REVIEW

GRASSLAND AGRICULTURE IN CHINA—A REVIEW

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KEYWORDS

food security, ruminant agriculture, herbivove agriculture, crop-livestock interaction, energy balance analysis

HIGHLIGHTS

- Grassland-based livestock production systems cover large areas in China.
- China is facing degradation of rangeland and has great shortage of forage.
- Five types of mixed crop-livestock systems in China described.
- Improving crop–livestock integration requires S&T and policy supports.

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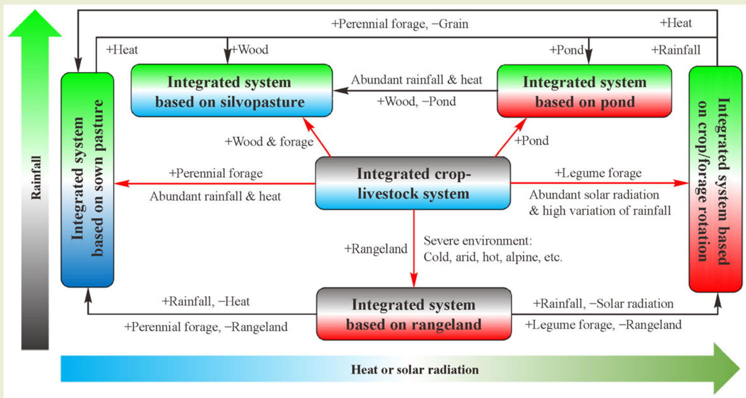
GRAPHICAL ABSTRACT



ABSTRACT

Interactions between crops and livestock have been at the core of the evolution of many agricultural systems. In this paper, we identify the development and characteristics of mixed crop-livestock systems, with a focus on grassland-based systems, as these cover large areas in China, and face several challenges. Following the transition from the original hunting and foraging systems to a sedentary lifestyle with integrated crop-livestock production systems some 8000 years ago, a range of different mixed systems have developed, depending on rainfall, solar radiation and temperature, culture and markets. We describe 5 main types of integrated systems: (1) livestock and rangeland, (2) livestock and grain production, (3) livestock and crop – grassland rotations, (4) livestock, crops and forest (silvo-pasture), and (5) livestock, crops and fish ponds. Next, two of these mixed systems are described in greater detail, i.e., the mountain-oasis-desert system and its modifications in arid and semi-arid regions, and the integrated crop-livestock production systems on the Loess Plateau. In general, crop-livestock interactions in integrated systems have significant positive effects on crop production, livestock production, energy use efficiency and economic profitability. We conclude that improved integration of crop-livestock production systems is one of the most important ways for achieving a more sustainable development of animal agriculture in China.

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1 INTRODUCTION

Changes in the interactions between crop production and livestock production have been a key driver in the evolution of agricultural systems. The diversity of agricultural production systems mainly depends on interaction patterns between crop and livestock sectors. Integrated crop-livestock production system is a vital component in global agriculture. These integrated or mixed crop-livestock systems include sown grassland-based and rangeland-based systems, which play an importance role in the supply of animal-source food in the world[1]. Grassland-based systems support about 70% of the total global sheep and goat production, and a significant percentage of the total global dairy and beef production[2].

During the last 100 years, with the advance of mechanization and the use of mineral fertilizers and agrochemicals, the structure of crop and livestock production systems has changed worldwide[3–5]. The grassland-based livestock systems in semi-arid areas face many challenges now. Large areas of natural rangelands have degraded. Meanwhile, the area of improved-reseeded rangeland is still small, and herbage yield and quality have not much increased during the last decades, in contrast to many arable and vegetable crops. As a consequence, the development of grassland-based livestock production has been limited, especially in semi-arid areas in China.

This paper firstly summarizes the main challenges of grassland-based livestock production in China. Secondly, the diversity of integrated, mixed crop and livestock systems is reviewed and described, and the possible options for improving grassland-based livestock production systems are discussed.

2 CHALLENGES OF GRASSLAND-BASED LIVESTOCK PRODUCTION IN CHINA

The animal food consumption is expected to continue growing in the coming years, in particularly in developing countries, such as China[6]. Per capita meat consumption from ruminants in China is relatively low currently. Per capita beef consumption is 4.86 kg, while the world average is 9.65 kg and the consumption in the developed countries 10.3 kg. Although per capita milk consumption in China has increased rapidly from 7 to 29 kg over the last 20 years, it is still lower than the world average of 108 kg[3]. The growing demand on ruminant-sourced food gives pressure on the natural ecosystems, including the grassland ecosystems.

One of the key challenges is degradation of rangeland in China. About 41% of all agricultural and natural land is occupied by rangeland, 14% by cropland, 22% by woodland, and 23% is desert[7,8]. However, rangeland has suffered from serious degradation for the past several decades as a consequence of frequent and strong anthropogenic activity (e.g., overgrazing and land-use change to cropland, road, township, etc.) and large-scale environmental changes (e.g., climate change, etc.). Degradation of rangelands proceeds at a rate of 2 $\mathrm{Mha \cdot yr^{-1}}$, which is equivalent to an annual loss of 0.5% of the grassland biome area in China[3].

Another challenge is deficiency of sown grassland and of improved-reseeded rangeland (with more productive and resilient species). The improved rangeland and sown grassland are vital for enhancing herbivore production. In developed countries, animal production ranges from 0.02 animal production units (APU)$\cdot \mathrm{ha^{-1}}$ in some tall grass prairie to 1.94 $\mathrm{APU \cdot ha^{-1}}$ in semi-arid rangelands, such as the Kansas and Patagonian (Table 1). Animal production density is relatively high in China, e.g., in the typical steppe of Xilingol (0.40 $\mathrm{APU \cdot ha^{-1}}$), desert steppe of Ulanqab (1.62 $\mathrm{APU \cdot ha^{-1}}$) and meadow steppe of Hulun Buir (2.03 $\mathrm{APU \cdot ha^{-1}}$). However, the proportion of sown grassland to rangelands or to croplands in China is lower than that in other countries (e.g., Argentina, Canada and the USA)[4]. There is clear lack of herbage feed for local livestock production in these regions. The mean economic benefit derived from animal productivity of rangelands in China (109 $\mathrm{USD \cdot ha^{-1}}$) was lower than that of rangelands in the UK (1979 $\mathrm{USD \cdot ha^{-1}}$), USA (527 $\mathrm{USD \cdot ha^{-1}}$), Argentina (514 $\mathrm{USD \cdot ha^{-1}}$), and Russia (368 $\mathrm{USD \cdot ha^{-1}}$)[9]. The difference in animal productivity can mainly be attributed to the low-productivity of the rangeland and the shortage of sown pastures in Chinese agriculture[10]. From 2013 to 2017, the import of alfalfa increased from 0.76 to 1.5 Mt with an average annual growth rate of 19% and accounts for 87% of the total current alfalfa consumption in China[10]. The relatively low profits from livestock production in pastoral systems results in a lack of initiatives among farmers to improve the management of rangeland.

In most areas of north China, livestock graze on rangeland throughout the year. Livestock nutrition is mainly reliant on the forage supply from rangeland. Herbage dry matter yields and nutrient contents have a great seasonal variation, whereas animal nutrient requirements are relatively constant throughout the year. There is a large gap between forage supply and livestock requirements during the cool or dry season (Fig. 1) when only poor-quality crop straw and a small quantity of forage hay are available. This forage supply deficiency can be balanced by either reducing the number of livestock kept over winter (or drought)

Table 1 Agricultural land for herbivore production

Area	Rangeland type	Animal production (APU·ha^{-1})	Sown grassland/rangeland	Sown grassland/cropland
Utah, USA	Sagebrush rangeland	0.39	0.015	0.232
New Mexico, USA	Short grass prairie	1.44	0.012	0.274
Kansas, USA	Tall grass prairie	0.02	0.079	0.045
North Dakota, USA	Mixed prairie	0.57	0.068	0.030
Saskatchewan, Canada	Mixed prairie	0.83	0.195	0.022
Patagonian, Argentina	Semi-arid rangeland	1.94	0.011	0.508
Ulanqab, China	Desert steppe	1.62	0.000	0.000
Xilingol, China	Typical steppe	0.40	0.009	0.321
Hulun Buir, China	Meadow steppe	2.03	0.006	0.058

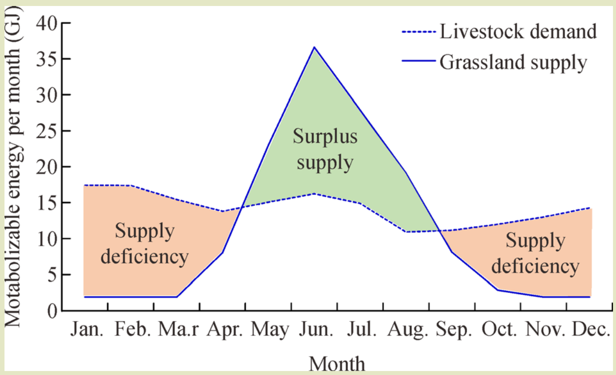

Fig. 1 Feed balance in a sheep grazing system in north China[11].

or by reducing livestock productivity. In current farming systems, the effect of overgrazing on rangeland was found to be aggravated in winter and spring (or in drought season) because there is no essential support from forage crop production[3].

3 GRASSLAND-BASED LIVESTOCK PRODUCTION SYSTEMS

3.1 Evolution of integrated crop–livestock production systems in China

The relationship between crops and livestock production constitutes the main stream of agricultural evolution. From the original hunting and foraging system, the evolution of agricultural systems has gone through six main stages (Fig. 2). In the Paleolithic Age, fishing, hunting and gathering dominated human food acquisition[3]. The Neolithic age was the beginning of late society and agriculture, which accelerated the development of human society[12]. Crops and livestock species were gradually domesticated and managed by humans[12]. In the late Neolithic Age, livestock production was partly separated from the original integrated crop-livestock production system during the first substantial social division of labor. Humans had moved into the era of metals[13], and the separation of livestock production and crop production developed. This stage was a feudal society in which productivity depended on intensive farming and self-sufficient small-scale peasant economy. In extensive integrated crop-livestock system, there was a shortage of external input. The intensive specialized production system began with the industrial revolution in developed countries and after World War II in developing countries, and this system mainly included fattening barn feeding. Mechanization started to be implemented in crop production. Intensive integrated crop-livestock system first started in Europe and North America, and along with it, the awareness of the importance of sustainable development arose. This has turned agriculture in the direction of improving productivity, environmental sustainability and agricultural diversity.

Climate and local population pressure are important parameters for the development of extensively managed agricultural systems, such as rangeland-based livestock production[12,14,15]. The development of intensive agricultural systems is mainly driven by population pressure, markets, advance in science and technology[15,16]. Specialized production system increased system productivity in four stages (Fig. 2): (1) original production systems depended on human power; (2) extensive production systems depended on livestock power; (3) intensive production system depended on mechanization using fossil fuels; and (4) specialized system depended on green energy in future.

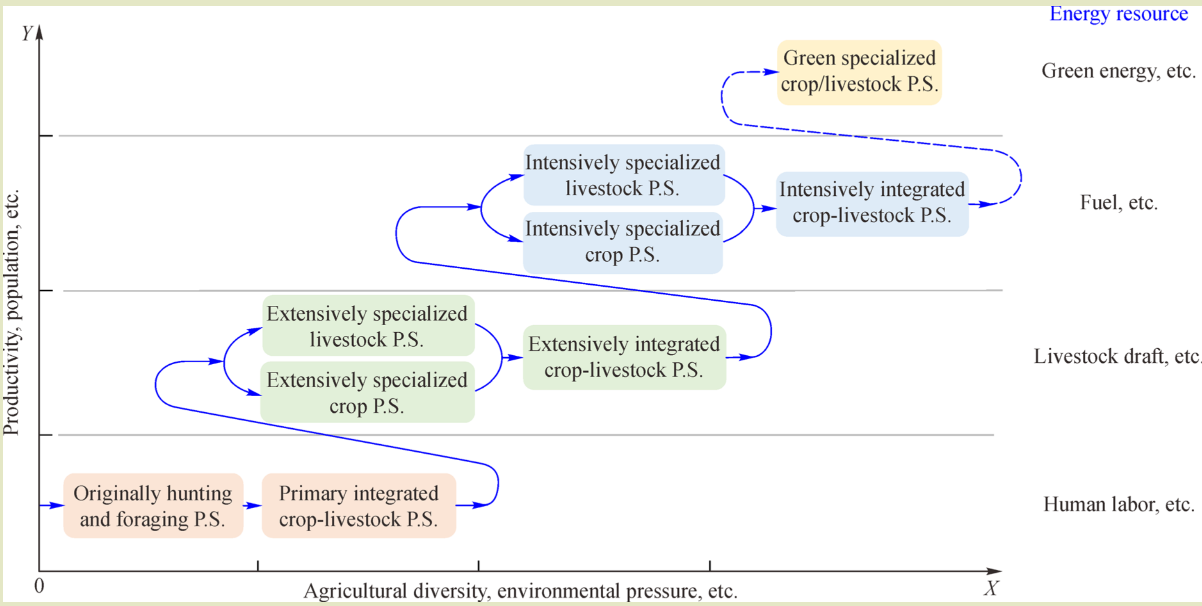

Fig. 2 Evolution of integrated crop-livestock production system, as function of environmental pressure (*x*-axis) and productivity (*y*-axis)[8]. The column on the right-hand side indicates the dominant external energy sources. P.S., production system.

3.2 Nature and evolution of grassland-based systems

Grassland-based or pastoral systems have four production subsystems or compartments: pre-plant production, plant production, animal production, and post-processing production[17]. In pre-plant production, ecological and natural landscape elements are the main sources. The main objective of plant production is to produce forage and its byproducts. Ruminants are at the core of animal production in pastoral systems; by integrating plant and animal production, the solar energy captured by grasses is transferred into animal products. The objective of post-biological production is to process and circulate the animal products to markets.

The integration of crop-livestock in grassland-based systems can be considered as phases of a successional process under the influence of the interaction between biotic (e.g., forages, cereal, ruminants and rodents), abiotic (e.g., rainfall, heat, topography and atmosphere) and social factors (e.g., policies, grasslant management and labor allocations) (Fig. 3). Interaction patterns of crop and livestock are the basis of differentiating these integrated systems[8]. The adaptive management of the interactions between livestock production and crop production will determine the stability of integrated farming systems. Increasingly hot and dry periods may be disastrous for farming systems when livestock and crops are not able to adapt to climate change[18]. Climate change will induce natural selection of new breeds of livestock and new crop cultivars.

Integrated crop-livestock system may develop in two directions, with convergence and divergence pathways in space and time: (1) longitudinal evolution, through evolution in time; and (2) transversal evolution, through spatial (regional) differentiation. Regional distribution of natural resources is a dominant factor influencing the composition and interaction of plants and animals in grassland-based systems. The difference between productivity level and social demands leads to the formation of different types of integrated systems in different agroecoregions. The original systems along the line of rainfall and temperature have transformed into five distinct types of integrated crop-livestock production systems in China, with different proportions of rangeland, grain crops, crop/pasture rotations, silvopasture and ponds (Fig. 3). These are further discussed below.

3.2.1 Integrated systems based largely on rangeland

This system is predominant in arid areas (with mean annual rainfall below 250 mm) of northwest China, but are also in central and west Asia, middle and south USA, most of Australia, central and north Africa. In this system, the coupling of mountain-desert-oasis landscape elements is important. This system also exists in some semi-arid areas (with mean annual rainfall between 250 and 500 mm), including the steppe in the Eurasian Continent, the short-grass and mixed-grass prairies in north American, the pampas in south American and the savanna in Africa. The rangeland-based system exists in the Qinghai-Tibetan Plateau of China and other high altitude or latitude areas

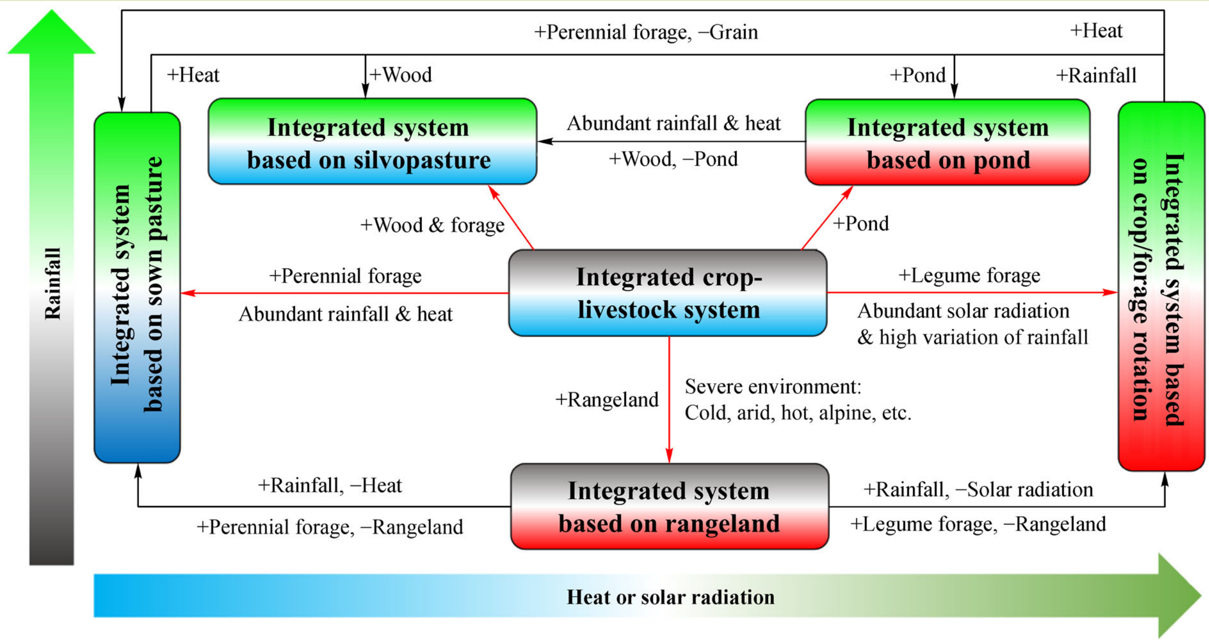

Fig. 3 Succession of integrated crop-livestock production system[8], as function of solar radiation intensity and temperature (*x*-axis) and rainfall (*y*-axis), leading to 6 distinct integrated crop-livestock production systems in China.

with large consists of tundra, alpine steppe and alpine meadow (Table 2). In Central Asia, about 45% of the total land area is rangeland, where typical landscapes are mountains, deserts and oases[19].

Rangelands and livestock interact with each other in five ways: (1) livestock graze in rangelands throughout the year; (2) livestock often graze the fallow cropland and stubble cropland after crop harvesting; (3) livestock supply draft power and manure for crop production; (4) crop residues and forage crops are used by livestock in the cold season; and (5) in a year with abundant rainfall, herbage is harvested in rangelands and processed into hay to feed animals during the cold season. There is a flow of nutrient elements from rangeland to cropland, because livestock graze in rangelands during the day and often stay in fallow cropland overnight, near the homestead, or grazed in rangelands during the day and stay overnight in corrals or feedlots, and the collected excrements are then applied to cropland. These extensive rangeland systems have low input of external resources and often a high ecological efficiency.

3.2.2 Integrated systems based on grain crops

This farming system is a classical mixed farming system in China and conducted on the plains and in oases surrounded by desert, where cropping activity is feasible because of sufficient rainfall or because of the availability of irrigation water (Table 2). These systems often have cash crop production (e.g., cotton). The interaction between crop production and livestock production mainly occurs in the following four ways[8]: (1) crop residues and grains are fed to livestock throughout the year in variable proportions; (2) livestock supplies manure and draft power (especially in extensive systems in developing regions); (3) livestock grazes the fallow cropland, stubble cropland, and rangeland; (4) livestock sometimes grazes small grain crops, such as wheat, barley and rye as multipurpose crops used for ground cover, energy, grain production and forage. The incorporation of small grain crops into these grazing systems can overcome the feed gap in early spring and winter and can also exchange nutrient elements between different components of these mixed systems.

3.2.3 Integrated systems based on crop-pasture rotation

This system mainly exists in the transitional zone from the nomadic to cropping areas or from the nomadic to forest areas in China (Table 2). These areas have sufficient rainfall and appropriate temperature, and most of the original rangelands and woodlands have been transformed to cropland to cultivate crops, already a long time ago. Livestock has enriched crop rotation patterns and crop-livestock interaction pathways. The system is mainly found in monsoonal (temperate, subtropical

Table 2 Main characteristics and distribution of the five main integrated crop-livestock systems in China

System types	Distributions	Main livestock
System based on rangeland	The arid area of north-west China; the semi-arid area; Qinghai-Tibetan plateau	Sheep, goats, cattle, camels, horses, donkeys, yak (*Bos grunniens*), Tibetan sheep
System based on grain crops	The north-east China plain, the north China plain, the regional plains of the Yangtze River Middle and Lower reaches	Cattle, goats, sheep, donkeys
System based on crop/pasture rotation	The Karst region of south-west China and the Loess Plateau in north-west China	Goats, sheep, cattle, donkeys and pigs
System based on silvopasture	The south-east of China in regions between the grain production based crop-livestock systems and the pond based crop-livestock systems	Cattle, goats, pigs, ducks (*Anhina cornuta*) and chicken
System based on pond	Southern China where there is high rainfall and flat land	Buffalo, fish, pigs and ducks

and tropical) and Mediterranean climatic zones. Crop and legume rotations and herbage-livestock production are characteristic of such systems. Biological nitrogen fixation provides soil fertility and nutritious herbage during dry and/or cold seasons. Some small grain crops such as foxtail millet (*Setaria italica*) and broom millet (*Panicum miliaceum*), and some legume crops such as pea and beans are the main crops grown in the farming system, with crop residues usually fed to livestock. Frequent droughts are the main risk for crop production, especially in spring, because of large year-to-year variation in rainfall[11]. Crop and livestock production are integrated into these systems in four ways[11]: (1) forage crops and residues of other crops are fed to livestock in pens; (2) livestock supplies manure and draft power for crop production; (3) livestock grazes the stubble cropland, fallow cropland, and sparse rangeland; and (4) livestock grazes the crops after failed harvests (because of diseases and/or drought).

3.2.4 Integrated system based on silvopasture

This forest-based system is operated mainly in temperate forest areas, forest zones in high mountains, and some subtropical forest areas (Table 2). The dominant crops in these systems are wheat, soybean, maize and rice. The main livestock species are goats, buffalos, cattle and deer. There are five ways in which livestock, crops and forests interact[8]: (1) livestock grazes the harvested cropland, forage cropland and fallow cropland; (2) livestock grazes in forests; (3) livestock supply draft power and manure for crop production and timber production; (4) grain and crop residues are supplemented to livestock in pens; and (5) forests provide shade and windbreaks for both crops and grazing livestock. Forests and croplands exchange nutrient elements through livestock movement, but the net nutrient flow is directed from forest land towards cropland because farmers collect manure from the pens where livestock is kept overnight and apply this manure to cropland.

3.2.5 Integrated systems with cereals, livestock and fish ponds

Integrated systems based on ponds are located in tropical or subtropical areas with abundant rainfall (Table 2). This type of system gradually spread to inland areas, particularly in large river basins and river deltas. This farming system contributes to over half of the total production of rice, pork and chicken and most buffalo production in China. The main ruminants are goats and cattle/buffaloes. Interactions between livestock production and crop production in this system include[8]: (1) crop residues are fed to livestock; (2) crop residues, as well as livestock excrement along with some forage crops are used as resources for feeding fish and other animals in ponds; (3) livestock excrement along with pond sludge is applied to cropland as fertilizers; (4) buffalo and cattle supply draft power for crop production; and (5) livestock graze the sparse rangeland, forest and cropland after harvesting. These mixed farming systems have a key role in food production, recycling of nutrient elements and in energy exchange.

4 ANALYSIS OF TWO TYPICAL RANGELAND-BASED LIVESTOCK PRODUCTION SYSTEMS

Two typical grassland-based livestock production systems in China are analyzed in greater detail, in terms of geographic location, interaction between crop and livestock, and agronomic and socioeconomic performances.

4.1 The mountain-oasis-desert system

Mountain-oasis-desert system (MODS) is a typical grassland-based system found in arid and semi-arid regions. It has high socio-economic and ecological value in the world[20,21]. The oasis subsystem is the centre of energy intersection with high production and openness. The cropland in the oasis can be used to plant high-quality forage species for supplemental feeding of livestock that grazes in desert and mountain rangelands. The oasis subsystem drives and integrates the desert and mountain subsystems[21].

The grassland-based livestock production in the Hexi Corridor of China is an example of a classical mountain-oasis-desert system[20]. At present, the proportion of animal production in mountainous areas accounts for about 95% of the total agricultural production, whereas animal production only accounts for about 32% of total agricultural production in the oasis system (Fig. 4(a)). After the implementation of a series of improvements and better system integration through pre-plant production (ecological restauration and protection measures of rangeland both in mountain areas and desert areas), and preliminary processing of animal and plant products as well as the development of exo-biological production, total agricultural production increased, while the proportion of plant and animal production in the various subsystems changed dramatically (Fig. 4(b)). With the development of the oasis, the contribution of pre-plant production to total agricultural production was 10%, and the development of pre-plant production in the other subsystems accounted for 20%–40% of total production. In desert areas, plant production was abandoned and efforts were concentrated on the development of pre-plant and animal production. These optimizations and improved system integration realized overall benefit, which was increased by more than three times[22].

In oasis, small grain species, such as wheat, rye and barley, are high-quality forage crops which generally meet the nutrient requirements of grazing livestock[2,23]. Integrating the forage crops, cash crops and beef cattle increased the economic outputs and decreased land water consumption and improved soil health, increased soil organic carbon, and reduced the need for N fertilizers compared with those of the monocultural cotton system typical in arid region[24].

4.2 Grassland-based systems on the Loess Plateau

The Loess Plateau in China is a typical rainfed agricultural area in which the integrated crop-livestock production system is predominant. Its structure and functions show spatial differences due to rainfall gradients[25]. From north to south, three main areas can be distinguished (Table 3); the mean cropland area per farm decreases from 2.8 to 1.5 and to 1.1 ha, while the number of livestock breeding units per farm (SU, sheep unit) decreases from 34 to 20 and to 12 SU, respectively[25]. The Loess

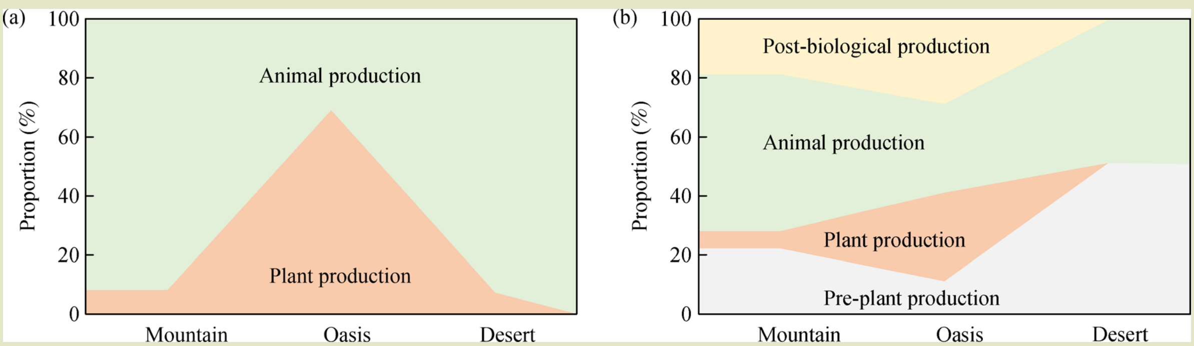

Fig. 4 Productivity of four production layers before (a) and after (b) the implementation of a series of improvements and improved system coupling[19].

Table 3 Energy balance analysis of farms in three areas of the eastern Gansu Loess Plateau[25]

Item	Crop farm			Livestock farm			Mixed farm		
	North	Centre	South	North	Centre	South	North	Centre	South
Rainfall (mm)	300	450	600	300	450	600	300	450	600
Input per farm (GJ)	68.5	146.6	73.3	140.1	75.9	193.1	41.0	21.2	34.1
Output per farm (GJ)	98.6	67.1	156	86.8	79.2	87.9	63.6	48.5	70.3
Output/input per farm (GJ)	1.4	0.5	2.1	0.6	1.0	0.5	1.6	2.3	2.1
Net income per farm (GJ)	30.1	–79.5	82.6	–53.3	3.3	–105.2	22.6	27.2	36.2

Plateau has historically made a disproportionately large contribution to Chinese food production despite its harsh climate with low and variable rainfall[4]. However, over the last 50 years, population increase and associated overgrazing of grasslands has resulted in severe erosion and soil degradation[26], and grazing of rangelands was banned across a major part of the region[27]. Considering that livestock is an important component of traditional mixed farming systems[28], significant changes will be needed to improve the structure and production of the current systems on the Loess Plateau.

The most viable agricultural enterprises on the Loess Plateau are integrated crop-livestock systems in regions with relatively high rainfall (Table 3). The net energy yield through crop production significantly increases with increasing rainfall (Fig. 5(a)), whereas the energy output/input ratio first increased and then decreased, the latter is mainly because the proportion of grain crops increased from north to south. Early season droughts may occur frequently in spring and summer on the Loess Plateau, and then crop growth and develop decreases or even completely stops, thereby limiting the system energy output[25]. The net energy yield and the energy output/input ratio of livestock production decreased as the rainfall increased (Fig. 5(b)). Furthermore, the net energy yield was negatively correlated with livestock production. The utilization of crop straw and livestock manure is also a key aspect[11]. The energy utilization efficiency of mixed farms in the study area was significantly ($P < 0.05$) higher than that of crop farms. Mixed farms here have an average net energy yield of about 29 MJ[25], while livestock producers often have a net deficiency of energy. The energy utilization efficiency of integrated crop and livestock system can be improved by 30%–40% through more smart coupling and integration of crop and livestock production. Properly integrated crop-livestock systems may also better resist the impacts of climate change and market fluctuation[29].

5 CONCLUSIONS

Grassland-based livestock production systems in China integrate social, abiotic and biotic factors. There is a large diversity in grassland-based, integrated crop-livestock systems due to regional differences in history, culture, environment, vegetation, and animals. Grassland-based livestock systems cover large areas in China, but these systems are relatively fragile and sensitive to changes in weather, climate, socio-economic conditions, and culture. As a result, the sustainability of these systems is threatened. Main challenges include degradation of rangeland due to overgrazing and climate change, and low animal production. As a result, the income of farmers relying on these systems is low. There have been a great opportunities for livestock production coupling other productions. Smartly integrating specific cash crops into these integrated crop-livestock production is suggested as an important measure to achieve a more sustainable development of the grassland ecosystems.

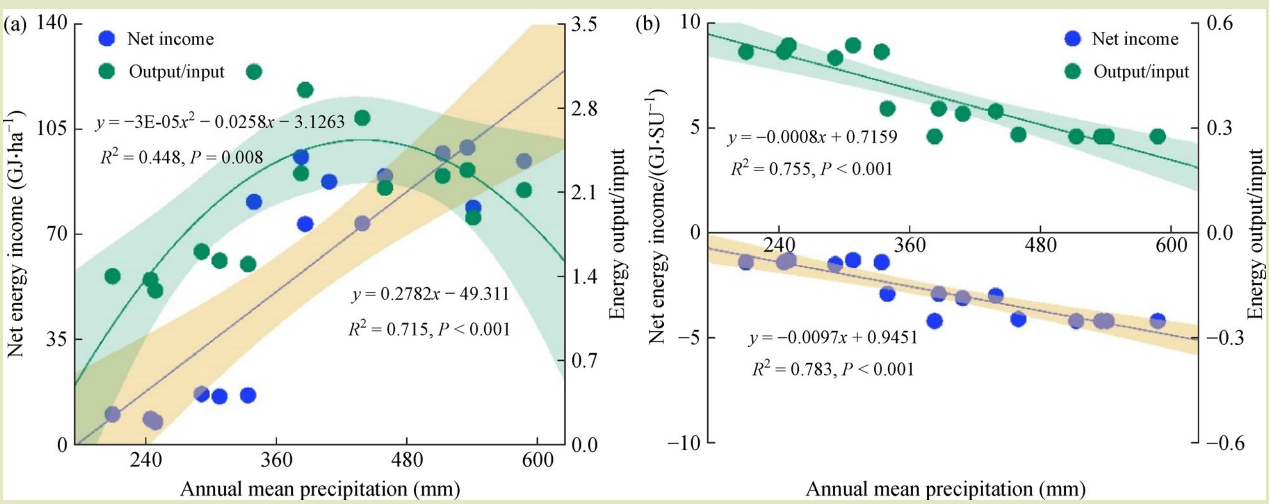

Fig. 5 Relationship between rainfall and energy balance in Loess Plateau. (a) The relationships between net energy income and energy output/input of crop production, and rainfall. (b) The relationships between net energy income and energy output/input of livestock production, and rainfall.

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Compliance with ethics guidelines

Fujiang Hou, Qianmin Jia, Shanning Lou, Chuntao Yang, Jiao Ning, Lan Li, and Qingshan Fan declare that they have no conflicts of interest or financial conflicts to disclose. This article does not contain any studies with human or animal subjects performed by any of the authors.

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