Supplementary Material S1:

Generation of the regional livestock distribution map

This section of the Supplementary Material is to describe how we generated a livestock distribution map, which is a necessary model input to calculate the regional grazing consumption. The goal is to downscale the province/prefecture scale of the livestock distribution to the pixel scale.

We first incorporated official province/prefecture level statistics to generate the regional administrative map of livestock distribution. The use of official statistics largely excludes factors of political/social heterogeneity that control and alter the regional livestock distribution pattern. The reason we are excluding human factors from our model is because in TES, the livestock distribution pattern is relatively simple in ecological terms but is much more complicated in anthropogenic terms. The anthropogenic factors that relate to politics and economics exist widely in the different countries or sub-regions. These factors largely influence the livestock distribution pattern at both spatial and temporal scales among provinces and prefectures. For example, the recent boom of economic development and animal product needs in China has caused animal husbandry in Inner Mongolia to grow rapidly since 2000. The livestock number is almost doubled in 2008 relative to that in 2000; in contrast, the collapse of the USSR caused a rapid decline of livestock in Kazakhstan, which lost 70% of its total livestock. Regarding the spatial scale, there are obvious imbalances of livestock distribution throughout TES. Even before the collapse of the USSR, the livestock number in Kazakhstan was lower than that of Inner Mongolia, China, while the absolute pasture areas in Kazakhstan were much larger than that in Inner Mongolia.

Moreover, the independence of countries in the Kazakh Steppe also largely obstructs the traditional seasonal migration path for livestock [Mirzabaev et al., 2016]. Therefore, without excluding heterogeneity due to anthropologic factors among different administrate units, the natural mechanisms of livestock distribution could not be effectively used.

We summarized the major livestock species, including sheep, goat, cattle, horse and camel. The total livestock number was calculated in sheep units based on the FAO conversion ratio (**Table S1**).

Table S1. Conversion rate of daily diet of livestock compared with sheep/goat

Type of herbivores	Ratio compared with sheep/goat
Sheep/goats	1
horses	10
Cattle and buffaloes	6.4
Camels	10
Mules/asses	6

After the map divided by countries and provinces or prefectures was created, we applied a resource-oriented scheme to predict the pixel level of the livestock distribution pattern following McNaughton et al. [1989] and Oesterheld et al. [1992]. The concept is that at large scales, the herbivore distribution is proportional to the net primary productivity (NPP). We first tested the NPP-driven livestock distribution at the inter-province/prefecture level. The result at the inter-province/prefecture level indicated that this distribution pattern widely exists in major parts of the TES **(Fig. S1)**. Thereafter, we used the NPP-driven livestock distribution to predict livestock distribution to the pixel level. Geographical factors (i.e., slope and elevation) were considered as constraints to livestock movements. That is, if the slope and elevation are higher than 40% and 5000 m respectively, then the specific area is not suitable for grazing. To simplify the scheme, regional livestock were distributed in a single vegetation type of grassland. After we generated a pixel-based livestock distribution map, we validated it using an established dataset of livestock distribution, the Gridded Livestock of the World (GLW) from FAO.

The temporal dynamics of livestock spatial distribution were updated every month considering the spatial memory of livestock [*Benhamou*, 1994; *Laca*, 1995]. A maximum stocking rate of 5 sheep unit/hm^2 was set to avoid an unreal livestock concentration during the non-growth season.

The linear relationship indicated that our model fit the GLW dataset ($R^2 = 0.49$, $p < 0.001$, **Fig. S2**).

Figure S1. The province/prefecture level relationships between grassland NPP and

livestock number in Inner Mongolia (IM), Mongolia (MON) and Kazakhstan (KAZ). Logarithms are on a decimal base.

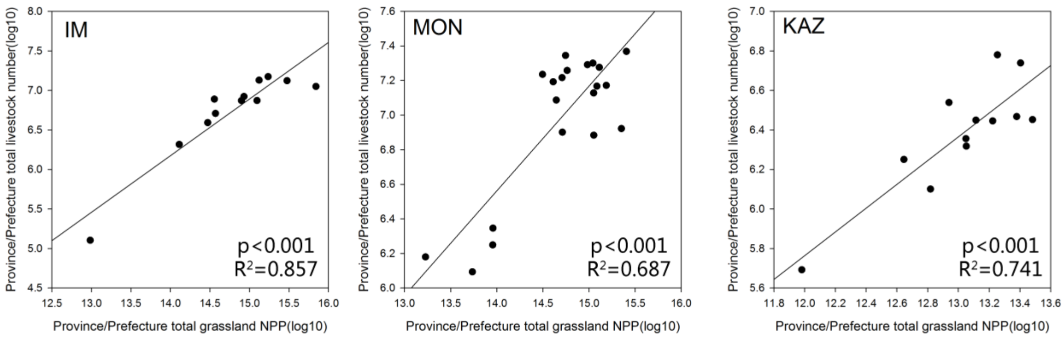
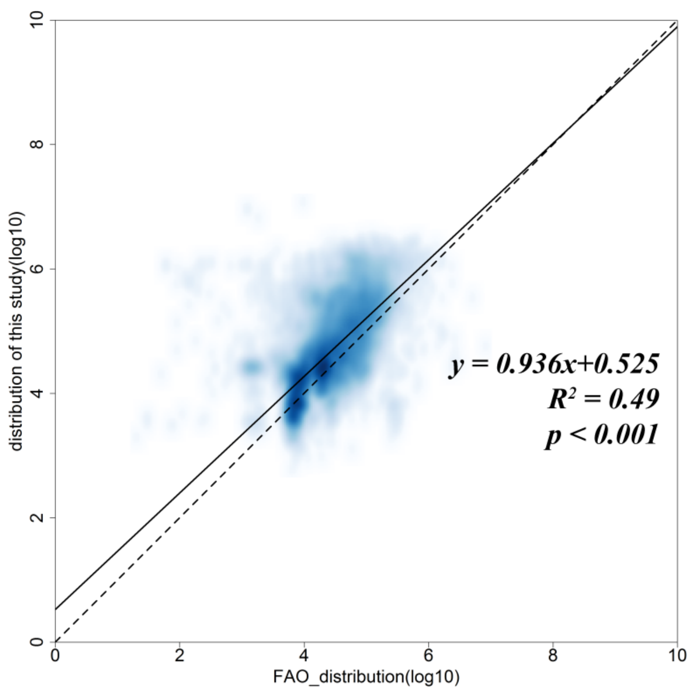


Figure S2. The linear relationship between the modeled annual livestock density in this study and the GLW dataset. Blue indicates pixel density, with dark blue as the highest pixel density. The livestock density in sheep unit/hm^2 was multiplied with a rate of 10^5 and then log transformed.



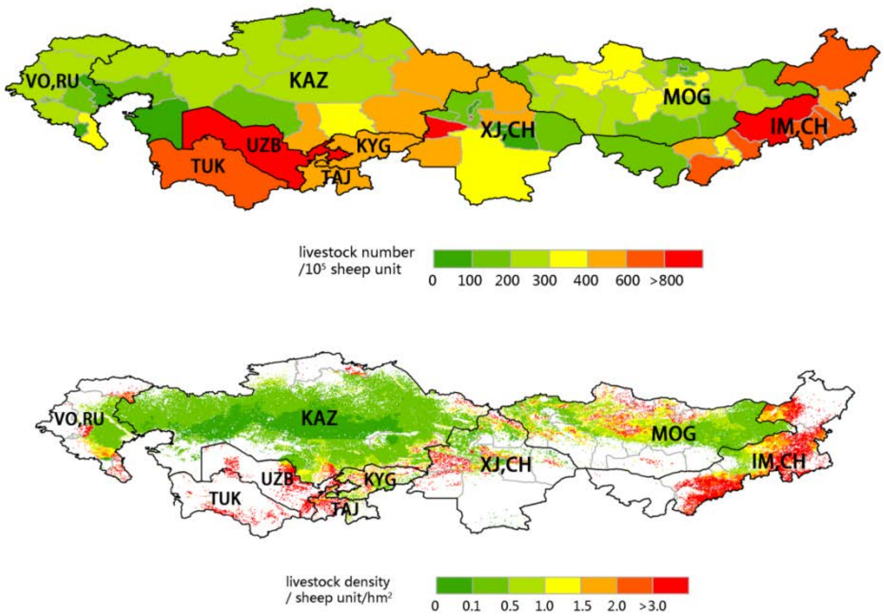
The livestock distribution based on provinces or prefectures is shown in **Fig. S3(a)**.

The result indicated that regional grazing consumption had an uneven spatial distribution. A large number of livestock were concentrated in Inner Mongolia, China, Uzbekistan, and Turkmenistan, where the livestock numbers were more than $8.0 * 10^7$ sheep unit. Medium livestock numbers were located in the Western part of Xinjiang, China, Central Mongolia, and the Eastern parts of Kazakhstan, Tajikistan, and Kyrgyzstan. The numbers in these regions ranged from $3.0 * 10^7$ to $8.0 * 10^7$ sheep unit. Light livestock numbers were located in the north and central parts of Kazakhstan, Central Mongolia, and Volgograd Oblast, Russia.

Accordingly, the pixel-based livestock density is concentrated in Turkmenistan Uzbekistan and Tajikistan **(Fig. S3(b))**. The highest stock density, over 3 sheep unit/hm^2, covers the entire grassland areas in UZB and TAJ, and most of Inner Mongolia. For the conditions in Russia, Xinjiang, China and Mongolia, livestock were mainly concentrated in some part of the country or province, such as northern areas in Mongolia and western prefectures near the mountainous range in Xinjiang. The livestock density is low in Kazakhstan due to its widespread grasslands. Even in southeastern provinces with relatively high livestock total numbers, densities were low at around 0.1 to 0.5 sheep unit/hm^2.

Figure S3. The livestock distribution map in TES: (a) the

province/prefecture level distribution, (b) the pixel level distribution.



Supplementary Material S2:

Introduction to the grazing model

To simulate the impact of grazing on grassland carbon sequestration, the Shiyomi grazing model was revised and coupled with BEPS. As we introduced in the manuscript, livestock cycling is linked to ecosystem cycling by four processes: 1) direct consumption of aboveground biomass; 2) livestock respiration to the atmosphere; 3) excretion that adds carbon back to the soil; and 4) detrimental physical and chemical effects to the grassland.

The direct consumption of aboveground biomass by livestock was considered as a piecewise function depending on forage availability. If the available above-ground biomass ($Biomass_{above,ava}$) is sufficient for the livestock, then the following equation would be used:

$$Biomass_{graze} = n \times W \times q \times r_{intake} \quad \text{for } Biomass_{above,ava} \geq n \times W \times q \times r_{intake} \times 2$$

Where $Biomass_{graze}$ is the grazed biomass per unit area (g/m^2); n is the livestock density in the specific pixel (sheep unit/m^2); W is unit weight of livestock (g), which is updated with each time step; q is a ratio of aboveground biomass in the livestock's diet, equal to 0.95; r_{intake} is the daily intake rate of livestock (%).

If $Biomass_{above,ava}$ is not sufficient for the livestock, 20% of the existing $Biomass_{above,ava}$ will be consumed:

$$Biomass_{graze} = 0.2 \times Biomass_{above,ava} \quad \text{for } Biomass_{above,ava} < n \times W \times q \times r_{intake} \times 2$$

The rest of the consumption is from the surface dead material:

$$P_{graze,dm} = n \times W \times (1-q) \times r_{intake}$$

Where $P_{graze,dm}$ is the grazed dead plant material from the surface litter pool.

In the model, the grass offset was considered in the calculation of forage availability (*i.e.*, $Biomass_{above,ava}$) using an algorithm derived from the Biome-BGC v. 4.1.2 and CLM 4.5 models [*Oleson et al.*, 2013; *Thornton et al.*, 2002]. The deciduous process is triggered by the day length, which is calculated following *Forsythe et al.* [1995]. If the day length is less than a specific value (set as 39300 s), the deciduous process will lead to a carbon transfer from the leaf pool to the surface litter pool.

The offset rate (R_{off}) is calculated as:

$$R_{off} = \frac{2\Delta t}{t_{off}^2}$$

Where Δt is the time step of the model (i.e., daily in this study), the t_{off} is the offset period left during the year. The initial value is set to 15 days (i.e., the length of the offset process). This function produces an increasing litterfall rate during the offset period.

The weight dynamic of livestock (W) is updated daily as follows:

$$W = W_{ini} + F_{in,lb} + F_{in,db} - F_{rp} - F_{ex,lb} - F_{ex,db}$$

Where W_{ini} is the initial weight of unit livestock, $F_{lb,}$ F_{db}, and F_{rp} are the fluxes from live vegetation biomass, dead material to livestock and the maintenance respiration of livestock, respectively. The intake rate of digestible matter from aboveground plant parts is 65%, while the corresponding rate is 45% from standing dead material (i.e. surface litter pool):

$$F_{in,lb} = Biomass_{graze} \times 0.65$$

$$F_{in,db} = P_{graze,db} \times 0.45$$

F_{rp} represents the daily respiration consumption to maintain regular animal activity. It equals 1.5% of the sheep weight:

$$F_{rp} = weight \times 0.015$$

$F_{ex,lb}$ and $F_{ex,db}$ are the fluxes of outflow by excretion from live biomass and dead material. The excretion rates of live aboveground material and standing dead material are 0.35 and 0.65, respectively:

$$F_{ex,lb} = Biomass_{graze,lb} \times 0.35$$

$$F_{ex,db} = P_{graze,db} \times 0.65$$

The excretion first goes to the surface litter pool.

The negative effect of trampling and urine ($Biomass_t$) are considered as a function of livestock numbers following *Vuichard et al.* [2007]:

$$Biomass_t = n \times p$$

Where p is the effect coefficient, equal to 0.008.

At the current stage, we assume that slaughter and birth rates do not change, so the livestock numbers is kept constant throughout the year. The major regional parameterizations of the grazing model were summarized from the national survey, a search of the literature, and a previous model set.

The dry matter values were converted to carbon assuming a proportional factor of 0.475 [*Garbulsky and Paruelo*, 2004]

Table S2.Information on sites at which observations were used for model validation

Site	Data type	Long.	Lati.	Climate type	Time extent
CN_XL	FLUX	116°40'E	43°33'N	BSk	2004
CN_TY	FLUX	122°52'E	44°25'N	Dwa	2008
RU_HA1	FLUX	90°0'E	54°43'31"N	Dfc	2002-2004
RU_HA2	FLUX	89°57'24"E	54°46'23"N	Dfc	2002-2003
RU_HA3	FLUX	89°4'40"E	54°42'16"N	Dfc	2004
IT_MBO	FLUX	11°2'48"E	46°0'56"N	Dfb	2003-2006
US_AUD	FLUX	110°30'36"W	31°35'26"N	BSk	2003-2006
US_BKG	FLUX	96°50'10"W	44°20'43"N	Dfa	2004-2006
TKS (14 sites)	Field	72°43'E-73°37'E	48°52'28N-48°55'N	Dfb, Dfa,BSk	2004
IM (54 sites)	Field	111°6'E-118°20'E	42°19'12"N-46°9'N	BSk,Dwb	2004-2008
XJ(52 sites)	Field	88°37'E-88°40'E	44°29'N-44°31'N	Bwk	2010
Fenced observation	Field	116º04'E-117º05"E	43°26'N -44°08'N	BSk	1990,1993,1997

* Climate type of grassland is based on Koeppen-Geiger classification (http://koeppen-geiger.vu-wien.ac.at/). BSk: main climate --- arid, precipitation --- steppe and temperature --- cold arid; Dwa: main climate --- snow, precipitation --- desert and temperature --- hot arid; Bwk: main climate --- arid, precipitation --- desert and temperature --- cold arid; Dwb: main climate --- snow, precipitation --- desert, temperature --- warm summer

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