybrid approaches may offer significant advances.

Across approaches reviewed, environmental outcomes received greater attention than economic indicators. Simulation and hybrid studies allocate a larger share of applications to environmental impacts than to economic indicators. This imbalance reflects increasing policy pressures to reduce ruminant agriculture's environmental footprint (*Halpern et al., 2022*). It also reveals a methodological bias toward environmental assessment, at the expense of integrated economic-environmental trade-offs (*Breure et al., 2024*). For a sector increasingly concerned with supporting sustainability transitions, this imbalance constrains policy relevance, especially where micro-level behavioural heterogeneity and macroeconomic spillovers are important determinants of farmer behaviour and policy outcomes.

5.2.1 Drivers of modelling

The drivers of model development differ across approaches. Simulation and hybrid models are shaped by environmental, economic, and biophysical concerns (*Bolte et al., 2007; Lieffering et al., 2016*). Optimisation studies are motivated by profitability and resource allocation, while econometric and statistical models respond to data availability and market-oriented research questions (*de Oliveira Silva et al., 2017; Hanrahan et al., 2018*).

Microsimulation and agent-based models are applied more frequently to policy and behavioural questions at unit level, enabling analysis of heterogeneous farm responses to incentives or policy (*O'Donoghue, 2017; Ryan et al., 2018*). Input-output and CGE are shaped by economic, environment, and markets considerations at aggregate scale. These patterns across approaches suggests that environmental and economic drivers dominate modelling applications, while social and genetic drivers are less frequently represented in the studies.

5.2.3. Data and Scale of Analysis

Data accessibility conditions methodological choice for evaluation of sustainability in pasture-based agriculture. The reviewed publications show a clear asymmetry across production systems, and approaches. Farm survey and field experiment data are the most frequently reported sources, indicating the empirical origins of many models. Most simulation and hybrid models rely on farm surveys and field experiments, whereas econometric and macro approaches draw from national statistics and published datasets.

Microsimulation and ABM studies use disaggregated farm or household survey data but remain constrained by data availability outside Europe (*Li and O'Donoghue, 2012*). Market and national statistics are underutilised, thus impeding the integration of models with sectoral and macroeconomic contexts. Scale of analysis was concentrated at the farm and regional levels, with partial integration of household, sectoral, or multi-scalar approaches. This gap impedes the ability to link

micro-level behaviour to macro-level sustainability outcomes which is a core strength of microsimulation approaches.

5.2.3. Software and programming

Software choices were skewed to traditional tools and programming languages. This also shows methodological demands for advanced software across published articles. Simulation models and hybrid models used Microsoft Excel and R (*The R Foundation, 2018*) due to accessibility and flexibility. The optimisation models and CGE methods used GAMS in the review, while econometric studies commonly used R, Stata, and SAS to support data-intensive estimations (*Maseko et al., 2024*). On the other hand, system dynamics models employed Vensim and STELLA in their analyses. Microsimulation studies combined the use of Stata, Java, and GIS, reflecting their micro data and spatial focus. These patterns suggest that methodological traditions drive software choice. This comes with implications for reproducibility and integration across modelling domains.

5.2.4. Model behaviour and validation strategy

Deterministic designs account for the largest share of studies, followed by dynamic, static, and stochastic model structure (*Figure 14*). This distribution reflects the suitability of these approaches for representing biological processes and long-term system trajectories (*Stürck et al., 2018*). Stochastic approaches are less common despite the relevance of uncertainty in agricultural production (*Bewley et al., 2010; Kakeu, 2023*). The relative low use of stochastic methods suggests that variability and uncertainty remain insufficiently incorporated in pasture-based sustainability assessments.

Validation strategies show a parallel pattern of emphasis. Scenario or face validation (82%) and comparison with observed data (81%) were the most common approaches. Sensitivity analysis (67%) ranked third, indicating increasing attention on parameter uncertainty, a core principle of robust model design (*Iooss and Saltelli, 2017*). Stochastic approaches, including Monte Carlo analysis, were used more selectively, as illustrated in studies such as *Finneran et al. (2012)* and *Zehetmeier et al. (2014)*. In contrast, benchmarking with other models (45%) and expert validation (1%) were rarely employed, despite evidence of their potential to strengthen robustness and credibility (*Awasthi et al., 2024*). This difference shows methodological tendency toward internal and empirical checks.

5.3. Sustainability, production systems, and policy instruments

5.3.1. Impact assessment

The review shows that environmental and economic impacts have been the analytical focus of model development in the past two decades, while the other sustainability dimensions remain comparatively underexplored. Simulation and hybrid models had a broad coverage but prioritise environmental and economic effects. Partial treatment of social and welfare-related outcomes was observed in the review. Optimization and econometric approaches similarly emphasised environmental, economic, and policy impacts reflecting their area of focus on resource allocation and decision-making. The biophysical models focused on environmental and policy impacts of the system. Microsimulation and ABM models were evenly applied to simulate social and policy dimensions in the ruminant systems reflecting their focus on micro-level household and behavioural dynamics. On the other hand, macro approaches displayed distinctive patterns, with input-output models modelling environment, economy and policy. Emerging modelling techniques such as machine learning in the review, remained focused on environmental and technological dimensions. Although environmental and economic impacts are the focus of pasture-based models, some dimensions such as biodiversity, ecosystem services, and animal welfare remain rarely investigated. This shows a gap between the breadth of sustainability goals in agricultural policy and the domains currently prioritised in modelling studies.

5.3.2. Economic and environmental indicators

The disaggregated sustainability indicators broken down in *Figure 17*, highlights the environmental focus of modelling studies over the last two decades. This emphasis is reflected in the strong attention given to land and nutrient use, agrochemical use, and nitrogen inputs. Soil and water quality are more

prominent in the literature than biodiversity or carbon sequestration, suggesting that local biophysical processes are prioritised over broader ecosystem services.

The review also shows that modelling of economic themes was skewed towards productivity, costs, and profitability. This shows a farm-level efficiency outlook within the literature, with limited studies of macroeconomic levels such as trade or GDP contribution and fiscal effects. This shows that the literature remains focused at farm-scale assessments of technical efficiency and environmental pressure. Aside from this, sectoral spillovers, biodiversity outcomes, and sustainability trade-offs received less attention in literature. The finding is in line with previous reviews which stated that agricultural modelling is typically focused on measurable biophysical and economic outputs and less on social and ecosystem dimensions (Reidsma et al., 2018; van der Linden et al., 2020).

Organic, and other alternative low-input systems were rarely studied. By contrast conventional dairy and beef systems were most commonly modelled reflecting both data availability and their economic importance. The limited coverage of agroecological approaches, in particular organic production systems is problematic in light of European policy commitments to organic transitions and agroecological farming. The EU Farm to Fork Strategy and the Biodiversity Strategy has set an EU target of 25% of agricultural land under organic farming by 2030 and Member States, have committed to expanding organic and agroecological farming under their CAP Strategic Plans. However, without comparative analysis across systems, it becomes difficult to assess the efficiency, trade-offs, and viability of transition pathways. This divergence suggests that modelling coverage does not fully align with current policy priorities. These shortcomings in system coverage are closely connected to how policy and regulations are incorporated in modelling studies.

5.3.3. Policy and Regulations

Policy instruments assessed in this review were more focused on regulations and subsidies. Taxes, levies, and other instruments were less common, despite their role in economic theory. This difference restricts exploration of alternative instruments that may deliver environmental objectives more efficiently. The findings of the results also show that policy simulation in pasture-based systems were frequent in conventional systems, similarly environmental regulation. In organic systems the frequency was only 7% of the studies. However, subsidies, taxes/or levies, and other policy instruments were similarly rarely studied. This shows structural realities, where conventional systems dominate agricultural output, provide more robust data for modelling, and remain the main target of policy interventions (Azarbad, 2022). On the contrary, organic and low-input systems are smaller in scale, more heterogeneous, and are often constrained by limited data availability. This makes them less frequent in quantitative modelling (Rigby and Cáceres, 2001). Institutional priorities, historically are centred on productivity and market stability, reinforcing the focus on mainstream production.

The limited representation of organic and low-input systems in policy-oriented modelling creates a gap. Extending coverage beyond conventional systems is important for evaluating how subsidies, regulations, and taxes affect adoption and environmental performance of alternative systems. Addressing this gap would align economic modelling with the current European sustainability commitments, which prioritise organic and agroecological transitions in ruminant production.

6. Conclusion and Future Research

The study reviewed 173 farm level microsimulation and other modelling studies that examine the economic and environmental outcomes of pasture-based agriculture. The review covered a range of approaches, regions, and production systems in the past two decades. The findings of this review show an increasing trend in publication of models since 2010, pointing to increasing global demand for policy and sustainability data. The published model studies show geographical heterogeneity, with Europe dominating research. Latin America, Africa, and Asia are less represented in the reviewed literature. Conventional dairy and beef systems account for the majority of applications, while organic and low-input systems appear less frequently. Such regional disparity constrains the generalisability of modelling results and reduces policy relevance in emerging economies where pasture-based systems are most extensive.

Farm-level simulation and hybrid bioeconomic models account for the largest share of applications and are primarily implemented at the production-unit scale. Optimisation and econometric approaches are applied to resource allocation and profitability analysis, while microsimulation, input-output, and

computable general equilibrium models are comparatively limited. Most studies operate at a single scale of analysis.

Farm-level simulation and hybrid bioeconomic models account for the largest share of applications mostly at the farm level. Optimisation and econometric models extend to resource allocation and profitability analysis but rarely integrate biophysical processes. Whereas microsimulation models, agent-based models, input-output and CGE remained scarce despite their ability to simulate micro-macro linkages. Most studies operate at a micro scale of analysis. In general, the current literature is focused on environmental performance, with little focus on economic trade-offs or complex inter-sectoral linkages.

The distribution of sustainability indicators varies across domains. Environmental indicators, particularly land use, nutrient use, and greenhouse gas emissions account for the largest shares of reported environmental indicators. Biodiversity, ecosystem services, and animal welfare remain peripheral in literature in the last two decades. Whereas economic indicators focus largely on productivity and farm profitability, with fewer studies addressing trade, income distribution, or macroeconomic contributions. Policy modelling is centred on regulations and subsidies, with limited coverage of market-based instruments such as taxes, and levies. Policy evaluations were more frequently conducted within conventional systems than organic and low-input systems despite their policy relevance in the ongoing agri-environmental transitions.

Farm surveys and field trials are most common data sources. Integration of national statistics, market data, and remote sensing is less frequent. Most published model studies operate at farm or regional scale, with little effort to connect micro-level decisions to macro-level outcomes. Validation strategies in the literature rely mostly on scenario testing and comparison with observed data, while expert validation strategy and cross-model benchmarking appear less often. These patterns reflect a focus on internal consistency and empirical grounding are prioritised in literature, broader methodological robustness is less developed which is a gap.

Microsimulation in our review extends its scope into pasture-based agriculture, showing that many existing farm-level simulation models share features with microsimulation. Recognising this overlap clarifies the analytical relationship between these modelling traditions and also provides a basis for examining micro-macro linkages in sustainability assessment. This reconceptualization is important for advancing sustainability analysis in ruminant agriculture.

The review indicates limited integration between farm level and sectoral modelling frameworks in assessments of economic and environmental sustainability. Most studies remain confined to micro-scale analysis. Closer links between micro level simulation and aggregate modelling approaches would enable farm heterogeneity to be examined alongside sectoral and economy-wide effects. Comparative analysis across production systems is also required since organic and low-input systems remain less modelled despite their policy importance. Additionally, sustainability assessment of pasture-based systems would benefit from more systematic incorporation of biodiversity, ecosystem services, and animal welfare within modelling frameworks. The integration of these dimensions alongside economic outcomes remains methodologically challenging and relatively underdeveloped in the literature. Finally, modelling of policy instruments should be diversified, with greater focus on taxes, levies, and incentive-based instruments that are fundamental in economic theory but mostly absent in the reviewed literature. Addressing these caveats would improve the relevance of models for sustainability transitions in ruminant production systems.

Building upon these gaps in the literature, this review proposes the need for future research to develop frameworks that link farm-level microsimulation models to macroeconomic structures. In particular, constructing a disaggregated input-output or sectoral detailed framework that explicitly represent pasture-based farm sectors would allow micro-level decision-making to be directly connected to wider supply chain, and environmental spillovers. This in our view enable a more complete accounting of both farm-level heterogeneity and economy-wide consequences.

In parallel to that, future research should prioritise the systematic inclusion of organic and low-input systems. While we identified these as underrepresented in literature of models, we emphasise that their current policy relevance in the EU with explicit targets for organic expansion and agroecological transition, makes their omission problematic. Incorporating these systems into both farm-level and integrated economy-wide models is needed if modelling is to inform sustainability transitions and current policy in practice.

The extensions improve the path for advancing microsimulation and related farm level modelling approaches, from reinforcing methodological integration across scales, to ensuring that models adequately reflect the diversity of production systems that are central to contemporary agri-environmental policy.

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Conflict of Interest

No competing interests reported.

Data and code availability

The search strategy, databases used, and inclusion criteria are reported in the article, allowing replication of the review.

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