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Review

Assessment and analysis of yield gaps in pasture-based livestock systems: A review of methods

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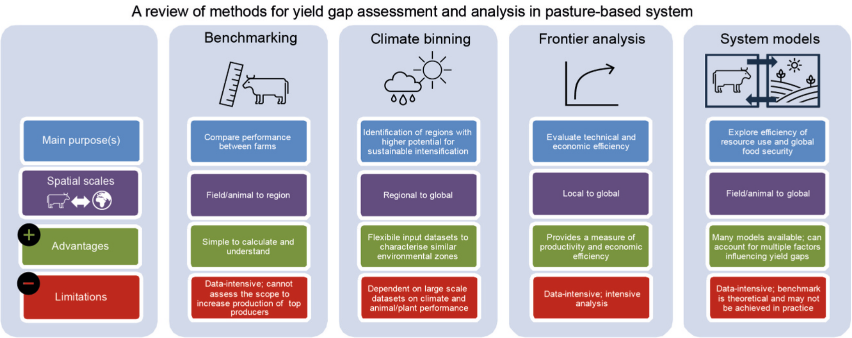
HIGHLIGHTS

- Methods for yield gap analysis have not been reviewed for pasture-based livestock systems.
- Four methods to assess and analyze yield gaps were reviewed.
- Methods need to be selected based on research objectives, spatial scale, data availability and processing capacity.
- Production systems models can be improved by better accounting for grazing strategies and pasture quality.
- Technical insights must be integrated into social, economic, and political frameworks to inform policy decision making.

GRAPHICAL ABSTRACT



A review of methods for yield gap assessment and analysis in pasture-based system

	Benchmarking	Climate binning	Frontier analysis	System models
Main purpose(s)	Compare performance between farms	Identification of regions with higher potential for sustainable intensification	Evaluate technical and economic efficiency	Explore efficiency of resource use and global food security
Spatial scales	Field/animal to region	Regional to global	Local to global	Field/animal to global
+ Advantages	Simple to calculate and understand	Flexibile input datasets to characterise similar environmental zones	Provides a measure of productivity and economic efficiency	Many models available; can account for multiple factors influencing yield gaps
− Limitations	Data-intensive; cannot assess the scope to increase production of top producers	Dependent on large scale datasets on climate and animal/plant performance	Data-intensive; intensive analysis	Data-intensive; benchmark is theoretical and may not be achieved in practice

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ABSTRACT

CONTEXT: Grazing landscapes cover a substantial portion of global agricultural land and are essential for the provision of ecosystem services, food security, and rural livelihoods. The yield gap concept highlights the potential for increased agricultural production through sustainable intensification by quantifying the difference between current yields and maximum achievable yields. Assessing yield gaps is crucial for targeting public and private interventions and investments in regions with the greatest potential for production increases. However,

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Models
Ruminants

methods for assessing yield gaps vary, impacting their ability to identify underlying factors and assess yield risks consistently and accurately, particularly in pasture-based systems where interactions between plants and animals add complexity.

OBJECTIVE: The objectives of this review were to provide an overview of methods used to assess and analyze yield gaps in pasture-based livestock production systems and to discuss how they may aid decision-making processes.

METHODS: Review of literature.

RESULTS AND CONCLUSIONS: Different approaches have been applied for yield gap analysis of pasture-based livestock production systems. For benchmarking, climate binning, frontier methods, and production system models approaches we provide a brief description, examples of applications, data requirements, and advantages and disadvantages. The selection of specific approaches depends on the research questions addressed, spatial scale of the study, data availability and computational processing capacity. Benchmarking approaches are commonly used by farmers to compare the performance of their enterprise to others with similar characteristics. The climate binning approach is applied to larger spatial scales for identifying regions where sustainable intensification technically could be an option. Frontier approaches provide insights on both technical and economic efficiencies. Methods based on production system models may be applied for different purposes, according to the characteristics of the models. In general, mathematical models currently used for yield gap analysis in pasture-based production systems rarely account for the effects of different grazing strategies, plant species proportion, pasture nutritive value and selective grazing by animals.

SIGNIFICANCE: Methods for yield gap assessment and analysis in pasture-based systems can contribute knowledge and technical conditions to increase productivity and resource use efficiency from existing areas rather than expanding to new ones. This provides opportunities to meet the increasing demand for food while conserving land and natural resources. It is necessary to integrate technical insights from yield gap analysis into a broader social, economic, and political framework to support decision making by policy makers and farmers, highlighting the need for future research to improve the current methods.

1. Introduction

Grasslands cover 3.4 billion hectares and account for approximately 70 % of the global agricultural land area (FAOSTAT, 2023). They are responsible for the delivery of numerous ecosystem services, such as carbon sequestration, water purification, nutrient cycling, and erosion control (Bengtsson et al., 2019; Sollenberger et al., 2019; Dubeux et al., 2022). Grasslands are, even indirectly, of critical importance for the provisioning of food worldwide, playing a significant role in global food security (O'Mara, 2012; Fetzel et al., 2017). Ruminants convert grassland biomass into human-edible products, such as meat and milk. On lands that are only suitable for grasslands feed-food competition is avoided (Van Zanten et al., 2018).

Global food consumption is expected to increase by 1.3 % per year over the next decade (OECD-FAO, 2023). More specifically, the global average per capita demand for meat and milk is expected to increase by 2 % and 0.8 % per year, respectively, from 2020/22 to 2032 (OECD-FAO, 2023). To meet this demand, an increase in total livestock production from existing grasslands is generally preferred over increasing the grassland area through land conversion (O'Mara, 2012; Herrero and Thornton, 2013). Increasing production per unit of land area while reducing its environmental impacts is referred to as sustainable intensification. Sustainable intensification may be a way to achieve more sustainable food systems (Tilman et al., 2011), making better use of land and natural resources, while improving farm incomes.

The scope for increasing agricultural production per unit land area or per animal is reflected by the yield gap, which is generally defined as the difference between a potential production level and the actual production level. Potential production levels have been defined in numerous ways (Lobell et al., 2009) and can be assessed at different spatial scales (field, animal, herd, farm, region within a country, country, globe). In cropping systems, the yield gap is often defined as the difference between the potential and actual yield of a crop species in a specific location (Lobell et al., 2009; van Ittersum et al., 2013). The potential yield is the maximum theoretical yield under best management practices, without water and nutrient limitation and biotic stresses (Van Ittersum et al., 2013; Fischer, 2015). The water-limited yield is often used as the maximum theoretical yield in rainfed systems (Van Ittersum et al., 2013), which makes this benchmark relevant to many pasture-based systems. In production systems where access to inputs is limited, use of potential yields may create unrealistic expectations of what is achievable. In these cases, it may be better to use the local maximum attainable yield as a benchmark, which considers the maximum yield achieved locally given the limited resources and technologies available (Tittonell and Giller, 2013). In livestock systems, yield gaps for meat and milk production have been formulated along the same lines as in cropping systems, with potential production and feed-limited production (Van de Ven et al., 2003) or maximum local yields as benchmarks (Mayberry et al., 2017).

Assessment of yield gaps is important to identify regions with the greatest (theoretical) potential to increase production. At a local scale, yield gap assessment can be used by producers to compare their farms with similar businesses and serves as a starting point to identify areas for improvement. Currently, benchmarking services are provided by farm consultants and advisors, with a focus not just on productivity, but also profitability and sustainability. Analysis of yield gaps involves the identification of factors contributing to the gap. Once these factors are identified, investments and interventions can be prioritized (Van Ittersum et al., 2013). Yield gap analysis has contributed to yield gap mitigation in food production systems in various areas of the world (Breman and de Wit, 1983; French and Schulz, 1984; Kropff et al., 1993; Mueller et al., 2012; McLean and Holmes, 2015; van Ittersum et al., 2016; Mayberry et al., 2017).

Methods to assess and analyze yield gaps have been widely reviewed and discussed (Lobell et al., 2009; Van Ittersum et al., 2013; (FAO and DWFI, 2015). These reviews focused on crop production systems, but not on livestock systems or systems with both crops and livestock. Specifically, they did not address pasture-based systems with grazing animals, which are characterized by a direct interaction between plants and animals. In such pasture-based livestock systems, yield gap analysis is more complex, since the gaps can be attributable to either or both pasture and animal performance-associated factors and their interactions (Van der Linden et al., 2018).

Several methods have been proposed to assess and analyze yield gaps in pasture-based systems, including the benchmarking method (Mayberry et al., 2017; González-Quintero et al., 2022), the climate binning method (Monteiro et al., 2020), frontier methods (Henderson et al., 2016; Mayberry et al., 2017), and production system models (Mayberry et al., 2018; Santos et al., 2024). These methods differ in how the potential or attainable production levels are calculated, in the data inputs needed and in the software requirements. They assess yield gaps at different spatial and temporal scales and for different livestock species, animal life stages, farm types and agro-ecological conditions. Each method may be appropriate to meet specific research objectives given the conditions and scales the method was developed for.

The objectives of this study are to (i) provide an overview of methods used to assess and analyze yield gaps in pasture-based livestock production systems and (ii) provide criteria for selection of methods to meet research objectives. We first review the methods used for assessing yield gaps in pasture-based systems. Thereafter, yield gap estimates from different methods are reviewed. Based on the characteristics of each method, we then discuss the major challenges in assessing and analyzing yield gaps, some criteria to guide the selection of optimal methods to meet study objectives, and the application of methods in decision-making processes. Finally, we offer suggestions for future research on yield gap analysis in pasture-based livestock production systems.

2. Methods for assessing and analyzing yield gaps

2.1. Benchmarking method

2.1.1. Description of method

The benchmarking method is an empirical method where the yield gap is calculated as the difference between the average yield of the top percentiles achieved, the benchmark, with that of average yields (Mayberry et al., 2017). This is also referred to as the empirical yield gap. The benchmark used in studies is usually the average of the top 10 to 25 % of productivity levels.

2.1.2. Examples of applications in pasture-based systems

Mayberry et al. (2017) employed the benchmarking method for smallholder dairy production in Ethiopia and India, using the top 10 % of farms as the benchmark. Similarly, González-Quintero et al. (2022) assessed the yield gap of milk and meat production in Colombian cattle systems in different agro-ecological zones, also considering the upper 10 % of farms as the benchmark. The same percentage was used to assess yield gaps in Kenyan smallholder dairy systems (Graham et al., 2024). Stocco et al. (2020) used the average of the top 10 % of municipalities in a region as a benchmark to calculate yield gaps for beef production per region in Brazil. Next to the top 10 % of farms, milk production levels at research stations were used as an empirical benchmark to assess yield gaps in dairy production in India (Kemboi et al., 2021). The maximum average milk yield per parity group was used as a benchmark in a study on *B. taurus* cows from small and medium scale farms in Western and Central Kenya (Bateki et al., 2021).

The benchmarking method is commonly used by agricultural companies as a means for farmers to compare the performance of their enterprise to others with similar characteristics, recognizing that yield is not the only metric driving on-farm decisions. Those comparisons often include a wide range of business productivity, profitability and sustainability metrics reported for different types of enterprises based on herd size, market or agro-ecological zone, with a liberal estimate of attainable performance (e.g., top 25 % of businesses, McLean et al., 2023; McCosker et al., 2020). Those figures often have commercial value, with producers and agricultural companies willing to pay for information acquired from entities offering different services based on systematization of data (e.g. Global Agribenchmark Network – http://www.agribenchmark.org/home.html, and International Farm Comparison Network – https://ifcndairy.org/).

2.1.3. Data requirements and software availability

The benchmarking method requires actual data on livestock yields (e.g., volume or weight of milk, live weight, or weight of meat or wool produced per unit area or per animal). While there is no specified minimum data set to include in a benchmarking analysis, larger datasets will provide more meaningful comparisons. No specific software is required to calculate yield gaps using the benchmarking method.

2.1.4. Advantages of the method

The main advantage of this method for calculating yield gaps is its simplicity. If required, other production metrics, such as reproductive performance (McCosker et al., 2020) generally can be derived. The method is also easily understood by a variety of stakeholders, ranging from producers to policy makers. As actual yields are used, the benchmarking method accounts for socio-economic and biophysical factors influencing livestock production.

2.1.5. Limitations of the method

A main limitation is that the top 10–25 % yields are set as the benchmark, and hence the scope for increasing the yields and productivity of top producers cannot be assessed. Furthermore, this output-oriented method does not account for the input use, unless applied to groups of similar animals or farms. In a study on regional yield gaps, the top 10 % of municipalities in Brazilian regions were often situated in the best agricultural areas within a region. Therefore, yield gaps were corrected by a weighting factor for land aptitude for pasture (Stocco et al., 2020). Depending on the scale of the analysis, obtaining suitable datasets with sufficient observations of yields can be an issue. Collection of data at the field, animal and farm scale is time consuming and expensive, and datasets cannot always be combined if differences exist in variables reported, year, or the calculation method, as this all influences the value of the benchmark yield.

2.2. Climate binning method

2.2.1. Description of method

The climate binning method categorizes geographic regions or areas having similar climatic characteristics. The range of either measured or simulated yields is assumed to represent the range of what is currently achievable under a given set of climatic conditions and production practices. Areas that may be geographically disparate are grouped with their climatic peers using bins defined by climate drivers of crop growth (e.g. temperature and precipitation). This leveling of the climatic playing field enables meaningful comparisons of animal production after controlling for basic climate differences. Thus, intra-bin differences in production per unit area and time are due to factors other than the climate binning variables, notably management.

This method has been used for both annual crops (Mueller et al., 2012) and pasture-based systems (Monteiro et al., 2020) at a global scale. For pasture-based systems, Monteiro et al. (2020) considered three inputs for their yield gap analysis (raster file format): climate variables (annual precipitation and growing degree-days); fraction of pasture within the pixel (later converted to pasture area); and ruminant outputs (i.e., production of milk and meat). First, a climate space was generated based on annual precipitation and growing degree-days, resulting in 100 bins across the globe of equal pasture area. The raster file containing the climate space (i.e., the 100 bins) was overlapped with the raster file containing ruminant production data. Next, the smallest-area grid cells (for a total of 5 % of the bin area) were discarded to remove potential outliers from the yield dataset. An attainable yield was then defined as the area-weighted 95th percentile observed yield within a climate bin. For each bin, production data were sorted from the lowest to the highest levels, and then the yield gap was calculated by the difference between the attainable and actual yield. This was repeated for each bin, with total global attainable and actual production calculated as the sum across all bins for each of the 100 bins. More details and a full description of the method used for pasture-based systems at global scale can be found in Monteiro et al. (2020).

2.2.2. Examples of applications in pasture-based livestock systems

The utilization of the climate binning method in yield gap analysis remains relatively underexplored within the existing literature, with a notable absence of research addressing the animal component of agricultural systems. The closest approximation to this endeavor can be found in Monteiro et al. (2020), who aimed to quantify the yield gap in pasture production on a global scale using a database partially provided by Herrero et al. (2013), merged with a global classification of pasturelands generated by Ramankutty et al. (2008). Herrero's dataset contains gridded data on milk and meat production from cattle, goats and sheep. The animals were considered mature (i.e., adults capable of reproduction) and healthy. The dataset has a global coverage with around 9-km spatial resolution (pixel size) at the equator. Due to the large diversity in livestock systems around the world (e.g., animal species and purpose, animal and pasture management), Monteiro et al. (2020) converted the animal productivity of each grid-cell to protein productivity using nutritional conversion factors (available at www.fdc.nal.usda.gov). Hence, the authors generated an explicit assessment of yield gaps of pasture-based ruminant production systems.

2.2.3. Data requirements for method and software availability

The methodology is largely dependent on global scale datasets of climate variables (e.g., air temperature and precipitation) and target variables (e.g., milk and meat production). Currently, there are many gridded global scale datasets with air temperature and precipitation freely available (e.g., NASA/POWER, AgERA5, WorldClim and CRU). They are usually available in gridded format (NetCDF or GeoTiff files), which allows relatively easy manipulation and extraction of the data. Data processing is often done through geographic information systems (GIS) or via scripts written in widely known programming languages like Python and R. The milk and meat production per area dataset was estimated around the year 2000 (Herrero et al., 2013) using previous livestock classification systems (Kruska et al., 2003) and agroecological characteristics to define zones with high probability of a given type of livestock production system (e.g., dairy cattle). Then, due to lack of more recent data or maps, Herrero et al. (2013) used dynamic herd models parameterized for each agroecological region to generate the final dataset of ruminant production at ~9-km resolution for the whole globe.

2.2.4. Advantages of the method

The climate binning method is suitable for application at the broadest possible scale. This suitability arises from the spatial stratification strategy inherent to climate bins, which necessitates a substantial range in spatial variability of the components under analysis (Monteiro et al., 2020). The advantages of the climate binning technique are that it facilitates targeted research and interventions, enables the transfer of successful practices between regions with similar climates, and possibly supports the adoption of similar management practices.

In addition, the method is quite flexible for adaptation to regional characteristics or for incorporating other variables such as climate characteristics in addition to temperature and precipitation, soil organic carbon and soil texture, which can provide finer insight in the potential for intensifying production systems. For example, Monteiro et al. (2020) refined their yield gap analysis of pasture-based systems at global scale using the livestock categories from the FAO (Arid, Humid and Temperate-Tropical highlands), finding that most space for intensifying pasture systems was in arid zones. The authors investigated the contribution of different ruminant species (cattle, goats and sheep) and types of outputs (milk and meat) on the total yield gap from animal production in grazed pasture systems. Since the database was built based on different datasets of animal species and their outputs separately, this allowed identification of which combination (animal species versus type of output) contributed more significantly to the total gap.

2.2.5. Disadvantages and limitations of the method

This method represents the average conditions regarding climatic characteristics for those regions where the method is applied. Since this is a method applied at global scale, one of the limiting factors is the availability of global datasets for performing this analysis for other periods. Typically, the target dataset (in this case, ruminant production) is a snapshot of what is ongoing in a particular year, under average climatic conditions. Another disadvantage of global scale methods such as climate binning is that information regarding level of inputs (e.g., fertilizer, seeds, irrigation, veterinary care, concentrate supplementation) is not explicitly accounted for, basically due to the lack of those data at global scale. Just like the benchmarking method, an underlying assumption of the climate binning method is that all farmers can increase their level of inputs to the same level of top producers, and potentially also achieve the same yield levels.

2.3. Frontier methods

2.3.1. Description of method

Frontier analysis contributes to our understanding of yield gaps by offering insights on both technical and allocative efficiency. Common frontier approaches to yield gap analyses emphasize technical efficiency, i.e., the ability to obtain maximum output from a set of inputs given available technologies (Fischer, 2015; Lobell et al., 2009; van Dijk et al., 2017; van Ittersum et al., 2013; Silva et al., 2017). As such, yield gaps are often interpreted as measures of farm technical inefficiency (Antle and Ray, 2020). From a practical perspective, the allocative efficiency is often more relevant. The allocative efficiency reflects the ability to use inputs in optimal portions, given their respective prices and available technologies (Beattie et al., 2009; Beddow et al., 2014; Coelli et al., 2005; Farrell, 1957; Silva et al., 2017, 2019; van Dijk et al., 2017). The combination of technical efficiency and allocative efficiency provides a measure of economic efficiency (Beattie et al., 2009; Coelli et al., 2005; Farrell, 1957; Fried et al., 2008). Whilst agronomic and economic approaches each have their merits, combining them benefits yield gap analysis and increases its usefulness in supporting public and private decision making (Beddow et al., 2014; Tittonell and Giller, 2013; van Dijk et al., 2017).

Computing the technical and allocative efficiency measures involves estimating the unknown frontier, which can be input- or output-oriented. An input-oriented technical inefficiency, given the available technologies, reflects an excessive input use for a certain output level. The allocative inefficiency reflects that these inputs are being used in inappropriate proportions, given relative prices and available technologies. Conversely, an output-oriented technical inefficiency indicates that for a certain level of input, given available technology, more output could be produced (Beattie et al., 2009; Beddow et al., 2014; Coelli et al., 2005; Van Dijk et al., 2017; Silva et al., 2017; Farrell, 1957; Fried et al., 2008; Gomes and Baptista, 2004).

Regardless of how the productivity is measured, it is inevitably tied to measuring production relationships, such as transformation functions and cost functions (Miti et al., 2024; Ray et al., 2022). Frontiers can be estimated using many different approaches, but the two principal methods used are data envelopment analysis and stochastic frontier analysis. The former involves mathematical methods to construct a non-parametric frontier over data. The latter centers on statistical and econometric methods to estimate the parameters of a given functional form specified (Coelli et al., 2005; Conceição, 2004; Fried et al., 2008; Gomes and Baptista, 2004; Lovell and Schmidt, 1988; Miti et al., 2024; Ray, 2022; Ray et al., 2022; Silva et al., 2017).

Data envelopment analysis, introduced in the 1970s (Charnes et al., 1978), has the advantage that it can be implemented without knowledge of the algebraic form of the relationship between inputs and outputs, which makes it computationally simple. However, the estimated data envelopment frontier can be biased if the data used are associated with statistical noise (Coelli et al., 2005; Fried et al., 2008; Gomes and Baptista, 2004; Lovell and Schmidt, 1988; Ray, 2022). If statistical noise exists, defining the relative influence of other factors that are not explicitly included in the model is not possible (Đokić et al., 2022). In contrast, early studies with the stochastic frontier analysis highlighted the importance of random factors on the output variability (Aigner et al., 1977; Meeusen and van den Broeck, 1977). The incorporation of the statistical error allows this approach to deal with statistical noise arising from measurement errors, data anomalies and uncertainties, and the incomplete specification of functions (Henderson et al., 2016).

2.3.2. *Examples of applications in pasture-based systems*

Henderson et al. (2016) applied stochastic frontier analysis to calculate yield gaps in livestock and crop production in six African countries. Similarly, Mayberry et al. (2017) applied frontier analysis to quantify yield gaps for dairy production in Ethiopia and India. While data envelopment analysis has not been adopted in pasture-based systems, this method has been used to assess the efficiency of production of dairy systems in Greece (Theodoridis and Psychoudakis, 2008) and in integrated crop-livestock systems in Malawi (Berri et al., 2017). Beyond the livestock sector, this method has also been used to assess the yield gap in rice production in Tanzania (Van Dijk et al., 2017) and The Philipines (Silva et al., 2017) and in oil palm in Indonesia (Soliman et al., 2016).

2.3.3. *Data requirements and software availability*

Data required for frontier analysis include the quantity of inputs and outputs (land, labor, machinery, fertilizers usage, etc.), input prices and total expenditures. While R packages for frontier analysis are available (e.g., Coelli and Henningsen, 2014), the method can also be implemented in other software.

2.3.4. *Advantages and disadvantages of the method*

An advantage of frontier analysis is that total economic efficiency is obtained by combining technical efficiency and allocative efficiency (Beattie et al., 2009; Coelli et al., 2005; Farrell, 1957; Fried et al., 2008). Contrary to the benchmarking method and climate binning method, frontier analysis accounts for the use of inputs. On the downside, the method requires both input and output data. For analysis of technical efficiency based on output (e.g. production function), data acquisition generally centers on the quantity of inputs and outputs. On the other hand, for estimation of economic efficiency, data must include input prices and total expenditures and the output quantity. The applied stochastic frontier analysis method requires the specification of a functional form for the relationship between output and inputs, making this method less flexible and more computationally demanding than the data envelopment analysis (Coelli et al., 2005; Conceição, 2004; Fried et al., 2008; Henderson et al., 2016; Lovell and Schmidt, 1988).

2.4. *Production system models*

2.4.1. *Pasture carrying capacity models*

2.4.1.1. Description of the method. In pasture-based production systems, productivity (kg of animal product/ha) depends on pasture primary production (kg herbage dry mass/ha), grazing efficiency (the proportion of herbage dry mass produced ingested by the grazing animals), and the conversion efficiency (the ratio between consumed herbage dry mass and animal product). Although it does not consider the conversion efficiency, pasture carrying capacity has been used as a proxy of productivity in pasture-based systems, taking into account information on both pasture primary productivity and grazing efficiency.

The pasture carrying capacity is defined as “the maximum stocking rate that will achieve a target level of animal performance, in a specified grazing system that can be applied over a defined time without deterioration of the grazing land” (Allen et al., 2011). For yield gap analysis, the stocking rate should be expressed as animal units (AU) or forage intake units per unit of land area. These standard units equate grazing animals from different species, breeds, live weights, and physiological states in terms of forage demand (Allen et al., 2011). This allows estimation of yield gaps based on pasture carrying capacity while taking animal characteristics into account.

Pasture production can be calculated by either mechanistic or empirical models. Mechanistic, dynamic models simulate the effects of various management practices on pasture production as well as calculate pasture growth and nutritive value based on actual soil, plant, and weather conditions (Romera et al., 2010; Andrade et al., 2016). Santos et al. (2024) used the CROPGRO Perennial Forage Model to estimate pasture primary production for a yield gap analysis of pasture-based beef cattle production in Brazil. This mechanistic model allows incorporating different parameters of the climate, soil, plant genotype, agronomic practices, and pasture management (dos Santos et al., 2022).

Empirical models are typically generated by statistical methods, such as regression analysis between pasture productivity and one or more variables such as temperature, radiation, water availability, nutrients, and vegetation indices derived from remote sensing images (Numata et al., 2008; Andrade et al., 2019; Bayma-Silva et al., 2016; Ara et al., 2021; Cisneros et al., 2020). Arantes et al. (2018) estimated pasture primary production with remote sensing data to conduct yield gap analysis of pasture-based livestock production systems in Brazil. Remote sensing enables large scale pasture production monitoring with high temporal resolution.

Besides pasture production, pasture carrying capacity models assess feed demand by livestock. Two feed demand approaches are identified, one based on mean daily dry mass consumption of animals (Arantes et al., 2018), and another based on a cumulative forage deficit method (Santos et al., 2024). To calculate the mean daily dry mass consumption per unit area, the annual pasture primary productivity is divided by feed demand per animal unit (Arantes et al., 2018; Piiponen et al., 2022), assuming that all feed will be supplied by the pasture and a maximum grazing efficiency is achieved. Often, seasonal and interannual variation impair maximum utilization of forage produced in grazing systems because feed requirements must be met year-round and part of the forage surplus senesces and decays before being conserved for the next season (Fetzel et al., 2017). This limitation is overcome by the cumulative forage deficit method, which accounts for primary pasture productivity variations and allows the estimate of several metrics, (i) the maximum stocking rate, that expresses the productive potential, which may be achieved in systems characterized by a variable stocking rate, allowing a better use of the forage produced throughout the year, and (ii) the critical stocking rate, that expresses the productive potential and carrying capacity of pastures managed with a fixed stocking rate, in which the stocking rate is limited or defined by the seasonal and interannual variations of herbage production (Santos et al., 2024).

2.4.1.2. Examples of application in pasture-based livestock systems. Pasture carrying capacity models were used to estimate yield gaps in pasture-based livestock production systems in Brazil by Arantes et al. (2018) and Santos et al. (2024). Both studies were conducted on a regional scale and aimed to support public decision making in Brazil related to identification of areas suitable for intensification of pasture production. Arantes et al. (2018) applied empirical models based on satellite images to estimate pasture primary productivity and a daily dry matter consumption approach to estimate pasture carrying capacity, while Santos et al. (2024) combined a mechanistic model to estimate pasture primary productivity with a cumulative forage deficit method to estimate pasture carrying capacity, confirming the flexibility of these methods to combine different models. Yield gaps were expressed in animal units per hectare in both studies.

2.4.1.3. Data requirements for the method and software availability. Data requirements depend on the model used to estimate pasture primary productivity and feed demand. For mechanistic models, data on weather conditions, soils, plant genotype, and agronomic and pasture management practices will generally be required. Mechanistic models may be run using different software and programming languages (e.g., R, Python, Fortran). Besides that, some of these models were incorporated into modular simulation platforms allowing people with no specific programing skills to run simulations more easily. For example, in the Agricultural Production Systems Simulator (APSIM) there is the APSIM-Tropical Pasture model, and in the Decision Support System for Agrotechnology Transfer (DSSAT) there is the CROPGRO Perennial Forage Model. Empirical models used to estimate pasture primary productivity generally require weather data (i.e. temperature, radiation, water availability, nutrients) and/or vegetation indices derived from remote sensing images. No specific software is required for these models.

2.4.1.4. Advantages of the method. The pasture carrying capacity models are useful for policy makers concerned with questions about land use and food production at regional and global scale. These models have been designed to allow empirical estimates of pasture carrying capacity with a lower input demand compared to the models based on concepts of production ecology. However, using less input data impairs the simulation of physiological feedback between the animal and plant components of the system, particularly for undergrazing and overgrazing conditions.

Estimating pasture production by mechanistic models provides flexibility to adjust the input parameters and estimate pasture growth and nutritive value based on actual soil, plant, and meteorological conditions. Mechanistic models may also provide simulation capabilities to evaluate the potential outcomes of different management scenarios. On the other hand, empirical models often require less data and are simpler and easier to develop and use than mechanistic models.

2.4.1.5. Disadvantages and limitations of the method. Pasture carrying capacity models have the disadvantage that their resulting yield gaps are expressed as stocking rates (animal units/ha) and not as animal productivity, which explains only part of the productivity observed in pasture-based systems (Martha Jr et al., 2024). The limitations of using mechanistic, dynamic models for estimating pasture growth are their complexity, as model users need a thorough comprehension of the underlying mechanisms that control crop growth in relation to grazing management. Additionally, data requirements for calibration and evaluation of mechanistic models are large. Also, these models may not always be able to estimate pasture development effectively (Woodward and Rollo, 2002; Romera et al., 2010; Bosi et al., 2020). Empirical models for estimating pasture growth have limited comprehension of underlying processes. Empirical methods have limited applicability, as they are based on statistical relations that may not apply to different conditions than the model was developed for. Finally, empirical models may be difficult to develop and test due to a lack of accessible data for pasture systems (Woodward and Rollo, 2002; Bella et al., 2004; Murphy et al., 2021).

2.4.2. Models based on concepts of production ecology

2.4.2.1. Description of method. Mechanistic, dynamic models based on concepts of production ecology describe the biophysical processes in animals and in crops and pastures over time, and at the field, animal, or herd level. The processes included in the models, such as photosynthesis by crops and feed digestion by animals, are based on universal biophysical laws. A hierarchy in growth factors is used for both crop and livestock production (Van de Ven et al., 2003). In crops and pastures, the biophysical growth factors are the genotype (i.e. of a species or crop cultivar within a species), climate, water availability, nutrient availability, pests, and diseases (Van Ittersum and Rabbinge, 1997). Mechanistic crop models based on concepts of production ecology usually simulate the interactions between the genotype, climate, water availability, and sometimes nutrients such as nitrogen are included. Effects of pests and diseases are generally excluded, because outbreaks are difficult to predict. In livestock, the biophysical growth factors are the genotype (i.e. of a species or breed within a species), climate, feed quality and availability, diseases, and stress (Van de Ven et al., 2003; Van der Linden et al., 2015). Mechanistic livestock models based on concepts of production ecology generally simulate the interaction between genotype, feed quality and feed quantity over the lifetime of an animal, but the climate can also be considered via direct impacts on the animal (e.g., heat stress) or through impacts on the feed base (e.g., changes in feed quality and availability). Livestock yield gaps quantified using this approach are calculated as the difference between potential production (defined by genotype and climate only) and the actual production (Van de Ven et al., 2003). These models can also be used to estimate the yield gap based on future climates (Van der Linden et al., 2016).

2.4.2.2. Examples of applications in pasture-based livestock systems. Many different mechanistic, dynamic models are to at least some extent based on the described concepts of production ecology and can be used to simulate livestock production and yield gaps in diverse production systems. These models vary in their complexity from simple herd dynamic models (e.g., DynMod; Lessnoff, 2008) to whole-farm models that explicitly consider soils and plant growth as well as livestock (e.g., FARMSIM; Tittonell and Giller, 2013), and may also extend to economic analyses (e.g., CLEM; Holzworth et al., 2018). While specific examples are described below, most mechanistic, dynamic models of livestock production systems could be used in similar ways with no or relatively minor adjustments. Some examples of such models are found in Bateki et al. (2019).

The bio-economic optimization model FarmDESIGN was used to assess attainable production in 6 dairy farm types in Mexico. Yield gaps were calculated as the difference between attainable production and actual production on reference farms. For each farm type, yield gaps were split in parts related to suboptimal herd management and livestock densities, suboptimal proportions of cultivated crop areas and suboptimal crop productivity (Cortez-Arriola et al., 2014).

The Livestock Simulator (LIVSIM) is a sub-model of FARMSIM, a model simulating interactions among the crop, livestock, manure, and soil components of mixed smallholder farms in Africa (Rufino et al., 2009; De Ridder et al., 2015). In LIVSIM, cattle can be fed napiergrass (*Cenchrus purpureum* syn. *Pennisetum purpureum*) (cut-and-carry) and crop residues produced on-farm. An estimate of grass intake from communal grazing lands can be used as an input for the model, but grass growth on communal grazing lands is not affected by the cattle and vice versa. The biophysical factor climate is not included in LIVSIM, but the weather data are used to simulate crop production on-farm. LIVSIM was later modified to simulate small ruminant production, particularly West African dwarf goats in Nigeria (Amole et al., 2017). Although the model, explicitly developed according to concepts of production ecology, can be used to calculate yield gaps, no publications exist wherein the model has been used for that application.

The Integrated Assessment Tool (IAT) has been used to calculate yield gaps for meat and milk production in smallholder systems with cattle and goats across Ethiopia, India, and Indonesia (Mayberry et al., 2017; Mayberry et al., 2018; McDonald et al., 2019). In these studies, the authors simulated grazing and cut-and-carry production in smallholder systems under current management and under interventions, including changes to herd size, supplementation, and genetic improvement. In a similar approach, Ash et al. (2015) used the Northern Australian Beef Systems Analyser (NABSA) to estimate potential productivity improvements for a range of extensive beef systems in northern Australia. A feature of these analyses is that the model calculates gaps in both productivity and financial performance of the livestock enterprise. Both the IAT and NABSA model have been replaced by the Crop Livestock Enterprise Model (CLEM) within the APSIM NG framework (Holzworth et al., 2018).

The Livestock simulator for Generic analysis of Animal Production Systems (LiGAPS) is available in versions for beef cattle and dairy cattle (LiGAPS-Beef and LiGAPS-Dairy). The model simulates cattle growth and milk production daily based on interactions between genotype, climate, feed quality, and feed quantity (Van der Linden et al., 2019a, 2021). The model versions have been evaluated for diverse agro-ecological conditions with experimental datasets from the Netherlands, Uruguay, Australia, and South Africa (Van der Linden et al., 2019b; Van der Linden et al., 2021; Magona et al., 2023). Yield gaps have been identified for beef cattle in pasture-based systems in France (Van der Linden et al., 2018) and for dairy cattle in the Netherlands (Van der Linden et al., 2021). Models can also be combined to capture whole-system impacts. For the assessment of yield gaps in pasture-based beef production systems in France, the model LiGAPS-Beef was combined with a water-limited version of the mechanistic grass growth model Lintul Grass (LINGRA, Schapendonk et al., 1998) to include the interaction between perennial ryegrass (*Lolium perenne*) and grazing beef cattle (Van der Linden et al., 2018). This integration also allowed assessment of climate change scenarios and stocking rate on beef production per hectare under continuous stocking (Van der Linden et al., 2016).

2.4.2.3. Data requirements for method and software availability. The choice of model is generally driven by the research question, characteristics of the system that is being analyzed, and data availability. Model inputs are parameters related to the livestock breed or crop species or cultivar, management of both pastures (e.g., grazing or cutting frequency, fertilization) and livestock (e.g., buying and selling rules, mating management), inputs (e.g., quality and volume of purchased feed), and long-term weather data for specific locations. Weather data are available for many years and for many geographical locations in the Global Yield Gap Atlas (www.yieldgap.org). Data on livestock productivity is also required to calibrate models and to evaluate model outputs. Model source codes and other software are generally available online or after contacting the developers.

2.4.2.4. Advantages of the method. An advantage of the mechanistic nature of the models based on concepts of production ecology is they could be used outside the range of conditions for which the model was initially calibrated. In addition, yield gaps obtained with these models have a stable biophysical benchmark, which is disentangled from the more variable economic, social, and cultural factors. The hierarchy in growth factors in the models allows segregation of yield gaps into components related to the limiting factors (water and nutrients for grass, feed quality and available biomass for livestock). Identification of factors that make up the yield gap allows establishment of management strategies to mitigate yield gaps (Van Ittersum et al., 2013).

2.4.2.5. Disadvantages and limitations of the method. A disadvantage of using mechanistic models based on concepts of production ecology is that data requirements are relatively high in comparison with other methods. Accurate parameterization of the models requires a detailed understanding of the target livestock system. Longitudinal data for pasture nutritive value are not available in most grazing systems, which hampers the accuracy of model estimates (Magona et al., 2023). Although previously referred to as an advantage, the theoretical, biophysical benchmark for the production level can also be a disadvantage, because economic, social, and cultural constraints hardly play a role. This means that yield gaps cannot be fully closed in practice where these constraints are important, and hence the scope to increase production in practice could be overestimated (Tittonell and Giller, 2013).

Another major disadvantage is the learning curve for using models based on concepts of production ecology usually takes a considerable amount of time. Furthermore, the only model used for yield gap analysis that included the direct interaction between grass and animals so far was the combination of the models LiGAPS-Beef and LINGRA. This combined model only simulates continuous stocking on perennial ryegrass swards.

2.5. Yield gap estimates and factors contributing to yield gaps from the different methods reviewed

Comparing yield gap estimates among methods is nearly impossible due to the limited number of publications, the differences in the methods used, the animal species and products considered, and the scale and countries selected in studies (Table 1). Bateki et al. (2021) and Graham et al. (2024) both used the benchmarking method for dairy cows in Kenya and their relative yield gaps partly overlapped. The same held for studies on beef cattle in Brazil, although Stocco et al. (2020) used the benchmarking method and others the pasture carrying capacity models. Relatively large yield gaps were reported in the study using the climate binning approach (Monteiro et al., 2020). The average global yield gap of 80 % suggests a fivefold increase of animal protein production from grazed permanent grasslands (Table 1). Yield gaps of beef production systems in France obtained with models based on production ecology were also large, especially when benchmarked against potential animal and crop production (Table 1). In this study, the yield gaps of cattle (expressed in kg beef per t DM feed) and feed crops (expressed in t DM per ha per year) were multiplied to express yield gaps at the farm scale in kg beef per ha per year. Likewise, yield gaps of up to 92 % were obtained for dairy farms in Mexico where yield gaps of livestock and crops were combined (Cortez-Arriola et al., 2014). Hence, the relative magnitude of yield gaps obtained from models based on production ecology is highly dependent on the selected benchmark and the system components included (only livestock or both livestock and feed crops).

Similarly to the yield gap estimates, comparing the factors contributing to yield gaps is nearly impossible. Factors contributing to yield gaps varied considerably (Table 1), which can be explained by differences among the methods themselves, the objective of the analysis, and the enormous heterogeneity in livestock production systems the methods were applied to. Differences among analytical approaches, methods, and their required input data will result in differences in the factors considered to explain yield gaps. Another explanation for the variation in factors contributing to the yield gap is that the benchmarking method alone cannot identify these factors. This method only assesses the magnitude of the yield gap by calculating the difference between top-producers and average farmers. Therefore, different additional methods were generally applied next to the benchmarking method to identify those factors. For example, Bateki et al. (2021) applied the benchmarking method to assess yield gaps and the fodjan feeding app to identify nutritional factors limiting production. Graham et al. (2024) applied the benchmarking method to assess yield gaps and the GLEAM-*i* tool to identify the contribution of nutritional factors and reproductive management to yield gaps.

The objectives of the analysis may also contribute to differences observed in factors contributing to the yield gaps. Studies based on the climate binning method, for which the main objective is to identify regions with technical potential for productivity increase, explain yield gaps by the factors climate and type of production system and not by factors like grazing strategies, animal nutrition, and pasture management.

Furthermore, heterogeneity in animal production systems contributes to the differences observed in yield gaps and the factors contributing to the yield gaps. In a subsistence farming system, labor and land are generally the primary factors of production, with tools and agricultural/husbandry practices tending to be less advanced as compared with more commercial systems (Martha and Alves, 2018). As livestock production systems gain complexity, they incorporate increasing amounts of modern inputs (improved seeds, genetics, machinery, equipment, fertilizers, pesticides, advanced digital tools and analytics, etc.). Improvements in the production environment are likely to enable commercial farming systems to better cope with weather variations.

Table 1
Overview of yield gap estimates and underlying factors contributing to yield gaps in pasture-based systems. Publications are chronologically ordered per method.

Method	Animal species	Product	Spatial scale	Countries	Units yield gap	Yield gaps (relative to benchmark)	Factors contributing to yield gaps[a]	Reference
Benchmarking method	Cattle, buffalo	Milk	Farm	Ethiopia and India	kg milk per head per lactation	Ethiopia: 53–69 % India: 59–72 %	Livestock nutrition and animal breeds	Mayberry et al. (2017)
	Cattle	Beef	Region	Brazil	animals per hectare	56 % (28–82 %)	Effect of a theoretical gap closure on land use change	Stocco et al. (2020)
	Cattle	Milk	Farm	India	liters of milk per day	90 %	Size shed, farming experience, concentrate price, labor	Kemboi et al. (2021)
	Cattle	Milk	Cow	Kenya	kg of milk per animal per day	47 % in parity 2, 52 % in parity 1 and ≥ 3	Metabolizable energy content of diet	Bateki et al. (2021)
	Cattle	Milk and beef	Farm	Colombia	Milk: kg of fat corrected milk per cow per year Beef: kg of life weight gain per animal unit per year	Milk: 45–50 % Beef: 34–51 %	Infrastructure, machinery and equipment, and feed, reproductive, and pasture management practices	González-Quintero et al. (2022)
	Cattle	Milk	Farm, country	Kenya	kg of milk per cow per year	39–49 %, depending on agro-ecological zone	Feed quality, feed quantity, reproduction	Graham et al. (2024)
	Cattle	Milk	Country	England, Wales	Yield gap is included in a loss gap of the profit margin, which is expressed in £ per head	Relative yield gap is not provided, loss gap is broadly between 50 and 60 % of the profit margin under ideal conditions	Costs veterinary services and medicines, herd replacement costs, costs culled cows[b]	Sucena Afonso et al. (2024)
Climate binning method	Cattle, sheep, goat	Protein in milk and meat	Globe	Countries with grazed-only, permanent grasslands	kg of protein per square kilometer per year	Global average: 80 % Temperate regions: 72 % Arid regions: 85 %	Climate effect and production system groups	Monteiro et al. (2020)
Frontier methods	Cattle, sheep, goat, chicken	Milk, meat and eggs	Farm	Burkina Faso, Ethiopia, Kenya, Senegal, Tanzania and Uganda	potential percentage increases in multiple outputs	28–57 %	Market participation, age and gender of farm household head	Henderson et al. (2016)
	Cattle, buffalo	Milk	Farm	Ethiopia and India	potential percentage increases in multiple outputs	Ethiopia: 32–62 % India: 31–40 %	Livestock nutrition and animal breeds	Mayberry et al. (2017)
Pasture carrying capacity models	Cattle	Beef	Region	Brazil	animal units per hectare	73 % (57 % in North; 75 % in Southeast and South)	Gross primary productivity	Arantes et al. (2018)
	Cattle	Beef	Region	Brazil	animal units per hectare	Potential production: 85–89 % Water-limited production: 76–86 % Nitrogen-limited production: 60–77 %[c]	Water limitation: 21–40 % of potential production Nitrogen limitation: 24–36 % of potential production	Santos et al. (2024)
Production system models based on production ecology	Cattle	Milk	Farm	Mexico	kg of milk per hectare	67 % (41–92 %)	27 % herd management, 34 % crop area proportions, 26 % crop productivity	Cortez-Arriola et al. (2014)
	Cattle	Beef	Field, animal, herd, farm	France	kg edible beef per ha per year	Farm: 85 % (80–88 %) of potential production;47 % (30–56 %) of resource-limited production	Yield gap under potential production: 49 % sub-optimal diet, 36 % water limitation in feed crops[d]	Van der Linden et al. (2018)
	Cattle	Dairy	Animal	The Netherlands	kg fat- and protein-corrected milk per lactation	11 % of potential milk production	Protein deficiency (39 %), body weight gain (36 %), feed intake capacity, (23 %), heat stress (1 %)	Van der Linden et al. (2021)

[a] Since the benchmarking method only assesses the magnitude of yield gaps, studies using the benchmarking method applied additional methods to identify the factors contributing to the yield gaps.

[b] Factors contribute to the loss gap, defined as the percentage profit margin lost compared to ideal scenarios, which includes the yield gap. See Sucena Afonso et al. (2024) for a detailed overview of all factors contributing to the loss gaps.

[c] Yield gaps are based on simulated critical stocking rates.

[d] See Van der Linden et al. (2018) for a detailed overview of all factors contributing to the yield gaps.

Furthermore, the portion of the product not explained by inputs – e.g. the total factor productivity – is likely to vary substantially given the heterogeneity of these systems. Therefore, factors of production across systems, from subsistence to high-technological ones, will vary dramatically as will the yield gap estimates and their contributing factors.

Although comparisons of both yield gap estimates and factors contributing to yield gaps among methods and approaches are difficult, there is value added in applying multiple methods and approaches simultaneously to the same system (Mayberry et al., 2017; Bateki et al., 2021; Graham et al., 2024), as this may result in different insights and perspectives on how different stakeholders could mitigate yield gaps. Therefore, studies on yield gap analysis should clearly define what stakeholders, such as farmers and policy makers, can act to mitigate particular yield gaps and address particular factors. As emphasized by Beddow et al. (2014), mitigating particular gaps – for example, the gap between actual yields and allocatively efficient or technically feasible yields, and the gap between that yield level and the water-limited yield potential – requires distinct policy strategies.

3. General discussion

3.1. Major challenges in assessing and analyzing yield gaps

The benchmarking method, climate binning method, frontier methods, and production system models were reviewed for their potential to assess and analyze yield gaps in pasture-based systems (Table 2). This review described the methods currently used to assess yield gaps in pasture-based livestock systems. Methods that are theoretically suited but have not been used to assess yield gaps in pasture-based livestock systems were not included in this review.

A major challenge is the selection of an appropriate method for yield gap assessment and analysis. Selection criteria for the methods are i) the research objectives to be met, ii) the spatial scale, iii) data availability (e.g., weather, soil, plant cultivars, animal breeds, management, production system characteristics and socioeconomic data), and iv) computational processing capacity. A research objective met with the benchmarking method is the comparison of a farm's performance with other farms having similar characteristics (Table 2). The climate binning method is generally applied to higher spatial scales as a first step for identifying regions on the globe where productivity increase could be an option. Frontier methods provide insights in both technical and economic efficiencies for policies and system development. Methods based on production system models may be applied for different purposes, according to the characteristics of the models (Table 2).

Data availability could be a major criterion in selection of methods. Soil and climate data from regional to global scales may be obtained from freely available regional or international databases (e.g., NASA/POWER, AgERA5, SoilGrids, FAO). The Global Yield Gap Atlas project (www.yieldgap.org) provides a soil and climate database for many countries across the world, which can be downloaded for free. Yield gaps at field, animal and farm scales can be assessed also with weather data from agrometeorological sensors installed in the field or in stables.

Computational processing capacity is generally not a limiting factor, except for methods involving remote sensing. However, advancements in computing technology, including parallel processing and machine learning algorithms, have significantly enhanced the efficiency of handling remote sensing data. Accessible tools such as open-source software libraries and online platforms further streamline the processing and analysis of remote sensing imagery, making it more manageable for researchers and practitioners.

Furthermore, pasture-based livestock production systems generally exhibit significant heterogeneity, involving diverse combinations of plant species and cultivars and animal species and breeds. Each approach to yield gap analysis addresses this heterogeneity in its own way. In some methods assumptions are made that generalize heterogeneity while in others heterogeneity is accounted for. The benchmarking and frontier methods account for heterogeneity by grouping similar agro-ecological zones or similar farms, including livestock species, to assess yield gaps of the group. The climate binning methods deal with heterogeneity allowing the incorporation of other variables (e.g. soil organic carbon, soil texture, livestock categories, etc.). Pasture carrying capacity models assume stocking rates as a proxy of pasture productivity, avoiding the heterogeneity due to animal factors. Models based on concepts of production ecology account for differences in plant species and cultivars and animal species and breeds, weather conditions,

Table 2
Main characteristics of methods used to assess and analyze yield gaps in pasture-based systems: benchmarking method, climate binning method, frontier methods, and production system models.

Method	What determines the benchmark yield	Examples	Scales	Use	Advantages	Disadvantages
Benchmarking method	Yields of top producers	Benchmarking against top producers	Field and animal to region	Compare performance between farms	Simple to calculate and understand	Cannot assess the scope to increase production of top producers; no insight in underlying causes of yield gaps
Climate binning method	Statistical analysis of current yields	Climate binning method based on satellite data	Regional to global	Governmental organizations to identify regions with technical potential for productivity increase	Large flexibility in terms of input datasets to characterize similar environmental zones and then calculate the associated yield gaps	Method depends on availability of large-scale datasets of climate and animal/plant performance
Frontier methods	Technical efficiency and allocative efficiency	Stochastic frontier analysis (SFA) Data envelopment analysis (DEA)	Local to global	Public and private partners for priority setting of policies and strategic planning	Provides insight into the relative performance of agricultural production and economic efficiency of systems with comparable characteristics	Data requirements are high; analysis is computationally intensive. DEA can be biased if the data is associated with statistical noise. Insights might be influenced by the functional form.
Production system models	Simulated yields based on model inputs (e.g., weather, management, remote sensing data). Potential production is often defined by genotype and climate.	Pasture carrying capacity models Models based on concepts of production ecology: Dynmod, LIVSIM, FARMSIM, CLEM, IAT, LiGAPS-Beef and LiGAPS-Dairy	Field and animal to farm, depending on specific models used. Results can be scaled up to the regional and global scales.	Researchers, consultants, farmers (efficient use of resources), policy makers (food security)	Models available for different purposes and a wide range of biophysical conditions; estimates are often not affected by differences in socio-economic conditions; many of the models are open source; contributions of different factors to the yield gap can be calculated	When focused on biophysical aspects only, the benchmark is theoretical; interaction between animals and grass is often not considered in detail; requires extensive data on weather, soil, plants, animals, and management practices

and soil types in their input parameters, but usually do not account for spatial heterogeneity in fields.

Another challenge is to account for multiple outputs of livestock production systems. If multipurpose breeds are used, two or more outputs should be considered. Also, multiple outputs should be considered at the field and farm scale if different animal species graze pastures ahead of each other, for example in leader-follower grazing. Outputs of livestock production systems are generally expressed as total weights, but the output in protein, essential amino acids, fatty acids, micronutrients and vitamins could be more relevant from a nutritional perspective. For example, summing the human digestible protein in each of the outputs can be applied to express the production of human digestible protein per hectare of grassland (Wilkinson, 2011, Van Zanten et al., 2016).

Keeping animals in different geographic regions can complicate yield gap assessments. Production of some agricultural commodities, such as beef, can be segmented into stages, each of which occurs in a different geographic region (Berton et al., 2017; Castaño-Sánchez et al., 2023). In the US for example, cow-calf systems, stocker-rearing (post-weaning) systems, and fattening systems can routinely occur in different states or regions, making it challenging to accurately estimate productivity and yield gaps per stage and region. In this context, yield gaps of stocker-rearing systems must be expressed on a live weight basis (e.g., kg live weight gain per hectare or per animal), whereas yield gaps of fattening systems can also be expressed based on the amount of beef produced (e.g., kg of equivalent carcass per hectare or per animal).

3.2. Improving the application methods for yield gap assessment

Despite methodological advances in calculating yield gaps at different spatial and temporal scales and the substantial academic contribution in this area of knowledge in the past 20 years, the use of yield gap knowledge and analyses is viewed mostly as being of academic interest. To move from science to mitigating yield gaps in practice requires identifying and properly addressing the constraints underlying agricultural production which include a wide range of biophysical to social, economic, and political factors varying over space and time (Beddow et al., 2014; Snyder et al., 2017).

Furthermore, for a given set of interventions to succeed, the results need to be tailored as closely as possible to farm or regional reality. Farmers' decisions about the use of resources and inputs, given their perspectives on opportunity costs, risks and own values, are unique to a given farmer-farm combination (Martha Jr, 2023). Additionally, every method involves simplification of reality. Hence, some aspects are not accounted for by default (Table 2).

To date, the potential positive environmental impacts of mitigating yield gaps have been poorly addressed (Snyder et al., 2017), which limits the design and implementation of policies focusing on sustainable intensification approaches from a more comprehensive perspective (Silva et al., 2021; Suh et al., 2020). Therefore, there is an urgent need to make knowledge on yield gaps more accessible for guiding public and private decisions. It is imperative to better integrate technical information and insights offered by yield gap analysis into a wider social, economic, and political context that ultimately will shape policy development and farmers' decision making in agricultural production. This requires better integration of knowledge from agronomy, climate sciences, crop sciences, ecology, social sciences and economics (Beddow et al., 2014; Snyder et al., 2017; Tittonell and Giller, 2013).

3.3. Directions for future research

Limitations of available methods for yield gap assessment and analysis provide entry points for future research. Benchmarking and frontier methods seem to be already well developed and most opportunities of improvement were identified for the production systems models.

Production systems models used for yield gap analysis of pasture-based livestock systems could be improved by accounting for pasture species composition, different grazing strategies, pasture nutritive value and selective grazing by animals. Few mechanistic grass growth models represent the actual species composition of pastures poorly because they are parameterized for a single grass species, assuming a homogeneous pasture dominated by one species. For example, the LINGRA model has been parameterized for perennial ryegrass (Schapendonk et al., 1998) and timothy (*Phleum pratense*) (Höglind et al., 2001). Including multi-species swards and semi-natural grasslands would require reparameterization of models. In addition, they generally lack a spatial representation of individual fields. Therefore, some of these models can only simulate continuous stocking (Van der Linden et al., 2016, 2018), but not rotational stocking.

The production system models simulate the quantity of pasture biomass, but sometimes not the nutritive value. In the combined LiGAPS-Beef and LINGRA model, digestibility was influenced by grass growth and grazing (Van der Linden et al., 2016, 2018). Another complicating factor in model simulations is selective grazing behavior. As a result, the nutritive value of grass consumed by animals is nearly always higher than that of the average pasture biomass. Assuming the average nutritive value of grass consumed equals the average nutritive value of the whole pasture may result in an underestimation of livestock growth and production. Other factors that are usually not accounted for in the production systems models are livestock diseases and pests. Future research should focus on how to include grazing management, pasture species composition, and pasture nutritive value, since these factors can have a large effect on livestock productivity.

Production data are essential inputs for the benchmarking approach and frontier methods. Despite being outputs of the production systems models, production data are essential to evaluate whether simulated production levels correspond to measured ones. Pasture-based systems are characterized by direct interaction between grazing animals and the sward. If either forages or animals are not represented well in these models, reinforcing loops may cause increasing deviations between simulated and measured variables. Therefore, future applications of the methods must thus go hand in hand with experiments where productivity and other key metrics are measured.

4. Conclusions

Yield gap assessments and analyses in pasture-based livestock production systems were performed using the benchmarking method, the climate binning method, frontier methods and various production system models. The benchmarking method is simple to apply, but provides much less insight into the full scope and factors underlying the yield gaps than the other more complex methods. The specific approach and method selected in each study depends on the research questions addressed, the spatial scale of the study, available data and data requirements of methods, and computational processing capacity. In future research, the production systems models would particularly benefit from better including the effects of different grazing strategies, pasture species composition, pasture nutritive value, and selective grazing by animals. Integration of technical insights from yield gap analysis into a broader social, economic, and political framework is necessary to influence policy makers and farmers' agricultural decisions toward the sustainable intensification of pasture-based livestock systems.

CRediT authorship contribution statement

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& editing, Writing – original draft. **Fábio R. Marin:** Writing – review & editing, Writing – original draft. **Dianne Mayberry:** Writing – review & editing, Writing – original draft. **Sandra Furlan Nogueira:** Writing – review & editing, Writing – original draft. **Gustavo Bayma:** Writing – review & editing, Writing – original draft. **Nicolas Caram:** Writing – review & editing, Writing – original draft. **Gerrie W.J. van de Ven:** Writing – review & editing. **Lynn Sollenberger:** Writing – review & editing.

Declaration of competing interest

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

Data availability

No data was used for the research described in the article.

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