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REVIEW

Sustainable management of Chinese grasslands—issues and knowledge

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Abstract China has almost 400 Mhm^2 of grasslands, 90% of which is considered degraded to varying degrees, on which 16 million herders depend for their livelihoods and many more indirectly, along the value-adding chain. Since 1950, average stocking rates across China have increased 4-fold. National policies have focused over recent decades on finding ways to rehabilitate the degraded grasslands, to sustain livestock production from them, and to improve the livelihoods of herder households, who are among the poorest people in China. A large collaborative program commenced in the early 2000s to help find solutions to the sustainable management of grasslands. This paper summarizes key findings of many research projects, identifies where knowledge is weak and argues that the successful rehabilitation of grasslands will also require policies that provide incentives and support for herders as they move from a focus on survival to a focus on production of higher quality products, for which consumers are increasingly willing to pay. A key focus is to emphasize the improvement of animal production per head. When this is done, it naturally leads to lower stocking rates, which in turn provides the opportunities for grasslands to recover. Across a range of experiments, farm demonstrations and analyses using models, in Inner Mongolia and Gansu, a consistent result has been that a 50% reduction in stocking rates, improves net household income and starts the process of grassland rehabilitation. Rather than focusing on stocking rates, better management of grasslands could be achieved by maintaining the grasslands above critical values for herbage mass, values that help optimize botanical composition, reduce soil erosion, optimize animal growth rates and aid ecosystem functions. Managing to critical values for herbage mass is likely to be more effective than efforts to calculate sustainable stocking rates. An early summer rest is valuable for aiding grassland rehabilitation and summer productivity, but a total grazing ban (typically for 5 years) may not achieve its aims as evidence shows it may take 10–15 years to achieve a better grassland state. Less-desirable plant species often increase in degraded grasslands that are rested and grazing can help manage those species. Surveys of herders indicate they have very mixed views on the benefits of total grazing bans that are unlikely to rehabilitate grasslands to an ideal botanical composition. The current objective is to work with grasslands that herders now have and optimize the existing composition. Grazing grasslands in winter results primarily in weight loss by animals and there is now evidence of how winter grazing reduces grassland growth in the next summer. It is better to keep animals in well-built sheds and feed them better, improved feeding through the cold months is required. In addition to the application of results from national programs designed to improve grasslands, it will be important to train herders as they move from survival to production, to foster the development of better markets for their livestock products, to devise better financial support for herder businesses and to revise land tenure arrangements so that herders can expand the area of land they graze on better terms than apply at present.

Keywords China, grasslands, management, rehabilitation, stocking rate, income, system analysis

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1 Introduction

The grasslands of China are vast (400 Mhm^2); collectively they comprise one of the world's largest land-based ecosystem, are part of the extensive Eurasian grasslands, and have supported the livelihoods of millions of people over millennia. Today some 90% of the Chinese grasslands are considered degraded to various degrees[1–6]. Grassland ecosystems throughout Central Asia have similar problems. There is a common objective among herders and officials to find better ways of managing the grasslands, rehabilitate them where required and to improve the livelihoods of herder households. Concern about the condition of Chinese grasslands is longstanding[7] and particularly focused on devising better policies for their management[8]. There has been considerable research into the state and management of Chinese grasslands[9–13]. Often though, that research has focused on individual aspects of the grassland-livestock-herder system, drawing conclusions that have not been implemented as the benefits were not always clear, nor consistent with other results. While much of the past research has shown how grazing intensity affects soils and grasslands, or how plant productivity has changed, there was often no associated data on animal production to help identify the effect of intensity of grazing on livestock productivity and herder livelihoods. From 2000, a new program was developed that took a systems approach, involving many of the key grassland scientists of China with experienced researchers from Australia[14,15].

The grasslands of China are part of an agro-ecological system. This involves soils, plants, animals, climate, herders, economics, marketing and policies. It was acknowledged that sustainable solutions are more likely to be found from a better appreciation of how system components interact, including what would motivate herders to change practices that help rehabilitate grasslands and improve herder household incomes[14,16,17]. The challenge is to achieve a win-win outcome, where possible.

In this overview paper our aim is to provide some background on livestock in China and then summarize several key studies (managing degraded and reasonable grasslands, winter grazing and use of sheds, defining sustainable stocking rates, precision livestock management and achieving change) that affect the management of grasslands and the closely allied issues of improving herder household incomes. The principle guiding this overview is that ways need to be found of improving herder household incomes that give them the incentive to manage grasslands better. Herders would then change practices as they would directly benefit, though other changes could require policy changes or government payments. Various policy changes for grassland improvement over the years have not always delivered the outcomes desired, arguably in part due to limited consideration of how to also reorganize the livestock production system to improve herder household incomes[8,13]. The objective in this paper is to present key pieces of evidence, rather than an exhaustive review of all the work done on China's grasslands. An aim is to provide information of value for policy advisors and researchers. On some topics, new recommendations are now possible, but in other cases, while more is now known to help decision makers, there is still a clear need for research to find workable solutions. Areas for future research are identified. In this paper, the unit of land managed by a herder household is referred to as a farm, as this is the more widely understood term, especially since the land is now often fenced and allocated to individual households.

2 Methods

Herders are the primary land managers of the grasslands of China. Understanding why herders do what they do, and what can be changed to improve their livelihoods, is critical to developing sustainable solutions[18,19]. Through the course of the research considered here there were regular discussions with herders and the information they provided was used to structure and calibrate models of the grassland-livestock system to help understand how this system functions. Those models were then used to test the effects of changes in management practices that were then tested in practice. As the grassland-livestock system is a feed-limited system, where animals only grow during summer and lose weight through autumn, winter and spring, the models primarily analyzed the energy balance between feed supply and demand[14,20]. More data are needed though on the digestibility and metabolizable energy values of species in grassland through the year to improve the models. The models included a financial analysis to identify the potentially more profitable solutions. The more applicable of those proposed solutions were then tested in whole-farm enterprise demonstrations, where within a village, control and demonstration farms were established. The farm demonstrations became a national research program across many villages in northern and western China. In parallel with these activities were a series of local and national field experiments that aimed to understand the optimal grazing management practices for different grassland types. Many of these are still being analyzed so it is only possible to provide some general outcomes from a few, key grassland sites.

The surveys, field experiments and farm demonstrations provided much of the data needed for models and where not, the literature was used to fill information gaps. This only provided part of the information required for system analyses. In addition, we sought to understand what motivates herders, what was their understanding of constraints on their productivity, and how the financial and marketing systems affected a herder's ability to change management practices. The aim in this paper is not to report on all modeling and other studies within this program, as much will be reported elsewhere. Rather, all the information from these many sources within one large program was considered when developing the ideas and recommendations presented here.

3 China's grazing livestock

The number of livestock in China that graze grasslands has risen dramatically since 1950 (Fig. 1) and this is the central issue for this paper. The data show that when they are expressed on a sheep equivalent (SE) basis, the average stocking rate has risen 4-fold from 0.6 SE·hm^{-2} in 1950 to 2.4 SE·hm^{-2} in 2014. China now has about a billion SE. These changes had four general phases. From 1950 to 1957, there was a steep increase, then a slower rate of change from 1958 to 1984, followed by a rapid increase until 2008, but since then there has been a slight decrease in numbers.

Beef cattle, including yaks, have been the greatest contributor to total SE. These data exclude dairy cattle, as throughout the period from 1950 there were only small numbers of dairy cows on grasslands. Sheep and goat numbers are the next largest group. Due to problems in collecting these statistics[22] there are well known problems in assessing the relative numbers of sheep to goats in the earlier years of this data set, hence it is often better to consider the combined numbers of both as indicators of the relative importance of small ruminants. Sheep plus goats were about one-third of the total SE.

The 4-fold increase in average stocking rates since 1950 illustrates the problem confronting China. Arguably from 1950 to 1957 some recovery in livestock numbers probably occurred after the prior years of conflict. Unfortunately, there are no equivalent pre-1950 data sets for comparison, hence it is difficult to know what may have been the long-term livestock carrying capacity for China. However, the period 1960–1970s, after the phase of rapid initial recovery, may reflect what were considered to be prior capacities. If that was the case then current stocking rates are still, at least twice those levels. Given the recent stabilization of numbers, the acknowledgment that grasslands are degraded and an increasing focus on more animal product than maximizing animal numbers, the data on livestock numbers could suggest that stocking rates may need to be reduced by half to achieve reasonable levels of production from grasslands in line with previous historical trends. Today, the quantity of supplements, including crop residues, fed to livestock has increased and livestock are less dependent upon grasslands for production, though they probably require grasslands for maintenance. The area of grasslands has been reduced by expansion of cropping, urban development and other infrastructure. However, while some allowance for these effects would influence livestock productivity, most of these animals are still taken out to graze and the increased pressure on grasslands has been widely acknowledged as generally severe.

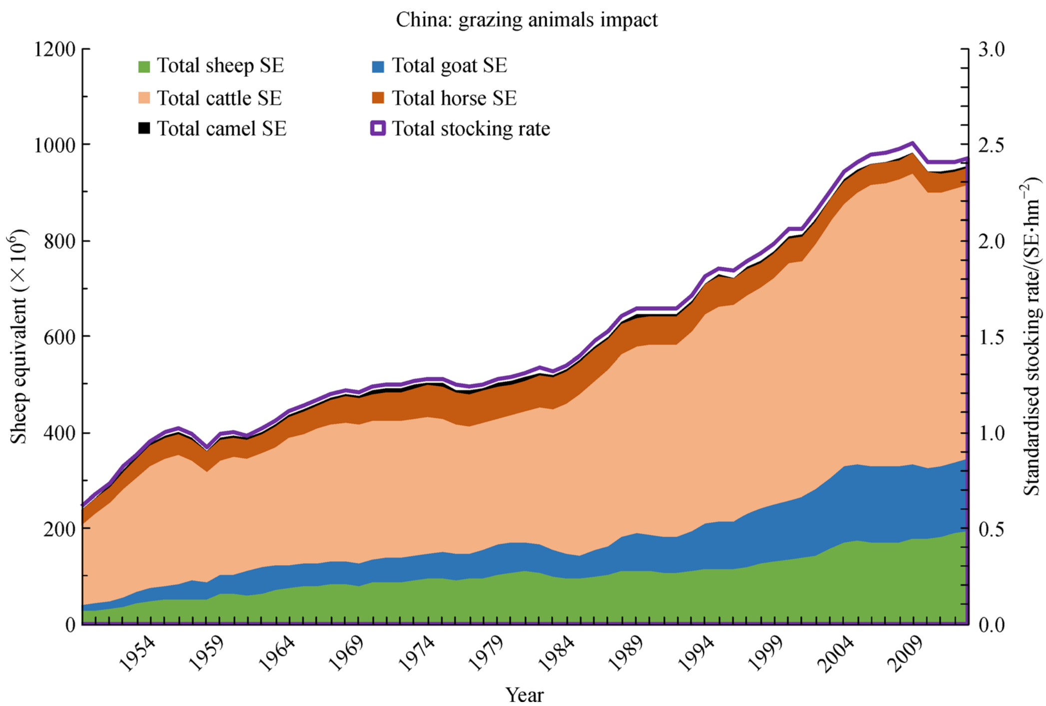

Fig. 1 Cumulative sheep equivalents for China from 1950 to 2014, for sheep, goats, cattle, horses and camels[21] and the standardised stocking rate in sheep equivalent per hectare

4 Managing degrading grasslands

The first signs of degradation in an overgrazed grassland is an increase in the proportion of less-desirable/digestible plant species compared to the more-desirable components. As overgrazing continues, total growth and quality of the grassland then declines, while the area of bare ground increases[3]. The less-desirable species will vary over time in a grassland, depending upon the stage of degradation; at first these may be species that are of lower nutritive value (with more fiber in leaves and stems, and with thorns), or are less productive, compared to other species—sometimes noxious species may increase. Less-desirable species increase in overgrazed grasslands, because the more-desirable plants are grazed first, are overused and cannot recover as effectively as in a grassland in good condition. Across China, the early, less-digestible, increasers from overgrazing are often shrubs (*Artemisia* spp.), but there can also be less-palatable grasses (*Stipa breviflora*) or forbs. Unpalatable species typically become dominant, providing almost no useful nutrition for livestock. Fortunately, only 10% of the grasslands have reached the stage where few plant species remain, bare ground dominates[3,9] and long-term exclusion of grazing is arguably the only pathway to rehabilitation, or replanting if the area involved is small. The majority of grasslands need to be brought back to a reasonable state, though it may not be possible to rehabilitate them to an ideal condition.

Where there is still a mixture of desirable and less-desirable species, and total net primary productivity is similar to grasslands in better condition, grazing is the main tool available to herders to rehabilitate the grassland. Grazing has several components, intensity when grazing, stocking rates, consumption rates, frequency of graze or rest periods, and timing of graze or rest periods[23]. The more-desirable species benefit from lower grazing intensity and tactical rest periods, while the less-desirable species can be reduced by higher grazing intensities. Where the ability of livestock to select what they eat is limited, physical damage occurs to plants from grazing, and more frequent graze periods. Plants are most sensitive to grazing when regenerating from buds or seeds, when under stress, or when flowering, as these stages restrict tillering and shoot growth.

In China, policies have been to impose partial or total grazing bans to aid rehabilitation of grasslands. Partial grazing bans apply in spring and early summer and have been particularly useful where C_4 grasses (*Cleistogenes*) have become dominant[9,24] reducing the length of the growing season. In these cases, heavy early summer grazing results in the loss of C_3 grass species (*Leymus chinensis*) which reduces the active growth period to about half that expected, as the C_4 grasses need higher temperatures for growth. Early summer grazing rests allow recovery of the C_3 species and enable more growth of all species before grazing. Grassland growth rates are directly related to the amount of green leaf, and higher growth rates through summer can result if the average area of green leaf is higher, particularly in the earlier part of the summer.

In practice, early summer grazing bans are typically based on calendar dates, assuming an average pattern in grassland growth. These practices could be refined to delay grazing until the herbage mass reaches a target value[25]. Research on the typical steppe in Hebei Province, showed that a high proportion of *L. chinensis* remained if the grassland herbage mass averaged above 0.5 $t \cdot hm^{-2}$ dry matter (DM) through summer[26]. Grassland growth rates were higher when above that target value of 0.5 $t \cdot hm^{-2}$ DM. Further research is needed to test using herbage mass as a criterion for graze or rest periods, but the benefits would be that in years of higher rainfall, grazing could start earlier than in dry years, which would help sustain the grassland. In very dry years, it may mean that almost no grazing occurs, but a consequence could be that in the following year, grassland growth is greater resulting from plants being in better condition.

Total grazing bans have been the other common technique used to aid rehabilitation of grasslands. The assumption is that succession is reversed when the more-desirable species are ungrazed. However, when the less-desirable species are long-lived perennial plants that dominate the plant community, and produce more seeds and other propagules than the other species present, and the stocking intensity is insufficient to cause livestock to eat or physically damage them, it is less certain that they will be replaced by more-desirable species within the grassland. Without any special grazing tactic, the only chance for more-desirable species to regain dominance is where those species can outgrow the less-desirable, as during a grazing rest, capture more resources and gradually reduce the incidence of the less-desirable plants. This could happen over the long-term, though only limited research has investigated this problem.

Total grazing bans normally apply for 5 years, but in the typical steppe at Xilinguole League, Inner Mongolia Autonomous Region (IMAR) it took 15–20 years for a grassland to be rehabilitated to a desirable state, in a grassland that was reasonable to start with[14]. Analyses of other data sets collected over long periods in typical steppe plots where grazing was excluded, showed that climatic changes (drier conditions) caused a shift from C_3 to C_4 species, but no significant effects in other plant functional groups[10].

A long-term experiment on the desert steppe at Siziwang Banner, IMAR has shown that *S. breviflora*, which is a less-palatable species than other grasses, increased in all plots over 12 years, unaffected by whether it was rested or grazed at three different intensities, while the more-palatable shrubs, *Artemisia* spp., only increased significantly in ungrazed or lightly grazed plots. The trajectories from 2004 to 2015, between the two principal species in this experiment shows that ungrazed and lightly grazed plots maintained close to a 1:1 ratio for most of the time (Fig. 2), whereas moderate and heavy grazing, greatly reduced the shrub component leading to dominance by the less-palatable grass. Both species declined significantly after the first year (2004) when the plots were heavily grazed through winter. In this experiment, it took 8 years before the treatment differences were clearly evident. *Artemisia* decreased when heavily grazed each summer, remained at a low level, was only exceeded by the less-palatable *S. breviflora* after about 8 years, and the general result was still a degraded grassland. After 5 years, the typical time for a grazing ban, there was no clear result from the different grazing practices. Light grazing at half the district stocking rate, resulted in more profitable animal production and the grassland in a reasonable state—as effective as a total grazing ban.

The desert steppe experiment shows where tactical grazing could be used to reduce less-desirable species. In the first year, the experiment was inadvertently grazed by a large number of sheep, which did not happen in later years. The average treatment biomass of *Artemisia* in the following summer (Fig. 2), declined from 619 (peak biomass in 2004) to 150 (peak biomass in 2005) kg·hm^{-2} DM and the *Stipa* breviflora from 162 to 45 kg·hm^{-2} DM, a 76% and 72% decline, respectively. Indicating that the heavy grazing pressure applied did not allow the animals to be selective. These data are the averages for all four treatments. Over the 12 years of this data there was no evidence that rainfall had any consistent effect on this species interaction. To make use of this tactic it is important to have more-desirable species within the grassland that could then be managed to a more dominant position, after applying heavy winter grazing, with a rest, or light grazing, in summer to keep herbage mass above a desired target. In this case, *Artemisia* would be the preferred species. This result was probably achieved by sheep physically damaging the plants, which exposed buds to cold damage and/or reduced the number of growing points, and reduced grassland growth by over 70% in the following year. More research is needed to understand and refine these tactics as the opinion is often expressed among herders and officials that grazing in winter has no impact.

Less-digestible noxious plants on the Tibetan Plateau at Gannan, Gansu were found to increase under no grazing and decrease when grazed[29] and unpublished data by Sun Yi, contrary to expectations. In addition to these results, surveys of herder attitudes have found that they do not always believe that total grazing bans help to rehabilitate grasslands[19]. Collectively these results show that total

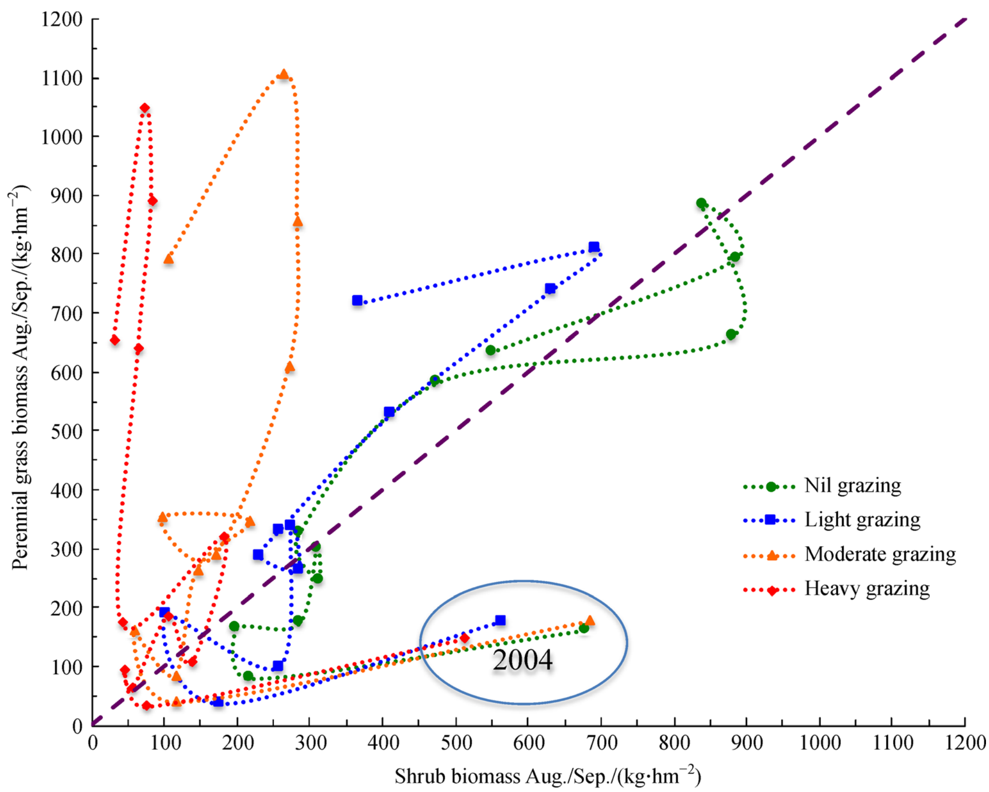

Fig. 2 Biomass trajectory over the years for the two principal species (shrubs, *Artemisia frigida*, and grass, *Stipa breviflora*) over 12 years in a grazing experiment on the desert steppe, at Siziwang Banner, Inner Mongolia Autonomous Region. 2004 identifies first measurements[27,28].

grazing bans need to be carefully considered and tailored for each circumstance. A more tactical approach is arguably needed as often low levels of stocking rate achieved as good a result as no grazing[26]. The grazing pressure needs to be heavy at times to harm the less-desirable species, and then grazing rests (bans) used at times that allow the more-desirable species to recover faster than the less-desirable ones. Research is needed to identify the times when these techniques work.

5 Winter grazing and sheds

Grazing grasslands every day through the year, including winter, has been a traditional practice across Chinese grasslands. Livestock graze on dead grassland residues, with poor quality, meadow hay or straw being the common supplements available and usually fed at a minimal, sub-maintenance, level. The low temperatures of winter, and the poor quantity and quality of grassland residues, mean that grazing animals lose 20% to 30% of their bodyweight as the energy costs of walking exceed that obtained from dead forage[30,31]. With more options to now sustain livestock through the cold months of autumn, winter and spring, a rethink of winter grazing and livestock management practices is needed.

It has been speculated that winter grazing of grasslands is not only inadequate for animal maintenance, but could also be deleterious to the grassland[14]. The data considered earlier showed that heavy winter grazing on the desert steppe grassland at Siziwang Banner, IMAR significantly reduced regrowth in the next year, and this was the first time this has been shown. Such tactics should only be used where the aim is to reduce less-desirable species in grasslands that still contain more-desirable components. The principle coming from a lot of research is to only graze grasslands when they are green and above critical values of herbage mass. Economic ways of doing this need to be investigated.

Management through winter has been aimed primarily at survival of animals, as herders were more focused on maximizing animal numbers, whereas now there is more interest in production to sell more animal product and increase household incomes. A production focus means herders need better sources of fodder and better shelter for their livestock through the cold months.

Sheds provide protection from wind chill and help to replace the lack of quality forage, reducing some of the weight loss in livestock[31]. Sheds can be categorized as traditional, warm (some modifications) through to greenhouse/modern designs, with increasing insulation, good air flow and improved livestock performance. Some sheds now incorporate methane digesters and have heaters to keep temperatures closer to 0°C. Simple shelters can reduce wind-chill, but do not control temperatures, and have been shown to be of marginal value[32].

The data obtained[32] were re-analyzed to determine how weight loss of ewes and weight gain of lambs varied with mean daily temperature in a traditional and a modified warm shed (Fig. 3). The data showed a similar response and that the responses overlapped between the two sheds. A new outcome from this work was the evidence that weight loss started above 0°C, probably a result from insufficient fodder quality, even though the animals were fed better than normal. The close interaction between ewes and lambs (Fig. 4) shows how the weight loss from ewes was contributing to weight gain by the lambs, indicating the importance of keeping the ewes in the best condition possible.

Modeling, research and herder experience has shown that keeping animals in better designed sheds in winter, even with no change in the feed supply, does improve animal performance. Across northern and western China, more fodder is now available to feed animals better through winter. Only where there is a high level of better quality winter fodder will animals get closer to satisfying their energy requirements. Grazing grasslands in winter is no longer necessary in many parts of northern and western China as warm sheds can reduce weight loss and more higher quality fodder is now available to sustain livestock. Research is needed, however, to improve the quality of crop residues and other food sources to improve livestock production.

6 Sustainable stocking rates

The challenge is to determine the sustainable stocking rate (SSR), one that rehabilitates and then maintains grasslands in a desirable state, while optimizing animal production to improve herder household incomes. This is most important in summer when grasslands and livestock are growing, and will be considered here. Winter grazing is a separate issue and was discussed earlier; it is better solved through improved feeding in warm sheds. In earlier times herders focused on maximizing survival of as many animals as they could manage, and policies encouraged more animals. With the developing markets in China, production issues are becoming more important as payments are reflecting the quantity and quality of animal products, which means production per head is now more important than per unit area. Governments want to improve the environmental services provided by grasslands. The sustainable stocking rate is then one that enhances the environmental values of the grassland and net herder incomes. This means a range of criteria need to be evaluated in order to determine the optimal SSR. It is also important to consider if SSR is the best way forward or if other criteria, such as managing on herbage mass, are more useful.

The typical steppe in northern Hebei Province has been studied in detail to define SSR. This study found that restricting grazing to summer and managing the herbage

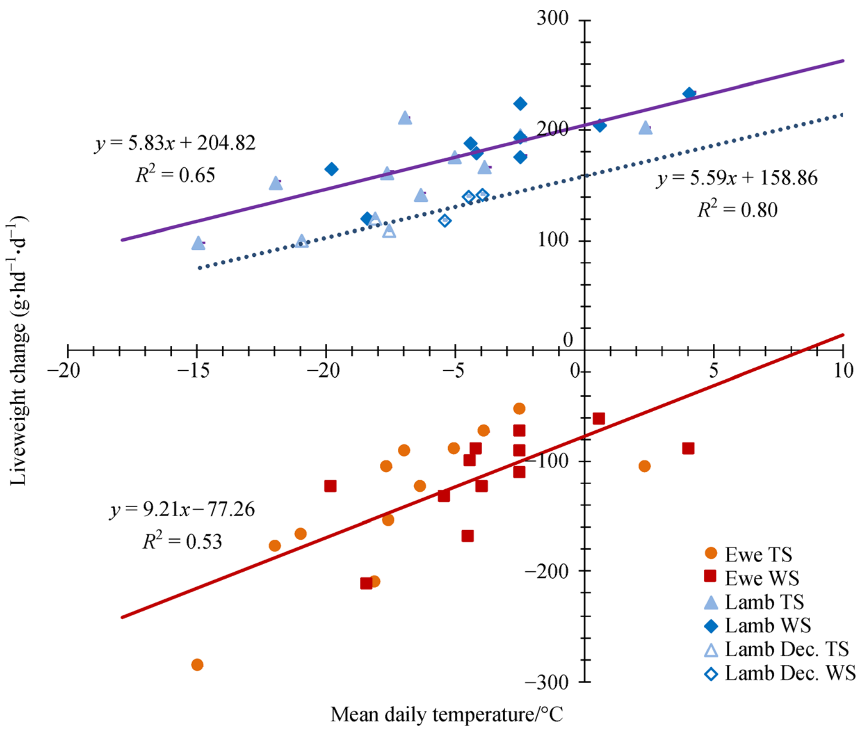

Fig. 3 Decline in daily lamb growth rates and ewe weight loss with mean daily temperatures in a traditional (TS) or warm (WS) shed (dotted line, lambs in first month after birth; data reanalyzed[32]). $g \cdot hd^{-1} \cdot d^{-1}$, gram per head per day.

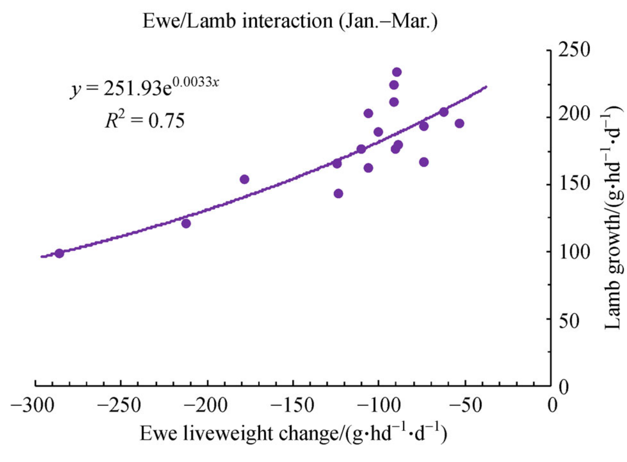

Fig. 4 Decline in daily lamb growth rates with decline in ewe weight loss—combined data from traditional and warm sheds (data reanalyzed[32]). $g \cdot hd^{-1} \cdot d^{-1}$, gram per head per day.

mass above 0.5 $t \cdot hm^{-2}$ DM maintained a desirable botanical composition, limited greenhouse gas production, and optimized grassland and animal production[26]. As treatments varied the frequency and intensity of grazing, the number of sheep equivalent grazing days (SEGD) over summer were calculated for each treatment, and the SEGD that maintained the average herbage mass above the critical value of about 0.5 $t \cdot hm^{-2}$ DM [400 sheep grazing days per hectare, equivalent to an SSR of 4 $SE \cdot hm^{-2}$ or 2.2 sheep units (SU) per hectare, as discussed later]. Sheep grazing days over summer can be a better, more flexible way to manage SSR, as the daily stocking rate can then be varied through the season until the total sheep grazing days are achieved. The estimated SSR, was found to be about half that of the district stocking rate at the time the experiment started, and toward the lower end of the range (1.8–4.0 SU $\cdot hm^{-2}$) found in other studies[9]. Similarly, in an experiment on a desert steppe[27,28] the stocking rate that was close to optimal for the grassland condition was about half the district average. Farm demonstrations have supported these conclusions[33]. In contrast, in a review of the conclusions from grazing experiments across China, it was estimated that overgrazing, i.e., the actual stocking rate compared to the SSR, varied from 27% to 89%[9]. However, many of those studies focused primarily on maximizing productivity per unit area, which is not necessarily the more profitable position, and did not consider other system components. Detailed studies are needed over the medium-term, to identify the SSRs that optimize all key functions of grasslands.

In determining SSRs, a core issue is the relationship between production per head and stocking rates. In China, the relationship between animal production per head and stocking rates has been shown to fit a linear decline in production per head as stocking rates increase[14,34]. In that model, net income is commonly maximized when the animal production per head is about 75% of the potential, equating to animal production per unit area of about 75% of the biological maximum per unit area[14]. In the Chinese literature, optimal stocking rates have often been decided as the stocking rate at the biological maximum production per unit area, without any consideration of optimizing plant species, biodiversity or financial optima[9].

To date though, there have only been a limited number of grazing experiments done in China that clearly identify an SSR. An often-proposed alternative is to calculate SSR using the formula:

$$\mathrm{SSR} = \frac{\{A^*\}(G^*U)}{\{A^*\}(D^*C)}$$

where:

• **SSR** is defined in standard units, e.g., $\mathrm{SE \cdot hm^{-2}}$, then converted to what is appropriate for a local district.

• ***A*** is the area of grassland ($\mathrm{hm^2}$). This can be included or excluded in the calculations, it is included here as sometimes the total herbage mass for the grassland at a specified scale, but only as an intermediate term, since area is then canceled out when estimating the SSR.

• ***G*** is the growth of the grassland ($\mathrm{kg \cdot hm^{-2}}$ DM). When using this formula, it is not always clear if G is defined as the standing biomass at the peak growth for the season (which can be an index for total growth), or the total growth over the growing season determined from measurements every few week, or only the biomass of palatable species. Users vary their practice and no research has been done to identify which definitions are the more useful.

• ***U*** is the proportion of total herbage to be utilized/eaten by livestock (non-dimensional). Some researchers use the difference between the amount of herbage inside and outside a grazing exclusion cage to estimate this, but the difference measured this way can be 50% to 100% greater than what the livestock may have actually eaten—this only estimates the relative difference, which may not be the same as that eaten by livestock. The methods and definitions being used need to be specified. Unfortunately, many experiments use insufficient cages to use this technique reliably—at least 50 cages per hectare (i.e., 0.5% of the total area) may be needed, depending upon grazing pressures, to overcome the natural variability in a grassland. Sampling is needed every 2 weeks to minimize losses other than consumption, and cages need to be changed at those times, not fixed in the one place. Limited research has been done in China, to define how total losses vary with grasslands, seasons and other factors. Better techniques are required for estimating U[26] based on direct modeling of consumption (rather than utilization) based on quantity and quality of forage available and animal live weight change.

• ***D*** is number of days animals will graze a given field or area (d). In China, this is best defined as the total number of grazing days on the area of grassland of interest, over the growing season in summer. Any grazing during the cold seasons when plants are not growing, needs to be analyzed separately.

• ***C*** is the consumption rate ($\mathrm{kg \cdot SE^{-1} \cdot d^{-1}}$ DM) of the livestock—best expressed per SE, SU or animal (beef) unit; C is defined as the actual average amount eaten by livestock, which can be readily estimated from the literature. It is easy to get the terms *U* and *C* confounded by not using clear definitions or precise methods. A common standard for sheep equivalent is a 50-kg sheep, neither growing nor losing weight, not pregnant nor lactating, where $C = 1\ \mathrm{kg \cdot d^{-1}}$ DM of reasonable forage[35]. An alternative definition for a SU in China is a 50-kg lactating sheep with a suckling lamb that would consume $1.8\ \mathrm{kg \cdot d^{-1}}$ DM. Sheep equivalent and sheep units are not the same. Using the differences in standard consumption rate means that 1 SE = 0.55 SU. As these different definitions are widely used, it is important to define SSR correctly, as SSR(SE) or SSR(SU). Unfortunately, research papers have not always clearly defined how calculations of SSR have been made[9].

thus:

$$(\mathrm{SSR})\mathrm{SE \cdot hm^{-2}} = (\mathrm{hm^2} * \mathrm{kg \cdot hm^{-2}}\ \mathrm{DM} * \mathrm{U}) / (\mathrm{hm^2} * \mathrm{d} * \mathrm{kg \cdot SE^{-1} \cdot d^{-1}}\ \mathrm{DM})$$

To illustrate some of the difficulties in using this formula for SSR, data from the typical steppe study is used[26] with alternative sets of values:

(1) At the optimal stocking rate ($400\ \mathrm{SE \cdot d^{-1} \cdot hm^{-2}} = 4\ \mathrm{SE \cdot hm^{-2}}$ over 100 d of grazing), the pasture growth rate over summer averaged $30\ \mathrm{kg \cdot hm^{-2} \cdot d^{-1}}$DM then $G = 3000\ \mathrm{kg \cdot hm^{-2}}$ DM (100 d of growth) and using the 20% consumption/utilization rate by livestock found to apply at the optimal stocking rate[26] and a SE consumption rate of $1\ \mathrm{kg \cdot hm^{-2} \cdot d^{-1}}$DM that meant the SSR(SE) would be $6\ \mathrm{SE \cdot hm^{-2}}$, some 50% higher than what was determined by the grazing experiment. If $C = 1.8\ \mathrm{kg \cdot d^{-1}}$ DM then SSR

(SU) = 3.3, but as 4 SE = 2.2 SU, again 50% above SSR still results.

(2) If U is defined as the total losses of herbage from all sources (as determined by the difference between measurements inside and outside a grazing exclusion cage) and estimated at 30% of G (i.e., 50% greater than estimated SE consumption rate), then this results in an SSR(SE) of 9 SE·hm^{-2}, 125% greater than the result found from an analysis of the system. If C = 1.8 then SSR(SU) = 5 SU·hm^{-2}, 125% above the experiment determined result of SSR(SU) = 2.2 SU·hm^{-2}.

(3) If G is defined as the peak standing herbage mass in summer, as this is easier to measure (e.g., 2.5 t·hm^{-2} DM in this case) and U was 20% then the calculated SSR(SE) would be 5 SE·hm^{-2}, if U was 30% then the SSR(SE) is 7.5 SE·hm^{-2}, 25% and 88%, respectively, above the known SSR. Similar differences apply if SSR(SU) is calculated.

(4) G could be defined alternatively, as the total growth (3000 kg·hm^{-2} DM) less a residual quantity of herbage required to maintain ground cover and to aid regrowth by desirable species (e.g., a non-grazed residual of 1000 kg·hm^{-2} DM, judged appropriate to sustain the optimal average level of herbage mass, i.e., 500 kg·hm^{-2} DM, allowing for an equal amount of other losses), G then becomes 2000 kg·hm^{-2} DM and with U at 20%, SSR(SE) is 4 SE·hm^{-2} and SSR(SU) is 2.2 SU·hm^{-2}, the SSR found in the experiment.

The examples considered here illustrates the problems and confusion, of deciding on appropriate values for the calculation of SSR. It is evident that it does not greatly matter if SE or SU is used as a basis for these general calculations, though users need to clearly state the definitions they are using. If animals are monitored for weight and condition then it is possible to refine estimates of their consumption rates[35] but only a few herders in China could reach those skills in the near future. A simple definition of sheep equivalent would be sufficient. These calculations support the view that U is best defined as the actual proportion consumed by livestock and not confounded by including other losses. Research is needed to carefully define the values for U that apply across a range of conditions, and how best to use such information when calculating SSR. It is reasonable to assume that U would vary from low values in desert steppe to higher values in the meadow steppe. The range might be limited though to say, 5% to 30%, as any higher values could result in overstocking. Research also needs to carefully define how to calculate G so that a common standard would apply across all grassland types. The solution could be option four above where the residual herbage mass values considers the minimum required to sustain the grasslands, but this may not apply in all circumstances and would need to be determined by experiments. In practice estimates of C would be better derived from standards based on the literature. Calculations of SSR would need to be made at the start of summer, based on historical expectations, and then again in mid-summer to take into account climatic effects in the current year. For some grasslands in China it may be possible to establish a workable relationship between grassland growth in June, and the peak growth in August–September, as found for a desert steppe in IMAR[36]. Across large areas it may only be feasible to do those measurements using remote sensing.

It is anticipated that the direct calculation of SSR will remain popular, with results of variable quality, until more research is done to resolve the better definitions for terms in the equation and to analyze how those terms relate to grazing management practices. At present the obvious inconsistency in calculations arising from researchers varying how SSR is calculated, mean that alternative ways of managing grasslands, rather than using an estimated SSR alone are needed. As argued in this paper, sustainable grassland management could be achieved by managing to keep grasslands above a critical value for herbage mass, once this is better defined for different grassland types and regions. Research is needed to define how herbage mass relates to the key components of a grassland; grassland and animal growth rates, plant species composition, erosion risk, biodiversity, greenhouse gas production. Managing to maintain herbage mass above critical values, means actual stocking rates could vary through the main grazing season over summer, though it would be in the interest of herders to keep stocking rates low as that would increase productivity per head. Setting a critical herbage mass value could also be useful in early summer as the trigger for when grazing should commence, rather than using a calendar date. Herders who have well managed grasslands could then commence grazing earlier. Herbage mass could be monitored by remote sensing. As the objective is usually to improve system sustainability, larger herbage mass values are arguably better in practice. Herders can be trained to recognize critical values and trained to understand the implications of grazing below them.

7 Precision livestock management

Livestock are the source of income for herders and are culturally important for them. On the grasslands of China there are few if any other income sources that all herders could consider. Improving the income from livestock is as important for herders as improving the grasslands. By improving the income per head from livestock, herders can improve their household income, without the need to increase animal numbers. To achieve a 50% reduction in stocking rates, as discussed earlier, it is necessary to achieve a similar increase in income per head from the reduced livestock numbers, so that herder household incomes do not decline.

Within a flock or herd of animals there are always some that are highly profitable and others that cost more money than they return. Herders may see all their animals as an asset, but an analysis of net income per animal shows this is not true[14]. A first step in improving flocks and herds is to evaluate the net income from each animal and from that it is possible to rank them from the most to the least profitable[37,38]. In demonstrations farms, it was shown that up to half the animals could be culled without reducing the net household income from livestock. If these animals are culled then it is expected that the remaining animals will increase their net returns as the system is feed-limited, resulting in more forage and supplements being available to the remaining animals, thereby increasing their productivity and net household incomes. These predictions have been supported in farm demonstrations. The conclusions about the need to cull less-productive animals, from evaluating individual animal productivity are consistent and of the same order, as the need for similar reductions in animal numbers within a flock or herd, derived from considerations of sustainable grassland management as discussed earlier.

Culling of the least-productive animals is only the first step, however, in flock or herd improvement. Many flocks/herds comprise animals of poor quality. Detailed monitoring of animals in field demonstrations showed that herders tended to sell their best animals as traders demanded them[14]. The result was a gradual reduction in the productivity of animals, an increasing age of the flocks or herds, which were only renewed when seasonal conditions resulted in higher death rates of animals, e.g., from higher snow falls in winter, and then a high birth rate of young in the following years, with more animals available for the markets and lower prices causing herders to retain more in their flocks or herds. Renewal of flocks and herds is then closer to how wild animal populations change, than efficient livestock production. Herders need training in more precise management of their flocks and herds so that they increase their efficiency of production. There is considerable room for improvement. For example, lambs for sale for meat in Australia reach 50 kg live weight at 6 months old, whereas in China they take from 18 to 24 months to achieve the same weight. Merino sheep when initially brought to China produced 6 kg of wool or more per head, but after a few generations they only produced 2–3 kg per head.

An advantage of culling the least-productive animals is that this provides some extra cash that can, in part, be used to improve flock or herd productivity, without the need to borrow funds from banks at high interest rates on short-terms. Animals of higher genetic merit could be purchased, as could fodder of better quality for use through winter. Self-financing of flock and herd improvement is a viable option for herders, though few at this stage appreciate this option is possible.

There are other aspects of livestock management that can be changed as herders move from maximizing the survival of their animals to optimizing the production of meat, milk or fiber, while aiming to achieve sustainable grassland management. Modeling in districts of IMAR and Gansu showed that lambing times could be changed from mid-winter to early summer to better align feed supply with animal demand[20,37]. Lamb survival is likely to be better in warmer weather, the demand by ewes for better quality forage then coincides more closely with grassland growth, while over summer grazing pressures are less as the lambs are not grazing, particularly in the first half of summer. Herders in study areas of IMAR and Gansu have now changed practices to gain these advantages from changing lambing times. An associated practice is the implementation of early weaning practices as there are limited benefits from having suckling lambs after 8 weeks from birth. Early weaning also means that the ewes demand for forage is then reduced and grazing pressures on the grassland become less after weaning. More efficient animal production could now be achieved by some districts focusing on breeding and others on finishing animals for markets. These trends are starting to occur.

Allied to the general need for better selection and management of animals is the need to do a more thorough evaluation of the type of livestock production that is best suited to an area. Often herders in drier climates are focused on meat or milk production from their animals, because they have traditionally used their animals to provide those products for household use. Today with better markets, herders can focus on what is the more efficient system for their district and only have a few animals for their own meat and milk needs. In desert grasslands, the production of fiber (wool and cashmere) is arguably more effective than trying to finish animals for meat markets, as they cannot achieve the same productivity as herders from more productive environments. A focus on a single product often means that a herder does a better job. Trying to produce several things at once, e.g., fiber, meat and milk, means than none are produced at the best levels of efficiency. Allied to these changes is the need for herder training in the use of condition scoring of animals so that they can better manage the feeding of supplements.

Precision livestock management with the focus on improving the productivity of individual animals is a desirable pathway to greater incomes from livestock, and complements the tactics and strategies discussed in this paper for better management of grasslands.

8 Achieving change

Achieving significant change on the grasslands of China, rehabilitating them to a productive state and improving the incomes of herders, requires not only better knowledge of how grassland-livestock systems function and the management directions required for change. Additional policy and other changes are needed that can provide knowledge and incentives for herders to move from their current states to ones that achieve the policy objectives of the Chinese Government. The changes needed have become evident from working with herders and local officials, and through testing changed practices on demonstration farms.

8.1 Herders from survival to production

Traditional herders have an impressive amount of knowledge about how to achieve high levels of animal survival in the tough environment of Chinese grasslands. However today, many herders are engaging more in the developing markets of China and wish to increase their household incomes so they can acquire the goods and services they want (e.g., education, health, phones and vehicles); to do this they need new skills in how to increase the quantity and quality of animal products, they need to develop a production focus[25]. Markets are developing in China and the markets for animal products are paying differential prices based on the quantity and quality of animal products. No longer are all animals worth the same price. However, many herders are still price-takers, rather than price-setters. When herders are obtaining higher incomes because they are producing more of the products markets want, this provides a natural incentive for change. The core issue is to obtain higher net incomes per head from livestock. Per head productivity of livestock increases as stocking rates on grasslands decrease. Herder training needs to promote the idea of becoming animal production experts, building on their expertise as animal survival experts.

Herder training needs to include all aspects of the production system, such as using better criteria (herbage mass and plant species composition) for when to rest or graze a grassland, selecting the more profitable animal products for each region, selecting, breeding and monitoring more efficient animals, understanding the importance of energy in animal feeds and other feed quality components, identifying optimal least-cost fodders, using and improving warm sheds to reduce feed costs and animal live-weight loss through winter, and identifying how to optimize production system components.

8.2 Grassland improvement by improving markets

Markets are part of the grassland-livestock system, but traditional practices mean the markets have encouraged overgrazing and kept herder incomes low, as herders often see maximizing animal numbers as the way to increase incomes. Like many farmers elsewhere, they look at gross income, whereas what is far more important is net income. Markets are though now developing in China and higher prices per head are possible for the more productive animals. Markets need to be efficient, with fewer traders between herders and the ultimate consumers, more transparency about prices and improved transport systems. Payments also need to account for the differences in quality and quantity of livestock and their products—prices are yet to consistently reflect these aims. It has been established that a focus on improved production per head is the pathway to higher herder household incomes and reduced stocking rates on grasslands[14]. Efficient markets paying for quantity and quality of livestock products encourage herders to improve productivity per head and to sell products that consumers want and are willing to pay for, rather than maximizing the number of animals per unit area, producing low quality product and then having to sell them when the market is oversupplied.

Visits by officials and herders to Australia have shown them open-cry, transparent livestock markets and published sales grids from meat processors, where farmers can readily see which animals get the highest prices and which get the poorest price. This includes weighing beef animals before sale so both the buyer and seller know the weights. Sale prices are often negotiated on the basis of price per unit weight, rather than per animal. In China, some of these changes are also occurring, but a lot more needs to be done. Government policies need to encourage better marketing practices. Part of these improvements would be to train herders in how best to deal with traders and deliver animal products to achieve the highest prices. Herder associations are one of the groups who could encourage these developments, and some are already doing so.

Market improvement includes bringing consumers into the discussions. When urban residents know that dust storms can be reduced by lower stocking rates and maintaining higher levels of herbage mass, they can be encouraged to pay premiums for livestock products from certified areas where district management plans are in place—promotion of eco-labeling can help educate consumers. Enabling markets to help support the process of grassland rehabilitation means that Government payments can be better targeted to where problems are more severe, and herders can achieve the same or higher incomes, while grassland improvement occurs.

8.3 Financing change

Herders on the grasslands of China are among the poorest people in China and they have very limited resources to improve their situation. At present herders go into debt every year[39,40] simply to survive, with few being able to use loans to develop their livestock enterprise. The terms of the loans rarely consider the economics or time frames of livestock production—usually the loans are short-term (less than one year) with high interest rates. Loans for herders are similar to those for cropping farmers, where it is easier to repay the loan once the crop is harvested and sold—in contrast the lifetime, and time for redesigning livestock production systems, is over several years as the cost of an animal is not easily repaid within a year. Good livestock management requires a medium-term (3–5 years) continuous, approach as there is a lag between when an animal is born, purchased or fed better supplements, and when that investment achieves a profit. Grassland recovery can take 5–20 years depending upon the state of the grassland and the district—the full benefits of reduced stocking rates and improving animal production per head cannot be achieved within the term of normal bank loans. Finance needs to be for a business plan over the medium to long-term with the ultimate goal of improving grasslands and household incomes.

8.4 Land tenure

In China, the land is state owned, but various regulations have been developed so that those who directly use the land are able to improve their livelihoods—of most importance is the land allocated (under the user-right system) to herders. Some herders have been changing from traditional survival practices based around providing food and shelter for their families where only a small amount of their livestock products are traded or sold, to being producers where their livestock enterprise is now managed as a business which increases the proportion of animal products for sale. Other herders now prefer to rent their allocated land to neighbors and seek work in cities or towns—in some districts up to half of the herders have done this[39,40] and moved to towns, particularly where local authorities have assisted with housing and small areas of land to grow vegetables. The herders who rent land from others, typically use the rented land for summer grazing and there is increasing evidence from discussions with herders that they tend to overgraze rented land—summer is the time of maximum animal numbers and the land is not theirs—they keep their own allocated land for winter, which aids grassland recovery and reduce the grazing pressure used in winter. The incentive to manage rented land better is low as rental agreements are often only annual—better long-term rental arrangements would encourage herders to manage rented land better.

There are potential benefits from allowing herders to increase the area of the land they use for grazing. Surveys are showing that as the managed area increases the average stocking rate decreases[33] (Fig. 5). In 2012, the average stocking rate for these 92 farms was 0.8 $SE\cdot hm^{-2}$, a decline from 1 $SE\cdot hm^{-2}$ found in surveys done 10 years before. However, other modeling has suggested that the sustainable stocking rate was about 0.5 $SE\cdot hm^{-2}$, which some herders are now achieving. If this relationship is a key driver then enabling herders to double their land area would achieve a halving in stocking rates, as it may not be feasible for herders to increase their flock or herd size.

While this data suggests a useful policy strategy for reducing stocking rates, several factors that need to be considered, may be contributing to this result.

- There is now less labor on farms and as the area managed by an individual herders increases, it is not as easy to utilize all grassland intensively—lower stocking rates are important for grassland rehabilitation.
- The lower stocking rates for herders with more animals could be reflecting the increased use of rented land, with a smaller proportional increase in total animal numbers. In summer, these animals overgraze the rented land, while in winter they are more in sheds, reducing grazing on the herders own land, which is not an ideal result.
- Herders may have the goal of owning a preferred number of animals more than having access to an ideal area of land—their preferred number of animals reflecting their current needs to improve household incomes and the number of animals they consider they can manage effectively. Traditionally, herders would have thought in terms of animal numbers, rather than land area.
- Experience around the world shows that as herders become more efficient their preferred number of animals increases—this also depends on the prices they receive for animal products—policies need to allow for a continuing increase in the area of grassland managed by individual herders.

These trends all show that policies need to be developed so the herders who wish to remain in livestock production can expand their livestock enterprises in ways that are both profitable and sustainable—initially this means that the herders who remain in livestock production need more land. In addition, changes in land use arrangements need to allow herders to use that land as an asset against which

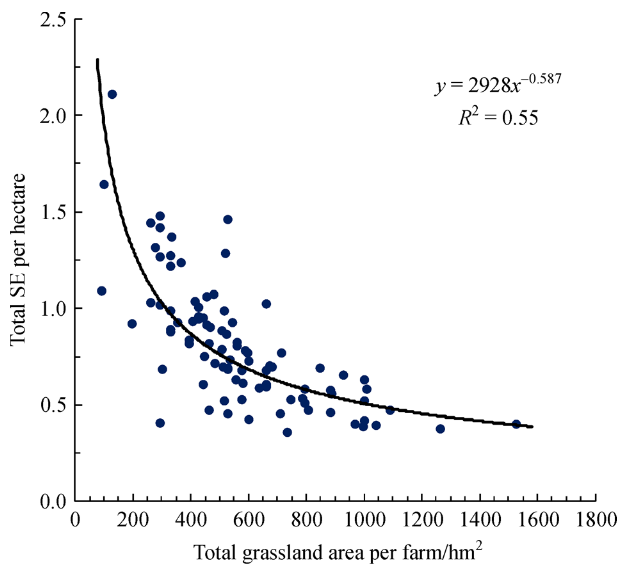

Fig. 5 The relationship between grassland area and standardized stocking rate for 92 desert steppe farms at Siziwang Banner, Inner Mongolia Autonomous Region in 2012

loans can be guaranteed—the asset value could be the guaranteed rental value of the land—this would build the confidence of herders to improve their livestock enterprise, but not at the expense of the grassland. Policies need to be developed so that the land user rights of herders who wish to give up herding can be transferred to other herders, who would then be given the responsibility to manage it sustainably and can use its income potential as an asset.

9 Conclusions

This paper brings together information and the key outcomes of a large collaborative China-Australian program of relevance to policymakers as they develop their plans, with recommendations for system improvements. In this paper, we have summarized the current state of knowledge and where research is needed to define better recommendations. Many of the changes outlined are being trialed in various districts of China, where it is evident that both herders and local officials are endeavoring to improve grasslands and herder household incomes. The clear scientific outcome from this large program is that a focus on production per head of livestock directly relates to reducing stocking rates and improving the output of quality products desired by consumers. Grassland and grazing livestock research needs to be evaluated within a systems context as considered here, so that more robust solutions are found. Herders are unlikely to change practices unless they can see clear advantages. Government support needs to be targeted on topics that achieve both the policy goals and herder household improvement.

An assumption in this paper is that the social goal for Chinese grasslands is to: *improve and maintain the grassland environment while improving herder livelihoods to then deliver the best social outcomes.*

The key steps to deliver this are as follows:

• Identify and encourage more appropriate livestock enterprise systems for the environment, manage stocking rates sustainably, including managing plant species to increase desirable components, improve winter feeding and use of sheds, apply precision livestock management, and improve methods of financing change.

• Develop markets that return high prices efficiently, for better quality products, to herder households and increase training in how herders can move from a focus on survival to one on production.

• Plan these changes in ways that rehabilitate and sustain productive grasslands, including policies to adjust land tenure arrangements so that herders can adapt to changing circumstances.

• Use Government payments to help herders change to self-sustaining practices that are profitable.

The proposition that a 50% reduction in stocking rates to a sustainable level, based on the results of research presented here, needs to be seen against the increase in average stocking rates of 4-fold, experienced since 1950 (Fig. 1). The context considered here is where the grasslands are no longer in an ideal state, but have been modified since 1950, such that it may not be possible to return them to their earlier condition, but herders and officials have no choice but to work with what they have and aim to optimize the condition of grasslands despite their less than perfect state. An objective definition of what is now a sustainable grassland, by necessity, will be different to what would have applied 50 years ago.

Chinese policies now focus more on achieving a balance between feed supply and demand. Monitoring herbage mass critical values, determined so that ecosystem functions are optimized, provides a simple tool that relates to the balance between feed supply and demand[41]. Although, research needs to clarify, for the range of circumstances, how best to use herbage mass criteria where there is a dominance of unpalatable species that may help manage system functions such as soil erosion but are of no value for sustaining herder livelihoods. In these conditions, the refinement proposed is to monitor the herbage mass of desirable species. Desirable species being those species that in summer would maintain or increase animal growth rates. To support this, herders will need training in order to monitor herbage mass correctly.

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