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Modelling Chinese grassland systems to improve herder livelihoods and grassland sustainability

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Abstract. Recent degradation of Chinese grasslands has contributed to declining herder productivity and profitability, increased incidence of dust storms and regionally reduced air quality. Overgrazing due to a doubling of stocking rates since the mid-1980s has been identified as a key contributing factor. Several pathways and strategies exist to improve grassland management; however, there remains uncertainty around the long-term sustainability of alternative systems. Nineteen years of grasslands research in China has produced a suite of models designed to improve understanding of grassland systems and investigate options for change. The *StageTHREE* Sustainable Grasslands Model was used to evaluate the ability of selected strategies to meet economic, production and environmental objectives. Sets of strategies that focussed on flock size, lambing and selling times, supplementary feeding rules and grazing management were simulated for a typical herder located in the desert steppe of Siziwang Banner, in the Inner Mongolia Autonomous Region of China. The results from the risk efficiency analysis indicated that no single strategy set clearly dominates across all objectives. Although the current practice of herders was found to be risk-efficient, it did not achieve the highest rate of grassland recovery, minimise soil erosion or minimise the greenhouse gas (GHG) emission intensity for sheepmeat production. Targeting further improvements in these attributes could be at the detriment of herder livelihoods. The analysis indicated that if herders adopted biomass-based grazing management and improved supplementary feeding they would be able to improve grassland resilience and maintain positive long-term economic performance under reduced flock sizes. Individual decision-making units, however, would still need to trade off the importance of different attributes to identify the strategy set, or system, that best meets their objectives and attitude to risk.

Keywords: bioeconomic modelling, climate risk, efficiency frontiers, grazing management, greenhouse gas, sheepmeat.

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Introduction

The 400 million hectares of grasslands in China are a significant part of the Eurasian grasslands and support more than 40 million low income herders (Suttie *et al.* 2005; Kemp *et al.* 2018). Since the mid-1980s livestock numbers have doubled and, with the traditional practice of year-round grazing, this doubling has led to grassland degradation and gradual desertification, with 90% of grasslands now degraded (Akiyama and Kawamura 2007; Briske *et al.* 2015; Kemp *et al.* 2018). This degradation has had significant ecological and socioeconomic consequences at both regional and national scales (Liu and Diamond 2005; Akiyama and Kawamura 2007), and for herders dependent upon grasslands, this has contributed to declining herder productivity and profitability (Briske *et al.* 2015; Kemp *et al.* 2018). The incidence of dust storms has increased, and the air quality in populated urban areas across northern Asia has been reduced (Liu *et al.* 2004; Shao and Dong 2006). To remain globally competitive and sustain or improve their livelihoods, Chinese herders will need to improve grassland resources, increase productivity and economic performance and, at the same time, meet the demands of evolving markets for their products (Kemp *et al.* 2013, 2018, 2020*a*; Behrendt *et al.* 2016*b*).

A key challenge in making decisions regarding the operational management of a grassland resource is its complexity and intractability. Decisions need to consider the interactions between grassland ecology, the use of technology to improve and manage the resource, environmental externalities, utilisation of the resource by grazing animals, and the short and long-run profitability of the whole farming system (MacLeod and McIvor 2008; Scott *et al.* 2013; Behrendt *et al.* 2016*a*; Kemp *et al.* 2020*a*). In China, the identification of pathways to improve both grassland condition and the livelihoods of herders that depend on them, including the development of pragmatic criteria used to improve the management of grasslands, have been substantially researched (Kemp *et al.* 2013, 2018, 2020; Badgery *et al.* 2020).

Over the last 19 years of research into Chinese grasslands (2001–2020, supported by the Australian Centre for International Agricultural Research), a suite of models has been developed to help understand grassland systems and investigate options for improving herder livelihoods and environmental outcomes (Behrendt *et al.* 2020*a*). The two most widely used models from earlier work focussed on the energy balance of livestock (*StageONE*) and the optimisation of livestock, grassland, feed, crops, labour and other resources to maximise net farm financial returns through linear programming (*StageTWO*) (Takahashi *et al.* 2011). For applications of both the *StageONE* and *StageTWO* models see Kemp and Michalk (2011), Zheng *et al.* (2013), Li *et al.* (2015), and Kemp (2020). Additionally, another model was developed that identified the animals in a flock or herd that should be kept or culled (*PhaseONE*), an essential strategy shown to further increase the benefits from reducing livestock numbers and stocking rates (Takahashi *et al.* 2015; Kemp *et al.* 2018). These early models assumed steady-state systems, and did not take into consideration climate risk and the intertemporal and dynamic interactions within the grassland system that are necessary for the development of sustainable livestock systems beyond short-term profitability (Jones *et al.* 2011). To build on previous work by Jones *et al.* (2011), and address the challenge of searching for and identifying more efficient whole-farm systems under long-term timeframes and risk, and new technologies or systems as they emerge, a bioeconomic model (*StageTHREE*) was developed. The *StageTHREE* model integrates the dynamics of grassland and soil resources, livestock production and herder household economics (Behrendt *et al.* 2020*a*) to provide a useful tool for finding sustainable solutions for grassland systems. It also enables more detailed analysis of possible solutions identified through in-field experimentation and steady-state modelling. The objective of this paper is to demonstrate the use of the *StageTHREE* model to identify sustainable livestock production systems on Chinese grasslands that balance environmental, production and economic outcomes over the medium to long-term temporal scale.

Sustainability modelling approach

The *StageTHREE* Sustainable Grasslands Model (*StageTHREE SGM*) predicts changes in grassland resource condition (defined as both the amount of grassland biomass and basal areas of functional group or species), soil erosion (caused by both wind and water), soil depth and fertility, deep soil water drainage and runoff, livestock production across multiple age cohorts and types (changes in liveweight, reproduction etc for sheep, goats, cattle or yaks), livestock greenhouse gas emissions (IPCC Tier 2 based GHG emissions expressed as a global warming potential) and herder household economics (short and long-term). Behrendt *et al.* (2020*a*) introduces the *StageTHREE SGM* with a full model description provided in Behrendt *et al.* (2020*b*). The *StageTHREE SGM* has been designed for research environments which often have limited access to complex data. It integrates both originally developed and externally published empirical and mechanistic/process based sub-models, some of which are parsimonious in approach (Behrendt *et al.* 2020*a*; Behrendt *et al.* 2020*b*). The *StageTHREE SGM* has been developed using Matlab (Mathworks 2019) with some specialised additional tools.

In this research, the *StageTHREE SGM* was used to evaluate and explore a range of strategies proposed for herders on the desert steppe in Siziwang Banner, Inner Mongolia Autonomous Region (IMAR) (Fig. 1). The 87 million ha of natural grassland in IMAR account for more than a fifth of China's grasslands, and represent a significant part of the Eurasian Steppe (Wu and Loucks 1992). This region is north of the Yellow River and shares the Mongolian Plateau with Mongolia. Elevation is around 1400 m above sea level with annual precipitation around 250–300 mm. Rainfall is predominantly distributed during the summer months, and average daily minimum and maximum temperatures range from –19°C to 29°C (Fig. 2). Research has shown that the IMAR is a primary source of dust storms for the populated areas of eastern China, including Beijing (Liu *et al.* 2004) with dust at times extending to Korea and Japan.

In the IMAR desert steppe, the summer grazing areas are often communally managed and leased areas, with an aggregation of livestock from several households around watering points, while the winter areas are fenced and allocated to individual households. Within this region, the stocking rates have declined over the past decade from 2 to 0.8 sheep equivalents per hectare (SE/ha) in response to successful research, farm demonstrations and knowledge exchange programs (Kemp *et al.* 2020*b*). This previous research, in conjunction with local farm surveys and measurements of grassland and animal productivity (Han *et al.* 2011; Wang *et al.* 2011; Li *et al.* 2015) provided the base parameters for model setup and calibration. The grassland data, including grassland composition change, were based on a grazing experiment at the Siziwang experimental farm in IMAR (Fig. 1) continuously operating since 2004 (Han *et al.* 2011; Wang *et al.* 2011, 2020; Badgery *et al.* 2020).

The regional emphasis is now on sheep production, the more profitable enterprise within the region (Han *et al.* 2011). The base livestock system being modelled is a typical Mongolian sheep enterprise based on Li *et al.* (2015). Table S1 in the Supplementary Materials (available at the journal's website) shows the initial base model input parameters for the typical herder system in the desert steppe of IMAR. To identify strategy sets that enable more sustainable livestock production systems, a range of options were tested.

(a) Flock size: the typical herder maintains in the vicinity of 425 females (all age cohorts) inclusive of progeny, which is assumed to be the initial starting flock size for all options tested. A range of 150–750 females were tested at increments of 150 females. The model automatically moves to these new flock sizes and maintains a specified level of target females over the simulation horizon. The resulting

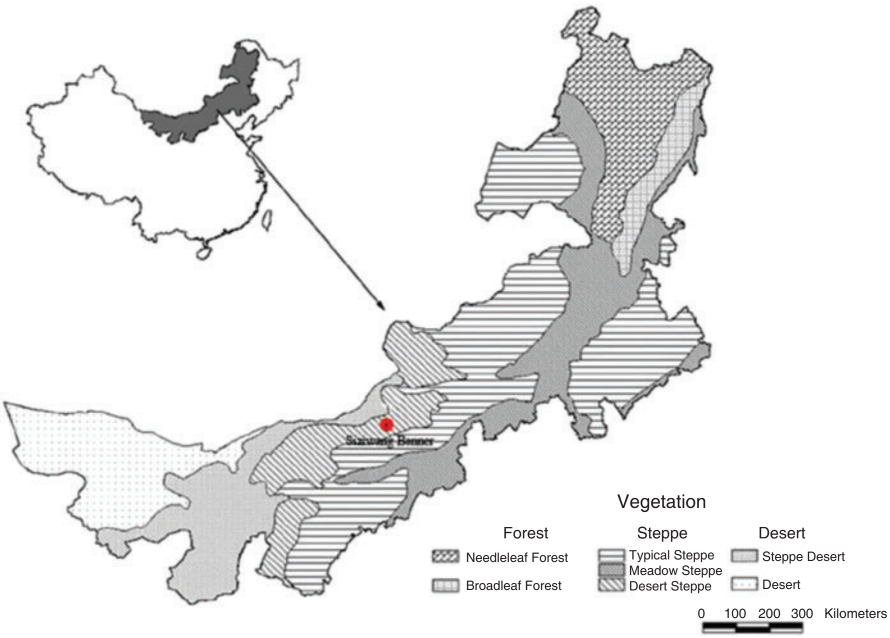

Fig. 1. Vegetation and location of the Inner Mongolia Autonomous Region case study. Adopted from Li *et al.* (2015).

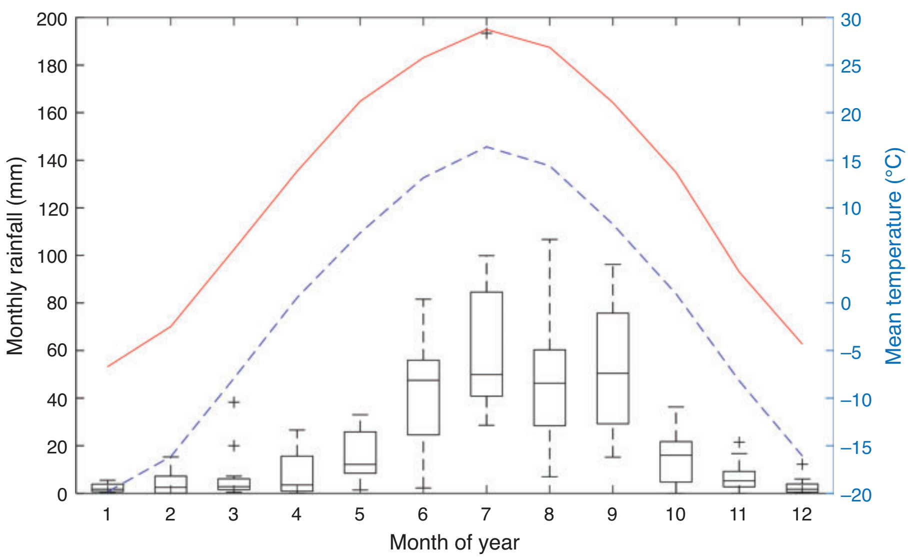

Fig. 2. Climatology of Siziwang Banner in the Inner Mongolia Autonomous Region (2006–2019) indicating monthly rainfall distribution (boxplots, + outliers), average maximum (—) and average minimum (- -) monthly temperatures. Adopted from Reliable-Prognosis (2020).

effective stocking rate is dependent upon seasonal conditions and predicted animal performance.

(b) Lambing and selling times: typically flocks still lamb during February/March, with sheep sold during September. Three alternative lambing (February/March – DOY69[1], April – DOY105, June – DOY165) and corresponding selling times (September/October – DOY280, October – DOY295, November – DOY320) were tested.

(c) Supplementary feeding rules: herders tend to only feed sheep for survival, and this is often constrained to periods over the winter when there is inclement weather or during late pregnancy and when animals are in poor condition. The

[1]DOY refers to Julian day with 1 January being DOY1. Represents median lambing day. February/March lambing scenario here forth labelled as February lambing, September/October selling scenario here forth labelled as September selling.

Table 1. Identifiers (No.) and strategy sets simulated for the IMAR desert steppe with the *StageTHREE SGM*
Bolded strategy set (No. 3) indicates the strategy set most similar to the current management practice of IMAR desert steppe herders

No.	Strategy Set*	No.	Strategy Set*	No.	Strategy Set*	No.	Strategy Set*
1	150/FL/S/T	16	150/FL/M/T	31	150/FL/P/T	46	150/FL/M/B
2	300/FL/S/T	17	300/FL/M/T	32	300/FL/P/T	47	300/FL/M/B
3	**450/FL/S/T**	18	450/FL/M/T	33	450/FL/P/T	48	450/FL/M/B
4	600/FL/S/T	19	600/FL/M/T	34	600/FL/P/T	49	600/FL/M/B
5	750/FL/S/T	20	750/FL/M/T	35	750/FL/P/T	50	750/FL/M/B
6	150/AL/S/T	21	150/AL/M/T	36	150/AL/P/T	51	150/AL/M/B
7	300/AL/S/T	22	300/AL/M/T	37	300/AL/P/T	52	300/AL/M/B
8	450/AL/S/T	23	450/AL/M/T	38	450/AL/P/T	53	450/AL/M/B
9	600/AL/S/T	24	600/AL/M/T	39	600/AL/P/T	54	600/AL/M/B
10	750/AL/S/T	25	750/AL/M/T	40	750/AL/P/T	55	750/AL/M/B
11	150/JL/S/T	26	150/JL/M/T	41	150/JL/P/T	56	150/JL/M/B
12	300/JL/S/T	27	300/JL/M/T	42	300/JL/P/T	57	300/JL/M/B
13	450/JL/S/T	28	450/JL/M/T	43	450/JL/P/T	58	450/JL/M/B
14	600/JL/S/T	29	600/JL/M/T	44	600/JL/P/T	59	600/JL/M/B
15	750/JL/S/T	30	750/JL/M/T	45	750/JL/P/T	60	750/JL/M/B

*Number is total number of females in the flock; FL, AL and JL are February/March, April and June lambing times; S, M and P, are survival, maintenance and production supplementary feeding rules; T and B, are time and biomass based grazing management respectively.

model is capable of triggering supplementary feeding under both low biomass (kg dry matter/ha) and poor livestock condition score (CS) thresholds during specified times of the year. Three alternative sets of supplementary feeding rules - survival (<200 kg DM/ha, CS 2.0 – the base strategy), maintenance (<400 kg DM/ha, CS 2.5), and production (<600 kg DM/ha, CS 3.0) were tested. These rules are applied for the majority of the year (DOY345 to DOY300) to enable the feeding of animals during both winter and summer as required. The cost of supplementary feeding is calculated for each strategy and applied to the herder's household cash flow. Early assessments of livestock found most had CS <1–2 through winter (Kemp and Michalk 2011).

(d) Grazing management: herders typically graze their animals all year round, and use sheds overnight for animal protection (the sheds mainly reduce wind speeds). This traditional time based year-round grazing approach (set-stocking the winter grazing area from DOY330 to DOY120, and summer grazing area during the remainder) is the base strategy. This is tested against a biomass based rotational grazing system which has three key aspects which differentiates it from the time-based approach: (1) during winter all animals are destocked from grasslands into a warm shed (DOY340 – DOY120), (2) animals can only graze grasslands when biomass is above the minimum critical threshold of 600 kg DM/ha, and (3) when grazing, animals continually rotate between winter and summer grazing areas with movements between areas triggered by the minimum biomass threshold. The threshold level of biomass is similar to the sustainable values estimated in the Siziwang grazing experiment (Wang *et al.* 2020). Under this strategy animals only graze grasslands when there is greater than the minimum biomass threshold, and it is only simulated against a maintenance supplementary feeding strategy (i.e. adult animals only offered supplements during grazing if CS falls to 2.5).

In combination, these strategies interact to determine environmental, production and economic outcomes. In total, 60 different strategy sets were simulated and reported in the analysis (Table 1). Each strategy is simulated over 10 years starting from an identical base system (Table S1) with 200 iterations per strategy set. Uniformly distributed annual sequences of daily climate data from 2006–2019 are randomly drawn using Monte Carlo simulation procedures. The potential effect of price fluctuations has not been considered in this research as no significant correlations exist between climate, sheepmeat and wool prices in China given the spatially integrated nature of sheepmeat and wool markets (Brown *et al.* 2020).

To understand the longer-term implications of these strategies and how they performed against the assumed IMAR herder objectives, several attribute measures were reported in this research. To remove any short-term adjustment effects within the model, results for annual cash flow (ACF, excluding government financial support to the herders), grassland condition (proportion of desirable species), sheepmeat production and livestock GHG emission intensity are centred on the final year of the simulation horizon. Net cumulative soil loss (inclusive of both wind and water erosion, minus soil formation) and Net Present Values expressed as an annuity (NPVa)[2] represent the outcomes for a strategy set over the entire simulation period. Herders receive some payments from Government to compensate for reducing stocking rates, purchase fodder and other practices. These payments were not included in the model as they can be short-term and do not help to identify how a sustainable outcome could be achieved from the grassland/livestock system.

[2]Net present value (which is the discounted lump sum of all future cash flows over the simulation period) is converted to an equal annual amount that would be received in each year of the simulation.

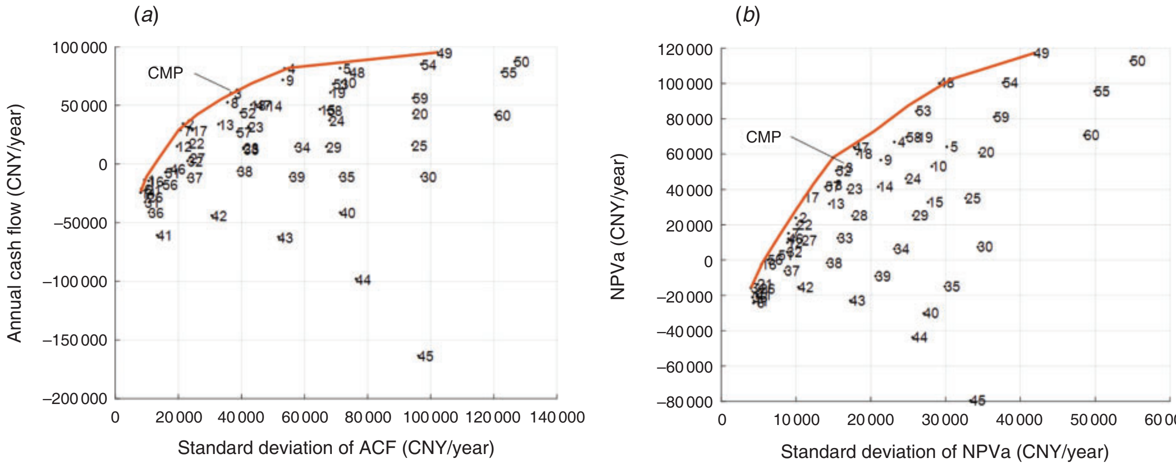

Fig. 3. Mean value and risk (measured as standard deviation) of (*a*) herder annual cash flows in the final year of the simulation horizon (Year 10), and (*b*) net present value expressed as an annuity. Numbers indicate the strategy set as per Table 1 with position of current management practice (CMP) shown for IMAR herders and the risk-efficient frontier (—) estimated from a minimum of 10 strategy sets.

The simulation outputs for NPVa and ACF are used to derive risk-efficient frontiers that enable the ranking of strategy sets on the basis of expected returns and risk, and the identification of optimal risk-efficient sets of strategies (Cacho *et al.* 1999; Behrendt *et al.* 2013). The efficiency analysis approach does not require assumptions regarding the risk aversion of herders to establish the frontier, and demonstrates the trade-offs between economic returns and risk (Cacho *et al.* 1999; Behrendt *et al.* 2006; Hardaker *et al.* 2015). Similarly, production and environmental outcomes are compared based on their mean outcomes and variation, measured as standard deviation (across 200 iterations). The identified optimal strategy sets are considered to be derived from the ACF risk-efficient sets of strategies and assume herders have the concurrent objective of maximising grassland condition and minimising environmental externalities (such as GHG emissions and soil erosion). Concurrently, herders are assumed to have the objective of minimising the variability in production, grassland and environmental outcomes at a given attribute level, as a proxy for improving farming system resilience to climate variability. This analytical framework was necessitated by the absence of, and difficulty in, deriving defined herder utility weightings for different attributes and combinations (Hardaker *et al.* 2015).

Results

In combination, 60 different strategy sets were simulated. No single strategy set clearly dominated, and achieved the assumed multiple objectives of IMAR herders (Table S2 reports the mean and standard deviation for each strategy set for each attribute, and Fig. S1 (see Supplementary Materials, available at the journal's website) shows a trade-off plot indicating the interactions between mean attribute values). A primary driver for most herders is achieving higher financial returns over time. This can be assessed as annual cash flows (Fig. 3*a*), as herders are arguably more motivated by cash flows than other more theoretically comprehensive economic criteria. Risk neutral herders would choose between the risk-efficient strategies 49 and 54. For herders with increasing risk averseness, strategies 5, 4, 9, 3, 8, 2, 7 and 12 represent risk-efficient strategy sets. Although strategies 1, 6, and 11 are on or near the frontier, they all produce negative mean annual cash flows, and so would be illogical choices for herders. The risk-efficient strategy sets with the highest returns are characterised by a flock size of 600 ewes, February and April lambing, maintenance feeding rules and biomass-based grazing management. The risk-efficient strategy sets with the lowest ACF's are characterised by flock sizes of between 300 and 450 ewes, survival feeding rules and time-based grazing management.

Figure 3*b* indicates the long-run economic performance of strategies, measured as NPV expressed as an annuity, and includes both the benefits and costs of adjustment during the simulation period. The NPVa risk-efficient strategies from most risk-averse to most risk-neutral are 56, 51, 46, 7, 2, 17, 57, 3, 47, 4, 53, 48 and 49. Similar to the ACF frontier, another cluster of strategies are on the NPVa frontier, but produce negative economic outcomes (strategies 16 and 31). All other strategy sets are risk-inefficient as those on the frontier provide either higher returns for the same level of risk, or the same returns for less risk. Strategy set 3, the one most resembling herder current practice, is both part of the ACF and NPVa risk-efficient sets, and tends to be located mid-way between the risk-neutral and risk-averse regions of the frontier.

Notably, all strategy sets that involve biomass based grazing management achieve positive NPVa values, which is something not achieved under time based grazing. However, under very low flock sizes (150 females), annual cash flows tend to be negative under all strategy combinations.

For sheepmeat production per hectare (Fig. 4*a*), the strategies with highest levels of production and least variability tend to occur for strategy sets with production feeding (31–45). These strategies show increasing amounts of production with increasing flock size, albeit with a diminishing marginal gain, and produce notably higher amounts of sheepmeat under less risk than those found within the ACF risk-efficient set. As the level of feeding reduces (to maintenance and then to survival) and flock size increases, the variability of sheepmeat production also

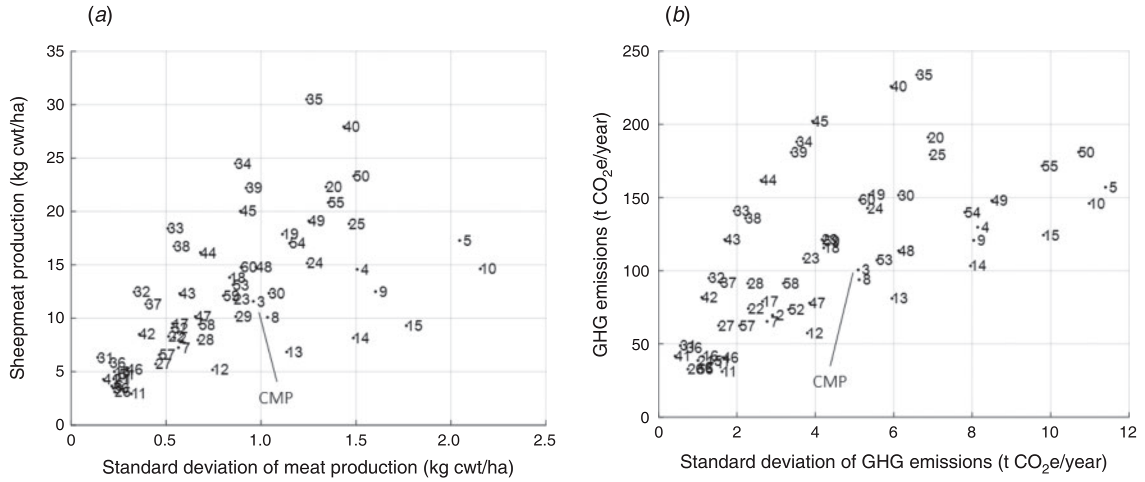

Fig. 4. Mean value and variation (measured as standard deviation) of (*a*) sheepmeat production, and (*b*) livestock methane emissions intensity in the final year of the simulation horizon (Year 10). Numbers indicate the strategy set as per Table 1 with position of current management practice (CMP) shown for IMAR herders.

increases, highlighting the exposure of these systems to climate risk. This is also, in part, highlighted by the effective stocking rates of each strategy set, with higher stocking rates (in terms of sheep equivalents per hectare) achieved under improved nutritional management options (Fig. S2). This essentially reflects higher liveweights, growth rates and reproductive rates being achieved at the same flock size, and is the result of animals being better fed and this interaction becoming more pronounced as flock size increases.

Figure 4*b* indicates the GHG emissions intensity of sheepmeat production for the strategy sets. The cluster of strategies in the bottom left hand corner, where emission intensity is at its lowest and with corresponding low variability, includes strategies 31–35 and 46–50. The first group are the February lambing/production feeding systems under time-based grazing management, whereas the second group are February lambing/maintenance feeding under the biomass-based grazing management. The least efficient and variable strategy sets are those with June lambing and either survival or maintenance supplementary feeding rules under time-based grazing management. In terms of total livestock GHG emissions and its variability in Year 10 of the simulation period (see Fig. S3), the results largely reflect the relationship with flock size, where the lowest total emissions occur under the smallest flock size (150 females) and total emissions increase in a curvilinear trend with increasing flock size. A difference of 230 t CO_2e per annum (or 457 kg CO_2e/ha.year) exists between the highest and lowest emitting systems.

In terms of grassland condition, indicated as the ratio of desirable to less-desirable functional groups at the end of the simulation horizon, the strategy sets with biomass based grazing management clearly maintain less variation in outcomes (left hand side of Fig. 5*a*). There is a clear stocking rate response, with a flock size of 750 females degrading grasslands to a ratio of around 0.6. At a flock size of around 450 females, grasslands are expected to continue degrading slowly (0.9 after 10 years). Only under smaller flock sizes are grasslands expected to improve in condition. A similar pattern exists within the strategy sets using time-based grazing management, and although having slightly higher mean ratio outcomes than biomass based options, they do have significantly higher levels of variation.

Figure 5*b* indicates the cumulative net soil loss over the entire simulation period. It indicates a clear trade-off between mean soil loss and its variability, albeit with a diminishing marginal increase with increasing flock size. The cluster of strategy sets in the bottom left hand corner, that minimise soil loss and its variability, are those with the lowest flock sizes. Under a flock size of 150 females, there is little effect of other management options that make up the strategy sets. These effects, however, become more pronounced as flock size increases.

Discussion

The results of the *StageTHREE SGM* presented illustrate how the bioeconomic framework developed can identify more sustainable livestock production systems on Chinese grasslands under climate risk. Combining this with an efficiency analysis, a large range of strategy sets were simulated and compared with the objective of balancing environmental, production and economic outcomes over the medium to long-term temporal scale. The strategy sets applied include combinations of several key herder decision variables such as enterprise scale (number of females), the time of lambing and sales, supplementary feeding rules and the criteria for controlling the grazing of animals. In comparison to the current management practices of typical herders in the desert steppe of IMAR, no single strategy set is clearly identifiable as dominating the attributes of the current management practice or any of the other strategy sets in achieving the assumed multiple objectives of IMAR herders. As such, individual decision-making units need to trade off the importance of different attributes to identify the strategy set, or system, that best meets their objectives and attitude to risk.

Although strategy set 3, most resembling the current management practice in the region, is a risk-efficient system for herders with intermediate attitudes to risk, it does not minimise soil erosion, GHG emissions or the emission intensity for sheepmeat production. Targeting improvements in these external attributes (being measures of grassland system externalities)

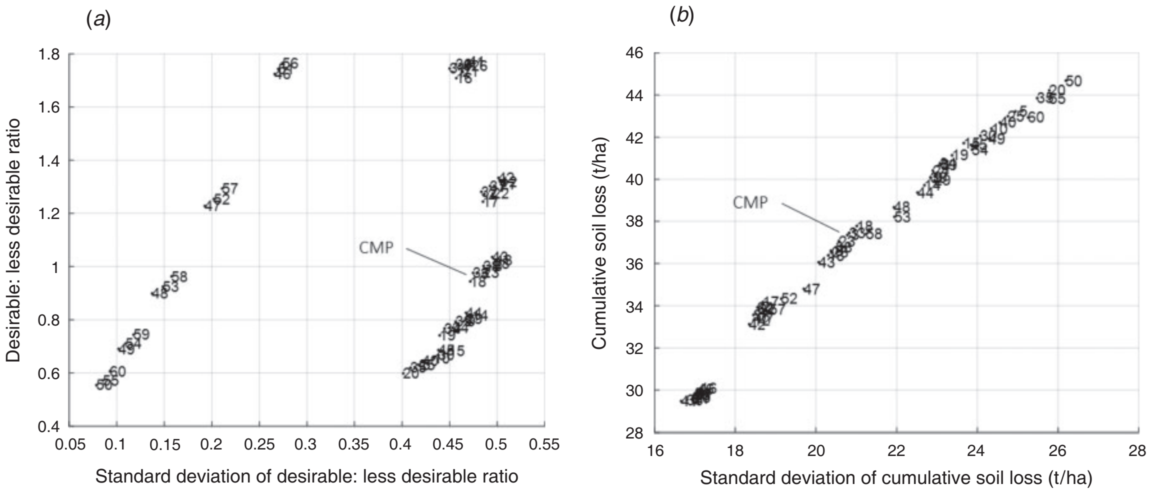

Fig. 5. Mean value and variation (measured as standard deviation) of (*a*) grassland condition indicated as the ratio of desirable to less-desirable species in the final year of the simulation horizon (Year 10, with a starting ratio of 1.0), and (*b*) net cumulative soil loss (wind + water erosion) over the entire simulation horizon. Numbers indicate the strategy set as per Table 1 with position of current management practice (CMP) shown for IMAR herders.

would be to the detriment of herder livelihoods and overall sheepmeat based protein supply. This becomes a question for national policy and areas where government payments may be necessary to achieve national objectives of better grassland management.

It is possible for herders to further improve grassland condition and maintain risk-efficient systems by further reducing flock size to around 300 females, however this will reduce overall cash flows and long-term economic performance, albeit with reduced risk. The effects on grassland composition in this analysis are consistent with what would be expected based on experimental results for the desert steppe (Badgery *et al.* 2020; Wang *et al.* 2020). In these experiments, there is evidence of *Stipa krylovii*, which is of higher nutritive value than *Stipa breviflora*, invading light and nil grazing treatments (Badgery *et al.* 2020; Wang *et al.* 2020). In this modelling, and in the experiments, the two main species considered are not ideal for livestock production. Over a longer-term, the ingress of such new species could become important and offer further sheepmeat production and economic gains from reduced flock sizes and stocking rates.

For the typical herder, switching from time-based grazing management to biomass-based grazing management would improve the resilience of grassland condition to climate variability, reduce GHG emissions intensity for the sheepmeat they produce, and improve their long-term economic performance (measured as NPVa). It would also be possible to maximise annual cash flows with a flock size of around 600 females with the adoption of biomass-based grazing management, but this would involve a trade-off against grassland condition and soil erosion. The economic relationships between grazing management and supplementary feeding strategies are subject to the price of inputs (supplements on a cost per unit of energy basis) and the price of outputs (sheepmeat and wool). However, with gains in grassland resilience and long-term economic performance under reduced flock sizes, the biomass based grazing management strategy tested in this research warrants further consideration by herders, advisors and researchers, as more biome specific optimal biomass thresholds could be identified.

To maximise sheepmeat production and economic performance, current herder practice of February lambing provides better overall outcomes (annual cash flows, NPVa, GHG emission intensity of sheepmeat production) as lambs are weaned around the time grassland growth commences in summer with more time for finishing younger animals. This system has an additional 21 and 56 days over the April and June lambing options. The trade-offs with this strategy include reduced grassland condition and increased soil erosion. An opportunity for herders would be to improve the nutrition available to sheep through higher quantities and quality of supplements that would increase growth rates or reduce ewe weight loss during late pregnancy/early lactation. This nutritional interaction is reflected by the performance of the June lambing system under lower nutritional strategy sets (survival or maintenance feeding with time-based grazing), where lower nutrition concurrently reduces productivity and increases risk. Herders could also modify selling and culling policies further, subject to markets or the availability of post-breeding farm finishing demand. An additional option is to wean lambs into a feedlot over summer, which reduces grazing pressures, but would then require market developments with increased prices for improved quantity of meat per head.

Achieving the objective of minimising grassland system externalities would be expected to come at a cost to herders. In the desert steppe, the grassland biomass never gets close to providing complete ground cover and some soil erosion is inevitable. The externality from the sustainable use and management of grassland resources is the additionality from herder induced dust events and soil erosion. The analysis in this research demonstrated a linear increase between flock size and net soil erosion and its variability. Much of this soil erosion is in the form of dust emissions, and as such, any increases in flock size by herders leads to an expected increased incidence of dust storms. However, the analysis also indicates that marginal reductions in soil erosion can be achieved through the adoption of the biomass-based grazing management strategy and through supplementary feeding for maintenance or production.

The emission intensity of GHG from livestock production is related to the efficiency of ruminant production (Eckard *et al.* 2010; Hegarty *et al.* 2010; Jones *et al.* 2014; McAuliffe *et al.* 2018). Consistent with other research, improved nutrition in grazing animals results in higher weight gains and production, lower GHG emissions per kilogram of meat produced and reduced total livestock emissions (Eckard *et al.* 2010; Hegarty *et al.* 2010; Jones *et al.* 2014; Zhang *et al.* 2015). In this research, this occurs for strategy sets that include production supplementary feeding rules or biomass-based grazing management in combination with a February lambing (due to the maximum time available for finishing young animals). The use of higher quality, cost-effective supplements to improve livestock weight gains can overcome known constraints to the global competitiveness of rangelands based livestock systems (Behrendt *et al.* 2016*b*). Alternatively, constraints could be addressed through the development of post-breeding farm demand for unfinished young animals that are differentiated on the quality produced (Briske *et al.* 2015; Kemp *et al.* 2018). In the interim though, this analysis suggests that herders can economically reduce their GHG emissions by adopting a biomass-based grazing management strategy when coupled with maintenance supplementary feeding rules, at a minimum.

Areas for further research

Under the relationships, assumptions and strategy sets analysed in this research, there are several additional strategies that may transform the expected environmental, production and economic responses. Some of the observed differences in the ranking of strategy sets, based on the ACF and NPVa attributes, are due to the capital proceeds from the sale of surplus animals when flock sizes are downscaled. Flock size reduction provides opportunities for improving livestock genetics through the accurate selection of more profitable animals during culling. This process has been shown to further increase flock performance (Takahashi *et al.* 2015; Kemp *et al.* 2018) and reduce the externalities of production such as livestock GHG emissions (Eckard *et al.* 2010; Hegarty *et al.* 2010). Surplus cash flow could also provide an opportunity for re-investment to improve warm sheds, which have been demonstrated to reduce ewe weight loss, improve progeny performance, and partly compensate for poor nutrition during winter (Zheng *et al.* 2013; Zhang *et al.* 2016). Research into the impacts of such strategies in the whole system over the long-term could lead to improved outcomes against the multiple objectives of sustainable grassland management.

Given the need to balance production, economic and environmental outcomes with sustainable grassland management objectives, it is important for herders and policy analysts to understand the interactions, trade-offs and uncertainty from different strategies. The capacity of the bioeconomic modelling framework applied in this research to derive probabilistic attribute measures provides an opportunity for future research to derive herders' multi-attribute utility functions for different attributes and combinations thereof, which could be utilised in many other forms of risky decision and policy analysis using multi-criteria decision analysis or modelling (Hardaker *et al.* 2015). This, in turn, could lead to a better understanding of herders' willingness to accept different policies and subsequently the effectiveness and economics of different policy options in achieving societal objectives.

With consideration of probabilistic outcomes relating to production, grassland and soil resource condition, herder household finances and economics, and the externalities of ruminant livestock production from grasslands, herders and policy makers will be able to identify more sustainable livestock management strategies. Experimental modelling of future potential strategies or technologies as they emerge, either in isolation or in combination, using the *StageTHREE* model provides an opportunity to enhance in-field experimental work, and more comprehensively inform decision making at the herder and policy level.

Conflicts of interest

The authors declare no conflicts of interest.

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Supplementary Material

Modelling Chinese grassland systems to improve herder livelihoods and grassland sustainability

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Supplementary Tables

Table SI: IMAR desert steppe initial parameters (DOY1 of the simulation, being 1 January) for the *StageTHREE* Sustainable Grasslands Model

Inputs	Units	Value
Geographic information		
Latitude of case study region	°	41
Altitude above sea level for case study area	m	1400
Case study general information		
Slope of grazing areas in degrees	°	5
Grazing areas	ha	Winter – 303; Summer – 200
Soil Information		
Starting available soil water on first day of simulation	gravimetric	0.44
Initial snow depth	mm	1
Proportion sand content in soil	0-1	0.65
Proportion clay content in soil	0-1	0.11
Rooting depth	mm	450
Management calendar		
Time spent in each paddock	day	Winter – 185; Summer – 180
Proportion of females sold	0-1	0.15 for sheep < 1 yr old; minimum of 0.01 for sheep > 1 yr old
Animal sale date	DOY	280
Purchase date for replacement breeding males	DOY	240
Lambing date	DOY	69
Lactation duration - Days post-partum	day	120
Wool or hair harvesting day (shearing)	DOY	150
Grassland information		
Proportion of legumes in the grasslands	0-1	0.1
Starting biomass of desirables in each grazing area	kg DM/ha	Summer & Winter grazing areas – 900
Starting biomass of undesirables in each grazing	kg DM/ha	Summer & Winter grazing areas - 900
Starting area proportion of desirables in each grazing area	0-1	Summer & Winter grazing areas – 0.5
Starting area proportion of undesirables in each grazing area	0-1	Summer & Winter grazing areas – 0.5
Soil Temperature Threshold	°C	8.0
Min/Optimal/Max Temperatures for plant growth	°C	5 / 19 / 35
Maximum leaf canopy height of grassland	m	0.3
Leaf Area Index at half maximum canopy height	m^2 leaf/m^2 ground	1.5
Canopy extinction coefficient	0-1	0.5
Mean monthly desirable Dry Matter Digestibility (DMD) – Jan to Dec*	0.3-0.8	0.48 0.48 0.48 0.33 0.68 0.63 0.58 0.58 0.63 0.53 0.48 0.48
Mean Monthly less-desirable DMD – Jan to Dec*	0.3-0.8	0.48 0.48 0.48 0.48 0.72 0.67 0.63 0.63 0.53 0.53 0.48 0.48
Grassland growth curve – alpha*	0-1	Desirable: 0.05778; Less-Desirable: 0.00422
Grassland growth curve – gamma*	1-2	Desirable: 1.001; Less-Desirable: 1.811556
Grassland Growth curve – Ymax*	Kg DM/ha	Desirable: 6000; Less-Desirable: 5000
Maximum Biomass Decay Rate*	0-1	Desirable: 0.015; Less-Desirable: 0.005
Change in the proportion of space occupied by desirables over time under no grazing*	0-1	Annually adjusted through stochastic multipliers – 30yrs for recovery from 0.3 to 0.9
Livestock Impact on Desirable group*	0-1	0.272
Animal information		
Standard reference weight (SRW)	kg	55
The normal expected birth weight of an animal	kg	3.5
Opening numbers of females and male progeny	head	425 ewes, 40 wethers
Joining rate	0-1	0.03
Basal mortality rate	0-1	0.0202
Standard greasy fleece weight	kg/head	1.5
Mean fibre diameter	µm	24

Standard fleece length	cm	6
Clean:Greasy ratio for wool/fibre	0-1	0.6

SM-Table I continued

Inputs	**Units**	**Value**
Supplementary feeding		
DMD of supplement feed	0.3-0.9	0.66
Ether extract value for supplement	g/kg	25.84
Dry:Wet weight ratio for supplements	0-1	0.88
Ration offered per head (adult @ SRW)	kg wet /hd/d	1.5
Cost of Supplement	CNY/t (Wet)	1650
Relative condition for initiating supplementary feeding – Control/Survival feeding scenario[#]	0-1	<1yr old – 1.0; 1-2yr old – 0.85; >2yr old – 0.7
Minimum grassland biomass threshold for initiating supplementary feeding – Control/Survival feeding scenario	kg DM/ha	200
Starting day for supplementary feeding rules	DOY	345
Ending day for supplementary feeding rules	DOY	300
Economic inputs		
Carcass: Liveweight Ratio	0-1	<1yr old – 0.465; > 1yr old – 0.45
Meat Sale Prices (2012-2018 average)	CNY/kg Cwt	Mean: 41; StDev: 0
Skin Price (2012-2018 average)	CNY/hd	50
Wool/Fibre Price (2012-2018 average)	CNY/kg clean wool	Mean: 17.5; StDev: 0
Enterprise Variable Costs	CNY/hd	12.25
Herder Family Costs (including opportunity costs of labour)	CNY/yr	35000
Herder Fixed costs	CNY/yr	30000
Herder equipment replacement value & expected life	CNY & yrs	CNY327600 & 10-70 yr effective life
Interest Rate for any borrowed money	%	7.0
Interest Rate for any saved money	%	0.5
Discount rate	%	2

* *Desirable species is based on perennial grasses (e.g. Stipa spp) and less-desirable group is based on perennial shrubs (e.g. Artemisia frigida). See Kemp et al. (2013) for an explanation to functional grouping and its interaction with grassland quality, quantity and livestock performance.*

[#] *Based on Freer et al. (2007), a Relative Condition (RC) of 1 equates to a Condition Score (CS) of 3.0, RC of 0.85 is around 2.5 CS, and RC of 0.7 is around a CS of 2.0.*

Table S2: Attribute outcomes for each strategy set. Mean and Standard Deviations are shown for Annual Cash Flow (Yr 10), NPVa, Cumulative Soil Loss, Desirable:Less-Desirable ratio (Yr 10), Sheepmeat production (Yr 10), GHG Emissions Intensity (Yr 10) and total system GHG emissions (Yr 10). For ACF and NPVa, risk-efficient strategy sets are bolded. The 'control' condition (3) is italicised

No.	Treatment Code*	Annual Cash Flow (CNY/year)		NPVa (CNY)		Cumulative Soil Loss (t/ha)		Desirable:Less-Desirable ratio[#]		Sheepmeat production (kg cwt/ha/year)		GHG Emission Intensity GWP-100 (kg CO2e/kg cwt sold)		Total GHG Emissions (t CO2e/year)	
		Mean	Std	Mean	Std	Mean	Std	Mean	Std	Mean	Std	Mean	Std	Mean	Std
1	150/FL/S/T	-13542	9199	-17401	4946	29.90	17.08	1.73	0.45	4.33	0.26	17.04	0.49	37.03	1.37
2	300/FL/S/T	**34275**	**21495**	**23927**	**9983**	33.94	18.57	1.27	0.49	8.15	0.55	17.04	0.53	69.72	2.91
3	*450/FL/S/T*	***60353***	***36619***	***52234***	***16166***	*37.36*	*20.78*	*0.97*	*0.48*	*11.58*	*0.96*	*17.32*	*0.68*	*100.60*	*5.09*
4	600/FL/S/T	**81486**	**53681**	**66904**	**23152**	40.64	23.03	0.77	0.45	14.57	1.51	17.79	0.86	129.75	8.14
5	750/FL/S/T	**81648**	**71254**	64188	30170	43.22	24.94	0.63	0.42	17.28	2.04	18.18	0.98	157.05	11.40
6	150/AL/S/T	-21100	8223	-24230	4319	29.56	16.81	1.76	0.46	3.64	0.21	18.62	0.62	34.02	1.09
7	300/AL/S/T	**28872**	**20658**	**15168**	**8988**	33.61	18.51	1.30	0.50	7.25	0.57	18.00	0.80	65.39	2.77
8	450/AL/S/T	**52527**	**35597**	42557	14717	36.61	20.37	1.00	0.49	10.08	1.03	18.62	1.09	93.87	5.12
9	600/AL/S/T	**71658**	**53094**	56677	21332	40.07	22.85	0.79	0.46	12.49	1.60	19.40	1.44	120.78	8.04
10	750/AL/S/T	69669	71753	53132	28159	42.41	24.35	0.66	0.43	14.62	2.15	20.09	1.72	146.00	10.99
11	150/JL/S/T	-24377	8017	-23495	4475	29.60	16.98	1.76	0.47	2.92	0.32	21.31	1.42	31.12	1.62
12	300/JL/S/T	**15153**	**19590**	10011	8857	33.32	18.46	1.32	0.50	5.17	0.75	22.38	2.04	57.43	3.80
13	450/JL/S/T	33955	32739	31923	14466	36.39	20.31	1.02	0.50	6.83	1.14	23.99	2.57	81.07	5.96
14	600/JL/S/T	49719	48247	41564	21002	39.72	22.69	0.82	0.47	8.14	1.49	25.75	3.02	103.32	7.96
15	750/JL/S/T	46669	64862	32822	27663	41.71	23.66	0.68	0.45	9.29	1.77	27.21	3.38	124.33	9.82
16	150/FL/M/T	-14417	10528	-2411	5372	30.08	17.15	1.71	0.46	5.00	0.23	16.54	0.41	41.53	1.13
17	300/FL/M/T	28747	24405	**35492**	**11095**	34.17	18.68	1.24	0.49	9.49	0.53	16.58	0.43	79.07	2.65
18	450/FL/M/T	50412	43081	60086	18194	37.78	21.01	0.94	0.47	13.82	0.83	16.66	0.46	115.60	4.22
19	600/FL/M/T	60977	68197	69433	26290	41.14	23.37	0.74	0.44	17.87	1.11	16.95	0.57	152.06	5.37
20	750/FL/M/T	43089	94504	60889	34507	44.21	25.78	0.60	0.40	22.31	1.34	17.07	0.64	191.16	6.88

SM-Table II continued

No.	Treatment Code*	Annual Cash Flow (CNY/yr)		NPVa (CNY)		Cumulative Soil Loss (t/ha)		Desirable:Less-Desirable ratio[#]		Sheepmeat production (kg cwt/ha/yr)		GHG Emission Intensity GWP-100 (kg CO2e/kg cwt sold)		Total GHG Emissions (t CO2e/yr)	
		Mean	Std	Mean	Std	Mean	Std	Mean	Std	Mean	Std	Mean	Std	Mean	Std
21	150/AL/M/T	-22091	9984	-13626	4887	29.79	17.03	1.73	0.46	4.31	0.22	17.89	0.55	38.72	1.01
22	300/AL/M/T	17977	23457	20134	10167	33.83	18.59	1.27	0.50	8.30	0.51	17.83	0.63	74.24	2.29
23	450/AL/M/T	31951	42200	40191	16907	37.07	20.57	0.98	0.49	11.80	0.86	18.30	0.80	108.30	3.70
24	600/AL/M/T	37140	67968	46276	24706	40.41	22.90	0.77	0.45	15.16	1.24	18.79	1.00	142.71	5.33
25	750/AL/M/T	16171	94198	35150	32687	42.99	24.76	0.63	0.42	18.84	1.46	18.98	1.00	179.32	6.92
26	150/JL/M/T	-27624	10297	-16470	5201	29.63	16.98	1.75	0.47	3.09	0.23	21.22	1.25	32.79	0.75
27	300/JL/M/T	5617	23668	11257	10803	33.42	18.56	1.31	0.50	5.71	0.45	21.90	1.29	62.61	1.53
28	450/JL/M/T	13961	40656	25136	17555	36.52	20.40	1.01	0.50	7.96	0.67	22.98	1.51	91.45	2.28
29	600/JL/M/T	14871	66891	25381	25675	39.95	22.94	0.80	0.47	10.15	0.87	23.86	1.65	121.23	4.17
30	750/JL/M/T	-10712	97064	7453	34308	42.06	24.07	0.67	0.44	12.34	1.04	24.56	1.71	151.70	6.12
31	150/FL/P/T	-32486	9456	-15673	3975	29.85	17.04	1.74	0.45	6.32	0.14	15.37	0.22	48.88	0.56
32	300/FL/P/T	2590	22932	4667	8814	33.92	18.55	1.28	0.48	12.45	0.33	15.17	0.25	95.02	1.29
33	450/FL/P/T	12816	40660	12578	15613	37.46	20.82	0.98	0.47	18.41	0.51	15.23	0.27	140.92	1.93
34	600/FL/P/T	14737	57122	6375	23162	40.77	23.08	0.77	0.44	24.50	0.87	15.28	0.37	188.10	3.52
35	750/FL/P/T	-10843	71240	-14916	29900	43.85	25.48	0.62	0.41	30.50	1.24	15.26	0.45	233.88	6.59
36	150/AL/P/T	-41257	10657	-20987	4189	29.53	16.80	1.76	0.46	5.84	0.20	16.16	0.37	47.40	0.71
37	300/AL/P/T	-11533	23057	-6179	8495	33.57	18.45	1.30	0.49	11.33	0.39	16.12	0.33	91.80	1.59
38	450/AL/P/T	-6023	38889	-1536	14161	36.77	20.49	1.00	0.49	16.74	0.54	16.15	0.31	135.93	2.22
39	600/AL/P/T	-10817	55396	-8995	20643	40.10	22.84	0.79	0.46	22.21	0.92	16.21	0.46	180.84	3.39
40	750/AL/P/T	-41406	71299	-30104	27085	42.69	24.56	0.65	0.42	27.93	1.44	16.11	0.61	225.92	5.93
41	150/JL/P/T	-60658	13247	-19735	4786	29.48	16.66	1.77	0.47	4.27	0.17	19.44	0.66	41.67	0.43
42	300/JL/P/T	-43910	30575	-15267	10321	33.13	18.35	1.33	0.50	8.49	0.36	19.17	0.62	81.80	1.10
43	450/JL/P/T	-62101	51744	-22909	17259	36.07	20.07	1.04	0.49	12.30	0.57	19.63	0.71	121.26	1.69
44	600/JL/P/T	-97954	76333	-43756	25590	39.37	22.52	0.83	0.47	16.15	0.68	19.95	0.66	161.81	2.61
45	750/JL/P/T	-163489	96091	-79508	33326	41.63	23.84	0.69	0.44	20.03	0.89	20.09	0.66	202.15	3.93

SM-Table II continued

No.	Treatment Code*	Annual Cash Flow (CNY/yr)		NPVa (CNY)		Cumulative Soil Loss (t/ha)		Desirable:Less-Desirable ratio#		Sheepmeat production (kg cwt/ha/yr)		GHG Emission Intensity GWP-100 (kg CO2e/kg cwt sold)		Total GHG Emissions (t CO2e/yr)	
		Mean	Std	Mean	Std	Mean	Std	Mean	Std	Mean	Std	Mean	Std	Mean	Std
46	150/FL/M/B	-4151	17595	**12044**	**8972**	30.04	17.07	1.72	0.27	5.21	0.29	15.58	0.37	40.76	1.64
47	300/FL/M/B	50618	44586	**63874**	**17771**	34.80	19.70	1.23	0.19	10.15	0.65	15.29	0.34	77.98	3.85
48	450/FL/M/B	78293	74351	**100224**	**29149**	38.67	21.93	0.90	0.14	14.81	0.97	15.28	0.29	113.71	6.12
49	600/FL/M/B	**95106**	**102038**	**117235**	**41818**	41.92	24.29	0.69	0.10	19.11	1.25	15.40	0.24	147.94	8.50
50	750/FL/M/B	87363	126603	112704	54721	44.68	26.19	0.55	0.08	23.31	1.49	15.45	0.24	181.07	10.72
51	150/AL/M/B	-7067	15897	**2678**	**7642**	29.85	17.00	1.74	0.27	4.76	0.25	16.17	0.38	38.66	1.43
52	300/AL/M/B	43752	39728	**50680**	**15361**	34.33	19.14	1.25	0.20	9.08	0.53	16.11	0.33	73.53	3.32
53	450/AL/M/B	68243	69068	**84307**	**26067**	38.22	21.95	0.92	0.15	13.13	0.85	16.25	0.32	107.19	5.57
54	600/AL/M/B	**85165**	**97017**	100436	37678	41.40	23.87	0.71	0.11	17.01	1.15	16.37	0.32	139.94	7.81
55	750/AL/M/B	78254	122508	95676	49926	43.81	25.79	0.57	0.09	20.83	1.35	16.39	0.30	171.63	9.78
56	150/JL/M/B	-17234	15068	**233**	**6231**	29.78	16.98	1.77	0.27	3.44	0.22	18.92	0.76	32.65	1.00
57	300/JL/M/B	27505	38628	**41504**	**13937**	33.81	18.85	1.29	0.21	6.57	0.46	18.95	0.82	62.44	2.07
58	450/JL/M/B	45875	67292	69706	24758	37.40	21.24	0.96	0.16	9.40	0.67	19.37	0.80	91.36	3.18
59	600/JL/M/B	56215	94422	81044	36490	40.68	23.09	0.74	0.12	12.10	0.80	19.77	0.70	120.13	4.22
60	750/JL/M/B	41954	120469	70739	48527	42.93	25.26	0.61	0.09	14.78	0.89	19.99	0.64	148.38	5.13

* Number is total number of females in the flock; FL, AL and JL are February, April and June lambing times; S, M and P are survival, maintenance and production supplementary feeding rules; T and B are Time and Biomass based grazing management, respectively.

Starting ratio was 1:1 (i.e. 1.0). Desirable species is based on perennial grasses (e.g. *Stipa spp*) and less-desirable group is based on perennial shrubs (e.g. *Artemisia spp*). See Kemp *et al.* (2013) for an explanation to functional grouping and its interaction with grassland quality, quantity and livestock performance.

Supplementary Figures

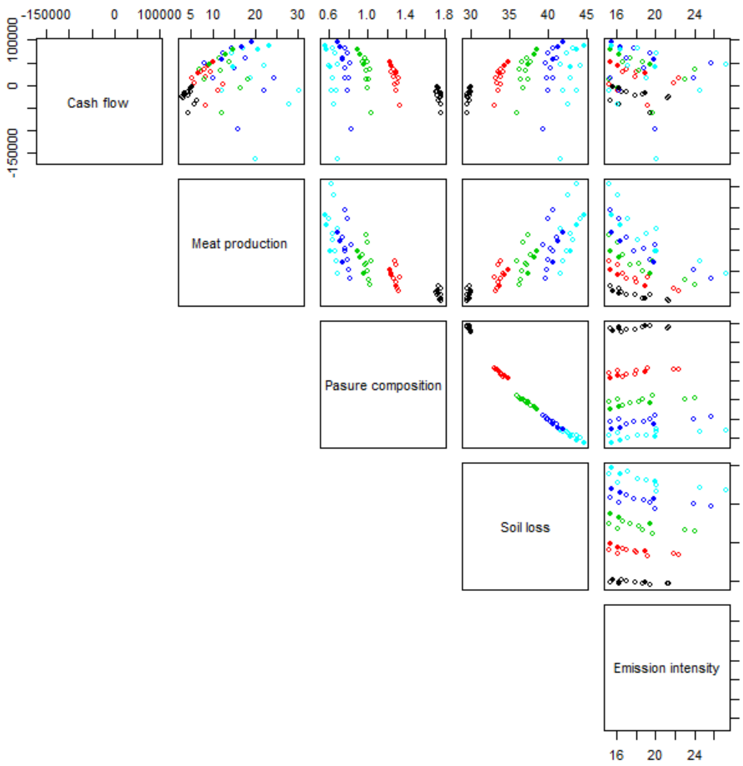

Fig. SI: Trade-off plot showing interactions between mean attribute values. Flock size shown: 150 (black), 300 (red), 450 (green), 600 (blue), 750 (aqua) with empty circles time based grazing management and filled circles biomass based grazing management.

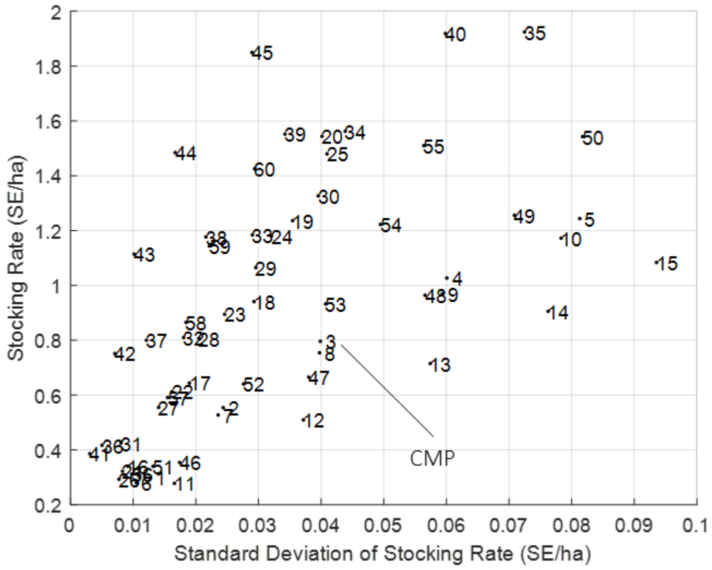

Fig. S2: Expected value and variation (measured as standard deviation) for stocking rates in the final year of the simulation (Year 10). Numbers indicate strategy set as per Table II, and a sheep equivalent (SE) is based on the energy maintenance requirements of a 50kg liveweight sheep. Numbers indicate the strategy set as per Table 1 with position of current management practice (CMP) shown for IMAR herders.

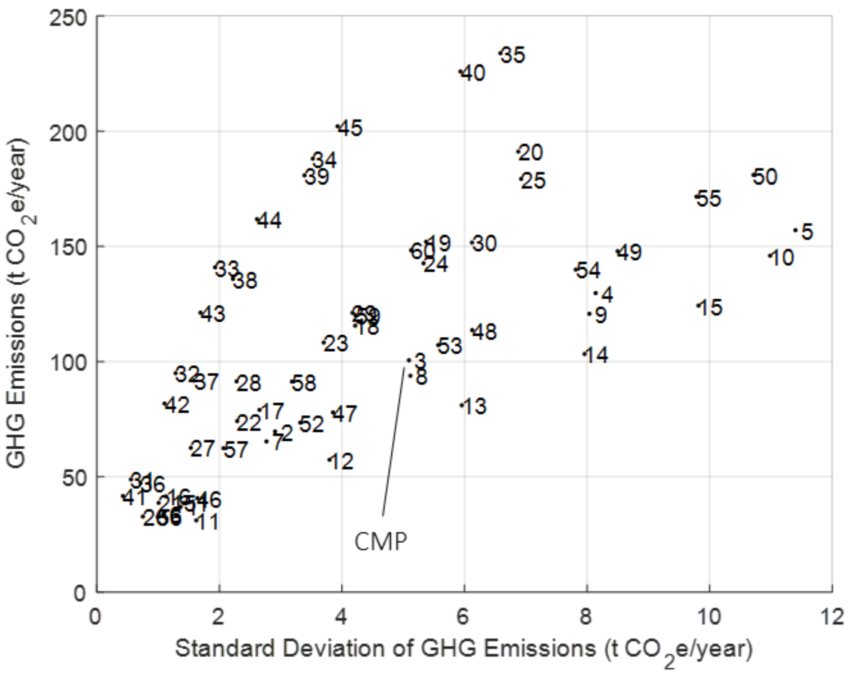

Fig. S3: Total farming system Green House Gas emissions based on 100-year Global Warming Potential (t CO_2e/year). Total Emissions from livestock modelled using IPCC Tier 2 methodology (De Klein *et al.* 2006; Dong *et al.* 2006). CO_2 Equivalents calculated using GWP100 based on IPCC (2014). Numbers indicate the strategy set as per Table 1 with position of current management practice (CMP) shown for IMAR herders.

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