



Review Article

Grassland-based ruminant farming systems in China: Potential, challenges and a way forward

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ABSTRACT

With an increasing demand for high-quality, eco-friendly food products and growing concerns over ecological conservation, the development of ecology-based alternatives for ruminant production in China is urgently needed. This review discusses the capabilities for integrating grassland grazing into existing livestock farming systems to meet the contemporary human needs for high-quality foods and ecologically stable environments. Additionally, this review provides a critical analysis of the challenges and future directions associated with grassland-based ruminant farming systems. Integrating nutritional manipulation with grazing manipulation is critical for improving the productivity of grassland-based ecosystems and natural ecological functions. Biodiversity is the primary determinant of grassland ecosystem functions, while the composition and function of rumen microbiomes determine ruminant production performance. Future studies should focus on the following aspects: 1) how livestock grazing regulates grassland biodiversity and the mechanisms of grassland biodiversity maintenance, offering an important scientific basis for guiding grazing manipulation practices, including grazing intensity, livestock types, and grazing management practices; to 2) characterize the microbial ecology within the rumen of grazing ruminants to offer clarified instruction for the nutritional manipulation of grazing ruminants. Our recommendation includes creating a transdisciplinary system that integrates ecology, animal nutrition, and animal behavior to develop grassland-based ruminant farming systems sustainably, thereby achieving high-quality animal production and environmentally sustainable goals.

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1. Introduction

Grasslands cover approximately 26% of the total global land area and are the most widely distributed terrestrial ecosystems on Earth (Steinfeld et al., 2006; Dong et al., 2020). In China, grassland areas cover over 2.6×10^8 ha, accounting for about 27% of the country's land area. Therefore, conservation and rational use of such

grassland resources in China have been the focus of scientists in various disciplines.

Grazing is the most important utilization practice of grasslands, and grazing livestock is considered one of the critical biological components of grassland ecosystems. From a historical perspective, the primary purpose of grazing has been producing meat and milk products for humans, which occurred at the expense of many other potential functions of grasslands (Ayantunde et al., 2011). In recent decades this perspective has changed due to several studies, which found that grazing by large herbivores (cattle and sheep) maintains the stability of grassland ecosystems and increases the multifunctionality of grasslands (Gong et al., 2014; Wang et al., 2019). Therefore, livestock grazing was determined to be an essential pathway to producing livestock products and maintaining and promoting grassland ecological service functions. Consequently, pasture-based ruminant farming systems with full- or part-time grazing have increasingly emerged as a strong option for achieving “win–win” outcomes between grassland ecological

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functions and livestock production functions (Dumont et al., 2018), which have significance in promoting the sustainable development of livestock farming.

The following passages discuss grassland-based ruminant farming systems' ability to meet current human needs for high-quality livestock products and grassland ecosystem services. We provide insights into the main challenges and future scientific research directions associated with the development of grassland-based ruminant farming systems.

2. The potential for developing grassland-based ruminant farming systems

The need to increase livestock production in China for food security appears to be at odds with the urgency to reduce the negative environmental impacts of existing livestock farming systems. Developing grassland-based ruminant farming systems can play a vital role in increasing livestock production (especially high-quality livestock products) while maintaining and improving grassland ecosystem service functions (Fig. 1).

2.1. Production of low-cost and high-quality livestock products

Grazing is the most economically conservative way to raise livestock because the cost of the herbage consumed by grazing ruminants is lower than that of mixed rations (composed mainly of silage, grain, added vitamins, and minerals). Additionally, in a grazing system, ruminants feed autonomously, with minimal mechanized equipment and labor. Hence, grassland-based livestock farming systems can be highly profitable, as shown by Mwebe et al. (2011), who found that farmers who allow grazing in small herds made higher profits than those who tried other feeding strategies. Apart from the low-cost production of livestock products, grassland grazing allows farmers to produce high-quality, niche foods with a higher market value than similar products derived from intensive, indoor livestock management. For example, higher antioxidant activity was observed in goat cheese from grazing goats (Hilario et al., 2010) due to greater quantities of

polyphenols, hydroxycinnamic acids, and flavonoids consumed during grazing—resulting in goat cheese with higher bioactivity. Previous studies have also demonstrated that grazing ruminants (compared to ruminants fed indoors) showed improved milk quality, with enhanced sensory properties (Valdivielso et al., 2015), increased mineral content (Gulati et al., 2018), and greater odd- and branched-chain fatty acid concentrations (Valdivielso et al., 2015).

Furthermore, grazing also improved the meat quality of ruminants by enhancing the fat color and increasing the n-3 polyunsaturated fatty acid and vitamin E content in the muscle (Hamdi et al., 2016; Carrasco et al., 2009; Lebret and Guillard, 2005). Higher-quality products may result from the fact that livestock welfare is improved within grassland-based systems (Crossley et al., 2021; Motupalli et al., 2014). Therefore, grazing systems can reduce feeding costs and produce high-quality livestock products.

2.2. Improvement of grassland ecological functions

Livestock grazing plays a vital role in regulating grassland ecosystems functions (Mcsherry and Ritchie, 2013), allowing suitable grazing systems have the potential to provide valuable ecosystem services for humans. For example, Sollenberger et al. (2019) reported that the excreta of grazing livestock was a source of nutrients for grasslands. Their study determined that managing livestock grazing to increase the uniformity of excreta deposition increased the efficiency of nutrient cycling and changed the composition of soil microorganisms and aboveground plants. Several studies have shown that moderate grazing improved grassland ecological functions: boosting plant productivity and biodiversity, improving soil structure, fertility, and microbial biomass, enhancing carbon and nitrogen storage, and limiting erosion. Gong et al. (2014) found that moderate grazing resulted in higher species diversity and belowground root biomass, driving greater productivity in grass species. In tropical grasslands, moderate grazing led to soil carbon storage and resulted in greater productivity and soil water-holding capacity, potentially enhancing grassland resilience to climate change (Teague et al., 2011). Mixed grazing of different livestock species at moderate levels promoted

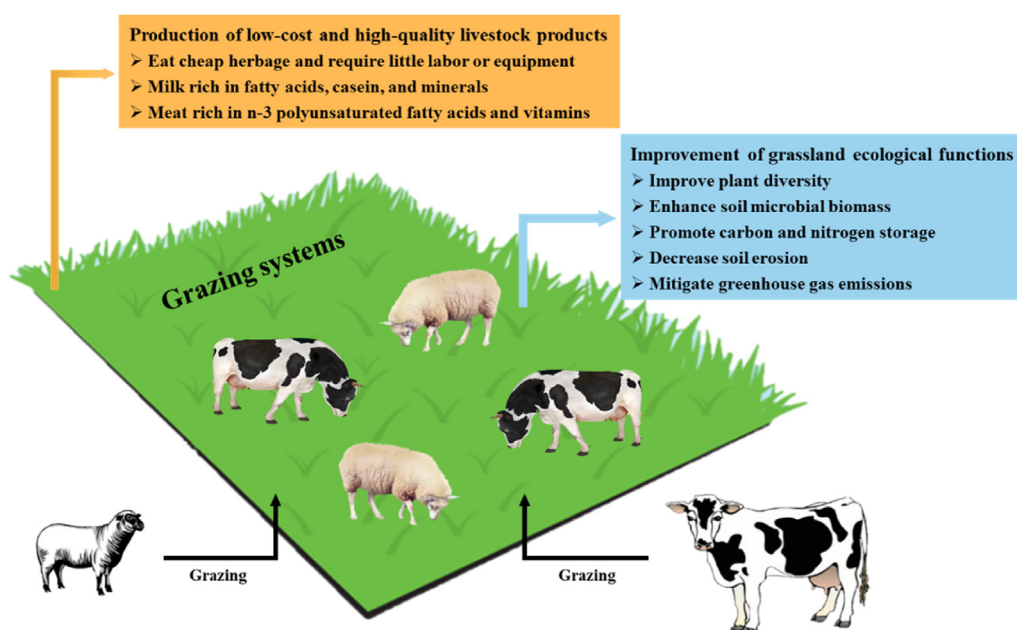


Fig. 1. Multiple benefits of grazing systems for humans: production of low-cost and high-quality livestock products (orange box) and improvement of grassland ecological functions (blue box). Grazing systems are considered to have the potential to play a key role in increasing livestock production and decreasing pressure on ecosystems.

higher diversity and ecosystem multifunctionality (Wang et al., 2019). Soussana et al. (2007), who accounted for greenhouse gas budgets at nine European grassland sites, found that grasslands have the potential to offset a significant proportion of global emissions of greenhouse gases as a result of livestock grazing. These findings have significant implications for achieving carbon neutrality and carbon peaking.

Altogether, integrating grassland grazing into existing livestock farming systems in China will undoubtedly meet the increasing human demand for high-quality foods and valuable ecosystem services.

3. Challenges to developing grassland-based ruminant farming systems

Despite the potential positive contributions to humans, grassland-based ruminant farming systems in China still face severe problems, such as low production output (Wang and Ba, 2008), greenhouse gas emissions caused by ruminants due to low-quality forage feeding (Audsley and Wilkinson, 2014), and grassland degradation caused by overgrazing (Suttie et al., 2005). We determined that the key reason for the emergence of these problems lies in the lack of knowledge and techniques for integration of nutrition manipulation and grazing manipulation. In grassland grazing systems, herbivore foraging behaviors are a central feature in the animal–plant interface (Agrawal, 1998). Herbivore foraging selection can directly influence plant community composition and diversity by changing competition among plants, affecting grassland ecological processes and ecosystem functions. Simultaneously, foraging selections of livestock under grazing conditions directly determine the nutrient supply resulting from grazing and forage resources, which are essential for nutrition management decisions. Therefore, accurately determining the diet selection of grazing ruminants relative to available herbage is necessary for future developments of these techniques. However, complex variables (see Sections 3.1, 3.2, 3.3, and 3.4.) create significant challenges for accurately predicting the foraging selection behaviors of ruminants under grazing conditions, making predictions extremely difficult. The challenges we explore are not exhaustive but are focused on key factors in developing sustainable grassland-based ruminant farming systems.

3.1. Animal factors

Animals may selectively adjust their dietary composition according to their individual experiences, nutritional status, and physiological status. Previous studies have shown that ruminants tend to choose specific plants and plant parts (leaf vs. stem) when grazing (Duncan and Young, 2002; Miller-Cushon and DeVries, 2017). Decisions about what to eat are based on expected rewards and previous experiences, affecting an animal's food preferences (Provenza et al., 2015). *In utero* and early life experiences of livestock may alter food preferences through elusive epigenetic effects that drive the voluntary forage intake of animals later in life (Villalba et al., 2015). For instance, Chadwick et al. (2009) found that lambs exposed to saltbush (*Atriplex* spp.) *in utero* grew faster and handled greater salt loads than lambs born from ewes grazed on monocultures of introduced grasses. Wiedmeier et al. (2012) demonstrated that cattle exposed to high-fiber forages early in life showed higher nitrogen retention and greater abilities to digest fiber during adulthood than cattle reared on low-fiber diets. Available evidence has also suggested that ruminants selectively balance their diet according to their nutritional requirements. For instance, grazing ruminants maximize their energy intake (to meet energetic demands) through selective feeding on forages, during a

day (Wallis de Vries, 1994), or within a specific feeding schedule (Fortin et al., 2002). Mineral-deficient cattle and sheep have been observed eating soil, licking urine patches, eating fecal matter, or eating dead rabbits, whereas animals without mineral deficiencies may sniff or lick these items but rarely consume them (Wallis de Vries, 1994; Villalba et al., 2008). Furthermore, ruminants may selectively feed based on their satiety and changing physiological needs, such as growth, lactation, pregnancy, parturition, and weaning (Miller-Cushon and DeVries, 2017).

3.2. Plant factors

Plant species growing in pastures also influence dietary selections made by grazing ruminants. Herbivores selectively consume individual plants based on their chemical composition, determined by secondary compounds, nutritional ingredients, and flavor substances. Typically, herbivores prefer to feed on plants containing only modest amounts of secondary metabolites. In small quantities, these compounds (e.g., tannins) reduce bloating and improve protein utilization, immune responses, resistance to gastrointestinal nematodes, and reproductive efficiency (Niezen et al., 2002; Min and Hart, 2003; Barbehenn and Constabel, 2011). However, excessive volumes of secondary metabolites in grassland plant species limit the forage chosen for ingestion by grazing livestock. For example, goats selectively reduce their intake of forages with a greater composition of secondary compounds such as tannins (Provenza et al., 1990). Lambs choose to reduce meal size and increase meal intervals when their diet is high in terpenes (Dziba and Provenza, 2007). Animals generally forage based on flavor profiles and nutrient content, especially when consuming different components of available plant anatomy (Galyean and Gunter, 2016). The spatial distribution of plant populations, plant species richness, and spatial relationships among different plant species in natural grasslands affect livestock foraging behaviors. Specifically, sheep increased consumption of high-preference species when low-preference species followed a clumped distribution rather than a random distribution (Wang et al., 2010a; Huang et al., 2012, 2018). High plant species richness enhanced the frequency that animals switched diets and weakened the ability of herbivores to choose food, increasing foraging costs and interfering with the herbivore's choice of foraging (Wang et al., 2010b). Herbivores consumed the largest number of palatable plants when 3 plant species were segregated into 3 patches independent of each other. In contrast, the total forage intake of herbivores for all plant species was reduced when the 3 species were homogeneously distributed through patches in a spatially equal neighbor relationship (Wang et al., 2010c).

3.3. Environmental factors

Local environments can influence dietary selections by grazing livestock. Extensive studies with pen-fed ruminants have shown that the ambient temperature affects feeding willingness (Young et al., 1989; West et al., 2003; Mader, 2003); however, very little empirical data is available describing the mechanisms affecting herbage intake in grazing ruminants under variable temperature management. Nonetheless, the physiological consequences of heat or cold stress may be similar for ruminants under housing or grazing. In beef cattle, feed intake increased at temperatures from -15 to 28 °C (FASS, 2010) but decreased at temperatures above 28 °C (NRC, 1987). For grazing ruminants, behavioral responses (such as reduced grazing time) amplified the effects of temperature stress on herbage intake under heat and cold stress (Galyean and Gunter, 2016). Studies examining the relationship

between temperature stress and foraging willingness have primarily exhibited inconsistent results. Adams et al. (1986) observed significant reductions (approximately 40%) in the herbage intake of grazing cattle under acute cold stress, whereas Beverlin et al. (1989) found only minor changes in herbage intake for cows experiencing changing temperatures (from 8 to 16 °C). Due to the inconsistent results, whether or not temperature stress affects forage intake in grazing ruminants remains ambiguous. The most relevant measurements to date are also relatively short-term, making it difficult to make recommendations on adjusting intake predictions. The effects of ambient temperature on forage intake may also be amplified by other environmental factors, like wind or precipitation conditions. For instance, wind velocity exacerbated the effects of low temperatures on grazing ruminants during winter but could help alleviate heat stress in summer (Mader, 2003). Previous studies also reported that rainfall events temporarily reduced the intake of grazing cattle by 10% to 30%, decreasing the cattle's average daily gain (NRC, 1981; Morrison et al., 1970). In addition, terrain plays a principal role in the forage selection of grazing livestock (Bailey et al., 2015; LarsonPraplan et al., 2015). When examining geographic and environmental factors affecting livestock feeding behaviors, cattle tended to avoid foraging on pastures with slopes greater than 10% inclines during grazing trials, and the number of grazing animals decreased as the slope increased. On slopes with a greater than 60% incline, almost no animals were found foraging (Corbett et al., 1961; Cook, 1966; Gillen et al., 1984). The location of water sources and social behaviors also affected foraging selection by grazing livestock (Smith et al., 2021).

3.4. Others

In addition to variable environmental factors, grazing regimes established by managers are also vital components of estimating forage intake in grazing animals. Kitessa and Nicol (2001) found that cattle continuously co-grazed with sheep showed a lower herbage intake than those rotationally co-grazed with sheep. Pérez-Ramírez et al. (2008) demonstrated that decreased grazing time of dairy cows strongly increased the pasture intake rate and decreased the foraging selectivity relative to available herbage. Congruently, dairy cows were more motivated to forage when receiving a low-supplement feeding regime. Furthermore, Savian et al. (2020) found that the sheep undergoing rotational stocking exhibited an increase in daily herbage intake and improved bite rates compared to those under traditional rotational stocking management, suggesting that rotational stocking maximized the herbage intake and optimized the grazing time of sheep.

Nevertheless, the factors influencing livestock dietary selections are also constantly changing (Guo et al., 2021), as grazing animals are foraging in a dynamic world. Herbage production, grassland community composition, and plant chemical composition fluctuate considerably in response to changing environmental and climatic conditions (Gillen and Sims, 2006; Ponce-Campos et al., 2013). This perspective has been supported by a longitudinal study of arid rangelands (Khumalo and Holechek 2005). Over the 37-year study period, herbage production varied annually between 4% and 307% of the median value. Simultaneously, temporal–spatial variations in the herbage's chemical composition, richness, evenness, and biomass led to heterogeneity. As a result of grazing, preferred plants and specific parts of the plant's anatomy are removed from the landscape over time, leading to continuous changes in the plant community composition within pasture environments (Bohman and Lesperance, 1967). The complex influencing factors, combined with continuously changing grassland herbage resources (both temporally and spatially), make foraging selections of grazing ruminants extraordinarily complex and unpredictable.

4. Future directions for developing grassland-based ruminant farming systems

In the future, continued research is necessary to clarify and explore the mechanisms underlying foraging behavior, thereby helping us better predict grazing ruminants' diet selection. Farmers, landowners, and livestock managers have an obligation to embrace vital agricultural and technological advances and establish new nutritional assessment methods for grazing ruminants. Implementation of nutritional intake assessments based on foraging selection behaviors assessment will allow stabilization and increased production in livestock agribusiness. Consequently, our knowledge regarding the nutritional requirements of grazing ruminants requires greater refinement (Tedeschi et al., 2017). Many additional elements (free-traveling behavior and constantly ambient temperature) have been identified to affect the nutritional requirements of grazed ruminants (Shinde and Karim, 2007; NASEM, 2016), so knowledge gleaned from animals kept indoors cannot be extrapolated to ruminants in outdoor pasture environments. Further data collection and longitudinal studies are necessary (from grazing conditions) to build mechanistic models of the nutritional requirements of grazing ruminants in terms of energy, protein, minerals, vitamins, and water.

Continued research should focus on the critical factors controlling grassland ecological and productive functions. Biodiversity has been identified as the primary determinant of grassland ecosystem services and functions (Tilman et al., 2012). Experimental studies have shown that the stability and functionality of grassland ecosystems require high plant species diversity and multi-trophic species diversity for co-regulation like that of belowground soil microbial diversity and aboveground community diversity (Lefcheck et al., 2015; Soliveres et al., 2016). Improving grassland biodiversity by systematically managing grazing practices is critical for grassland ecological service advancement. Therefore, future studies should target identifying mechanisms of grassland biodiversity maintenance and grazing regulations on grassland biodiversity, offering a scientifically reproducible basis for guiding grazing manipulation practices (grazing intensity, grazing livestock types, and grazing regimes and modes).

It has long been recognized within livestock production practices that rumen microbial communities play an essential role in improving ruminant production and health. The rumen microbiome, consisting of bacteria, protozoa, fungi, archaea, and viruses, composes a sophisticated symbiotic network essential to the maintenance, immune function, and overall production efficiency of the host ruminants (Cammack et al., 2018). Digestion performed by the rumen microbial community accounts for up to 70% of the total dietary energy in ruminants. The symbiotic metabolic operation between a ruminant host and the rumen microbiome results in many end products (synthesized by microbial fermentation) critical to other biological processes, including developing the rumen epithelium and establishing the immune system (Flint and Bayer, 2008). Ergo, improving our understanding of rumen microbial ecology in grazing ruminants promotes enhanced animal production efficiencies. Considering nutritional manipulation (concentrates and functional additives supplements) for grazing livestock should also be a management option to optimize rumen microbial communities.

Ultimately, this in-depth examination of livestock grazing management and nutritional practices aims to provide a blueprint for developing sustainable, grassland-based ruminant farming systems by integrating animal behavior analysis, animal nutrition principles, and grassland ecology, to achieve “win–win” outcomes for grassland ecological/ecosystem functions and livestock production policies (Fig. 2).

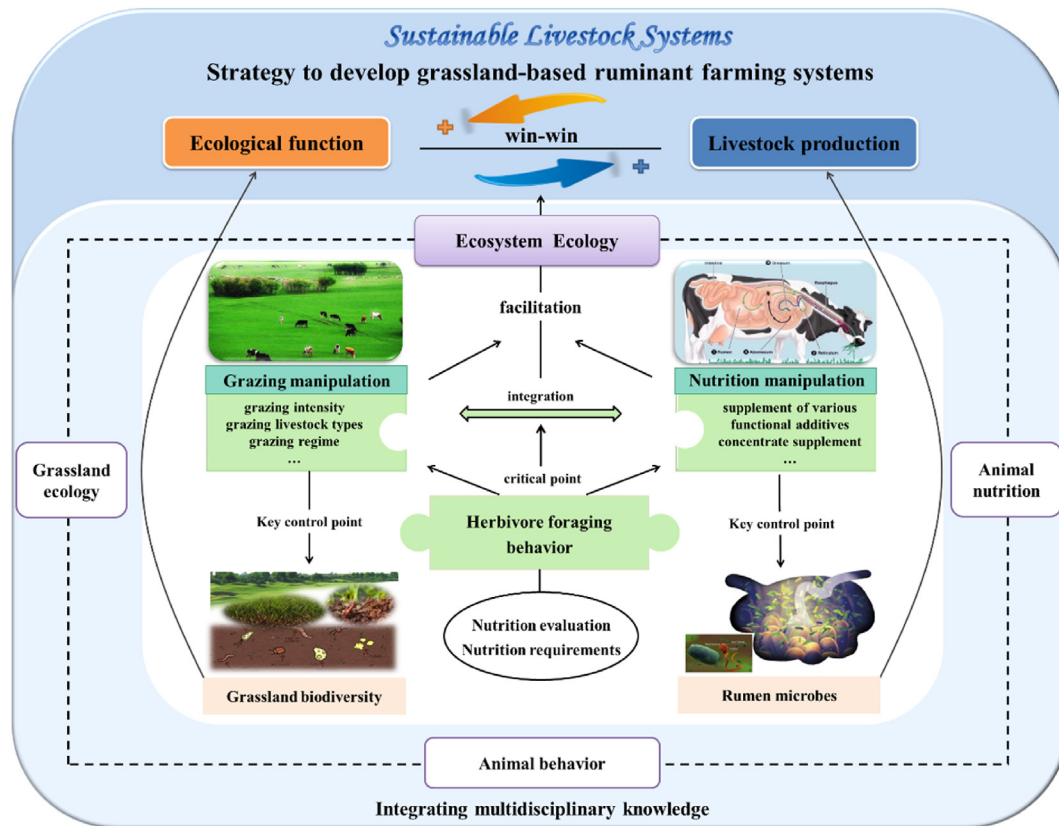


Fig. 2. Strategy for the future development of the sustainable grassland-based ruminant farming systems. The development of the systems requires consideration of how to ensure the effective production of livestock and maintain the ecological functions of grasslands. Firstly, we must clarify the underlying mechanisms of foraging behavior in herbivores, which is essential for guiding potential grazing and nutritional manipulations. Secondly, we must develop updated nutrition evaluation methods and establish nutrition requirement standards for grazing ruminants, thereby defining their nutritional status. Finally, we must implement grazing and nutrition manipulation based on foraging behavior and nutritional status of ruminants, thereby achieving a win–win situation between high-quality livestock production and environmental goals. Biodiversity is the major determinant of ecosystem functioning and stability. Future studies should focus on scientifically manipulating herbivore grazing modes to maintain and improve grassland biodiversity and ultimately achieve grassland ecosystem multifunctionality. Rumen microbes play an essential role in improving ruminant production and health. Hence, future research should optimize rumen microbial communities of herbivores by scientific nutrition manipulation to create efficient ruminant production.

Author contributions

Xin Jiang: Writing-Original draft preparation; **Ling Wang:** Writing-Review & Editing, Project administration and Funding acquisition. All listed authors have made substantial contributions to the research and publication.

Declaration of competing interest

We declare that we have no financial and personal relationships with other people or organizations that can inappropriately influence our work, and there is no professional or other personal interest of any nature or kind in any product, service and/or company that could be construed as influencing the content of this paper.

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