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Optimising grazing for livestock production and environmental benefits in Chinese grasslands

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Abstract. Overgrazing has extensively degraded Chinese grasslands. A reduction in stocking rate of 30–50% below the district averages is required to increase the profitability of livestock production and protect vital ecosystem services such as mitigation of greenhouse gases (GHG). Grazing experiments located in the desert steppe, typical steppe and alpine meadow verified the influence of stocking rate and grazing management on livestock production, grassland composition and associated ecosystem services. The desert steppe experiment found lower stocking rates of ~150 SE (where SE is sheep equivalent, which is a 50 kg animal) grazing days ha^{-1} (1 SE ha^{-1} over 150 days) enhanced botanical composition, maintained profitable lamb growth rates and reduced GHG emissions intensity. The typical steppe experiment found moderate grazing pressure of ~400 SE grazing days ha^{-1} (4 SE ha^{-1} over 100 days) maintained higher lamb growth rates, an average herbage mass >0.5 t DM ha^{-1} that maintained the content of *Leymus chinensis* above 70% and *Artemisia frigida* below 10% of the grassland and had the highest level of net carbon sequestration. In the alpine meadow experiment the district average stocking rate of ~16 SE ha^{-1} (1440 SE grazing days ha^{-1} over 90 days) was not too high, but extending grazing into the non-growing season had no benefit. The findings of these experiments highlight that many of the benefits to ecosystem services can be achieved with reduced stocking rates which also generate profitable levels of livestock production. In both the desert and typical steppe experiments, the results were optimal when the stocking rates were adjusted to maintain average herbage mass over summer above ~0.5 t DM ha^{-1}, whereas herbage mass was higher with the local, conservative stocking rates in the alpine meadow.

Keywords: alpine meadow, desert steppe, ecosystem services, grassland composition, grazing management, greenhouse gases, sheep production, typical steppe.

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Introduction

China has 400 M ha of grasslands (Jia and Su 1996), but since 1985, 90% of these have become degraded by overgrazing due to the large increase in the number of people and animals that depend on them (Kemp and Michalk 2011; Kemp *et al.* 2020*a*). It is acknowledged that a reduction in grazing intensity is required to prevent further degradation (Kemp *et al.* 2013), but this must be balanced against an imperative to increase red meat production by 50% globally by 2050 to meet the demands of a growing world population (Thornton 2010), many of whom will be in China (Michalk *et al.* 2019). To meet the dual objectives of increasing production and reducing degradation, we must investigate ways to economically improve efficiency, by closing the 'yield gaps' on under-performing lands (Alexandratos and Bruinsma 2012) while reducing livestock number and increasing the production efficiency of grassland-based livestock grazing systems. This would provide an opportunity for Chinese small holders to 'sustainably intensify' their production based on new technologies, practices and production systems, and produce 'more from less' (Michalk *et al.* 2019). While the area excluded from grazing in China has reached 26 M ha (11% of China's natural grasslands) since the 'Returning Grazing Land to Grassland' policy was implemented in 2003 (Xiong *et al.* 2016), low to moderate grazing levels should generate similar benefits in many areas and help maintain herder incomes.

Optimum animal production is best defined where net incomes for herders are maximised, at an acceptable level of risk, while maintaining the condition of the grassland in a desirable state. Herbage mass must ideally remain at a level that does not constrain intake (Ungar 2019), but there are also feedbacks on the quality of forage from issues such as deferment of grazing and stage of maturity of grassland species during grazing. As stocking rate increases, herbage allowance per head decreases and animal production (weight gain of young stock) decreases. Intake of sheep decreases substantially below ~0.5 t DM ha^{-1} (Freer *et al.* 2007; Kemp *et al.* 2015, Badgery 2017). However, production per ha generally increases with increasing stocking rate to a point, after which it decreases, with further reductions in per head production with more animals (Jones and Sandland 1974; Kemp *et al.* 2015, 2018). The economic optimum for the grazing system is at a stocking rate that is lower than the highest biological production per area, as the marginal return on inputs decreases in relation to the increases in production (Amidy *et al.* 2017). The exact level will vary, depending on issues such as the ratio of price of outputs to inputs, overhead costs, total productivity and management of risk. Managed grazing systems in China often have stocking rates so high that they exceed the level that produces optimum per area production and are far from the potential level of profitability (Kemp *et al.* 2013, 2020*b*).

The preferred grassland condition has higher levels of desirable species (species that typically decline under grazing (Vesk and Westoby 2001)) with less-desirable species (species that increase under grazing) being minor components. The first sign of degradation in a grassland is an increase in the proportion of less-desirable plant species, and a decrease in the more preferred plant types. With continued over-grazing, declining plant cover, increasing bare ground and patch size occurs, the risk of soil erosion is enhanced and productivity declines (Lin *et al.* 2010*a*, 2010*b*; Kemp *et al.* 2020*a*; Li *et al.* 2020). As stocking rates are reduced, this process is somewhat reversed, though the grassland is unlikely to return to an ideal state for livestock production or conservation. The growth and biomass of plant species need to be at a level that maintains sufficient ground cover to limit soil erosion to within what is feasible for the environment, sequesters carbon in the soil, minimises methane release to the environment and optimises biodiversity.

One of the key issues from previous studies investigating grassland composition change and grazing pressure is that composition shifts are often described in terms of species number, diversity and evenness indices (Zhang and Zhao 2015; Xiong *et al.* 2016). However, these measures do not give a useful indication of biomass, the biophysical mechanisms that are involved, nor of how these affect livestock production. It is often not clear which species are more sensitive to grazing and what level and timing (winter vs summer) of grazing is required to drive positive composition change. Furthermore, there are limits to composition change due to climate (Bai *et al.* 2004); landscape patch dynamics (Badgery 2017); or when irreversible thresholds are reached (Friedel 1991; Briske *et al.* 2005). The diversity measures do not give a clear indication of what management strategies are effective. For instance, Xiong *et al.* (2016) found that grazing exclusion had little long-term effect on recovering plant diversity in a meta-analysis with 447 data points from across China's grasslands, yet the response of grazing sensitive, high value plants was not reported. The degradation pathway is understood for some steppe types (e.g. *Stipa grandis* steppe; Tong *et al.* 2004), but what is not clear is how reversible this process is when grazing pressure is removed or reduced. A better understanding is needed of the interaction between grazing pressure and time of grazing for all major grassland types in China.

Grasslands are a major part of the world's land-based ecosystems, with functions beyond providing forage for livestock production. There are greenhouse gas (GHG) mitigation benefits from reducing grazing pressure on Chinese grasslands such as increases to soil carbon (Liu *et al.* 2012*a*; Xiong *et al.* 2016) and reduced methane emissions from livestock (Wang *et al.* 2014). However, although it is clear moving from traditional grazing to grazing bans will generally increase soil carbon (Wang *et al.* 2011*a*), it is equally clear that when grazing bans are imposed across large areas of grassland they either displace grazing to other marginal areas (in other regions/countries) causing further grassland degradation (Waldron *et al.* 2010), or to intensive feedlot production systems that require large amounts of grain, causing expansion of cropping into marginal areas. These land-use changes may lead to a greater production of GHGs (Vergé *et al.* 2012; Plevin *et al.* 2014; Liang *et al.* 2020). Moreover, there is evidence of soil carbon being lower when grazing is removed compared with light or moderate grazing (Liu *et al.* 2012*a*; Orgill *et al.* 2018). Therefore, when managing grassland composition and livestock numbers it is important to understand these implications for GHGs.

The first phase of the Australian Centre for International Agricultural Research (ACIAR) China Grasslands program on sustainable grazing in China (2001–2008) sought to understand exactly how farmers (herders) managed their livestock. Models were developed to analyse the livestock farming system and investigate options to improve management, including reducing stocking rates, improving feeding, introducing warm sheds, changes to enterprise and the timing of operations such as lambing (summarised in Kemp and Michalk 2011). On-farm demonstrations were then established to verify the improvement in herder's livelihoods with new management systems that reduced livestock utilisation rates while increasing productivity per animal and net financial returns (Li *et al.* 2014; Kemp *et al.* 2020*b*). However, the benefits to grassland composition and ecosystem services as a result of reduced grazing pressure with improved management required further verification. These processes can be difficult to model, and integrated data were needed to develop functions and the interrelation between them to investigate the sustainability and profitability of new management practices over longer periods of time and under climate risk (Behrendt *et al.* 2020). The task of the second phase of the ACIAR China Grasslands Program (2009–2017) was to generate the integrated data and framework necessary for long-term sustainability modelling (Stage THREE Model; Behrendt *et al.* 2020). Grazing experiments were established at Guyuan in Hebei Province (typical steppe; Zhang *et al.* 2015), Maqu in Gansu (alpine meadow; Sun *et al.* 2015) and a long-term experiment maintained at Siziwang in Inner Mongolia (desert steppe; Wang *et al.* 2011*b*). These experiments provided integrated data on the influence of stocking rate and grazing management on livestock production, grassland composition and associated ecosystem services (including GHG mitigation) across these three main grassland types.

The aim of this paper is to synthesise and review information previously published from both the ACIAR grazing experiments and modelling on managing grasslands to develop criteria for optimal grazing management and utilisation to enhance grassland composition, while maintaining livestock production and essential ecosystems services. Optimised scenarios are assessed against district average stocking rates and the implementation of partial or total grazing bans, policies currently used to restore degraded grasslands. The main hypothesis tested was that enhancing grassland composition, improving the efficiency of livestock production and improving ecosystem services (GHG mitigation) could be optimised with a stocking rate that is 30–50% below the current district averages, an estimate derived from initial modelling (Kemp and Michalk 2011). We also consider the management principles and tools herders could use to enable them to adjust stocking rates and other practices more effectively, particularly in systems where the area of grazing land is not discrete, nor is the number of animals is always controlled due to common grazing.

Grazing experiments

Herbage mass is a common factor that is related to grassland ecology and animal production (Noy-Meir 1975; Kemp *et al.* 2015, 2018; Ungar 2019; Kemp *et al.* 2020*a*). The three grazing experiments were analysed to identify the critical values of herbage mass that not only optimised animal production but also grassland composition and environmental services, particularly GHG emissions.

Desert steppe, Siziwang

The experiment at Siziwang (41°46′43.6″N, 111°53′41.7″E; elevation 1456 m) was established in 2004 to investigate the influence of grazing pressure on grassland composition and livestock production (Wang *et al.* 2011*b*). Annual precipitation is 223 mm per year, mostly in summer, and mean annual temperature of 3.6°C. There are 4–5 months for plant growth when temperatures are above zero. Four grazing treatments were established, nil, light (0.9 sheep equivalents (50 kg reference weight; SE) ha^{-1}), moderate (1.6 SE ha^{-1}) and heavy grazing (2.3 SE ha^{-1}) by sheep over the growing season. Eighteen-month-old sheep were allocated to each treatment, remained on the experiment for three years, and then were replaced with another group. This resulted in the SE ha^{-1} increasing over each three-year cycle. The SE ha^{-1} shown above are the means from 2004 to 2015. Heavy grazing represented the average stocking rate in the district at the beginning of the experiment (Li *et al.* 2014). The main plant species at the site were *Stipa breviflora* and *Artemisia frigida.*

There was an increase in productivity at the site, year-on-year, which was demonstrated by an increase in peak biomass from 877 kg ha^{-1} during 2004–2010 to 1798 kg ha^{-1} during 2011–2015 (Table 1; Fig. 1). The exception was in the winter of 2004–2005 (first year of experiment) when the whole site was inadvertently heavily-grazed by numerous animals that reduced biomass and influenced plant composition. The increase in productivity was a result of higher residual biomass remaining in autumn, leading to higher biomass the following June (summer). The biomass increase was driven by increasing tiller density of the dominant species (Fig. 2). This change in biomass suggests that the site was probably previously grazed at stocking rates above the highest stocking rate treatment and grazed through winter.

Composition change during this long-term experiment has been slow. *S. breviflora* was the most prevalent perennial grass and it increased on all treatments from 2004 to 2016. There was no stocking rate effect on the biomass of this relatively unpalatable grass (Fig. 1) although plant frequency was lower without grazing (Zhang *et al.* 2018). Initially the biomass of the edible semi-shrub *A. frigida* was 3–4 times higher than that of the perennial grasses, but the heavy grazing period in the winter of 2004–2005 reduced *A. frigida* content to a much greater extent than the grasses. Subsequently, the *A. frigida* content increased over time, mostly in the ungrazed control and least under the heavy grazing treatment, but with a similar plant frequency between treatments indicating existing plants were larger (Zhang *et al.* 2018). These results show that the sheep preferred to graze *A. frigida* and avoided *S. breviflora*, which was confirmed with observational studies (ZW Wang, unpubl. data). *S. breviflora* was generally only eaten in October (autumn) when plant growth was frosted, but this had no effect on the subsequent botanical composition.

It took eight years of this desert steppe experiment before the relative proportions of *S. breviflora* and *A. frigida* started to differentiate, significantly longer than the normal five-year grazing bans used in Inner Mongolia to rehabilitate grasslands. After 12 years the palatable grass *S. krylovii*, started to increase within the nil and light stocking rates, but not under moderate to high stocking rates. This is a preferred species and in time it may become more important within this grassland under conservative management.

Dominance of the plant community by *S. breviflora* and *A. frigida* may not be ideal for livestock production, but sheep growth rates have been reasonable on the light grazing treatment where *A. frigida* was maintained in equal proportions to *S. breviflora*. In contrast, under heavy grazing (at the original district average stocking rates) the ratio of *S. breviflora* to *A. frigida* was 12 : 1 (Fig. 1). This clearly highlights the imperative to work within the current state of the system, rather than trying to aim for some ecological ideal. With careful management to avoid overgrazing, it may be feasible in the future to replace *S. breviflora* with more palatable grasses. It may also be possible to use tactical heavy-grazing in winter (as occurred in 2004–2005) every five years or so to shift the balance between *S. breviflora* and *A. frigida*.

Sheep liveweight gain over summer decreased linearly with increasing stocking rate from 112 g $head^{-1}$ day^{-1} at 0.9 SE ha^{-1} (Light) to 98 g $head^{-1}$ day^{-1} at 1.6 SE ha^{-1} (Moderate) and 69 g $head^{-1}$ day^{-1} at 2.3 SE ha^{-1} (Heavy) (Table 2). While the peak liveweight gain ha^{-1} was at the heavy stocking rate, a stocking rate of ~1 SE ha^{-1} (150 SE grazing days ha^{-1} $year^{-1}$; 150 days of grazing over summer and autumn; grazing days is a measure used to account for differences in grazing times and stocking rates within and between years) slightly above the light stocking rate is a sustainable optimum for desert steppe grassland

(Wang *et al.* 2020). This is the stocking rate over summer that generated around 75% of the maximum per head production, which equates to the point where net income per ha is often optimal (Kemp *et al.* 2018). A stocking rate of 1 SE ha^{-1} was half the average stocking rate in the district when the experiment began but is now close to the average for the region

Table 1. Peak herbage mass, stocking rate expressed as grazing days (sheep equivalent (SE) grazing days ha^{-1} year^{-1}) and consumption rates for the control (Nil), light (LG), moderate (MG) and heavy (HG) grazing treatments on the desert steppe for the periods of 2004–2010 and 2011–2015
Adapted from Wang *et al.* (2020)

Treatment	Peak herbage mass (kg DM ha^{-1})		Grazing days (SE grazing days ha^{-1} year^{-1})		Consumption rate (%)	
	2004–10	2011–15	2004–10	2011–15	2004–10	2011–15
Nil	877	1798	0	0	0	0
LG	684	1247	89	104	16	9
MG	580	976	164	175	41	22
HG	470	701	274	221	100	43

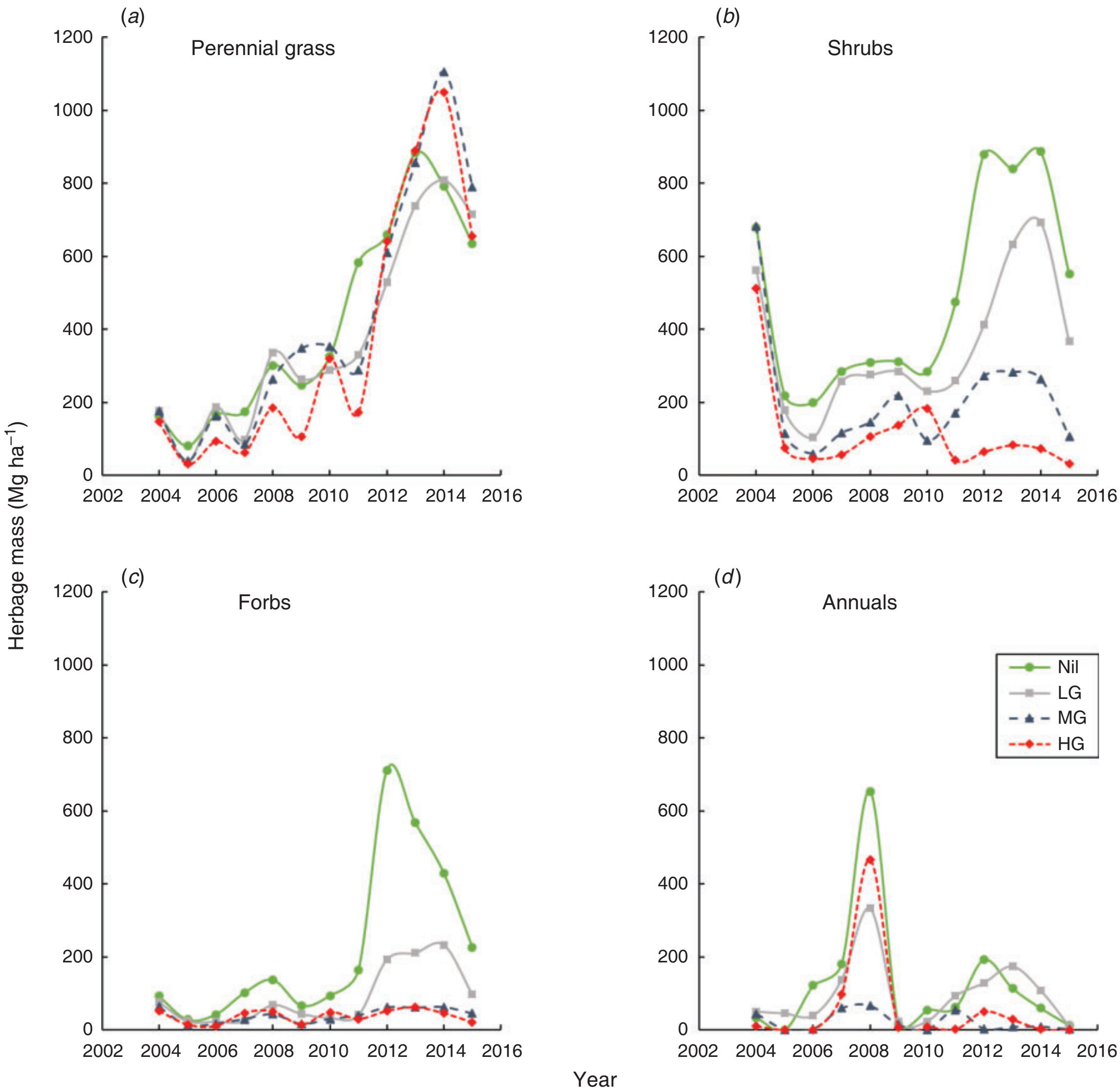

Fig. 1. Peak herbage mass of (*a*) perennial grasses, (*b*) shrubs, and semi-shrubs (*c*), perennial forbs and others, and (*d*) annuals and biennials from 2004 to 2015 under four grazing treatments Nil, light (LG), moderate (MG) and heavy (HG) stocking rates on the desert steppe (Wang *et al.* 2020).

(Kemp *et al.* 2020*c*). At 1 SE ha^{-1} the average herbage mass remained ~0.5 t DM ha^{-1} throughout the summer, and livestock consumed 10–15% of total herbage growth during summer. Initial modelling indicated that at this site, net income per hectare was maximised at stocking rates below 1 SE ha^{-1} (Han *et al.* 2011).

There was no clear evidence of changes to soil carbon with different grazing pressure (or no grazing) over the experimental period at Siziwang (Lin *et al.* 2010*b*; Zhang *et al.* 2018). However, heavy grazing did reduce the size of vegetation patches, and increased the homogeneity of the spatial distribution of plant biomass and soil carbon (Lin *et al.* 2010*b*). The desert steppe soils at Siziwang are a small CH_4 sink (Wang *et al.* 2011*c*), and increasing grazing pressure decreased the proportion of CH_4 uptake once stocking rates exceeded 0.9 SE ha^{-1} (light) in this experiment (Wang *et al.* 2012). Soil erosion and deposition may also be a cause of soil organic carbon (SOC) differences (Pei *et al.* 2008).

GHG emission from grazing sheep, primarily enteric CH_4 emissions, can be reduced by lowering the stocking rate, which decreases the overall emissions and emissions intensity (Kg CO_2-e kg liveweight gain $(LWG)^{-1}$). Based on production data from the Siziwang grazing experiment, annual livestock emission intensity was reduced by 35 and 26% when changing from heavy or moderate grazing pressure to a light grazing pressure respectively (Table 2).

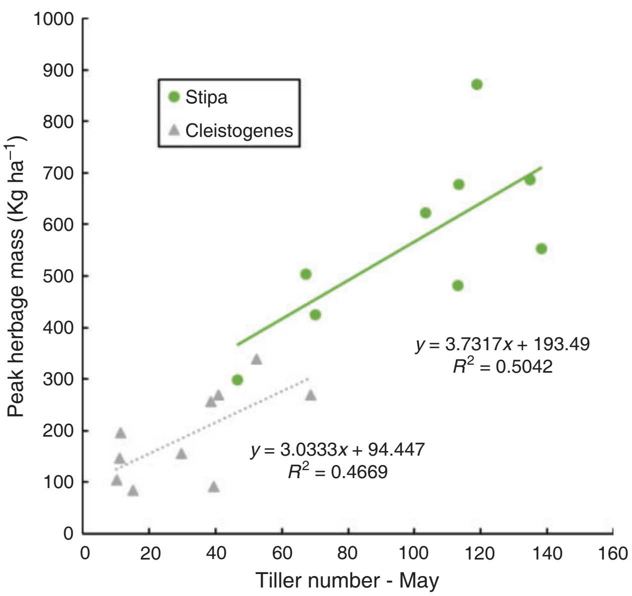

Fig. 2. Tiller numbers for *Stipa breviflora* and *Cleistogenes songorica* in May and peak biomass in late summer. Data for the desert steppe grazing experiment treatments in 2014 and 2015 (Wang *et al.* 2020).

The desert steppe experiment clearly shows that lower stocking rates are required to optimise the existing botanical composition, maintain more profitable rates of animal growth and lessen any adverse effects on carbon emissions. These components were optimal when the average herbage mass over summer was above ~0.5 t DM ha^{-1} and the optimal consumption rate of forage by livestock averaged 10–15%. This was the first study with evidence that grazing in winter has adverse effects on grassland productivity, although more information on the mechanisms involved is needed. The result that grassland productivity in one year directly relates to growth the following summer, shows there is a clear feed-forward effect that justifies lower stocking rates as an effective strategy to rehabilitate degraded grassland. The widespread adoption of this management approach is evident in the significant reduction in district stocking rates, which are now of the same order as the light stocking rate used in this experiment (Kemp *et al.* 2020*c*).

Typical steppe, Guyuan

The typical steppe grazing experiment was located at Guyuan, in Hebei province (41°45′N 115°39′E; elevation 1430 m) and operated between 2010 and 2013. Average annual precipitation is 430 mm, mostly occurring between July and September. The annual mean temperature is 1.4°C. *Leymus chinensis*, *A. frigida* and *Carex duriuscula* were the main plant species. The grassland condition before the experiment was considered desirable, due to the high proportion of *L. chinensis*. The treatments investigated selected combinations of rest (R), moderate (M) or heavy (H) grazing pressure through the summer growing season. Five grazing treatments were implemented: RMH, RHM, MMM, HHM and HHH through early, mid and late summer (Table 3). After three years (in 2013) the stocking rates on all grazed treatments were reduced by 25%. Further details of the experiment can be found in Zhang *et al.* (2015).

Grassland production was directly related to the SE grazing days ha^{-1} $year^{-1}$ (Fig. 3). There were different relationships between years, with herbage mass highest in 2010 but decreasing in subsequent years. The slope of the log-linear relationship increased in 2013 due mostly to low stocking rates increasing herbage mass to a greater degree than high stocking rates as a result of an overall decrease in grazing pressure during that year.

Grassland composition was closely related to biomass, with consistent relationships over treatments and years. There was an exponential decrease in the proportion of *L. chinensis* below

Table 2. Average liveweight gain (LWG) per head (hd) and per hectare (ha), methane emissions expressed as a GHG Emissions Factor per ha per year (derived from Grazfeed in the method described by Zhang *et al.* 2015) and emissions intensity per kg of LWG over the grazing season for the light (LG), moderate (MG) and heavy (HG) grazing treatments on the desert steppe

Treatment	LWG hd (g $head^{-1}$ day^{-1})	LWG ha (g ha^{-1} day^{-1})	GHG emissions factor (kg CO_2e ha^{-1} $year^{-1}$)[A]	Emissions intensity (kg CO_2e kg LWG^{-1})
LG	112.3	99.4	116.1	7.8
MG	98.1	159.9	213.9	8.9
HG	68.9	163.3	293.6	12.0

[A]Grazing period only.

Table 3. Average stocking rate (sheep equivalents (SE) ha^{-1}; 50 kg reference weight animal), total days of grazing, grazing days, consumption rate (estimate of intake using equations Freer *et al.* (2007)) for the typical steppe grazing experiment at Guyuan

The treatments represent high (H), medium (M) grazing pressure or rest (R) for three equal periods between June and September on the typical steppe. The average liveweight gain (LWG) per head (hd) and per hectare (ha) are presented, as is the emissions intensity per kg of LWG over the grazing season (kg CO_2e kg LWG^{-1}).

Treatment	Ave stocking rate (SE ha^{-1})	Total days	Grazing days (SE grazing days ha^{-1} $year^{-1}$)	Consumption rate (%)	LWG hd (g $head^{-1}$ day^{-1})	LWG ha (g ha^{-1} day^{-1})	Emission intensity (kg CO_2e kg LWG^{-1})
HHH	7.4	97	730	39	93.2	813.7	15.6
HHM	6.7	97	663	36	78.4	613.0	9.7
MMM	5.6	97	550	21	111.2	697.0	7.3
RHM	5.3	66	352	25	106.3	520.9	12.7
RMH	4.8	66	316	20	102.9	473.8	12.6

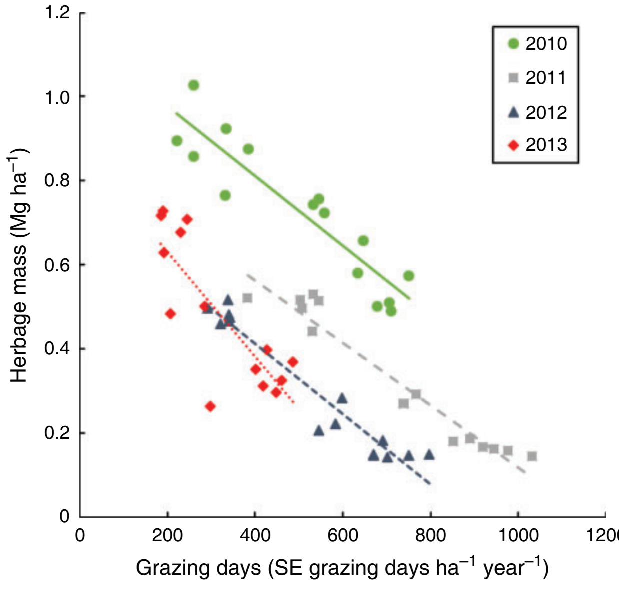

Fig. 3. The relationship between average grazing season herbage mass ln +1 (Mg DM ha^{-1}) and sheep equivalent (SE; 50 kg reference weight animal) grazing days ha^{-1} $year^{-1}$ on the typical steppe (Zhang *et al.* 2015).

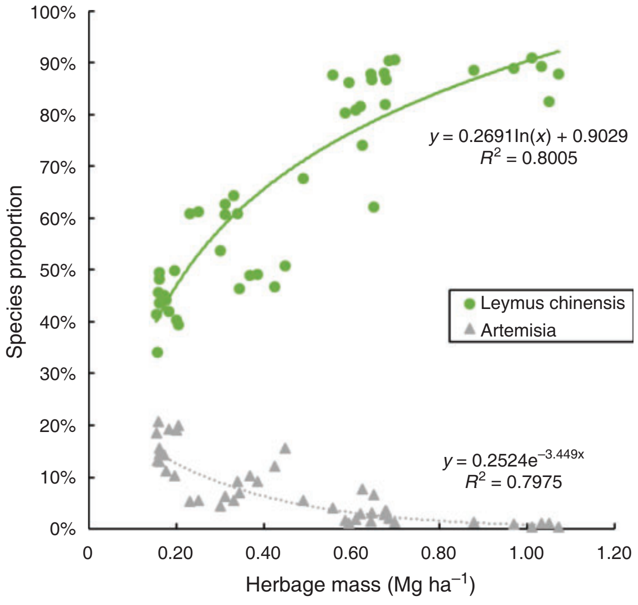

Fig. 4. The relationship between the average herbage mass and the average proportion of *Leymus chinensis* and *Artemisia* spp. in the typical steppe grazing experiment (adapted from Zhang *et al.* 2015).

70%, when the herbage mass fell below 0.5 t DM ha^{-1} (Fig. 4), while *Artemisia* spp. increased above 5% and forbs above 10% (data not shown) at the same point. The mean herbage mass (2011–2013) of 0.5 t DM ha^{-1} equates to ~400 SE grazing days ha^{-1} $year^{-1}$; lower than the mean of the Moderate grazing pressure treatment (550 SE grazing days ha^{-1} $year^{-1}$).

The change in grassland composition in this study shows the common pattern of species shift from over-grazing. This has been previously documented by Liang *et al.* (2009) who found that on a grazing gradient, from no grazing to heavy grazing, vegetation changed from the original dominant grass species *L. chinensis* to the semi-subshrub species *A. frigida*. There is evidence that the species composition change in typical steppe is reasonably resilient within the timeframe of this short-term experiment. When stocking rates were reduced in 2013, both *L. chinensis* and *Artemisia* spp. reversed treatment trends with reduced grazing pressure, but forbs were not reduced to a lower level. Early summer rest treatments maintained similar, desirable proportions of plant species across all four years, although forage quality declined such that when animals grazed those treatments, their growth rates were lower. The growth rate of lambs in the early summer rest treatments (33 kg ha $season^{-1}$) was lower than the mean of summer-long grazing treatments (69 kg ha $season^{-1}$). For all treatments, lamb growth rates increased with increasing herbage mass but at different rates (Table 3). The SE grazing days ha^{-1} $year^{-1}$ for optimal grassland condition was ~400 (4 SE ha^{-1} over 100 days of grazing). At this stocking rate the herbage mass averaged >0.5 t DM ha^{-1} and animal growth rates were >100 g $head^{-1}$ day^{-1} with season long grazing.

Methane fluxes were estimated on all treatments. Heavily grazed treatments had significantly higher CH_4 emissions from animals over the grazing season (22 kg ha^{-1} $year^{-1}$), compared with moderately grazed (17 kg ha^{-1} $year^{-1}$) and early season rest treatments (~14 kg ha^{-1} $year^{-1}$) The emissions intensity of CH_4 also increased at high grazing pressure and with early summer rest (Table 3). The moderately grazed treatment was a

Table 4. Average greenhouse gases (GHGs) fluxes monitored over the grazing season for the treatments represent either high (H), medium (M) grazing pressure or rest (R) for three equal periods between June and September on the typical steppe

The greenhouse gases fluxes have been standardised as carbon dioxide equivalents (CO_2-e). Least significant differences (l.s.d.) are presented (**, $P < 0.01$; ***, $P < 0.001$) (Zhang *et al.* 2015)

GHG fluxes	HHH	HHM	MMM	RHM	RMH	l.s.d.
SOC sequestration (kg CO_2-e/ha.year)	−164.7	−410.1	−4343.0	−2219.9	−2072.2	1156.7***
CH_4 uptake (kg CO_2-e/ha.year)	−36.6	−34.5	−103.0	−51.2	−39.4	28.0**
CH_4 sheep emissions (kg CO_2-e/ha.year)	651.6	597.8	470.7	424.2	380.7	43.9***
GHG flux (kg CO_2-e/ha.year)	384.4	92.9	−4014.7	−1886.8	−1767.4	1164.9***

little above the optimum stocking rate of 400 SE grazing days ha^{-1} year^{-1}, and this treatment also recorded a higher CH_4 uptake by the soil (3.7 mg m^{-2} day^{-1}) compared with other treatments (~1.5 mg m^{-2} day^{-1}) (Wang *et al.* 2015; Zhang *et al.* 2015), with greater sequestration of SOC (1.2 Mg ha^{-1} year^{-1}) than for treatments with an early season rest (~0.6 Mg ha^{-1} year^{-1}) or high stocking rates (~0.1 Mg ha^{-1} year^{-1}); the higher SOC sequestration was explained by greater root production (Chen *et al.* 2015). The main sources and sinks of GHGs were combined throughout the grazing season to estimate the systems level emissions. The moderately grazed treatment had the highest net sequestration of GHGs at 4 Mg CO_2-e ha^{-1} year^{-1}, whereas the high stocking rates actually emitted GHGs (Table 4). The largest sink in GHGs was due to increases in SOC, though the benefits are likely to decrease over time (He *et al.* 2008). Assuming all treatments reach an equilibrium soil carbon level at a similar time then moderate grazing pressure would still have lower GHG emissions than the high treatments.

The typical steppe experiment demonstrated that a moderate grazing pressure through summer of ~400 SE grazing days ha^{-1} year^{-1} (4 SE ha^{-1} over 100 days) maintained higher animal growth rates, plus an average herbage mass >0.5 t DM ha^{-1} that kept the content of *L. chinensis* above 70% and *A. frigida* below 10% of the grassland, and would likely achieve the highest net level of carbon sequestration. In contrast with the desert steppe study, where *A. frigida* was the more desirable species for livestock production, management of typical steppe should focus on minimising the amount of *A. frigida* and optimising the *L. chinensis* content as the most desirable grass. At 400 SE grazing days ha^{-1} year^{-1} sheep would consume ~20% of the total forage available. Of interest was the result that, when grazed at their optimum sustainable stocking rate, the average herbage mass for desert and typical steppe both averaged 0.5 t DM ha^{-1}. However, further study is required to determine if this critical herbage mass value applies to other grassland types when optimally grazed.

Alpine meadow, Maqu

The alpine meadow grazing experiment was done in Maqu county of Gansu province, situated on the east of the Qinghai-Tibetan Plateau (N35°85′, E101°85′; elevation 3500 m). Over the past 13 years precipitation averaged 616 mm and annual temperature 2.4°C, with 270 frost days year^{-1}. The grazing experiment investigated: continuous grazing (July–December) with a stocking rate of 4 sheep ha^{-1} vs short duration seasonal rotation (SDSR) treatments with 4 or 8 sheep ha^{-1} that were grazed through summer (July–September) in the growing-season pasture and then in autumn (October–December) in a separate 'autumn' pasture when there is no plant growth and frosts occur. Within the SDSR treatments in summer, animals were grazed around three subplots, moving every 10 days, then in autumn they were grazed around two subplots, moving every fifteen days. The SDSR treatments also compared a heavy stocking rate in the growing season and light stocking rate in the cold season (SDSR-HL) or light stocking rate in the growing season and heavy stocking rate in the cold season (SDSR-LH). Herbage mass was measured, before and after each graze period or at monthly intervals (in the continuously grazed plots). Further details of the experiment are in Sun *et al.* (2015) and Wang *et al.* (2018).

During the experiment grazing pressure was low compared with the other typical and desert steppe sites shown by high herbage mass (detailed below). Grassland composition did not change in the pastures grazed in the warm season at any stocking rate, but there was a small overall decline in species in the cold season pastures resulting in the loss of some minor species including the highly palatable *Stipa aliena* (Wang *et al.* 2018). The highest grazing pressure was insufficient to cause adverse changes to composition.

In the grazing experiment, seven-month-old Tibetan sheep were purchased each year in June, grazed on treatments until December, then sold. Under light stocking rates (4 sheep ha^{-1}) there was no difference in LWG between continuous stocking and short duration seasonal grazing treatments. Sheep on average gained weight between July and September then lost weight from October through December, when grazing summer and autumn pastures sequentially at both 8 and 16 sheep ha^{-1}. Liveweights were only maintained with a continuous grazing low stocking rate on a single pasture through both periods (4 DSE ha^{-1} from July to December; Wang *et al.* 2018). The difference in stocking rate over the grazing seasons explained most of the variation in average lamb growth rate (Table 5). The average potential sheep growth rate over summer was ~130 g head^{-1} day^{-1}, 75% of which (viz. 98 g head^{-1} day^{-1}) is about the value where livestock production is more profitable (Kemp *et al.* 2018). The stocking rate where livestock production is more profitable was estimated to be up to 22 sheep ha^{-1} over summer or 1980 SE grazing days^{-1} ha^{-1}. This result supports the view that for this site, the average stocking rates are arguably sustainable and the grasslands should not be over-stocked. This result was further supported by considering the residual herbage mass after grazing, which averaged 1.6–2.3 t DM ha^{-1}

Table 5. Average stocking rate (sheep equivalents (SE) ha^{-1}; 50 kg reference weight animal), stocking rates and months grazing in warm and cold grazing season areas, average grazing days (SE grazing days ha^{-1} year^{-1}), and average liveweight gain (LWG) per head (hd) and per hectare (ha) from June to December for the alpine meadow

Adapted from Wang *et al.* (2018)

Treatment	Average stocking rate (SE ha^{-1})	Warm stocking rate (SE ha^{-1})	Cold stocking rate (SE ha^{-1})	Months grazing warm area	Months grazing cold area	Grazing days (SE grazing days ha^{-1} year^{-1})	LWG hd (g head^{-1} day^{-1})	LWG ha (g ha^{-1} day^{-1})
SLC24	4	4		6		720	0.067	0.267
SDSR24	8	8	8	3	3	720	0.064	0.256
SDSR36 H-L	12	16	8	3	3	1080	0.056	0.337
SDSR36 L-H	12	8	16	3	3	1080	0.058	0.350
SDSR48	16	16	16	3	3	1440	0.051	0.404

(Sun *et al.* 2015). These values suggest that sheep intake is not limited by pasture availability. Further work is needed to identify critical herbage values for alpine meadows.

When this experiment started, the higher stocking rate treatments were set at the district average stocking rates. The field site was in the valley floor near a local village and had been typically grazed throughout the year because herders had regular access. After two years of the experiment, the herbage mass within the experiment was 2–4 times greater than that of the surrounding areas, even on the highest stocking rate treatment, an outcome reflected in the experimental results. This differential indicated that the effective stocking rate on farms in the valley floor was much greater than the district average suggested. This very high local stocking rate occurred because herders with farms located away from the villages and main road obtained permission to bring their livestock into that valley floor so they could sell them to traders. In reality, over-grazing was only occurring in part of the region. This means that an overall stocking rate equivalent to those identified by the experiment could be sustained when evenly distributed. To reduce overgrazing in the valley floor, the local community needs to determine better practices to avoid increasing grazing pressure on the valley floor such as dedicated feedlot areas in which herders can keep their livestock before selling.

In general, alpine meadow soils have a higher carbon content than other grassland soils, with a fewer months above freezing when losses can occur. The rate of methane uptake by the soil was lower than for other grasslands, and best under moderate grazing (Liu *et al.* 2012*b*). There was no change in soil carbon between grazing treatments measured over a five-year period (Wang *et al.* 2018). Further work is needed to better define how these effects relate to herbage mass.

This research done on alpine meadows did suggest that high average stocking rates may not lead to over-grazing, but local practices that affect animal distribution are a major problem for developing sustainable management systems. Stocking rates were also more important in determining livestock production than the patterns of grazing.

Discussion

Management of Chinese grasslands has been extensively studied in recent years, especially to examine the effect of altering grazing pressure on livestock production efficiency and grassland condition. The challenge is to use this knowledge to develop and promote evidence-based practices that improve sustainability of China's grasslands and the livelihoods of the millions of herders who utilise them for food, fibre and fuel production. This means that the multiple impacts of grazing need to be resolved in practical ways to derive methods that are understood and can be used by all those who manage grasslands and livestock.

Grazing management involves managing both animals and the grassland, ideally to optimise both within system constraints. Herders can manage the density of animals (stocking rate), the intensity and frequency they graze any given area of grassland, and the times when grazing starts and stops. The impact of these components needs to be standardised and is most conveniently expressed as a standard sheep equivalent. The collaborative work done in this Australia-China program clearly shows that stocking rate, the time when grazing starts in summer, and zero grazing in winter are the main components of grazing management where on-farm changes need to be implemented (Michalk *et al.* 2011). An important outcome from the results reported here is that grazing practices need to focus on working within the current state of a grassland, rather than trying to restore condition to some ideal state, unlikely to be achieved in the short to medium term. As argued by Westoby *et al.* (1989), the rehabilitation pathway for a grassland rarely follows the reverse trajectory of the degradation pathway, hence vital ecological functions cannot simply be restored to an original state.

In the desert and typical steppe, reduced stocking rates are vital for grassland sustainability. In general, a 50% reduction in stocking rates from the high levels reached in the 1990s is needed to improve or maintain a desired species composition and increase income from livestock (Michalk *et al.* 2011; Kemp *et al.* 2013, 2020*c*). The exception found was for alpine meadows, where over-grazing is a local problem caused by uneven animal distribution in the landscape. Infrastructure changes e.g. access roads, special stock routes, holding fields and market organisations are likely to be important in solving the local overgrazing in valley floors. The data on livestock numbers for the Maqu alpine meadow area showed there had been a smaller increase in animal numbers in recent decades than for elsewhere in China (Kemp *et al.* 2020*b*).

The desert steppe grazing experiment involved grazing through summer and autumn for 150 days. Summer was the only time that animals gained weight. In autumn, frosts are common, and at best animals lost a small amount of liveweight where monitored in the desert steppe and alpine meadow. Observations suggest that animal diet is more selective in summer, and hence there is a greater impact on plant species composition. Thus, the stocking rate over summer is more critical for grassland condition. More detailed work is required to clearly differentiate grazing effects in summer and autumn. The work discussed here concluded that the optimum stocking rate was 150 SE grazing days ha^{-1}, equally distributed over the 150 days of summer and autumn, or 100 SE grazing days ha^{-1} over summer and 50 SE grazing days ha^{-1} in autumn.

Although reduced stocking rates are clearly needed for most grassland types, setting an ideal stocking rate may not be the optimum strategy as this only defines forage demand, not the supply. A better strategy is to focus on managing livestock to maintain grasslands above a critical level of herbage mass through the summer plant growth period. Standing herbage mass in a grassland is the net balance between consumption and growth. Both the desert and typical steppe experiments defined this level as being above 0.5 t DM ha^{-1}. In practice, this would mean herders need to maintain an even higher dry matter level as a management buffer, as it would be difficult to precisely achieve exactly 0.5 t DM ha^{-1} across all their grasslands. This critical value is related to optimising plant species composition, optimising soil carbon and methane uptake and achieving animal growth rates near the financially optimum level. Herbage mass can be monitored remotely and technology exists in China to provide this information (Ma *et al.* 2019). The challenge now is providing this critical information directly to herders to guide their management decisions. In poor seasons livestock numbers or grazing time need to be less than the average optimal stocking rates to maintain critical values of herbage mass. Monitoring herbage mass would then provide managers with a warning about when to bring animals onto feed earlier or to sell when animals are in a better condition and so obtain a better price. In China, open and value-based markets need to be developed to accommodate this need. In a good season it may not be possible to breed or acquire enough animals to reduce the herbage mass to the set critical value. However, underutilisation provides the opportunity for grasslands to make incremental recovery.

Delaying the start of grazing in summer has been shown to improve herbage growth through summer and total production (Parsons and Penning 1988). This delay has become a standard part of grassland regulation, especially where local governments have implemented grassland 'balance' strategies designed to allow grazing to continue livestock production while rehabilitating degraded grasslands. However, in China the start of grazing is set by a calendar date which does not adjust for varying seasonal conditions. The work discussed here suggests that grazing should be delayed until the grassland reaches the critical herbage mass i.e. >0.5 t DM ha^{-1} for the typical and desert steppe. This would then allow adjustment for differing seasons. Further work is needed to define the critical herbage mass thresholds for different grasslands and regions. Herbage mass can be monitored by remote sensing and grassland surveys.

Grazing through winter has always been problematic in China as temperatures are very low and modelling indicates that the energy costs of walking and grazing in winter greatly exceed the energy obtained from eating the dead plant material available (Zheng *et al.* 2013; Jin *et al.* 2019). One piece of evidence obtained for the desert steppe was that plant growth was significantly reduced in the year following heavy grazing pressure in winter, but more research is needed to identify the effects of intensity of grazing through winter on the subsequent state of various grassland types. While previous work elsewhere has linked the reductions in production following winter grazing to lower photosynthetic material (Frame 1970; Wilman and Griffiths 1978), in Chinese grasslands where there is no actively growing material in winter, it appears the dominant mechanism in reducing production is reduced tiller density, which decreases the number of growing points. It is clear though that low temperatures and limited feed supplies lead to considerable liveweight loss through winter. Better design and use of warm (greenhouse) sheds can compensate for the lack of feed and achieve better livestock performance. Livestock survival through winter will be improved by foregoing grazing, keeping livestock in warm sheds and increasing the use of quality supplemental feed (Zheng *et al.* 2013). These are the key components of re-designed management systems needed to progress herders from a survival style livestock management system to a more market orientated production approach that improves household profitability by improving production efficiency and product quality (Michalk *et al.* 2015).

In China, five-year total grazing bans have been used since 2003 (Xiong *et al.* 2016) as a prime mechanism for rehabilitating degraded grasslands. However, the research presented here has found that application of a protracted grazing ban will not provide the best outcome. The desert steppe site took 8–10 years of no grazing to begin to show useful changes in plant species, herbage mass, carbon sequestration and methane exchange, and these changes were no better than those recorded in the optimal stocking rate treatment. Under reduced stocking rates, the net financial returns from livestock have increased (Kemp and Michalk 2011), and the level of government payments to achieve reduced stocking rates are significantly less than those required for a total grazing ban. It is also arguable that when the appropriate stocking rate is used, production efficiency (more product per head) and product quality (for which markets pay premium prices) increase, as shown by the Siziwang farm demonstrations (Li *et al.* 2014, 2020), and this negates the need for a government subsidy. Furthermore, while grazing ban policies are targeted at improving grassland composition, they may have unintended negative GHG outcomes by displacing production to other less sustainable areas in other countries or intensive feedlot production systems with higher production of GHGs (Plevin *et al.* 2014). The evidence in these (Chen *et al.* 2015; Zhang *et al.* 2015) and other (Liu *et al.* 2012*a*; Orgill *et al.* 2018) experiments indicates that light or moderate grazing can store as much or more carbon than grazing bans due to increased root production (Chen *et al.* 2015). It is clear that sustainable grazing practices can improve herder incomes and deliver gains for environmental services.

Conclusion

Reducing the grassland grazing pressure in China by 40–50% from traditional management in the desert and typical steppe maintained commercial levels of livestock production (measured as LWG), improved grassland composition and reduced GHG emissions, predominately through reduced enteric CH_4 intensity (and increased soil C in the typical steppe). The optimum stocking rate for the desert and typical steppe was demonstrated to be ~150 SE grazing days ha^{-1} (1 SE ha^{-1} over 150 days of summer) and ~400 SE grazing days ha^{-1} (4 SE ha^{-1} over 100 days) respectively. While profitability of the livestock system was not directly measured, the production per head for livestock at the optimal stocking rates (~75% of maximum) was around the values where net profit is maximised (Kemp *et al.* 2018). In the alpine meadow the district average stocking rate was not high, and there was little change in average LWG per head and grassland composition with increased stocking rates. In this region the distribution of animals and grazing at inappropriate times is the likely source of degradation, but these dynamics need further investigation.

The grazing management treatments based on time-based criteria in the typical steppe and alpine meadow did not demonstrate any consistent, positive outcomes; stocking rate was clearly of greater importance. The limited effects of grazing technique were probably due to the short growing season of 100 days. In the typical steppe, early season rest, while arguably aiding the grassland, did reduce livestock production because of the short grazing period of lower forage quality.

At all sites it was concluded that grazing can be managed sustainably by determining the critical average summer value for herbage mass, below which the grassland should not be grazed. This also helps manage the grasslands in areas where common grazing occurs, or herders collaborate to graze livestock together which results in setting stocking rates becoming problematic. Other details of when, what and how animals are grazed can be determined by herders. The role of grassland officials then becomes one of monitoring when to start and stop grazing, which will minimise the time spent monitoring stock numbers. Overall stocking rates in China are now four times that of 1950 (Kemp *et al.* 2020*c*). Reducing stocking rates has shown improvements in the grassland and greater incomes for herder households (Li *et al.* 2020).

Conflicts of interest

The authors declare that they have no conflicts of interest.

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