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Sound management may sequester methane in grazed rangeland ecosystems

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Considering their contribution to global warming, the sources and sinks of methane (CH_4) should be accounted when undertaking a greenhouse gas inventory for grazed rangeland ecosystems. The aim of this study was to evaluate the mitigation potential of current ecological management programs implemented in the main rangeland regions of China. The influences of rangeland improvement, utilization and livestock production on CH_4 flux/emission were assessed to estimate CH_4 reduction potential. Results indicate that the grazed rangeland ecosystem is currently a net source of atmospheric CH_4. However, there is potential to convert the ecosystem to a net sink by improving management practices. Previous assessments of capacity for CH_4 uptake in grazed rangeland ecosystems have not considered improved livestock management practices and thus underestimated potential for CH_4 uptake. Optimal fertilization, rest and light grazing, and intensification of livestock management contribute mitigation potential significantly.

Under the Kyoto Protocol of 1997, signatory countries can elect to report global greenhouse gas (GHG) emissions from managed lands (e.g., forest, cropland, grazing land and other managed lands), and can use verified emission reductions from managed lands to fulfill their emission reduction commitments. Continental rangelands are a widespread form of grazing land, which play an important role in the GHG budget. Methane (CH_4) is the second most important long-living, anthropogenically-modified GHG after carbon dioxide (CO_2)[1,2]. CH_4 sources and sinks in managed grazing lands are primarily influenced by farming and rangeland management practices[3]. However, quantitative estimates of CH_4 sources and sinks in managed continental rangelands are particularly uncertain because of high variation across different temporal and spatial scales[4,5]. Thus, the contribution of changes in management practices in grazed rangeland ecosystems that produce and sequester CH_4 remains uncertain.

There are 492.8 million ha of rangelands in China, of which 313.4 million ha are grazed. These rangelands are mostly distributed in Inner Mongolia, Xinjiang, Ningxia, and the Qinghai-Tibet plateau[6]. China's rangelands provide ecological services of global significance. However, provision of many of these services has been impaired over the past 60 years. Human activities, including uncontrolled livestock grazing, wood harvesting, and cultivation in semiarid and arid rangeland regions, are implicated as causes of rangeland degradation and declining ecological service provision. There is now widespread agreement that overgrazing over the past half century has contributed to degradation of more than 90% of Chinese rangelands[7]. To conserve rangeland ecology, mitigate degradation and desertification, and promote economic development in pastoral regions, since the end of the 20th century the Central Government has implemented a series of policies and programs to restore rangeland ecosystem functions (Supplementary Table S1). To evaluate the effects of these policies and programs on CH_4 emissions and uptake in grazed rangeland ecosystems, the overall CH_4 budget was quantified by developing an area-weighted average for year-round CH_4 fluxes in the main continental rangeland ecosystems of China (i.e., Inner Mongolia, Xinjiang and Ningxia autonomous regions, and the Qinghai-Tibet plateau). The CH_4 budget for livestock production was then deduced at the national scale. We then quantify the CH_4 mitigation effects of the

Table 1 | Mitigation management practices and explanation

Management	Detailed description and explanation of the management practices
1. Rangeland improvement	The focus of these measures is on restoration of degraded rangelands and recovery of rangeland ecosystem service functions.
(a) Reseeding	Reseeding legumes by no-tillage techniques to biologically fix nitrogen reduces requirements for nitrogen fertilizer use. The lack of disturbance can increase the rate of oxidation of CH_4 from the atmosphere.
(b) Irrigation	Irrigation experiments added 20% of annual average precipitation. Higher moisture content in soils can lead to anaerobic conditions and increase CH_4 emission. Irrigation is below threshold value of CH_4 emission in arid and semiarid rangeland.
(c) Fertilization	7500 kg/ha organic fertilizer ($N + P_2O_5 + K_2O$ more than 5.2%, sheep dung fermented under aerobic conditions) were applied to the rangeland before forage germination in spring.
(d) Grazing prohibition	Rangeland is not grazed throughout the whole year.
(e) Control area*	Rangeland is close to households and forage is harvested for feeding livestock.
2. Rangeland utilization	The focus of these measures is on appropriate stocking rates by ascertaining carrying capacity, calculated on the basis of rangeland species composition, biomass and ground cover, to balance livestock and rangeland resources during the grazing season.
(a) Rest from grazing	Rangeland is not grazed during early spring or germination.
(b) Light grazing	Forage utilization is 24–30%.
(c) Moderate grazing	Forage utilization is 40–44%.
(d) Heavy grazing*	Forage utilization is 65–70%.
3. Livestock production	The focus of the management is on optimizing the production system to improve livestock and rangeland efficiency and reduce CH_4 output per unit of livestock product.
(a) Intensive management	Management attempts to increase production or utilization per unit area or production per livestock through a relative increase in forage utilization, labor, and/or capital. Management includes change of production and management strategy (e.g., grazing in summer and indoor feeding in winter), balanced nutrition through strategic supplementation, forage processing, adjustments in dietary structure (e.g., adjust proportion of concentrate and roughage in the diets), applying feed additive, and improved feeding techniques.
(b) Extensive management*	The traditional livestock management system utilizes relatively large land areas per animal and a relatively low level of labor, and/or capital. The typical model involves free grazing of livestock on rangeland throughout the whole year. Natural hay is used as feed supplement during periods of severe cold and forage shortage in winter-spring.

The three stocking rates (high, moderate and light) were calculated based on the percentage of forage utilization. It was assumed that CH_4 mitigation management practices are adapted at a linear rate over time. The stocking rate for all types of livestock is standardized to the sheep unit (SU, one 50 kg adult female sheep with one suckled lamb) per ha, where one cattle is 6.8 SU and one goat is 0.87 SU.
*Control area (1e), heavy grazing (2d) and extensive management (3b) are used as the control for comparison with management 1a–1d, 2a–2c and 3a, respectively, and are not considered as mitigation management practices.

changes in management practice that are commonly promoted in the major policies and programs. The management considered include rangeland improvement (reseeding, irrigation, fertilization and grazing prohibition), rangeland utilization (rest from grazing, light grazing and moderate grazing), and livestock production (intensive feeding systems) (Table 1). These practices may affect CH_4 emission and uptake through two pathways: 1) an increase in CH_4 uptake associated with an increase in soil-atmospheric exchange due to rangeland improvement and improved utilization of degraded rangelands; 2) a reduction in CH_4 emissions from livestock associated with a decrease in the livestock population and/or an increase in livestock production.

Results

Rangeland improvement. Reseeding, irrigation, fertilization and grazing prohibition have been used to restore degraded rangelands in Ningxia autonomous region. Changes in CH_4 fluxes in the growing season under different treatments are shown in Supplementary Fig. S1. Measured CH_4 uptake under reseeding, irrigation, fertilization and grazing prohibition treatments were 5.61, 6.05, 6.23 and 5.27 kg ha^{-1} y^{-1}, respectively, which represent CH_4 mitigation potentials of 12.2%, 21.0%, 24.6% and 5.4% compared with the control treatment (5.00 kg ha^{-1} y^{-1}), respectively (Table 2, management 1a, 1b, 1c, 1d and 1e).

Rangeland utilization. Common practices promoted in government programs include rest from grazing, light grazing and moderate grazing. Dynamics of CH_4 fluxes during the growing season in three studied regions (Sichuan, Xinjiang and Inner Mongolia) are shown in Supplementary Fig. S2. The CH_4 flux of a heavily grazed area was also measured as a control for comparison with the improved grazing management practices. The measured CH_4 uptakes under rest from grazing, light grazing and moderate grazing were 5.04, 5.22 and 5.41 kg ha^{-1} y^{-1}, respectively, which represent CH_4 mitigation potentials of 107.4%, 114.8% and 122.6% compared with control treatment (2.43 kg ha^{-1} y^{-1}), respectively (Table 2, management 2a, 2b and 2c rangeland). CH_4 emissions from livestock under rest from grazing, light grazing, moderate grazing and heavy grazing were 2.73, 2.83, 5.49 and 8.23 kg ha^{-1} y^{-1}, respectively, in Sichuan province; 2.82, 2.75, 5.41 and 7.59 kg ha^{-1} y^{-1} in Xinjiang autonomous region; and 2.89, 2.81, 5.31 and 8.38 kg ha^{-1} y^{-1} in Inner Mongolia autonomous region (Fig. 1). Average CH_4 emissions from livestock under rest from grazing, light grazing and moderate grazing were 2.81, 2.80 and 5.40 kg ha^{-1} y^{-1}, respectively, which represent CH_4 mitigation potentials of 65.2%, 65.3% and 33.1% compared with emissions under heavy grazing (8.07 kg ha^{-1} y^{-1}), respectively (Table 2, management 2a, 2b and 2c livestock). Total annual CH_4 fluxes in the improved grazing ecosystems were -0.01 to -2.42 kg ha^{-1} y^{-1}, showing that grazing ecosystems under improved management can sequester CH_4.

Livestock production. CH_4 emissions from livestock production under intensive management were compared with emissions under extensive management in Sichuan, Xinjiang and Inner Mongolia. The average estimated CH_4 uptakes in rangelands under intensive management were 5.41 kg ha^{-1} y^{-1}, which represent a CH_4 mitigation potential of 7.8% compared with extensive management (5.02 kg ha^{-1} y^{-1}) (Table 2, management 3a rangeland). Estimated monthly CH_4 output from livestock in three study regions (Sichuan, Xinjiang and Inner Mongolia) are shown in Supplementary Fig. S3. Annual average CH_4 emissions from livestock under intensive management in Sichuan, Xinjiang and Inner Mongolia were 4.23, 1.88 and 5.56 kg ha^{-1} y^{-1}, respectively (Fig. 2), which represent an

Table 2 | The calculated CH_4 flux, emission and mitigation potentials for mitigation management practices

Management	Rangeland		Livestock and Excrement		
	CH_4 flux (kg ha^{-1} y^{-1})	Mitigation (kg ha^{-1} y^{-1}, %)	CH_4 emission (kg ha^{-1} y^{-1})	Mitigation (kg ha^{-1} y^{-1}, %)	Total CH_4 flux (kg ha^{-1} y^{-1})
1a. Reseeding	−5.61	−0.61, 12.2	-	-, -	−5.61
1b. Irrigation	−6.05	−1.05, 21.0	-	-, -	−6.05
1c. Fertilization	−6.23	−1.23, 24.6	-	-, -	−6.23
1d. Grazing prohibition	−5.27	−0.27, 5.4	-	-, -	−5.27
1e. Control area*	−5.00	-,-	-	-,-	-
2a. Rest from grazing	−5.04	−2.61, 107.4	2.81	5.26, 65.2	−2.23
2b. Light grazing	−5.22	−2.79, 114.8	2.80	5.27, 65.3	−2.42
2c. Moderate grazing	−5.41	−2.92, 122.6	5.40	2.67, 33.1	−0.01
2d. Heavy grazing*	−2.43	-, -	8.07	-, -	5.64
3a. Intensive management	−5.41	−0.39, 7.8	3.89	1.38, 26.2	−1.52
3b. Extensive management*	−5.02	-, -	5.27	-, -	0.25

Positive absolute values refer to a net emission to the atmosphere (source), while negative absolute values indicate a net removal from the atmosphere (sink).
*Control area (1e), heavy grazing (2d) and extensive management (3b) are used as the control for comparison with management 2a–2c and 3a, respectively, and are not considered as mitigation practices.

average CH_4 mitigation potential of 26.2% compared with extensive management (Table 2, management 3a livestock). The estimate of total annual net emissions (i.e., considering both soil-atmosphere exchange and livestock emissions) indicate that under intensive management the grazing rangeland ecosystem could become a net CH_4 sink (-1.52 kg ha^{-1} y^{-1}).

Discussion

Measures to restore degraded rangelands (i.e., reseeding, irrigation, fertilization, and grazing prohibition) are widely applied in China. The main objective of promoting these management practices is to stimulate an increase in net primary productivity, improve soil nutrients, and restore rangeland ecosystem functions. In the process, these managements can increase microbial activity, CH_4 oxidation and soil-atmospheric exchange of CH_4[8–11]. In terms of CH_4 fluxes, adoption of these practices can increase soil CH_4 uptake by 0.27 kg ha^{-1} y^{-1} to 1.23 kg ha^{-1} y^{-1} (Table 2 management 1a–d), representing a 5.4%–24.6% increase in CH_4 uptake compared with conventional practices. Moreover, these practices often increase plant photosynthesis and thus sequester atmospheric CO_2[12], which is also important in managing soil C stocks in rangelands. On the other hand, restoration of degraded rangelands may also lead to an increase in the organic matter digestibility of edible forage ingested by grazing livestock, which can increase livestock performance and reduce CH_4 production from grazing livestock when expressed in terms of CH_4 production per unit of livestock product output or per unit of daily weight gain[13].

Optimal stocking rates are required to maintain sustainable utilization of natural rangeland resources and are beneficial to the restoration of degraded rangelands. Compared to heavy grazing, a reduction in the number of grazing livestock per ha can significantly reduce CH_4 production under moderate and light grazing and under rest from grazing, as well as increase livestock productivity[13]. This study found that light and moderate grazing actively promote CH_4 sequestration by rangeland soils. The combined direct and indirect effects of change in rangeland utilization may be to transform rangeland-based grazing ecosystems from a CH_4 source into a sink. This strategy has additional mitigation potential if accompanied by livestock breed improvement[14].

Although livestock production is increasingly important in China's food system, livestock respiration is considered to be a net source of GHG. Increasing demand for livestock products must be met while addressing the challenge of balancing livelihoods and environmental protection in rangeland areas. Recent estimates suggest that livestock contribute about 14.5% of global anthropogenic greenhouse gas emissions[15]. Although intensive livestock production is expanding across the world, there are still vast rangeland areas in developing countries where extensive livestock production continues

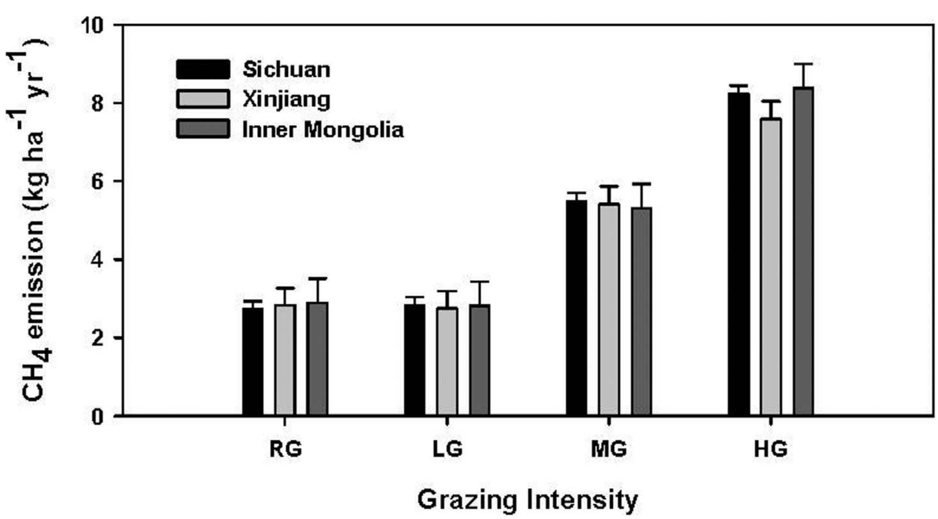

Figure 1 | Data on CH_4 emissions from livestock and excrement in Sichuan alpine meadow, Xinjiang temperate desert steppe and Inner Mongolia temperate typical steppe. RG: rest from grazing; LG: light grazing; MG: moderate grazing; HG: heavy grazing. Bars indicate the standard error of means.

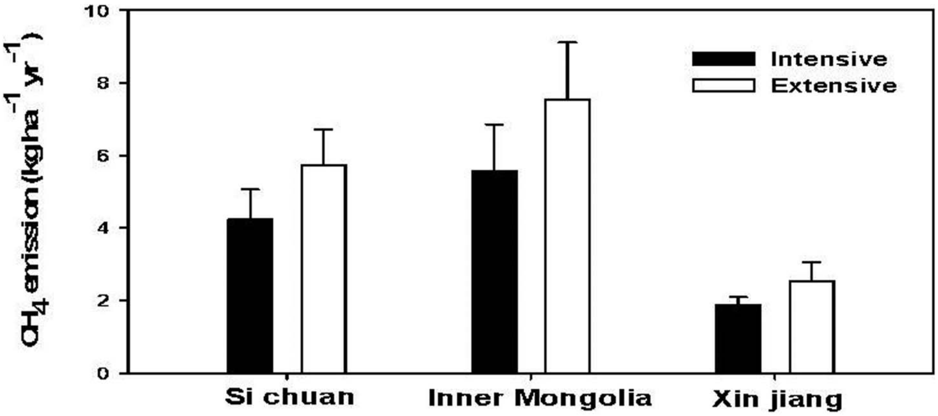

Figure 2 | Annual average CH_4 emissions from livestock production under intensive and extensive management in Sichuan, Xinjiang and Inner Mongolia. Each treatment was represented by three farms within each experimental site. Bars indicate the standard error of means.

under traditional feeding systems, accompanied by high CH_4 emissions from ruminant livestock[14]. CH_4 emission from ruminant livestock is an unavoidable and inefficient product associated with the specifics of the ruminant digestive system, but it can be significantly affected by regulating energy intake and the quantity and quality of dietary intake, thus reducing CH_4 emissions per unit of product[16]. Other techniques can also be deployed to reduce the activity of methanogenic bacteria and protozoa in rumen and to increase the digestibility of the diet, so that CH_4 emissions per unit of product are reduced[17]. In our study, CH_4 emissions from intensive livestock production presented a mitigation potential of 26.2% compared with extensive livestock production (Table 2, management 3a livestock), and also altered total CH_4 fluxes from a net source to a net sink in the grazed rangeland ecosystem.

Overall, present-day CH_4 uptake is underestimated and CH_4 emissions from livestock are overestimated, because the effects of rangeland improvement and intensive management promoted by ecological projects are not considered. This leads to uncertainty in the CH_4 budget for the agriculture sector. There is a growing interest in science-based solutions for reducing CH_4 emissions through improved rangeland and livestock management practices. There is no question that livestock in grazed rangeland ecosystems are a major CH_4 source. In this study, the estimated CH_4 production rates for all cattle, sheep and goats in China were 4.08, 1.00 and 0.89 Tg y^{-1}, respectively in 2011, which is different from the total production rates estimated using the IPCC inventory method (Table 3). Of 264 pastoral and agro-pastoral counties in China, more than 50% are overstocked[18]. It is, therefore, obvious that reducing livestock numbers may be an effective management for mitigating CH_4 emissions. However, implementation is a challenge since farmers' and herders' livelihoods depend on livestock. Therefore, continued improvement in the production efficiency of livestock while limiting CH_4 emissions is one potential pathway for balancing these diverse and sometimes conflicting objectives.

The integrated CH_4 mitigation potential of ecological conservation programs is mainly associated with stocking rate and the production system in grazed rangelands. Rangeland utilization currently has a large effect on environmental CH_4 balance, and is driven by growth in demand for livestock products and rangeland resource scarcity. Improvements in livestock performance and rangeland management practices will contribute to more effective regulation of CH_4 emissions. Data on the CH_4 budget of grazed rangeland ecosystems can support evaluations of the GHG mitigation effects of policies and programs in managed lands, and are a high priority for climate research.

Methods

Surveyed representative rangeland regions. The temperate typical steppe site is located in Xinbaer Right Banner (N 47°36′, E 115°31′), Inner Mongolia. The site has an elevation of 610 m and a temperate continental climate. Annual average temperature is $-2 \sim 1$°C with a frost-free period of 128 days. Annual mean precipitation is 350 mm. Government programs support improved rangeland utilization and livestock production (Management 2 and 3 in Table 1). The temperate desert steppe site is located in Linwu County (N 37°46′, E 106°43′), Ningxia. The site has an elevation of 1250 m with a continental monsoon climate. Annual average temperature is 8–9°C with a frost-free period of 157 days. Annual mean precipitation is 206 mm. Because grazing is completely banned in Ningxia autonomous region, the practices evaluated include only grassland improvement (Management 1 in Table 1). The alpine meadow site is located in Hongyuan County (N 33°56′, E 102°35′), Sichuan. The site has an elevation of 3600 m and a temperate monsoon climate. Annual average temperature is 1–2°C with no absolute frost-free period. Annual mean precipitation is 753 mm. Government programs promote improved rangeland utilization and livestock production (Management 2 and 3 in Table 1). The temperate desert site is located in Fuhai County (N 46°01′, E 87°53′), Xinjiang. This site has an elevation of 1400 m and a mid-temperate continental climate. Annual average temperature is 6°C with a frost-free period of 150 days. Annual mean precipitation is 110 mm. Government programs promote improved rangeland utilization and livestock production (management 2 and 3 in Table 1).

Experimental design and sampling of the surveyed rangeland improvement areas. The surveyed areas for management practices 1a–e were approximately 30 ha each, with three replications. The survey procedure was to identify and record the latitude and longitude of the central location of each study site using GPS, mark the location

Table 3 | CH_4 emission from ruminant livestock and excrement in China

Type	CH_4 production (kg head^{-1} y^{-1})	Population ($\times 10^6$)	Total CH_4 production (Tg y^{-1})
Cattle	49.1 (50.0)	83.0	4.08 (4.15)
Sheep	7.2 (5.5)	138.8	1.00 (0.76)
Goat	6.3 (5.5)	142.2	0.89 (0.78)
Total		364.0	5.97 (5.70)

Values in brackets are estimated using methods outlined in 2006 IPCC Guidelines for National Greenhouse Gas Inventories. CH_4 emission from ruminant livestock and excrement are estimated using a model of grass-livestock energy balance designed by Kemp and Michalk for development of sustainable livestock systems on grasslands in north-western China (ACIAR, Canberra, Australia 2011)[20]. Livestock population is adapted from FAO 2011. Available: http://faostat.fao.org/.

with a stake, and design a transect bearing of either 120°, 240°, or 360° (Supplementary Fig. S4). CH_4 fluxes of soil atmospheric exchanges were measured at 15 meters along each of the 3 transects lines. CH_4 fluxes of soil atmospheric exchange were measured using the closed static chamber method. The chamber had a dimension of 50×50×50 cm made of stainless steel. The chamber was placed on a steel base frame driven 10 cm into each site one month prior to the start of the experiment. The base frame had a channel in which the chamber was inserted and the channel was filled with water to seal the chamber atmosphere. A 9 VDC fan was fixed in to the top wall of each chamber to mix the chamber atmosphere. The chamber was covered with a shroud made of camel hair, aluminum foil and white canvas to limit heating of the chamber atmosphere during sampling. During gas flux determination, a disposable syringe (100 ml) with a 3-way valve was used to collect 200 ml of chamber atmosphere in a sample gas bag at 10 min intervals over a 30 min period. The CH_4 concentrations in the gas samples were analyzed using a wavelength scanning spectrophotometer (Picarro G1301, Santa Clara, USA). Gas fluxes were calculated using the following equation:

$$F = \frac{\rho \cdot V \cdot \Delta c}{A \cdot \Delta t}$$

where F is the flux (mg/m^2/h) of CO_2 or CH_4; ρ is the density of 1 mole CH_4 gas (kg/m^3); $\Delta c\ \Delta t^{-1}$ is the rate of change in gas concentration h^{-1}; V and A are the volume (m^3) and the chamber base area (m^2), respectively.

Experimental design and sampling of the surveyed rangeland utilization areas. The design of grazing study was modeled after a biosphere where grazing impacts radiate in a diminishing response away from the centre, which was the location of the holding pen and water source (Supplementary Fig. S5). The piosphere grazing gradient was sampled along three replicate transects radiating from the center. The boundaries of the three grazing intensity zones (rest from grazing, light grazing, moderate grazing and heavy grazing) were defined along each transect[19]. The zones and their boundaries were defined by sampling species composition and vegetation coverage along the transects at 50 m intervals, using a single 20 cm × 50 cm quadrat, and grouping the plots into one of the three grazing intensity zones using cluster analysis. The method for measurement of CH_4 fluxes of soil atmospheric exchange was the same as described for rangeland improvement areas above. CH_4 emissions from livestock were estimated using a model described below.

Method for estimation of emissions from livestock production. We used a model to estimate CH_4 emission from extensive and intensive livestock production systems[20]. The model was designed to analyze annual livestock feed supply and demand, livestock production, management practices, and CH_4 emissions from livestock and excrement on a typical farm in each production system. The parameters of the model included rangeland area, livestock number, bodyweight, forage growth rate, forage digestibility, and supplementary feeding. Primary data for the model came from farm surveys in each study site. In each site, three representative farms were selected to represent intensive and extensive management. Farm survey data were obtained 3–4 times through the year. The experimental animals were used with the approval of the Experimental Animal Committee of the Chinese Academy of Sciences.

Data calculation. The area-weighted average annual CH_4 budget was calculated by adding emissions (removals) from soil atmosphere CH_4 uptake and emissions from livestock and livestock excrement. The amount of annual CH_4 emission from livestock per ha was estimated and calculated by multiplying emissions per head by the stocking rate. The data of CH_4 emissions from livestock production estimated using the model was compared with the data calculated using methods outlined in IPCC 2006 Guidelines for National Greenhouse Gas Inventories[21]. In order to calculate the mitigation potential, data on soil-atmospheric CH_4 exchange were collected from a control area (non-measure, CK) and compared with data from sites under rangeland improvement and utilization. Data from heavily grazed (HG) areas and under extensive management were used as controls for comparison with rangeland utilization and intensive management, respectively.

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Author contributions

C.J.W., G.D.H., S.P.W., K.M.H., J.B., X.Z.M. and M.L.Z. designed the experiment. X.J.Z., S.M.T., P.Z., Y.Y.J., T.T.L., Z.W.W. and Z.G.L. carried out the flux measurements and laboratory analyses. C.J.W., S.P.W. and A.W. performed data analysis. C.J.W., S.P.W. and A.W. drafted the manuscript.

Additional information

Supplementary information accompanies this paper at http://www.nature.com/scientificreports

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