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REVIEW ARTICLE OPEN ACCESS

What Can We Do to Improve the Contribution of European Grassland to Net Food Security?

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Received: 3 November 2024 | **Revised:** 25 September 2025 | **Accepted:** 29 September 2025

Funding: The authors received no specific funding for this work.

Keywords: food security | food-feed competition | grasslands | ruminant production

ABSTRACT

Intensification of animal production systems over the last number of decades has increased the consumption of human edible protein by livestock, leading to increased competition for and cost of human edible protein. Grassland-based agriculture supports ruminant production systems, which convert human inedible proteins (grassland) into human edible meat and dairy products with high nutrient density. Grassland-based systems have a low reliance on human edible food for production, and therefore optimizing the use of grassland to produce animal protein contributes to food security. Grassland-based systems have conversion efficiencies of 2.5 to 4 in terms of kg human edible protein produced for each 1 kg human edible protein consumed by livestock, greater than that of confinement systems (≤ 1 for each 1 kg human edible protein consumed). Managed grassland offers a range of other ecosystem services including supporting plant and animal biodiversity, water resource management (e.g., water retention, provision of flood plains, water filtration), carbon storage and sequestration, and cultural services. Grassland management, sward species selection, and supplementation are amongst the strategies that can be used to optimise grassland production and utilisation by ruminants for human edible-food production to contribute to global net food security, as well as environmental conservation and management.

1 | Introduction

The global population continues to grow (UN 2024), and demand for food and animal protein in diets increases (Alexandratos and Bruinsma 2012). On a per capita basis, global meat consumption is expected to grow by 2% by 2032 compared to the base period of 2020–2022, driven by income and population growth (OECD-FAO 2023). To meet the food demand of this growing population, increased food production is required from approximately the same land area. In some regions such as Europe, increased food production will be required from a declining land area as a result of competition with other land uses such as bioenergy production and urbanisation (O'Mara 2012). Reduced land area for food production in Europe, coupled with reduced inputs as the sector strives to meet environmental targets outlined in the European Green Deal, will have consequences. These include increasing food costs, reduced food supply in some regions, increased carbon (C) footprint of animal feed and food as more is imported, intensification of livestock production systems, and loss of grassland for food production. Loss of grassland agriculture will ultimately have negative impacts on various environmental parameters and the capacity of land to deliver a range of ecosystem services.

Grassland covers a large proportion of the global land area (30%–40%; Blair et al. 2014). The provision of food from grassland-based production systems plays an important role in global food security, through the conversion of a low-cost human inedible food source (grassland) by ruminants into high-quality food for human consumption, and in many cases without competing with land for crop production (Van Kernebeek et al. 2016). In marginal areas unsuitable for crop production including, but not limited to, mountainous, remote, rocky and wet areas (Eisler et al. 2014), grassland production is generally higher and crop failures less severe than those of directly human edible crops. In these regions, the milk and meat produced by ruminants are largely supported by grassland, either grazed in situ or conserved as hay or silage, reducing the competition by ruminants for human edible food (Eisler et al. 2014). Smit et al. (2008) found that the spatial variability in grassland productivity in Europe compared well with the variability in milk productivity, indicating the importance of grassland for milk production. Grasslands also provide a wide range of ecosystem services, many of which are unlikely to be provided by conversion to cropland or even forest (Burrascano et al. 2016; Bengtsson et al. 2019).

Increasing the contribution of grasslands to net food security is challenging, requiring a combination of sustainable management practices that allow the production of grassland for feed production while minimising the negative impact on the ecosystem and the environment.

Research has identified many factors that can improve grassland production and utilisation, including incorporating legumes (e.g., Clavin et al. 2017; Egan et al. 2018; McClearn et al. 2019) and forbs, improving grazing management (O'Donovan and Delaby 2016), ensuring that the ruminants grazing the grassland are well adapted to grass-based systems (Delaby et al. 2021), and the development of tools to help anticipate and contribute to decision making (e.g., PastureBase Ireland, Hanrahan et al. 2017). Increased use of grassland for the production of human edible food must be implemented without damaging and, where possible, having positive effects on the ecosystem in which they exist. When well managed, grassland-based livestock systems are one example of sustainable intensification. Many policy drivers influence the sustainability of grassland-based systems. These are sometimes complementary and sometimes antagonistic. European agricultural policy has a large focus on robust and resilient food systems while reducing the impact of agriculture on climate change and environmental degradation and addressing biodiversity decline (e.g., The EU Green Deal, The Farm to Fork Strategy, EU Biodiversity Strategy 2030). Although food production is now largely at a global scale, food security is an important consideration in many regions. This paper will discuss the role of European grassland in producing human-edible protein, competition for biomass for fuel production, opportunities to increase grassland use for milk and meat production, and the unique benefits of managed grassland in addressing environmental challenges.

2 | Producing Human-Edible Protein From Grassland

The sources of nutrition from which animal-based food and protein are produced (e.g., home grown, imported, using human food for animal feed) are important. Ruminants (e.g., cattle, sheep, goats), due to their complex digestive system involving a pre-gastric microbial fermentation in the rumen, can efficiently convert forages with low nutritive value to protein-rich products for human consumption (Clauss et al. 2010), utilising land area to produce food that is not always suitable for the production of food crops. This is the primary means by which grassland can contribute to food security. In recent times, in many regions globally, ruminant production systems are becoming increasingly reliant on feed crops produced on arable land rather than grassland (Mottet et al. 2017). This is resulting in food-feed competition as arable land increasingly produces feed for livestock rather than food for humans. The level of food-feed competition varies between and within regions (Leroy et al. 2022), influenced by many factors including local practices, land type (Van Zanten et al. 2016), production costs (Dillon et al. 2005; Muscat et al. 2020), product price, scale of operations, logistics of feed supply (e.g., access to harbour for importation), and availability of resources. In many cases, ruminant production systems have moved to non-traditional regions/areas where forage production is low for specific local reasons including, but not limited to, excess or not enough rainfall, extreme temperatures (high or low), soil type, topography, and costs. Lack of grassland (forage) requires that these livestock are fed crops (e.g., silage maize and soya), meaning livestock are directly competing with humans for cereals and other human-edible crops including grains, vegetables, and potatoes.

Milk and meat from ruminants are important sources of food energy, amino acids, fatty acids and other nutrients of key importance for human health (e.g., O'Mara 2012; O'Callaghan et al. 2016; Leroy et al. 2022; Walther et al. 2022). Worldwide, livestock are net contributors to the production of human-edible protein (e.g., Mottet et al. 2018; Leroy et al. 2022). The net supply of edible protein by livestock can be considered using a number of metrics. Feed conversion ratio (FCR) is the kilogram of concentrate fresh weight fed per kilogram live weight gain or product fresh weight (Wilkinson 2011). The total protein efficiency is the ratio of total protein output to total protein input (Laisse et al. 2018), and net protein efficiency is the ratio of human-edible protein output to human-edible protein input (Laisse et al. 2018). The edible protein conversion ratio (EPCR) is the conversion ratio of edible food protein into animal protein (Wilkinson 2011; Laisse et al. 2019; Mosnier et al. 2021). The land-use ratio (LUR) estimates the capacity of a land area to produce human-digestible protein from food crops on all land used to cultivate feed required to produce 1 kg of animal-source food over the quantity of human-digestible protein in the feed used to produce that 1 kg (Van Zanten et al. 2016). A LUR <1.0 implies that animals produce more human-digestible protein on that land area than crops and is considered efficient in terms of global food supply (Van Zanten et al. 2016).

Globally, all ruminant production systems, including feedlot systems, require about 0.6 kg human-edible protein per kg of human edible protein produced (Mottet et al. 2017). Grassland-based ruminant production systems perform well in terms of converting feed protein to food protein. Laisse et al. (2018) showed that the net protein efficiency (conversion of human edible protein in the feed to human edible protein products) of grassland-based dairy cattle production receiving low concentrate input is up to 2.57

in France, while Hennessy et al. (2021) reported a net protein efficiency of 4.0 for Irish grassland-based dairy cattle production systems (Figure 1).

A recent report by the FAO (2023) identifies the important contribution of terrestrial animal-sourced food (milk, meat, eggs) to healthy diets for improved nutrition and health outcomes. Terrestrial animal source foods provide energy and many essential nutrients, such as protein, fatty acids, and several vitamins and minerals that are less common in other food types (FAO 2023). An adequate supply of protein in the diet is defined as the ability of the diet to supply proteins to meet the nutritional demands of the body and depends not only on the quantity of protein provided by the diet but also the quality of the proteins in terms of essential amino acids and their digestibility (Neumann et al. 2002; WHO, FAO and United Nations University 2007; Ertl et al. 2016). It is generally recognised that animal proteins are of higher nutritional quality for humans than plant proteins (e.g., Day et al. 2022; Karoui and Bouaicha 2024), due largely to their digestibility and amino acid composition, particularly the essential amino acids (Day et al. 2022) that must be supplied by food as they cannot be synthesised in adequate quantities in the body. The digestible indispensable amino acid score (DIAAS) is a measure of protein quality. Ertl et al. (2016) found that the DIAAS of food from Austrian dairy systems is up to 1.87 times greater than that of the potentially human-edible protein content of the feed input to the dairy systems. Hennessy et al. (2021) reported that the DIAAS of dairy systems in Ireland was up to 4.55 and suckler beef systems was up to 3.45 times greater than that of the potentially human-edible protein input fed to cattle. The high DIAAS in Ireland is largely driven by the high quantity of grass in the diet of livestock in dairy (O'Brien et al. 2018) and beef systems. Walther et al. (2022) compared the composition of full-fat milk and plant-based beverages (marketed as milk substitutes) and found that the protein quality of milk was greater than all plant-based drinks and exhibited higher calculated DIAASs; Khamzaeva et al. (2024) reported similar. The biologically higher value of milk compared to plant-based beverages was demonstrated by a study with over 5000 Canadian toddlers showing that children consuming milk were significantly taller than those using plant-based alternatives (Morency et al. 2017).

Milk and meat are rich sources of many other essential nutrients (e.g., Walther et al. 2022; Leroy et al. 2023) of key importance for human health. Many are considered crucial for the human brain, including iron, zinc and vitamin B12, and if not supplemented, these nutrients are either obtained exclusively from animal-sourced foods or are more bioavailable in those foods (Leroy et al. 2023). Beal and Ortenzi (2022) estimated that the bioavailability of iron and zinc in ruminant meat is 2 and 1.7 times, respectively, greater than that of pulses (e.g., beans, peas, lentils). Meat also supplies many of the other B vitamins, including niacin and thiamine that can be limited in micronutrient-poor diets based on non-fortified cereal staples (Leroy et al. 2023).

The longer chain forms of omega-3 fatty acids eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA), which are only found in marine organisms and land herbivores, are critical components of human nutrition in terms of cell membrane structure and tissue health (especially for the brain, heart, and retina). They also play a role in cardiovascular health and mitigation of chronic inflammation (Leroy et al. 2023). The fatty acid profile of grassland-fed milk and meat is generally more desirable than that of produce from livestock fed high-concentrate diets. Milks from grass-based diets have higher concentrations of omega-3 and conjugated linoleic acids, higher proportions of unsaturated fats, and higher unsaturation, health-promoting, and desaturase indices than livestock fed medium or low levels of grass (O'Callaghan et al. 2016; Timlin et al. 2023).

3 | Competition for Grassland

Apart from urbanisation and forestry, which will not be discussed here, another competition for grassland is energy production. Recently, bioenergy production is competing for biomass used to provide feed and food as countries transition from fossil fuels to greener, renewable energy sources (Muscat et al. 2020). The EU currently has a binding target of 42.5% renewable energy by 2030 (EU Renewable Energy Directive EU/2018/2001 amended in 2023 EU/2023/2413). Bioenergy produced from agricultural, forestry and organic waste feedstock continues to be the main source of renewable energy in the EU, accounting for

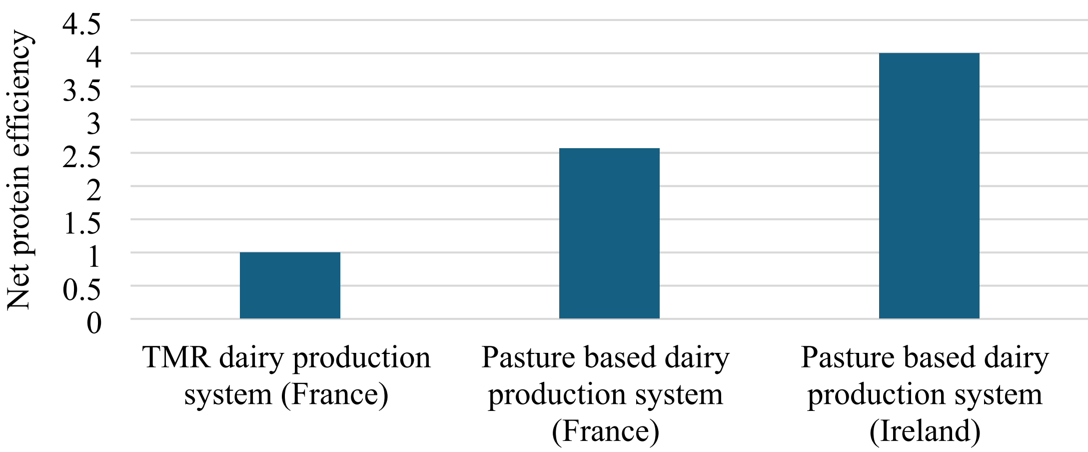

FIGURE 1 | Net protein efficiency of dairy production systems (kg human edible protein produced/kg human edible protein consumed by livestock) of dairy production systems in France (indoor feeding TMR and grassland-based; Laisse et al. 2018) and Ireland (grassland-based; Hennessy et al. 2021).

about 59% of renewable energy consumption in 2021 and agricultural biomass made up 8% of that bioenergy (EC 2021). In parts of Europe, there is direct competition for biomass for bioenergy, feed and food (e.g., Muscat et al. 2020), often driven by the EU target for renewable energy. In some parts of Europe, pulp from biorefinery, which includes grass, suitable for animal feed is being diverted to anaerobic digestion for biofuel production (e.g., Gaffey et al. 2023). In other regions, energy companies are paying high rent for land on which to place solar panels (solar farms) making land prices beyond the reach of livestock farmers. Utilising grassland area, and indeed arable area, for energy and fuel production ultimately reduces the quantity of food produced by agriculture. The FAO (2009) recommend that policies promoting the use of food-based feedstocks for biofuels production should be reconsidered to reduce the competition between food and fuels for scarce resources, including land, and more efforts should be made to develop forms of renewable energy that do not depend on food-biomass.

While energy production may be a threat to grassland for grazing, green biorefinery may provide an option for both energy production and production of feed for ruminants, thereby reducing the impact of energy production. Green biorefinery processes are being investigated and developed to capitalise on the potential of agricultural land, specifically growing grasses, legumes and other green plants, to produce sustainable food, feed, materials and energy in an integrated way (Gaffey et al. 2023). This may result in a situation where grasslands and the ecosystem services they provide can be utilised more widely (Jørgensen et al. 2022). The development of grass-based food products is, at least within Europe, limited due to the Novel Foods Act that requires authorization of novel food materials prior to the release to markets (EFSA 2024). However, experimentation to use grass protein (Møller et al. 2021) or even the fibre fractions (Csatári et al. 2022) extracted from green biomass as human food components has been conducted and may become a reality in the near future. While waiting for direct human consumption of grass protein and other nutrients, green biorefineries can potentially contribute to net food security from grassland by providing novel feed ingredients that replace human edible components of livestock diets. Extracted grass protein is currently commercially produced in Denmark based on positive results obtained in feeding trials for pigs and poultry (Stødkilde et al. 2020, 2023). In Finland, a low-cost approach of feeding mechanically separated juice from ensiled grass to growing pigs as part of their liquid feed resulted in similar pig performance and meat quality compared to feeding conventional feed components (Keto et al. 2021). However, the extraction of protein requires high investment and operation costs, and yields of protein are low. This can partly be compensated by the fact that simultaneously with feed production, the green biorefineries produce several other commodities such as pulp for animal feed, fibres, animal bedding, biochemicals, nutraceuticals, bioactive compounds, biogas and biochar (Gaffey et al. 2023).

4 | Improving the Capacity of Grassland for Food Production

Managers of grassland-based ruminant production systems must be cognisant of the impacts of grazing and grassland management on the wider ecosystem. Grasslands can contribute to net food security while also addressing many of the sustainability challenges relating to agriculture. Sustainable grassland production systems mean different things in different regions (Smit et al. 2008; Oenema et al. 2014; van den Pol-van Dasselaar et al. 2020; Dumont et al. 2022; Wróbel et al. 2023). In temperate climates, where a long grass growing season occurs, including Ireland, parts of the UK, North-West Europe, New Zealand, parts of Australia and parts of South America, grazed grass contributes significantly to milk and meat production, while in other regions, grassland provides the main source of forage for indoor feeding systems or for long winter periods (e.g., Dillon et al. 2005; Virkajärvi et al. 2015; O'Brien et al. 2018). Ultimately, sustainable grassland systems provide low-cost forage for ruminant production systems whether fed in situ via grazing or conserved as hay, haylage or silage. While there can be negative impacts of some ruminant production systems, well-managed grassland systems can contribute positively to ecosystem management and address sustainability challenges for agriculture, while simultaneously making use of inedible feed and marginal land for food production (Petermann and Buzhdygan 2021; Leroy et al. 2022; Thompson et al. 2023).

Sustainable grassland management maintains healthy grassland ecosystems, supports livestock production, and promotes environmental sustainability. There is a renewed interest in integrated crop-livestock farming or systems (e.g., De Wit et al. 2006; Sekaran et al. 2021). Such systems take advantage of the interactions between system components (e.g., soil, plants and animals) and offer the potential to reduce environmental impacts of agriculture by improving nutrient cycling while maintaining production (Ryschawy et al. 2017; Taube et al. 2023). In many regions, grass and livestock are being introduced or reintroduced to cropping systems as part of the rotation (Van Eekeren et al. 2023). Grassland plays an important role in maintaining crop production by conserving soil C, contributing to soil organic matter content, enhancing nutrient efficiency, providing N from grassland (especially containing legumes) and providing a better balance for crop rotations, contributing to reduced reliance on fertiliser and pesticide use (Martin et al. 2020; Malisch et al. 2023). This is possible because ruminants recycle nutrients back to the soil through urination and defecation or application of slurry and farmyard manure, promoting soil fertility and plant growth while producing food. Sowing of grassland leys allows for the selection of species and varieties for specific purposes which can contribute to forage production and nutritive value, as well as benefits for the following crop (Lüscher et al. 2014, 2022; Fox et al. 2020; Jaramillo et al. 2021; Suter et al. 2021). Understanding the impact of leys on the following crop can provide valuable information for farmers to ensure the species they sow have benefits, not just within the ley but in the following years. Benefits include, but are not limited to, soil N content, soil fertility, soil organic matter, soil drainage, and weed and pest suppression (van Eekeren et al. 2009; Albizua et al. 2015; Martin et al. 2020; Khosht et al. 2025). Khosht et al. (2025), using a long-term data set in Sweden, found long-term benefits of grass-legume and grass leys on arable crop yield and quality, and that leys containing legumes reduced the requirement for N fertiliser in the following crop. Projects like LegacyNet, which is a voluntary network of 32 international sites investigating the legacy effects of multispecies grassland leys on yield follow-on crop (O'Malley et al. 2023), provide valuable information for the incorporation of grassland leys in arable crop rotations.

Selecting the best plant species for grazed grassland contributes to forage accumulation, nutritive value and nutrient use efficiency. Optimising production of grassland from a given land area provides more feed for livestock. Species evaluation and breeding programmes provide important information for farmers who are sowing leys, reseeding grassland and enhancing grassland. Tools like the Pasture Profit Index (McEvoy et al. 2011; Tubritt et al. 2021) and the Forage Value Index (Chapman et al. 2017) provide a ranking of perennial ryegrass (*Lolium perenne* L.) cultivars in terms of forage accumulation, nutritive value, and persistence. Similar indexes or tools are not currently available in all countries or regions or for other grassland species. National recommended lists are valuable resources providing data on grasses and clovers at the region or country level.

Incorporating legumes into grassland systems has positive impacts on forage accumulation and nutritive value. Red and white clovers (*Trifolium pratense* L. and *Trifolium repens* L., respectively) are of particular importance in European grassland systems. The biological N fixation capacity of legumes reduces the requirements for inorganic N fertiliser input. Andrews et al. (2007), Enriquez-Hidalgo et al. (2018) and Dineen et al. (2018) are amongst numerous authors who have shown that herbage production can be maintained or increased when there is white clover in the sward, even with reduced inorganic N fertiliser input. Red clover has a significant capacity to produce large quantities of high-quality silage with little to no inorganic N fertiliser input (e.g., Clavin et al. 2017; Marshall et al. 2017; Holohan et al. 2022), making it an important contributor to grassland-based production systems. Incorporating legumes in grassland has been shown to maintain or increase herbage nutritive value at lower N fertiliser application rates compared to grass swards and often results in increased animal production. For example, Thomson et al. (1985) and Egan et al. (2018) reported similar herbage crude protein concentration on grass-white clover swards receiving lower inorganic N fertiliser input compared to grass-only swards, and Leach et al. (2000) and Riberio Filho et al. (2003) found that the digestibility of grass-clover swards was greater than that of grass-only swards at low inorganic N fertiliser input.

Sown multispecies swards (usually grasses, legumes, and forbs) are important in cutting and grazing systems across Europe. In terms of herbage production, there is conflicting data regarding the benefits of multispecies swards relative to grass-only swards, with many attributing the herbage production benefits to the legume component of the sward (Jaramillo et al. 2021; Moloney et al. 2021) and others finding benefits only under cutting (e.g., Jing et al. 2017). McCarthy et al. (2020), in a meta-analysis, reported milk production benefits of multispecies swards compared to grass-only swards, while Bryant et al. (2017) found no benefits of multispecies swards on milk production. The benefits of components of multispecies swards, however, are limited by the persistence of species, particularly forbs and some legumes in grazed grassland (Gilliland 2022).

Achieving high levels of production and optimum utilisation from grazed grassland requires the implementation of good grazing practices (Maher et al. 2025). Developing a grazing plan that considers factors such as stocking rate, feed demand, forage growth rates, annual grassland production and seasonal variations in grassland production delivers sustainable systems (Teague 2015; Teague and Kreuter 2020). Adjusting grazing intensity based on these factors prevents overgrazing and overuse of the pasture resources, which could degrade grassland (Hunt et al. 2014). Implementing appropriate grazing management systems to optimise the utilisation of high-quality feed will increase animal production through grazing (Parsons and Allison 1991). There are several types of grazing systems, each tailored to suit the specific environmental, soil, sward species composition, and herd characteristics of the farm or region, as well as the management objectives. Grazing managers strive to ensure an optimised supply of forage mass of adequate nutritive value for the grazing livestock. Some of the common grazing systems include continuous stocking systems, mob stocking, rotational stocking, strip stocking, and cell grazing (Allen et al. 2011). The objective of this section is not to delve into the detail of any particular grazing or stocking system, rather indicate that grazing management is one of the factors influencing food production from grazed grassland. Overall, well-managed grazing systems will promote high forage nutritive value and allow for effective utilisation of grassland, usually permitting adequate regrowth periods while minimising tissue turnover; for example, a 21-day grazing rotation in mid-season in perennial ryegrass swards in temperate regions ensures plants reach the three-leaf stage and are grazed before herbage senescence commences (e.g., Turner et al. 2006).

Quantifying the capacity of farmland to grow grass is an important consideration in promoting sustainable grazing systems. Data that can be used to provide informed grazing management decisions and promote utilisation (Hanrahan et al. 2018; Palma-Molina et al. 2023). Measuring weekly, seasonal, and annual grass production allows farmers to determine appropriate stocking rates and grassland management strategies (O'Donovan et al. 2020). Decision tools and/or systems are available in many countries to support grazing management; these include PastureBase Ireland (www.pbi.ie; Ireland; Hanrahan et al. 2017), the MoSt Grass Growth model (Ireland; Ruelle et al. 2018), Pâtur'Plan (France) and Beweidingswijzer (https://webapplicaties.wur.nl/software/beweidingswijzerfe/; The Netherlands).

Manipulating the grass silage to concentrate ratio in dairy cow diets can be conducted within a large range (e.g., Ferris et al. 2001: concentrate proportion 0.10–0.80 on a DM basis; Steinshamn and Thuen 2008: 0–0.39 on a DM basis; Sairanen et al. 2022: 0.34–0.54 on a DM basis) and it influences milk yield and obviously the quantity of milk produced from grass. These examples show that there is great flexibility in the proportion of grass-based feeds in dairy cow diets. The large variation observed in different European production systems is thus defined based on other factors such as bio-physical conditions affecting the relative competitiveness of grass versus other feed production possibilities, regulations (e.g., organic production), traditions, and, importantly, the price of different feeds relative to milk price. From a net food production perspective, there is

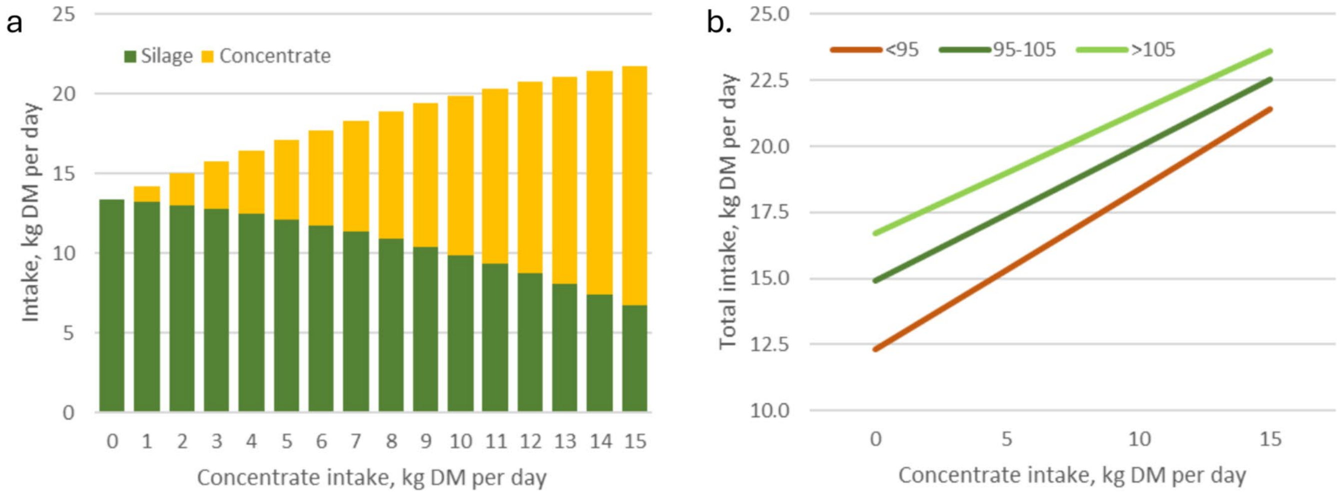

FIGURE 2 | Substitution rate is higher at (a) high concentrate inclusion levels and (b) when grass silage has a high DM intake index (Huhtanen et al. 2007). The relationships are based on Huhtanen et al. (2008).

much scope to reduce the human edible proportion in dairy cow diets if sufficient incentives are obvious for farmers. To make informed decisions in ration formulation, knowledge of the feeding value and potential dry matter (DM) intake of different feeds and the subsequent milk output is required. An important concept is the substitution rate, which describes the reduction in intake of grass silage offered ad libitum when concentrate input is increased. Huhtanen et al. (2008), in a meta-analysis, found that the substitution rate was, on average, −0.47 but varied depending on the feeding scenario (Figure 2). The authors concluded that the substitution rate is quadratic, that is, the reduction of silage intake is greater at higher concentrate inclusion levels (Figure 2a). In addition, when silage DM intake potential is high (both nutritional value and preservation quality), the substitution rate is greater than with lower quality grass silage (Figure 2b).

5 | Opportunities for Grassland Based-Agriculture

Grassland-based production systems are uniquely positioned to contribute to net food security while also addressing many of the environmental sustainability and biodiversity challenges faced by agriculture. These challenges include water quality, greenhouse gas (GHG) emissions, ammonia emissions, biodiversity loss, soil quality, and C balance. The Nitrates Directive (91/676/EEC) and Water Framework Directive (2000/60/EC) are targeting improved water quality. The EU Biodiversity Strategy 2030 addresses biodiversity decline and will be supported by the Nature Restoration Law (Regulation (EU) 2024/1991). The European Climate Law (Regulation 2021/1119) is focused on reducing net GHG emissions and achieving climate neutrality.

Recycling organic manure produced on farms, either through deposition by grazing livestock or through application to the land, reduces the requirement for inorganic fertilisers (N, phosphorus (P) and potassium) for grassland production. Applying slurry and manure using methods and at times of the year that minimise loss of N through volatilisation ensures that N is retained for plant growth (e.g., Lalor and Schulte 2008). Covering slurry storage tanks, reducing slurry pH via acidification, and shortening manure storage time are some of the means of reducing GHG emissions from slurry (e.g., Misselbrook et al. 2016; Petersen 2018). Adapting the type of inorganic N fertiliser used to low emissions fertiliser, for example, replacing calcium ammonium nitrate fertiliser with urea or urea combined with a urease inhibitor such as NBPT, 2-NPT or NBPT+NPPT, reduces ammonia emissions (e.g., Forrestal et al. 2017).

Incorporating legumes reduces the requirement for inorganic N fertiliser application in intensive grazing systems from 250+ $kg\,N\,ha^{-1}$ to less than 150 $kg\,N\,ha^{-1}$ (e.g., Andrews et al. 2007; Egan et al. 2018; Murray et al. 2024). Plantain in multispecies swards can reduce urinary N nutritive value (Bryant et al. 2017; Marshall et al. 2021), which may result in reduced nitrate leaching. In New Zealand, a number of large research projects are exploring the benefits of incorporating plantain in grassland swards to reduce nitrate loss (e.g., Rodriguez et al. 2020; Navarrete et al. 2022).

Technology and decision support tools are at various stages of development and are likely to provide greater opportunities to reduce inorganic N fertiliser use in the future. Some of these include tools and technologies to increase the precision of inorganic N fertiliser application (e.g., GPS, identification of N hotspots), estimate herbage mass and growth rates, and use remote sensing of herbage mass and rapid detection of soil nutrient status.

Enteric methane emissions are of concern in ruminant production systems. A peculiarity of grassland-based systems is that methane comes from a biogenic cycle, which in the case of grassland systems means that the decay of methane into CO_2 is compensated for by the fixing of CO_2 in the cycle into grassland through photosynthesis (Poux and Aubert 2022). Grassland-based milk production systems can have lower methane emissions per unit of livestock compared to indoor total mixed ration (TMR) systems (Robertson and Waghorn 2002; O'Neill et al. 2011; Koning et al. 2024). This can be due to lower milk production in grazed systems (O'Neill et al. 2011) as a result of lower DM intake and variability in feed nutritional value, and the effect may be seasonal, with lower emissions when grass nutritive value and digestibility are high, for example, in spring (Lahart et al. 2024). Other authors have found no impact on milk yield but a reduction in methane emissions when cows were fed grazed grass compared to TMR (Cameron et al. 2017). The forage-to-concentrate ratio in ruminant diets is highly variable as discussed previously. Although diets with higher concentrate proportion produce less methane per day or per kg energy-corrected milk yield (Lovett et al. 2005; Jiao et al. 2014), the human edible feed ratio is greater, and the source of the components of the ration can increase the C footprint of the product.

Improving the nutritive value of the grassland consumed by grazing livestock has positive impacts on methane emissions, as well as milk production. Grassland forage nutritive value can be increased through improved grassland management resulting in lower pre-grazing herbage mass (Wims et al. 2010), seasonal effects (O'Neill et al. 2011; Lahart et al. 2024), or sward composition, namely inclusion of white clover and the proportion of clover in the sward (Lee et al. 2004; Enriquez-Hidalgo et al. 2014). Selecting animals suited to grassland and forage-based systems will ensure good feed conversion efficiency, reducing methane emissions per kg food product. Lahart et al. (2024) found that higher genetic merit dairy cows (based on the Irish Economic Breeding Index) bred for pasture-based systems in Ireland had lower methane emissions than the national average dairy cow. There is conflicting evidence in the literature in terms of the benefits, if any, of multispecies swards in reducing methane emissions (e.g., Ramírez-Restrepo and Barry 2005; Loza et al. 2021), and the impact appears to be influenced in particular by the presence/absence of forbs and the species of forbs, as well as maturity and grazing intensity. Herron et al. (2021) found that grass-clover systems with reduced inorganic N fertiliser input reduced the global warming potential of pasture-based milk production systems by 5.4%, driven by reduced inorganic N fertiliser inputs and increased milk production from the same land area compared to a grass-only high inorganic N fertiliser input system. Multispecies swards containing legumes reduce nitrous oxide emissions (Luo et al. 2018; Cummins et al. 2021) through reduced inorganic N fertiliser input by up to 41%.

Grasslands play an important role in increasing C sequestration (or maintaining it in regions where there are already high soil organic C (SOC) stocks). Quantifying soil C sequestration and changes in SOC stocks is challenging as data are required over long periods. Up to 11% of the C applied in slurry to grassland is retained in the soil, building SOC (Jensen et al. 2022). Introducing grass-clover leys to the rotation in long-term arable ground for 2 years in a 6-year rotation increased SOC, more rapidly in the initial years of a long-term study by Jensen et al. (2022). Deeper rooting forbs associated with sown multispecies swards may result in increased C sequestration (e.g., Fornara & Tillman, Fornara and Tilman 2008). In a large review, Conant et al. (2017) found that improving grassland management (grazing management practices, fertilisation, incorporating legumes, and improving grassland species, as well as irrigation where used) and converting land use from crops to grassland increased soil C stocks at rates of 0.105 to more than $1\,\mathrm{Mg\,C\,ha^{-1}\,year^{-1}}$. Other authors, including Soussana et al. (2004), conclude that long-term grassland is important for increasing C sequestration, conserving C stocks, and reducing soil disturbance to avoid loss of C stocks.

Acknowledging that agriculture has in the recent past had a negative impact on water quality, grassland is an important land use in terms of mitigating nutrient loss to water. Nitrogen loss is a big risk to water quality. Within grassland systems, there are numerous sources of N including fertiliser, organic manures, soil N, biological N fixation, and dung and urine deposition, all providing N to satisfy the demands of productive grassland. However, N supply can be surplus to sward requirements for a variety of reasons and can potentially be leached. Strategic fertiliser application, taking consideration of sward demands and weather conditions as well as the presence/absence of legumes, can reduce the risk of surplus N. Poor soil fertility limits the capacity of grassland to utilise N, contributing to the potential for loss (e.g., Lawniczak et al. 2016). Intensively, well managed grassland can effectively use fertiliser N, even at relatively high application rates with limited additional leaching. Fontaine et al. (2023) reported no additional leaching from grass-clover leys receiving up to $150\,\mathrm{kg}$ fertiliser $\mathrm{N\,ha^{-1}}$, and at $200\,\mathrm{kg\,N\,ha^{-1}}$ around 5% of additional fertiliser-N was leached. Increasing N use efficiency, precision grassland management, reducing N surplus by reducing N inputs (purchased feed and fertiliser), and increasing the N products (milk and meat) sold from the farm are important farm-level actions to reduce nitrate leaching (Murphy et al. 2024). Riparian margins and buffer zones offer mitigation, especially for N and P likely to be lost in runoff and overland flow. Grasslands mitigate against flooding and soil erosion (Milazzo et al. 2023). They act as natural sponges, absorbing water during heavy rainfall events, reducing and slowing overland flow and subsequently flooding downstream. The extensive root systems in grassland help with water infiltration, and grassland cover reduces opportunities for soil erosion during flooding events. Although pesticides, usually herbicides, are used on grassland, they are generally used only at the time of sward renewal/reseeding or when significant weed encroachment occurs, so that the ecotoxicity pressure is smaller than from most other crops. Leys within crop rotations provide break crops, reducing the risk of pests and diseases in cereal and other crops (Martin et al. 2020), in turn reducing pesticide use and the risk of runoff to waterways.

Milk and meat production often conjures images of livestock grazing in green landscapes. Grasslands are an integral part of our landscapes, and grazing livestock deliver significant management of those grasslands. Managed grasslands provide scenic landscapes and offer recreational opportunities (e.g., walking, hiking) not available from other agricultural systems. They contribute to species richness within landscapes and play an important role in helping address the biodiversity crisis. Managed grasslands avoid scrub or forest encroachment, which can result in plant and animal species loss (e.g., Pornaro et al. 2013). A range of habitats within swards and on the margins occur in grassland farms. Short and tall grass areas in grazed grassland, extensively managed grassland, old permanent pasture, multispecies swards, meadows and legume-rich swards are among the habitat types provided by grasslands. In addition, grassland farms often have a range of other habitats, including hedgerows, trees, small woodlands, ponds, wetland/peat areas, old farmyard buildings and structures, historical ruins, and extensively managed areas, all providing habitats for a range of flora and fauna. Riparian margins, often established to reduce nutrient and pesticide losses to waterways, can be rich biodiversity habitats supporting flora and fauna. Increasing the species incorporated in sown grasslands has a role in reversing biodiversity decline. Incorporating a range of grass, herb, and legume species increases plant species richness, enhancing biodiversity both above and below ground (e.g., Grange et al. 2021).

6 | Conclusion

As the global population continues to grow, and the demand for human edible protein increases, grasslands play a unique role in global net food security through the provision of a low-cost, human inedible feed source for milk and meat production. Grassland ruminant production systems have a high net protein efficiency compared to other feeding systems that rely more heavily on grains and other crops and provide food (milk and meat) with a high digestible indispensable amino acid score for human nutrition. The land area under grassland is generally marginal and not suitable for crops for direct food production for site-specific reasons. Managing grasslands to optimise the production and nutritive value of feed for ruminant production systems contributes to net food security, while also providing a wide range of ecosystem services and addressing and providing solutions to many of the environmental sustainability and biodiversity challenges faced by agriculture.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

Data sharing is not applicable to this article as no datasets were generated or analysed during the current study.

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