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Supplementary Material

Modelling Chinese grassland systems to improve herder livelihoods and grassland sustainability

Karl Behrendt^{A,B}, Taro Takahashi^{C,D}, David R. Kemp^A, Guodong Han^E, Zhiguo Li^E, Zhongwu Wang^E, Warwick Badgery^{A,F} and Haibo Liu^{A,G}

^AGraham Centre for Agricultural Innovation, Charles Sturt University, Orange, NSW 2800, Australia.

^BHarper Adams University, Newport, Shropshire TF10 8NB, United Kingdom.

^CRothamsted Research, North Wyke, Okehampton, Devon EX20 2SB, United Kingdom.

^DUniversity of Bristol, Langford House, Langford, Somerset BS40 5DU, United Kingdom.

^EInner Mongolia Agricultural University, Hohhot, Inner Mongolia Autonomous Region 010011, China.

^FNSW Department of Primary Industries, Orange, NSW 2800, Australia.

^GGansu Academy of Agricultural Sciences, Lanzhou 730070, Gansu, China.

^HCorresponding author. Email: kbehrendt@harper-adams.ac.uk

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 area	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	<i>60353</i>	<i>36619</i>	<i>52234</i>	<i>16166</i>	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 CO ₂ e/kg cwt sold)		Total GHG Emissions (t CO ₂ e/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

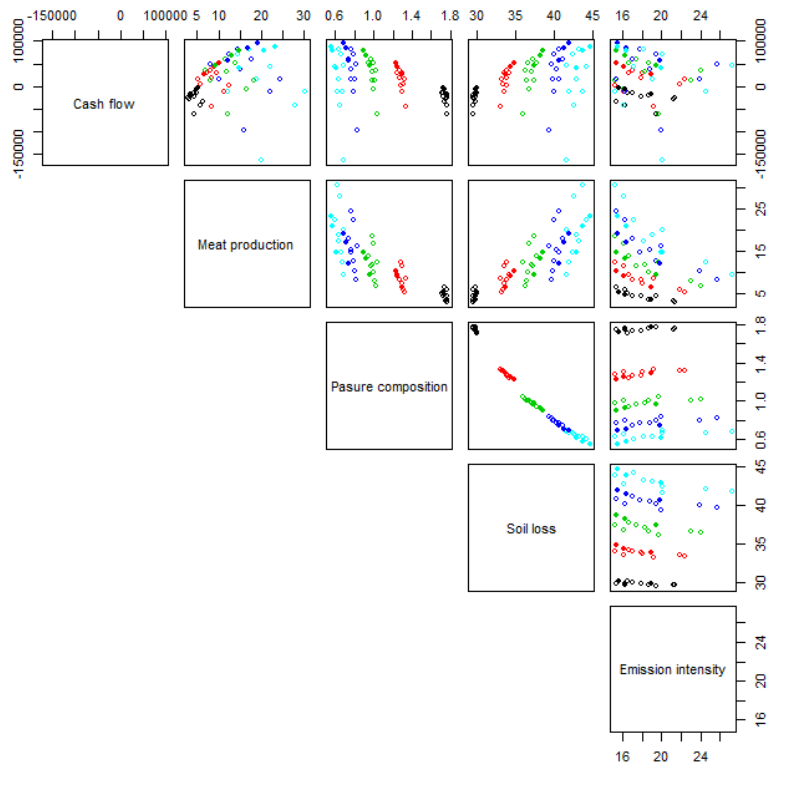


Fig. S1: Trade-off plot showing interactions between mean attribute values. Flock size shown: 150 (black), 300 (red), 450 (green), 600 (blue), 750 (aqua) with empty circles time based grazing management and filled circles biomass based grazing management.

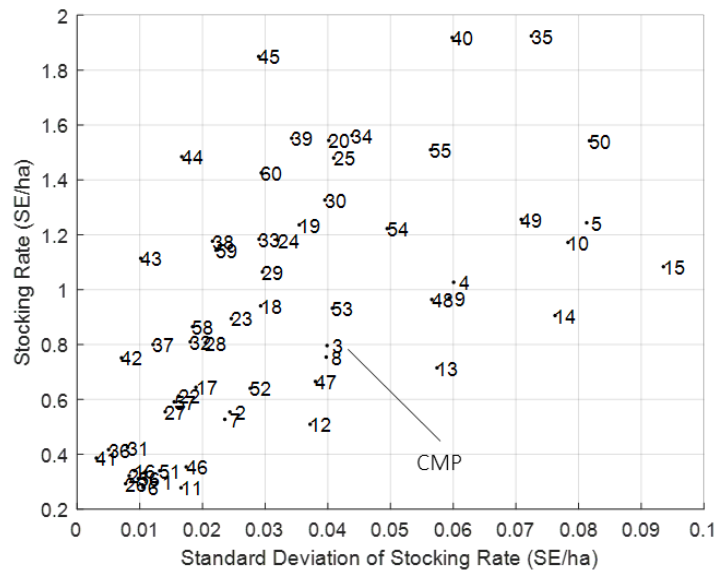


Fig. S2: Expected value and variation (measured as standard deviation) for stocking rates in the final year of the simulation (Year 10). Numbers indicate strategy set as per Table II, and a sheep equivalent (SE) is based on the energy maintenance requirements of a 50kg liveweight sheep. Numbers indicate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

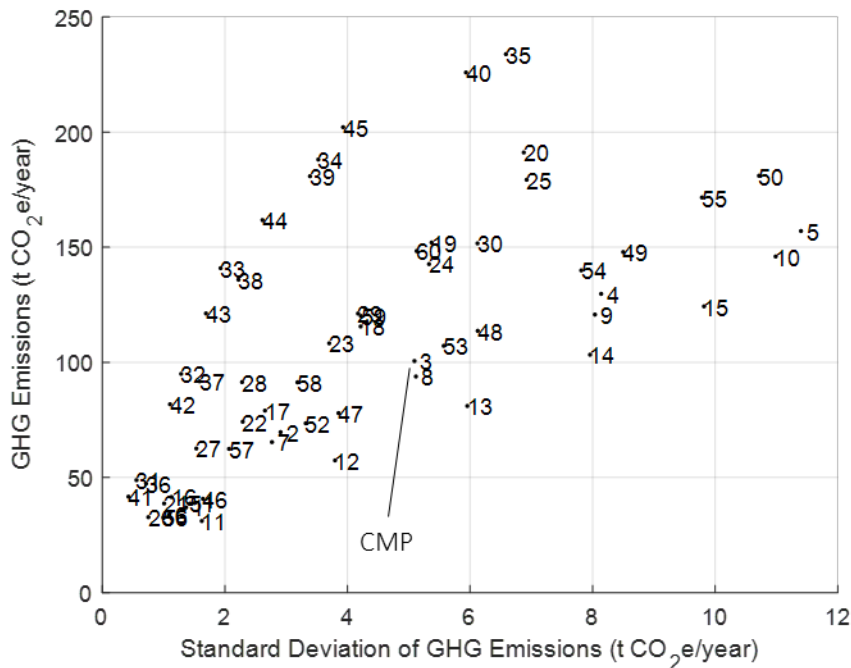


Fig. S3: Total farming system Green House Gas emissions based on 100-year Global Warming Potential (t CO₂e/year). Total Emissions from livestock modelled using IPCC Tier 2 methodology (De Klein *et al.* 2006; Dong *et al.* 2006). CO₂ Equivalents calculated using GWP100 based on IPCC (2014). Numbers indicate the strategy set as per Table 1 with position of current management practice (CMP) shown for IMAR herders.

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