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Review

Establishing the carrying capacity of the grasslands of China: a review

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Abstract. China is rich in grassland resources, with 400×10^6 ha of natural grasslands and 18 main types, mostly distributed in the north-east, north, Qinghai-Tibet Plateau and Xinjiang regions. Grassland-based livestock production is the foundation of the economy in these rural areas. Degradation of grassland has occurred to varying degrees in these regions. Mean overgrazing rates across the whole country were estimated to be ~30% in 2009. Considerable amounts of research have focussed, especially since 2000, on developing better ways of managing Chinese grasslands. Research concerning the relationship between forage production and animal performance, is reviewed for three important national grassland regions. For the three major grassland (steppes) types of Inner Mongolia, the stocking rates proposed as a result of research were 1.0–2.2 sheep units (SU) ha^{-1} for the western, drier *Stipa breviflora* desert steppe; 2.0–3.8 SU ha^{-1} for the steppe of *Artemisia frigida* and *Stipa grandis*; and 1.8–4.0 SU ha^{-1} for the eastern higher-rainfall *Leymus chinensis* meadow steppe in Hulunbeir. In the Qinghai-Tibetan alpine meadows, the stocking rate of grassland dominated by *Edelweiss*-*Potentilla* and *Kobresia parva*, proposed on the basis of research, was 1.0–5.8 SU ha^{-1}. In Xinjiang's desert steppe, the stocking rates of *Seriphidium transiliense* desert steppe were proposed on the basis of research were 1.2 SU ha^{-1} in spring and 1.8 SU ha^{-1} in autumn for non-degraded pasture, and 0.3 and 1.2 SU ha^{-1} for moderate-degraded pasture, respectively. These stocking rates were based on either annual net primary production or desired levels of livestock production and it is argued that there is a need to develop carrying capacities based on a wider range of sustainability criteria and with the most appropriate grazing systems.

Additional keywords: grassland, Inner Mongolia, Qinghai-Tibet, stocking rate, Xinjiang.

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Introduction

Stocking rate (SR) is one of the most important grazing management tools, since it has the largest impact on livestock performance and forage resources, regardless of the grazing system employed, vegetation type, or kind and class of livestock produced. Low SR result in low utilisation of grassland and low output of livestock produced per unit area, although generally the condition of the grassland does not deteriorate. High SR over-utilise grassland and create several problems, including reducing species diversity, reducing the composition of plant species preferred by livestock, and adversely affecting soil physics, hydrology, soil chemistry and ecosystem function at various spatial–temporal scales; and reducing livestock performance per head. This results in a decline in grassland productivity (Wang *et al*. 1999*a*; Kurz *et al*. 2006; Semmartin *et al*. 2008).

Setting the average annual carrying capacity for a particular type of grassland involves establishing the maximal SR that will achieve a target level of livestock performance in a specified grazing system that can be applied without deterioration to the grassland (Allen *et al*. 2011). It requires consideration of the amount of forage produced throughout the whole year and the nutrient requirements to meet the livestock performance targets of the type and class of livestock raised. Jones and Sandland (1974) described the now classical relationships between SR and individual liveweight gains (negative and linear), and SR and liveweight gain ha^{-1} (quadratic with a maximal value). In China, carrying capacity has often been determined by considering the maximum liveweight gain ha^{-1} or the aboveground net primary productivity (ANPP) of the grassland (Wang *et al*. 1999*a*, 1999*b*; Han *et al*. 2007; Yan *et al*. 2010). Wang *et al*. (1999*a*) reported that there was a negative linear relationship between SR and individual liveweight gains and that there was a quadratic relationship between SR and liveweight gain ha^{-1}, and the SR at which livestock production ha^{-1} was at a maximum was recommended as the optimum SR. Han *et al*. (2007) and Yan *et al*. (2010) showed that there was a negative linear relationship between SR and ANPP of grassland, and the

SR where the ANPP ha^{-1} had a maximum was recommended as the optimal SR. This earlier work emphasised livestock production with some consideration of grassland productivity, whereas there is now a stronger emphasis on achieving a 'balance' between grassland production and livestock output (Kemp and Michalk 2011; Zhang *et al*. 2013). Environmental considerations are viewed as part of achieving sustainable production from grasslands.

Grassland-based livestock production in China has been practised for millennia, yet in the past century grazing has caused serious degradation and desertification due to inappropriate grazing management. With the implementation of projects for grassland restoration by way of the national ecological policies of forbidden or rotational stocking, achievement of a balance between forage production and livestock performance has been given a high priority. Under these policies, there have been many studies investigating the balance between forage supply and animal demand of individual grassland types in different regions (Wang and Li 1997; Dong *et al*. 2003; Han *et al*. 2007; Zheng *et al*. 2010; Yan *et al*. 2011). The present paper reviews the results of a series of grazing experiments done to quantify grassland production and SR in the Inner Mongolian grasslands, Qinghai-Tibetan alpine meadow and Xinjiang's desert steppe. Most of these studies have been published in Chinese and are not cited in the international literature. This review highlights the amount of work that has been done to define suitable SR. The aim of this review is to explore whether the current criteria are the best to define carrying capacities for Chinese grasslands and to establish better practices for the sustainable management of grassland resources in China.

Location of research sites

The SR studies reviewed in this paper include those for grasslands in the Inner Mongolia, the Xinjiang Uygur and Tibet Autonomous Regions and Qinghai, Sichuan and Gansu Provinces (Fig. 1).

Terms used

Stocking rate is the number of animals allotted to a certain area of pasture for a given length of time. The optimum SR were recommended by the original authors (see Table 1). Carrying capacity is determined by dividing the amount of forage by the forage requirement by livestock to meet stated objectives. Actual SR is defined as the actual numbers of livestock on a certain area of pasture throughout a year. Overgrazing is defined as the practice of grazing livestock that exceeds the carrying capacity of a pasture; and undergrazing is the grazing of livestock below the carrying capacity. Overgrazing rate is calculated using the following equation: overgrazing rate = (carrying capacity – actual SR)/carrying capacity. ANPP on a dry matter (DM) basis was estimated by grab samples from 1-m^2 quadrats and a subsample of the quadrats was dried to establish the DM content. Growing season is defined as the average number of days per year with a 24-h average temperature of at least 5°C – this is typically between May and October in the regions of China studied.

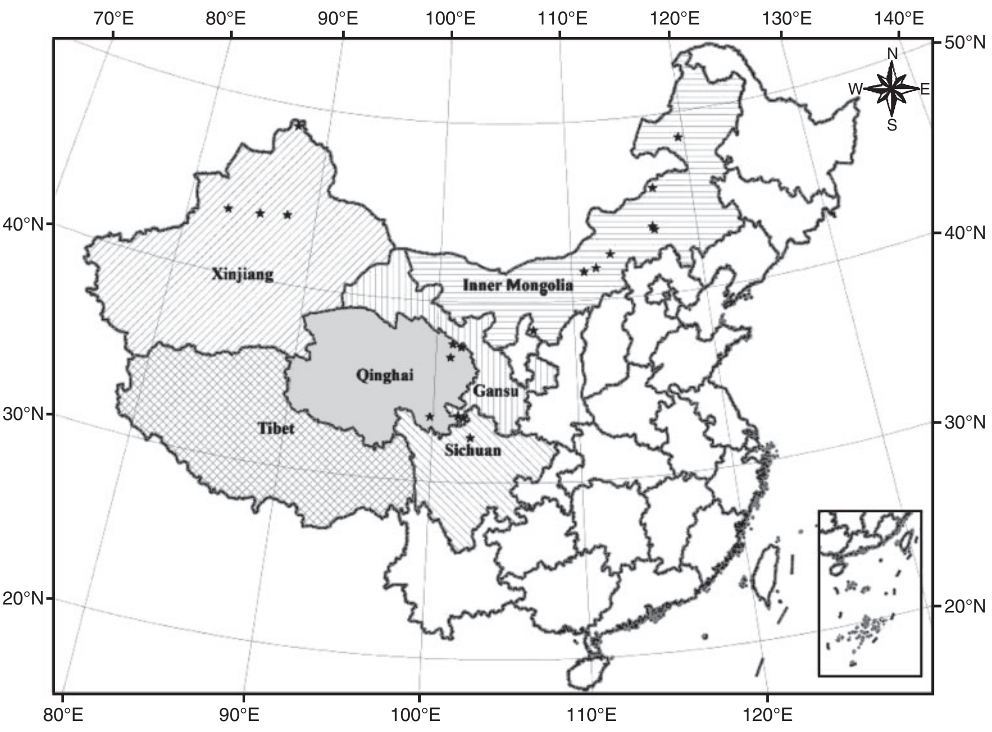

Fig. 1. Location of research areas. The regions distinguished are the location of Chinese grasslands reviewed in this article and the pentagrams in the regions indicate the research areas where the published studies on stocking rate were conducted.

Table 1. The annual net primary productivity (ANPP) and stocking rates (SR) recommended by the original authors of typical steppe, meadow, desert and Tibetan Plateau grasslands in China

SU, sheep unit; NM, not measured

Grassland type	Vegetation type	ANPP (kg D ha^{-1})	Recommended SR (SU ha^{-1} in summer)	Reference
Steppe desert	*Reaumuria songorica*	466	1.0	Sarulaqiqige (2007)
Desert steppe	*Stipa breviflora*	440	2.2	Han *et al*. (2000*b*)
Desert steppe	*Stipa breviflora*	500/440	1.3/2.0[A]	Han *et al*. (2000*a*)
Desert steppe	*Stipa breviflora*	500	1.0	Han *et al*. (2007)
Desert steppe	*Seriphidium transiliense*	NM	0.3/1.2[B]	Liu *et al*. (2013)
Desert steppe	*Seriphidium transiliense*	NM	1.2/1.8[C]	Liu *et al*. (2013)
Meadow	*Leymus chinensis*	1081	1.8	Yan *et al*. (2010)
Typical steppe	*Artemisia frigida*	1180	2.0	Wang *et al*. (2003)
Alpine meadow	*Kobresia parva*	1501	5.2–5.8[D]	Dong *et al*. (2003)
Alpine meadow	Grass-*Kobresia*	1535	1.8[E]	Ren *et al*. (2009)
Typical steppe	*Stipa grandis*	1606	3.8	An *et al*. (2002)
Meadow	*Stipa baicalensis* and *Leymus chinensis*	2001	4.0	Yang *et al*. (2006)

[A]1.3 was recommended as the SR for optimum net productivity of the plant community and 2.0 for the desired livestock production per head.
[B]0.3 was recommended as the SR of moderate-degraded desert in spring and 1.2 in autumn.
[C]1.2 was recommended as the SR of non-degraded desert in spring and 1.8 in autumn.
[D]The SR under rotational stocking during winter–summer.
[E]The SR in winter–spring.

Stocking rate research in Inner Mongolian grasslands

The Inner Mongolian grassland is an important part of the grasslands of Eurasia, with 78.8×10^6 ha of natural grassland, accounting for 67% of the total land area of Inner Mongolia, and 20% of the total grassland area of China. Of this grassland, 63.6×10^6 ha is used for grazing – the largest single grazing area in China. Within that grassland 9%, i.e. 7.1×10^6 ha, is mown for hay, mostly in the east of Inner Mongolia (Gu *et al*. 1997). These large natural grasslands are classified from east to west – with decreasing yield and nutritive value of forage – as meadow steppe (11.9%), typical steppe (35.1%), desert steppe (10.7%), steppe desert (6.8%) and desert (21.5%).

Inner Mongolia is the most important animal production region in China with 100×10^6 SU (sheep unit – defined as a 50-kg mature female sheep with one 0–6-month-old lamb and with a daily forage intake of 1.8 kg DM). Production of milk, mutton, cashmere and wool in 2009 was 9031, 882, 7.4 and 54 ($\times 10^3$ t), respectively, ranking Inner Mongolia number one relative to other regions in China (Zhao 2011). However, high grazing pressures have resulted in severe degradation and desertification, with decreased forage production as well as a deteriorating ecological environment. Since 2000, policies of grazing bans or rotational stocking management and projects, such as sandstorm source control, have been introduced by the central government to alleviate these problems.

Relationship between forage and livestock production

Long-term overgrazing has resulted in serious damage to grassland ecosystems and reduced livestock production. According to Yi *et al*. (2010), using vegetation data derived by remote sensing and livestock numbers provided by the local Bureau of Statistics, the total estimated forage yields were steady from 186×10^6 t in 2005 to 185×10^6 t in 2006, and reduced to 169×10^6, 181×10^6 and 128×10^6 t in 2007, 2008 and 2009, respectively (Fig. 2). Conversely, the actual SR increased from 113×10^6 to 136×10^6 SU during the same period, leading to an increase in overgrazing rate from 23 to 112%. In particular, the drought in eastern Inner Mongolia led to a 5.3×10^6 t decrease in forage and an ~112% increase in SR in 2009 compared with 2008 (Yi *et al*. 2010).

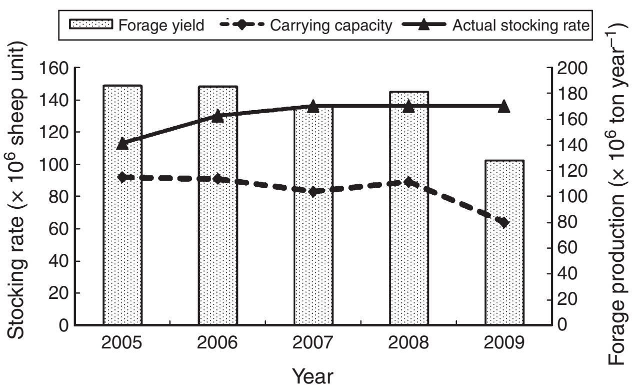

Fig. 2. Relationship between forage production and stocking rate for 2005–09 in Inner Mongolian grassland. Data from Yi *et al*. (2010).

The average annual increase in degradation and desertification area of grassland in Inner Mongolia was ~1.67×10^6 ha. In comparison with the 1950s, forage yield has declined by 30–50% and carrying capacity decreased by 4100×10^6 SU, resulting in US\$$80 \times 10^6$ loss per year due to decreased livestock production in Inner Mongolia (Duan 2006), a grassland-based livestock industry region. Researchers have proposed a variety of carrying capacity levels for the different steppe types of Inner Mongolian grassland, reflecting differences in climatic conditions (Table 1): these were 2.0–3.8 and 1.0–2.2 SU ha^{-1} in summer for typical and desert steppes of Inner Mongolia, respectively.

Status of stocking rate research

Stocking rate research on the Inner Mongolian grasslands has often focussed on the detailed effects on grasslands, vegetation and soils or animals. Less has been done linking typical and alternative animal production systems to plants and soils. Stocking rate significantly affects the vegetation community biomass (both above- and belowground), plant population dynamics and biodiversity of different grassland types (Wang and Wang 1999*a*; Wang *et al*. 1999*a*; Han *et al*. 1999, 2000*b*; Yan *et al*. 2010).

Typical steppe

The ANPP of *Stipa grandis* grassland were 1480, 1606 and 1260 kg/ha at SR of 2.5, 3.8 and 7.5 SU ha^{-1} in summer, respectively (An *et al*. 2002). The aboveground biomass declined from 2001 to 600 kg DM ha^{-1} as the SR increased from 1.5 to 9.0 SU ha^{-1} in summer (Xue *et al*. 2010). The belowground biomass (0–30 cm) dropped from 12 020 to 6003 kg ha^{-1} when the SR increased from 1.3 to 6.7 SU ha^{-1} in summer (Wang and Wang 1999*b*). There have been some studies of the relationship between SR and animal nutrition and performance for typical steppe dominated by *Artemisia frigida*, – a less preferred species by livestock but one that tends to become dominant when grasslands are overgrazed (Wang and Li 1997; Wang *et al.* 2003). These indicated that the average liveweight gain per ewe in 5 years decreased from 10.9 to 3.1 kg in summer as the SR increased from 1.3 to 6.7 SU ha^{-1}, but the liveweight gain ha^{-1} increased from 14.6 to 35.8 kg as SR increased from 1.3 to 5.3 SU ha^{-1} and then decreased to 20.3 kg for 6.7 SU ha^{-1}. The wool production increased ($P < 0.05$) by 50–200 kg ha^{-1} when SR increased from low (1.3–4.0 SU ha^{-1}) to high (5.3–6.7 SU ha^{-1}) rates. The authors attributed the changes in performance of livestock to the differences in DM and crude protein (CP) intakes and digestibility, with the highest DM and CP intakes at a SR of 2.0 SU/ha. Wurina (2010) showed that the DM intake by sheep reduced ($P < 0.05$) from 1230 and 1378 g DM day^{-1} at SR of 1.5 and 4.5 SU ha^{-1} respectively, to 1153 and 1033 g DM day^{-1} at 6.0 and 9.0 SU ha^{-1}, respectively; however, there were no significant differences in DM digestibility between the forage on offer in the various treatments (range 0.607– 0.625).

Stocking rates have a strong impact on the biotic properties of soil. Rong *et al*. (2001) found that total soil nitrogen (N) content increased but total phosphorus (P) and available P contents decreased as the SR increased from 0 to 13 SU ha^{-1} in a rotational grazing system. However, in another study total soil N and P contents (0–20 cm) decreased and the available N and P increased with increased SR in the range of 4–16 SU ha^{-1} (Zhang *et al*. 2000). The differences in studies above may be due to differences in the soil matrices or the difference in experiments' grazing periods of 103 days *v.* 6 years.

Low SR increased intake rates and reduced grazing times (Wang 1997; Wurina 2010; Lin *et al*. 2011). As SR increased, there was more time spent on grazing and less on resting, but there was a variable impact on ruminating time. Wang (1997) showed that sheep spent longer ruminating at a low compared with a high SR ($P < 0.05$) but Lin *et al*. (2011) and Wurina (2010) found no significant differences (Table 2).

Desert steppe

The proportions of dominant species of *Artemisia frigida*, *Stipa breviflora* and *Cleistogenes songorica* in vegetation were reduced by 24, 28 and 40%, respectively; biomass of DM, both above- and belowground (0–30 cm), decreased from 573 to 364 kg ha^{-1} (Jiao *et al*. 2006) and 2011 to 1808 kg ha^{-1} (Sun *et al*. 2010), respectively, when the SR increased from 1.0 to 2.7 SU ha^{-1} during the growing season. Han *et al*. (2000*b*) studied the effects of SR on plant community photosynthesis and energy utilisation in a sheep-grazing system, and found the net productive energy of the plant community was 79 270 at a growing season SR of 1.3 SU ha^{-1} and 49 265 MJ ha^{-1} at a growing season SR of 3.0 SU ha^{-1}, the corresponding metabolisable energy intakes by sheep and its digestibility that measured by grab samples were 18.6 and 7.6 MJ day^{-1}, and 0.71 and 0.49, respectively. Based on the energy utilisation by sheep, 1.3 SU ha^{-1} was recommended as the SR for optimum net productivity per ha of the plant community and 1.8–2.0 SU ha^{-1} for the optimal livestock production per head. As the SR increased from 1.3–2.0

Table 2. The behavioural activities (hour per daylight period) of sheep grazing at the different stocking rates of typical steppe in Inner Mongolia, China

Stocking rate	Behavioural activities				
(sheep unit ha^{-1})	Grazing (h)	Ruminating (h)	Resting (h)	Walking (h)	Reference
2	6.41	4.19	4.04	0.44	Lin *et al*. (2011)
3	5.87	3.83	5.09	0.31	–
4	7.45	3.76	3.28	0.42	–
6	7.15	3.73	3.77	0.29	–
8	8.27	3.80	2.74	0.19	–
11	8.96	2.86	2.89	0.38	–
1.5	6.25	4.10	3.88	0.43	Wurina (2010)
3.0	5.72	3.76	4.91	0.31	–
4.5	7.21	3.66	3.28	0.37	–
6.0	6.98	3.66	3.60	0.35	–
7.5	8.13	3.66	2.63	0.28	–
9.0	8.81	2.74	2.77	0.19	–
1.3	8.84	2.41	1.17	0.20	Wang (1997)
2.7	9.88	1.63	1.50	0.15	–

to 3.0 SU ha^{-1} in summer, liveweight of sheep was significantly reduced ($P < 0.05$) from 33.6–35.8 to 30.6 kg; and 2.2 SU ha^{-1} was recommended as the optimum SR for the maximum liveweight gain ha^{-1} (Han *et al*. 2000*a*). To achieve the highest recovery growth of plants, a SR of 1.0 SU ha^{-1} per year was suggested as optimal for this region (Han *et al*. 2007). These different SR recommended, based on the optimal production of animals or forage per unit, indicate that the earlier studies only emphasised livestock production or forage production rather than balancing forage utilisation with livestock output.

Stocking rates affect soil microbes and respiration from soil (Wang *et al*. 2009) and the soil seed bank (Li *et al*. 2010). Soil respiration rate decreased ($P < 0.05$) from 5.0 to 0.8 μmol CO_2 m^{-2} s^{-1} and the seed number ha^{-1} in soil between 0 and 20 cm accounted for 87–96% of total soil seed number ha^{-1} and decreased from 9312×10^3 to 7021×10^3 seeds ha^{-1} as the growing season SR increased from 0.9 to 2.7 SU ha^{-1}.

Meadow steppe

The aboveground biomass of *Leymus chinensis* meadow was 1081–650 kg DM ha^{-1} and daily net photosynthetic rate of *L. chinensis* leaves was 23.1–9.0 μmol CO_2 m^{-2} s^{-1} when the SR increased from 0.9 to 3.7 SU ha^{-1} in summer (Yan *et al*. 2010; Deng *et al*. 2012). Accordingly, 1.8 SU ha^{-1} was recommended as the optimal SR of meadow steppe in Hulunbeir. Moreover, the dominant *L. chinensis* tended to be replaced by *Potentilla bifurca* and *Carex siderosticta* when the SR reached 3.7 SU ha^{-1} (Meng *et al*. 2009). The aboveground biomass of *Stipa baicalensis*- and *L. chinensis*-dominated meadow, decreased from 2151 to 635 kg DM ha^{-1} as SR increased from 2 to 8 SU ha^{-1} in summer. The diversity indices (calculated by Shannon–Wiener index) of the functional groups of the plant community decreased from 1.92 to 1.81 with a peak of 2.35 at the moderate grazing of 4 SU ha^{-1}, and the perennial grass population in the meadow was replaced gradually with forbs when the SR reached 6–8 SU ha^{-1} (Yang *et al*. 2006). As SR increased, the numbers of soil microbes increased from 4.92×10^6 to 6.20×10^6 colony forming units and soil respiration rate decreased, non-significantly, from 3.71 to 2.64 mmol CO_2 m^{-2} s^{-1} (Chen *et al*. 2008).

Stocking rate research in Qinghai-Tibetan alpine meadow

The Tibetan Plateau, the special geomorphological unit known as 'the roof of the world', occurs mainly within Tibet, Qinghai, western Sichuan and the Gannan Prefecture of Gansu Province and covers 30% of the total grassland area of China. The area of natural grassland on the Tibetan Plateau is 118×10^6 ha, the second largest area of grassland in China, and more than two-thirds of the area of alpine regions in China (Ministry of Agriculture of People's Republic of China 1996). Qinghai-Tibet alpine meadow is the main vegetation type and accounts for ~50% of the total area of grassland in the Tibetan Plateau (Zhou *et al*. 1987) – it plays an important role in livestock production systems and ecosystem protection. Yak (*Bos gruniens*) and Tibetan sheep are the main livestock used (Cai 1992).

Alpine meadows have suffered serious damage and soil erosion due to overgrazing (Zou *et al*. 2003; Wang 2004), with the degraded area being 43×10^6 ha (Ma *et al*. 1999). The overgrazing rate in Tibet, Qinghai, Sichuan and Gansu in 2010 was estimated to be 38, 25, 37 and 36%, respectively (Ministry of Agriculture of People's Republic of China 2011). There is little research available concerning the relationship between forage and livestock production, including recommended SR, compared with that available for the steppes of Inner Mongolia.

Relationship between forage and livestock production

In recent decades, research has shown that pastures in the Tibetan Plateau were commonly overgrazed, with overstocking rates in the range of 27–89% in various regions (Table 3). The overgrazing rate in Qinghai-Tibet was 40% in 1996 (Yang and Yang 2000) and 57% in 2003–04 (Qian *et al*. 2007). Earlier estimates of overgrazing rates were 33–45% for 1996–2007 in Qinghai Province (Sanbairuizh and Zhao 1999; Su *et al*. 2009), and 37% in Gannan Prefecture of Gansu Province in 2008 (Wang 2011), suggesting that overgrazing has been occurring for some time. In Gannan, a seasonal imbalance in forage production and animal demand was shown: with 37% undergrazing suggesting that a further 970×10^3 SU animals could be raised in summer grassland, but an overgrazing of 1200×10^3 and 1193×10^3 SU in winter and all-season pastures, respectively (Fig. 3). Consequently, 2.6×10^6 t of forage was required annually, based on the survey of Liu *et al*. (2010). It has been predicted that the SR of alpine meadows will decline by 1.5 SU ha^{-1} due to climate warming, decreasing forage production by 1414 kg DM ha^{-1} using the Miami model for a temperature increase of 2°C by the 2050s (Li 2000).

Table 3. The actual stocking rates (SR) and overgrazing rates in Qinghai-Tibetan alpine meadow and Xinjiang's desert steppe

Grassland type	Region	Year	Actual SR ($\times 10^6$ sheep unit)	Overgrazing rate (%)	Reference
Tibetan Plateau	Hainan, Qinghai	1996	4.92	32.6	Sanbairuizh and Zhao (1999)
Desert steppe	Altay	2000	6.21	22.5	Liu and Wang (2008)
Tibetan Plateau	Gannan, Gansu	2008	7.13	36.6	Wang (2011)
Tibetan Plateau	Haibei, Qinghai	2007	7.87	44.5	Su *et al*. (2009)
Tibetan Plateau	Qinghai	2003–04	36.5	27.2	Qian *et al*. (2007)
Desert steppe	Xinjiang	2007	50.2	55.8	Dong and Liu (2009)
Desert steppe	Xinjiang	1999	33.6	68.9	Sabit *et al*. (2002)
Tibetan Plateau	Qinghai-Tibet	1996	110.9	39.8	Yang and Yang (2000)
Tibetan Plateau	Qinghai-Tibet	2003–04	87.4	57.3	Qian *et al*. (2007)
Tibetan Plateau	Tibet	2003–04	50.9	89.4	Qian *et al*. (2007)

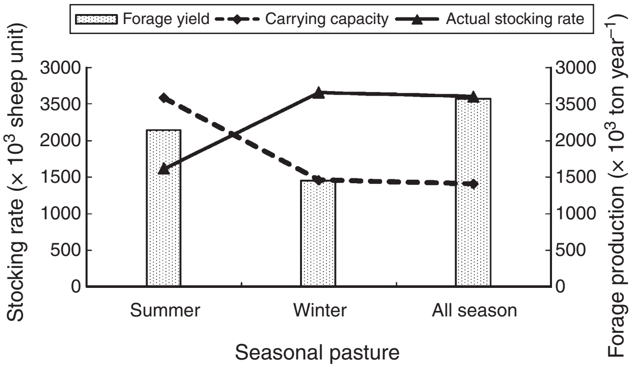

Fig. 3. Relationship between forage production and stocking rate from Gannan Prefecture of Gansu Province in 2005–07. Data from Liu *et al.* (2010).

Status of stocking rate research

Excess grazing pressure is considered the primary cause of degradation of the Tibetan Plateau (Wu and Du 2007). The cover and proportion of forage with a high nutritive value decreased as SR increased (Jiang *et al.* 2003). Few studies have estimated the carrying capacity for the alpine meadow of the Tibetan Plateau (Table 1). The average herbage mass of *Kobresia parva* alpine meadow that was measured at the end of each month from June to October decreased from 1651 to 1251 kg DM ha^{-1} when winter–summer rotational SR increased from 3.1–3.6 to 7.7–8.3 SU ha^{-1}, and a medium rate of 5.2–5.8 SU ha^{-1} was recommended as the optimum SR during winter–summer (Dong *et al.* 2005). Chen *et al.* (1994) reported that SR significantly ($P < 0.01$) affected the daily liveweight gain of yak grazed in Hongyuan (Sichuan Province) – the recommended SR of summer pasture was 1.0 SU ha^{-1}. Stocking rate had a significant ($P < 0.05$) impact on the nutritive value of alpine forage. The daily liveweight gain of Tibetan sheep was 25.0, 20.0 and 8.3 g when SR were 1.2, 1.8 and 2.4 SU ha^{-1}, respectively in autumn; 1.8 SU ha^{-1} was the recommended rate (Shen *et al.* 1996). Ren *et al.* (2008, 2009) analysed the effect of SR (0.0, 1.8 and 3.2 SU ha^{-1}) on vegetation community characteristics and their productivity of an alpine meadow in Maqu (Gannan Prefecture, Gansu Province), showing that the herbage mass decreased from 1892 to 938 kg DM ha^{-1} and the previous dominant species of *Cyperaceae* and *Poaceae* were replaced by the forbs, *Ligularia virgaurea* and *Leontopodium leontopodioides*, when SR increasing from 1.8 to 3.2 SU ha^{-1} in winter–spring. Accordingly, 1.8 SU ha^{-1} was considered an optimal SR for this Maqu meadow.

The numbers of tillers of *Kobresia humiilis* were 46.1, 68.1 and 46.0 m^{-2} at SR of 2, 4 and 8 SU ha^{-1}, respectively, and the greatest number of reproductive tillers (~55 m^{-2}) occurred after 5 years of moderate grazing of 4 SU ha^{-1} (Yang *et al.* 2011). The N required for forage production reduced from 82.2 to 41.7 kg ha^{-1}, while that for P reduced from 5.9 to 3.0 kg ha^{-1} as SR increased from 3.7 to 11.3 SU ha^{-1} in autumn–summer (Du *et al.* 2008). Rotational stocking, of 7 days' grazing each plot with a 42-days' rotation for winter–spring pasture in Menyuan County, increased the intake by sheep and forage utilisation, and resulted in a higher liveweight gain per head comparing with continuous grazing (Li 1998). Pei (2004) stated that the available N content in soil significantly increased ($P < 0.01$) from 41.5 mg kg^{-1} DM at 2 SU ha^{-1} to 47.5 mg kg^{-1} DM at 8 SU ha^{-1} in winter grazing, because the N amounts in faeces of grazing sheep was high at the high SR; while the available P (8.6–8.9 mg kg DM) was not affected by SR in winter–spring alpine meadow in Haibei Prefecture of Qinghai Province. The various results between experiments may be due to the differences in natural habitat in different regions.

Stocking rate research in Xinjiang's desert steppe

Xinjiang is in the hinterland of Eurasia, neighbouring Gansu and Qinghai Provinces and the Tibet Autonomous Region to the south-east and several Central Asian republics to the west. Xinjiang is the largest province in China, with a land area of 167×10^6 ha. It has typically an arid terrain with mountains and basins being common land types, accounting for 43 and 57% of its total area, respectively. The natural resources are rich with 11 categories of grasslands, 25 sub-categories and 687 vegetation types. The grassland area of 48×10^6 ha accounts for 22% of the total grassland area in China. Desert steppe is the main type of Xingjiang's grasslands and covers an area of 26.9×10^6 ha: including temperate steppe desert of *Seriphidium* spp., temperate desert of semi-shrub *Artemisia* spp. and alpine desert of *Seriphidium rhodanthum* (Xu 1993). The overgrazing rate of Xinjiang was estimated to be in the range of 33–40% in 2008–10 (Ministry of Agriculture of People's Republic of China 2011).

Relationship between forage and livestock production

Overgrazing is seen as the main cause of vegetation degradation. The degraded area of grassland increased by 10-fold in 27 years from 4.67×10^6 ha in 1980 to 45.8×10^6 ha in 2007 (Xinjiang Uygur Autonomous Region Environmental Protection Agency 2007). Grassland degradation results in huge annual losses of forage DM yield of 7.2×10^6 t, valued at approximately US\$$278 \times 10^6$ (Mansur·Sabit *et al.* 2002). Overgrazing has decreased forage production by 30–50% compared with the 1960s and the overgrazing rate was estimated at 69% in 2002 (Mansur·Sabit *et al.* 2002) and 56% in 2007 (Dong and Liu 2009) (Table 3). This decline reflects the efficiency of the central and local government programs in reducing grazing pressures.

Unbalanced seasonal forage production of pastures is an important feature in Xinjiang. The forage yield during summer–autumn exceeds the demands of livestock; the residual amount of forage could support 9.2×10^6 and 0.9×10^6 SU in summer and autumn, respectively. However, there is a serious shortage of forage during spring, with overgrazing of 5.9×10^6 SU (Xu 1993) (Fig. 4). Chen (2000) stated that the optimal utilisation of grassland was grazing for 185 days in summer and autumn, 60 days in early winter and spring and housed feeding for 120 days in mid winter in the Tianshan Mountain steppe, which increased liveweight gains of livestock from 3.6 to 8.1 kg head^{-1} over the experimental period compared with continuous grazing.

Status of stocking rate research

Few studies have linked the relationship between SR forage, livestock production and soil characteristics in Xinjiang's desert steppe. Liu *et al.* (2013) evaluated the soil characteristics of non-, moderate- and heavy-degraded desert steppe dominated by *Seriphidium transiliense*. The results showed that the

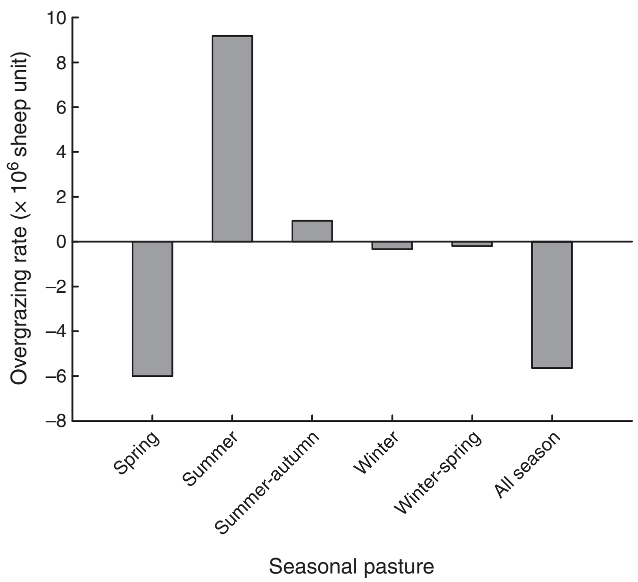

Fig. 4. Overgrazing rate in seasonal pasture in Xinjiang. Data from Xu (1993).

recommended SR in spring and autumn were 1.2 and 1.8 SU ha^{-1} for the non-degraded pasture, 0.3 and 1.2 SU ha^{-1} for the moderate-degraded pasture and 0.2 and 1.1 SU ha^{-1} for the heavy-degraded pasture, respectively. Rotational stocking at an average of 16 SU ha^{-1} with a 6–10 days' rotation resulted in a higher total herbage mass of 4101 kg DM ha^{-1} than continuous grazing (2212 kg DM ha^{-1}) over summer (Yan *et al*. 2011). Tao *et al*. (2008) evaluated the effect of different grazing disturbances on regeneration of *S. transiliense* in Urumqi through a simulation experiment using mowing at a height of 5 cm to represent light, at 2 cm to represent moderate, and at 0 cm to represent heavy grazing. This indicated that the regeneration height increased by 4.5 cm and regeneration intensity increased about by 2000 plants ha^{-1} for moderate compared with heavy grazing. As the mowing heights decreased, the herbage mass decreased from 3722 to 775 kg DM ha^{-1}, total N in soil (0–10 cm) decreased from 342.8 to 210.1 mg kg^{-1} dry soil and available P dropped from 10.6 to 7.8 mg kg^{-1} (Zheng *et al*. 2008). The diversity of the native and dominant plant species was significantly reduced under heavy cutting (Zheng *et al*. 2010).

Discussion

Chinese grasslands that were commonly grazed in Inner Mongolian grasslands, Qinghai-Tibetan alpine meadows or Xinjiang's desert steppe, were estimated to be overgrazed by averages of 27–89% over sites. Reduction in SR and improving the seasonal balance between forage supply and nutrient demands of livestock are the most important approaches for ecological environmental protection and sustainable development of grassland-based livestock production.

A well estimated SR is vital to a sustainable grazing operation, as it will optimise forage and livestock performance, maintain land resources and ensure consistent economic returns. Earlier studies defined the carrying capacity as the SR where ANPP of the grassland was high. From Wang *et al*. (1999*a*), Han *et al*. (2007) and Yan *et al*. (2010) significant and negative linear relationships ($R^2 = 0.820$, $P = 0.013$; $R^2 = 0.752$, $P = 0.005$; $R^2 = 0.958$, $P = 0.01$, respectively), between SR and ANPP were found. Nevertheless, this relationship did not apply for each site of the reviewed studies. For example, there was no significantly linear or quadratic relationship between SR and ANPP by An *et al*. (2002), Dong *et al*. (2003), Sarulaqiqige (2007) and Ren *et al*. (2009). It seems that the current criteria are not the best methods to define carrying capacity for Chinese grassland management. In fact, when establishing carrying capacity, land managers should balance livestock and forage production over the long-term rather than attempting to use only one factor. With this in mind, we suggest that an average annual carrying capacity should be defined as that at which livestock performance, forage production and economic income, as well as biological diversity criteria are all satisfied. Additionally, at the present overgrazing is defined as grazing livestock exceeding the carrying capacity of a pasture, where the carrying capacity of the pasture is narrowly defined. The current definition fails to take in to account the impacts of the grazing system as it impacts on frequency of defoliation, intensity of defoliation, and opportunity of the plant to grow or re-grow. Grazing Response Index, introduced by Reed *et al*. (1999), may provide a more useful criterion for describing carrying capacity.

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