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Supplementary Materials for

China's livestock transition: Driving forces, impacts, and consequences

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Supplementary Text

Definitions of indicators

Livestock units. The calculation of livestock units followed the procedure of Liu et al (*31*); 1 head of dairy cattle, beef cattle, pig, sheep and goat, layer, and broiler equal 1.0, 0.50, 0.35, 0.10, 0.012 and 0.007 LU, respectively. Monogastric animals include pigs, broilers and layers. Livestock number of different production systems in different years were derived from MOA database (*32*) and are shown in Fig S1.

Production performance indicators. The production of milk, egg, pork, poultry, beef and mutton (total and per animal head), and the protein, N and P contents of these products were used as production performance indicators (equations 7 and 8 main text). GDP of livestock production was derived from National Statistical Bureau of China (NSBC) (*23*).

Feed and land use indicators. Crop yield, feed use per animal product and the area of land required for livestock were the main indicators for feed and land use. The proportion of cereal feed to total feed was calculated as follows:

$$\text{Cereals to total feed consumption} = [(Ia_{\text{corn intake}} + Ia_{\text{soybean intake}} + Ia_{\text{wheat intake}} + Ia_{\text{rice intake}}) / Ia_{\text{DM intake}}] * 100\%$$

$Ia_{\text{corn intake}}$, $Ia_{\text{soybean intake}}$, $Ia_{\text{wheat intake}}$ and $Ia_{\text{rice intake}}$ are the amounts of corn, soybean, wheat and rice intake by each livestock category and production system, in kg.

The land requirement for the environmentally safe application of manure was based on the maximum manure application rate in Nitrate Vulnerable Zones in European Union, which was 170 kg N ha^{-1} (*39*). Manure N recycling was defined as the proportion of manure N returned to crop land and grassland in percent of the total N excretion by animals:

$$\text{Manure N recycling} = [(Oa_{\text{manure N dropping}} + Oa_{\text{manure N applied to cereals}} + Oa_{\text{manure N applied to cash crop}}) / Oa_{\text{nutrient excretion}}] * 100\%$$

$Oa_{\text{manure N dropping}}$ is the amount of manure N dropped during grazing on pastures, in kg N; $Oa_{\text{manure N applied to cereals}}$ is the amount of manure N applied to main feed crops, in kg N; $Oa_{\text{manure N applied to cash crop}}$ is the amount of manure N applied to vegetables and fruits, in kg N. The manure N recycling was calculated for each livestock category and production systems (*21*).

New N was defined as the amount of N entering China's crop-livestock production system, including feed import, chemical fertilizer, BNF and deposition) (Fig S7).

Environmental pollution indicators. GHGs emissions, NH_3 emissions, N losses to water courses and landfill, and P losses to water courses and landfill were used as environmental pollution indicators.

Detailed description of the SSP1 scenarios.

Scenario SSP1a: improved feed and herd management: Build on BAU, with technologies for improved feed and herd management. This scenario consisted of a package of three measures: ***A. Improved feed quality via increasing use of concentrate feed.*** The animal feed industry will increase the production of compound feed by 20% each 5 year (40). As a result, the total compound feed production will have increased by 250 Tg, which is around 10% of total feed consumption in China in 2050. We assume that the mean feed quality will have improved by 10% for each animal category, which means that the value of the feed conversion ratio (FCR) will have decreased by 10% at herd level. ***B. Precision feeding and herd management.*** Increased phase feeding may further increase animal productivity, lower the feed use and increase the nutrient use efficiency. We assumed that the mean crude protein (CP) content of the feed used in landless industrial systems will be lowered by 10%, through using synthetic amino acids (*41*). ***C. Genetic improvement.*** Through enhanced breeding and import of high-quality genetic material from abroad, the milk, egg and meat yield (kg per head) will increase by 20%, 20% and 40%, respectively (*42*).

Scenario SSP1b: whole chain manure management and coupled crop-livestock production: Build on BAU, with significant improvement of manure management, including three kind measures: ***A. Abandoning of the discharge of manure.*** Manure discharge to surface waters and landfills will have been abandoned and all manure will be recycled to cropland, with or without prior processing. This scenario basically follows from the 1972 Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter, which China also approved (*43*). ***B. Low-emission manure application***. All manure will be applied to crop land, and the N fertilizer replacement value will be 50% (*44*). The N losses in the field will have decreased by 1/3, according to result of Ju et al (2009) (*45*). ***C. Low emission housing and manure storages***. Here, we assumed that the gaseous N losses from manure in animal housing and manure storages will have reached the mean level of the EU in 2000 (*46*).

Scenario SSP1c: accelerated intensification: Build on BAU, but it is assumed that the number of animals in mixed crop-livestock systems and in grassland systems are halved, and that the additional animal protein will be produced in landless industrial systems.

Scenario SSP1d structural adjustment: Build on BAU, but it is assumed that all additional animal protein in 2050 will be supplied by monogastric animals, i.e., pigs, layers and broilers, and that the domestic production of milk, beef and sheep and goat meat remains at the level of that in 2010.

Scenario SSP1e: combined technologies: Combination of SSP1a and SSP1b.

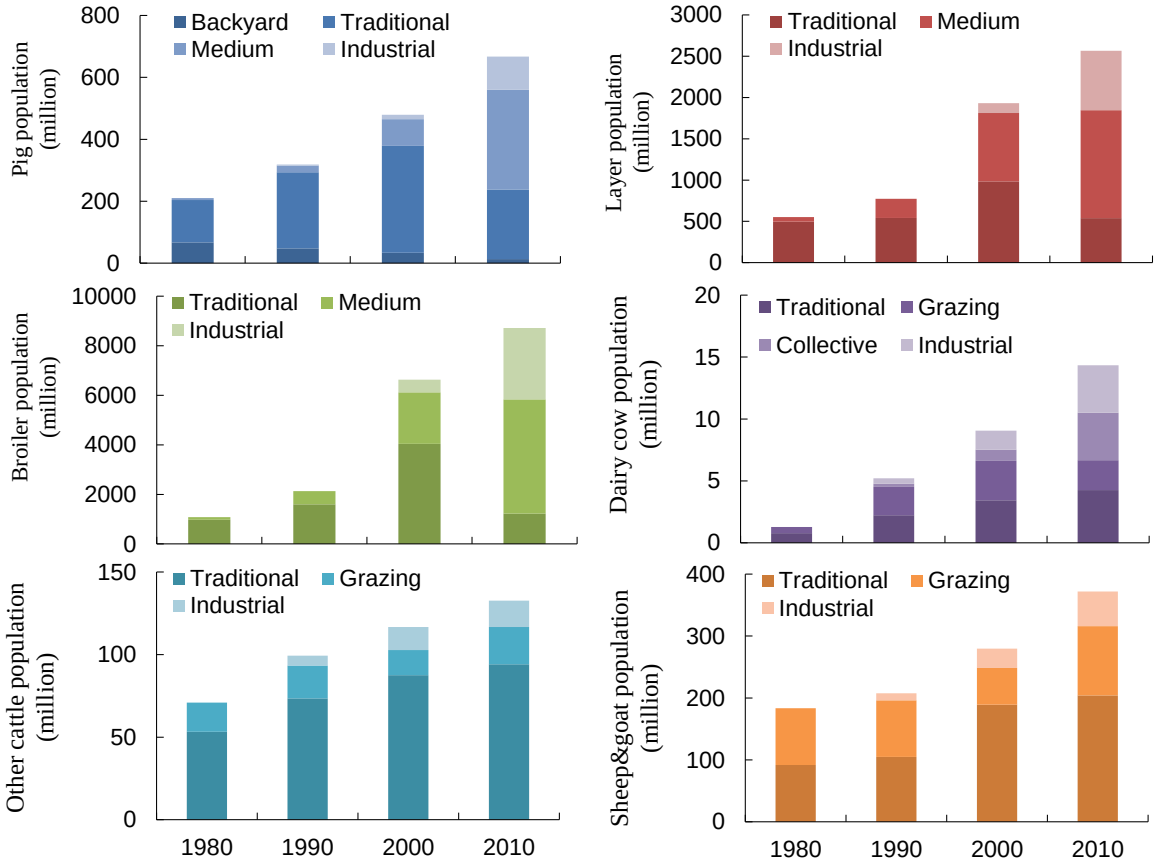

Fig. S1. Changes of livestock population structure of different livestock categories in China between 1980 and 2010.

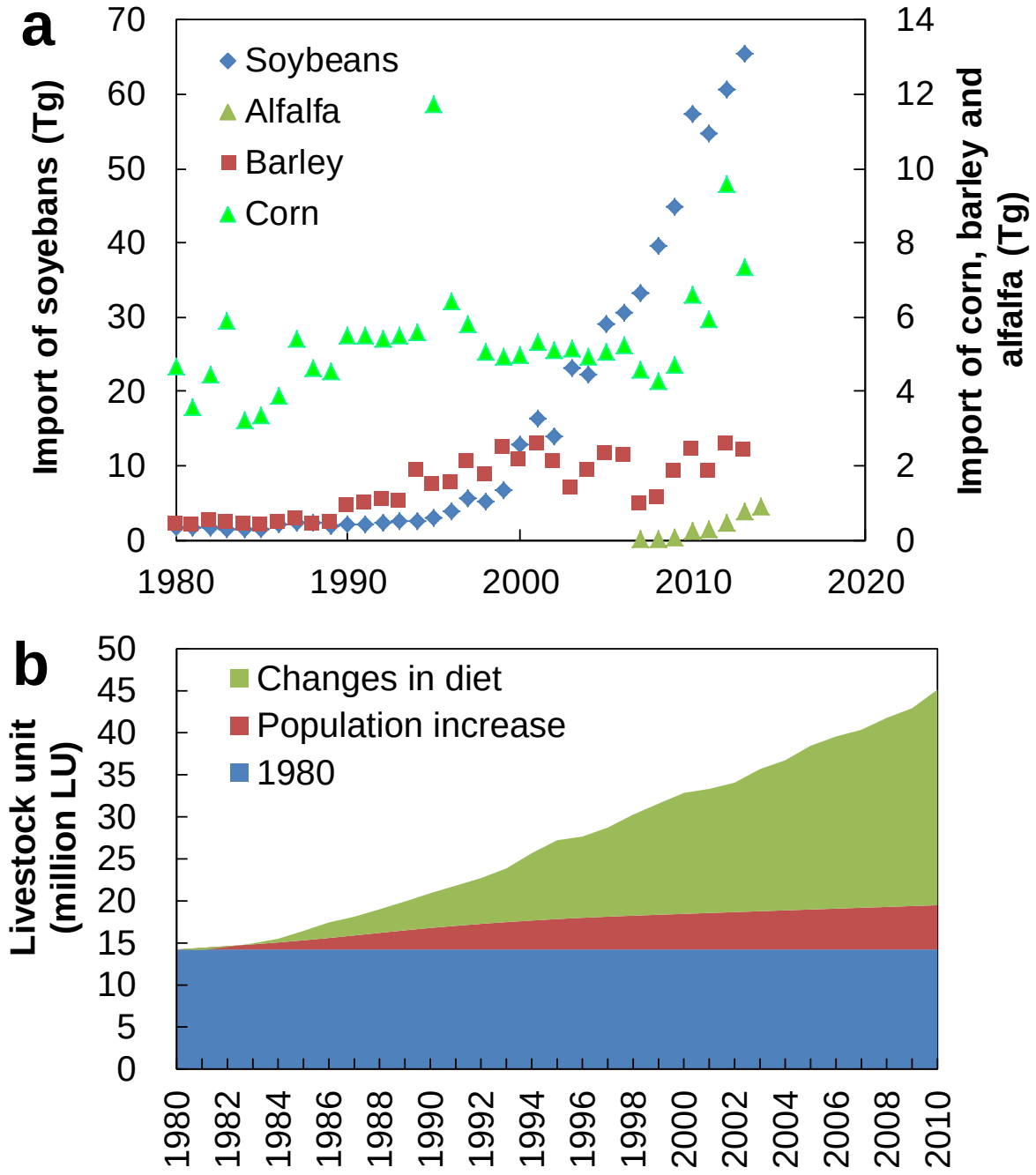

Fig. S2. Changes of feed import and contributions to livestock transition. Changes in feed import (**a**), and contribution of diet change and population increase to the changes in total livestock units (**b**) between 1980 and 2010 in China.

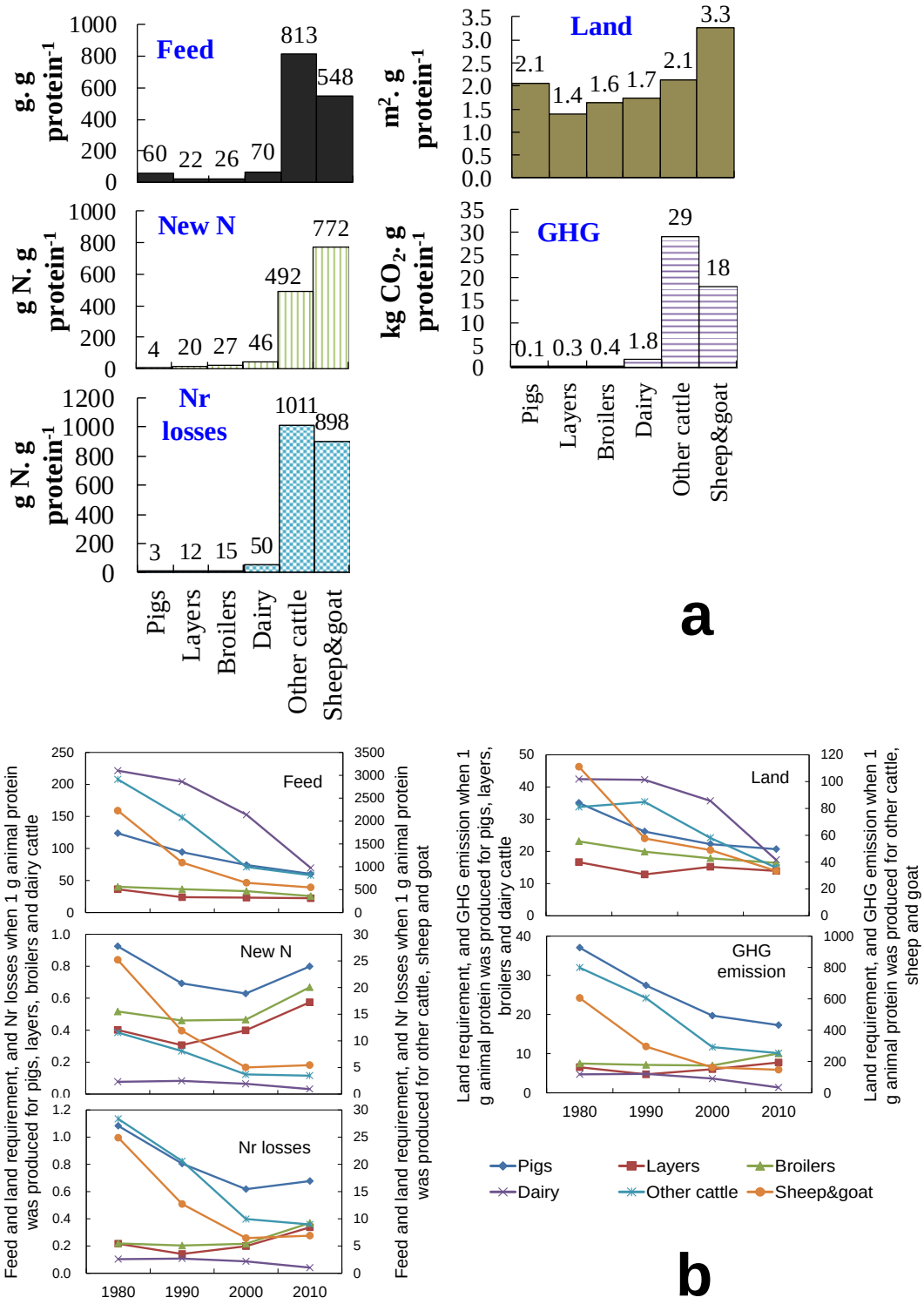

Fig. S3. Changes of livestock performances in terms of animal protein production. Resources demands (feed, land, irrigated water and new nitrogen) and environmental performances (greenhouse gas-GHG emission and reactive nitrogen-Nr losses) per g of protein produced by different animal categories in 2010 (**a**), and the respective changes for the whole livestock production between 1980 and 2010 (**b**).

Unit: Feed, g feed g protein $^{-1}$; Land, m^2 agricultural land g protein^{-1}; New N, g N g protein $^{-1}$; GHGs, kg $CO_{2\text{-equi}}$ g protein $^{-1}$; Nr loss, g N g protein $^{-1}$.

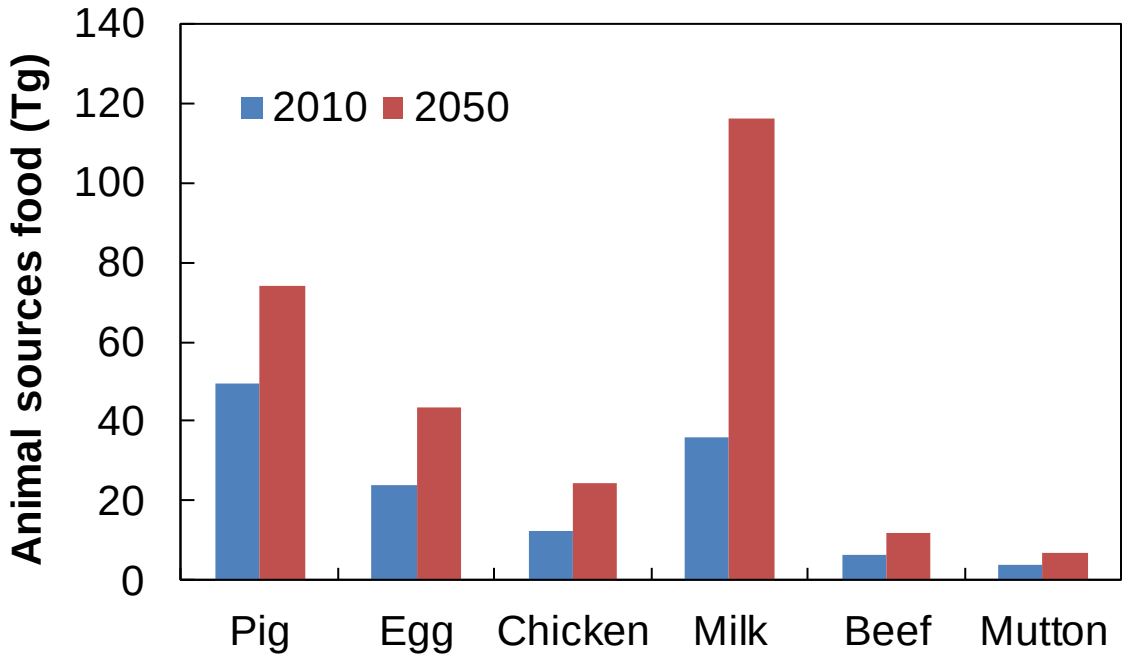

Fig. S4. Production of animal source food products in 2010 and demand for animal source food in 2050.

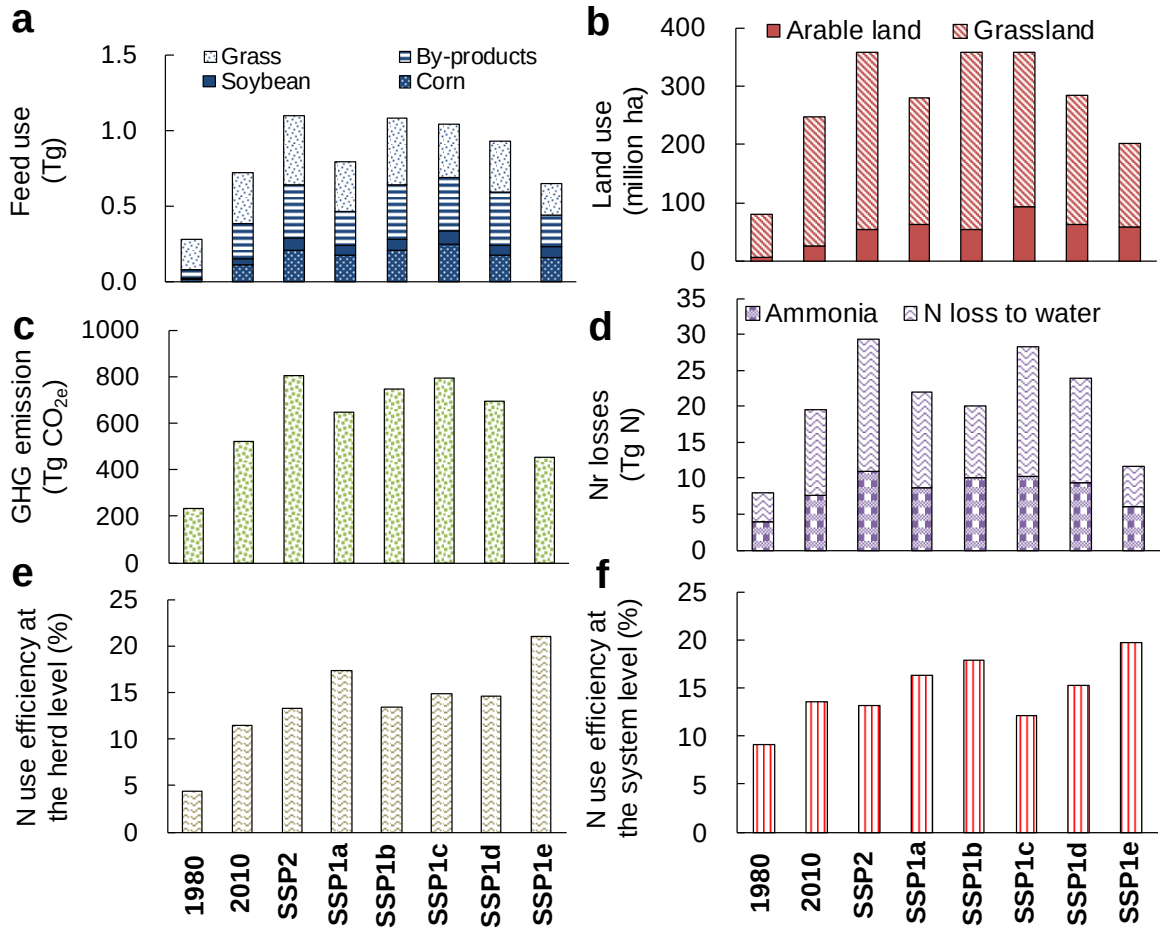

Fig. S5. Response of livestock transition under different sub-scenarios in 2050. Changes in livestock production performance between 1980 and 2010, and forecasts for 2050 following the Shared Socio-economic Pathways SSP2 and SSP1 scenarios: total feed use (**a**), total land use (**b**), total greenhouse gas (GHG) emissions (**c**), total reactive N (Nr) losses (**d**), nitrogen use efficiency (NUE) at herd level (**e**), and NUE at whole system level (**f**).

Note: SSP1a, b, c, d and e show various variants of the Shared Socio-economic Pathway SSP1 (see text). Soybean includes both soybean and soybean cake.

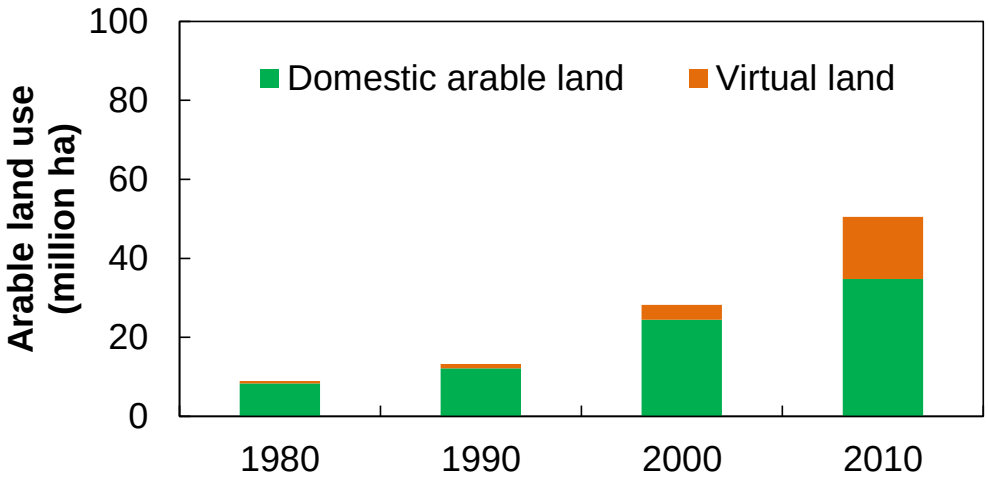

Fig. S6. Changes in the areas of domestic arable land used for feed production and virtual land via trade of feed products between 1980 and 2010.

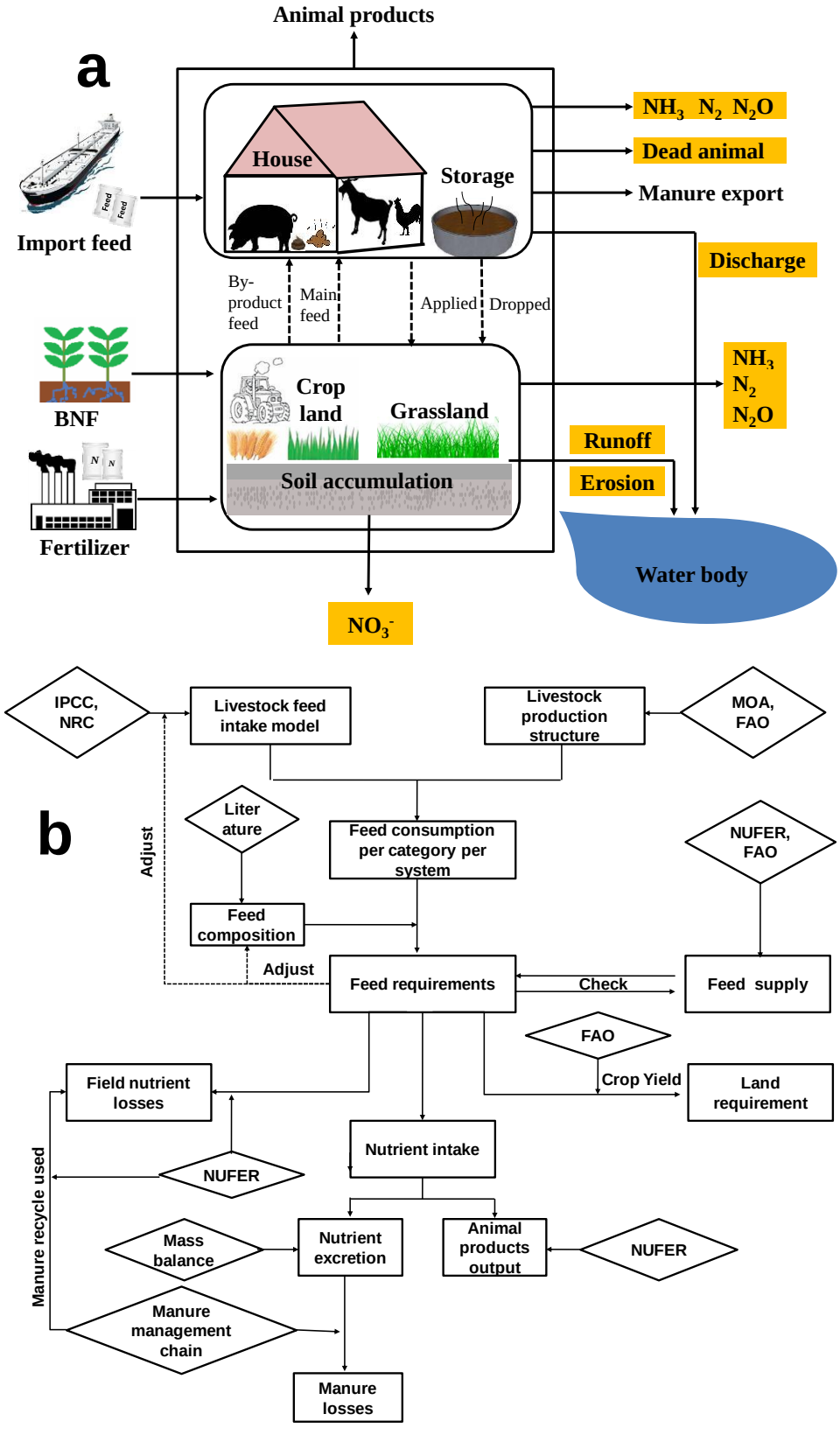

Fig. S7. System boundary and calculation compartment of livestock transition. The system boundary of livestock production in China, showing a livestock production compartment and a feed production compartment (**a**), and a flow chart for estimation of the resources requirement and nutrient losses of livestock production in China (**b**).

Table S1. Animal source food consumption in 2010, and projections of animal source food demand in 2050, according to different literature sources. (kg capita^{-1} year^{-1}).

Animal-Source food	1980	2010	2050				
			Urbanization	GDP	Year	FAO	Average
Pork	12	36	47	46	67	51	53
Chicken meat	1.7	13	19	19	29	35	25
Eggs	2.6	18	28	27	42		33
Beef	0.36	4.9	7.5	7.4	12	7.7	8.6
Mutton	0.45	2.9	4.2	4.1	6.3	5.0	4.9
Milk	3.0	31	85	38	73	56	82*

Projections were based on the correlations between changes in an index and changes in animal source food consumption for the period 1980 to 2010, and projections of these indexes for 2050. Indexes include urbanization, GDP, and historical change. In addition FAO predictions are presented, as well as all indexes. Detailed information can be found in Appendix of the paper.

*Also considered the diet recommendations.

Table S2. List of livestock production related policies and subsidies in China.

	Name of the policy	Description of the policy
Encouraging incentives	Autonomy right of animal production since 1980 (关于加快畜牧业发展的报告)	Allow the production team and private to raise livestock instead of produce in the collative way. The private person who raised animals could receive additional cereals feeds and bonus if the livestock grows well. Allow transportation of livestock between county borders, and abolish the ban of cattle slaughter.
	Free trade and market price of animal products since 1985 (关于进一步活跃农村经济的十项政策)	Change the system of unified and fixed state purchase of agricultural and sideline products policy. And liberate the trade and market price of animal products, which stimulate the livestock production.
	Vegetable Basket from 1988 (菜篮子工程)	The main purpose if this policy is to supply enough vegetables, fruits and animal products to the urban people. Responsible for this policy are city Mayors. This policy differs between regions (cities); the main instrument is subsidies for livestock producers around big cities.
	Abolish meat coupon since 1992 (取消票证制度)	This policy was differed between regions, Shenzhen canceled the meat coupon in early 1984, then Guangdong and Hainan province canceled the policy in 1991. While the official abolish of meat coupon was in 1992 for the whole China.
	Accelerate the livestock production (关于加快畜牧业发展的意见)	Since 2001, promote the collective livestock production and house-hold livestock production, and promote the beef, mutton and chicken meat production.
	Accelerate the modern industrial livestock production (关于推进畜禽现代化养殖方式的指导意见)	Since 2004, subsidies for the industrial livestock production, mainly for pigs and poultry, to accelerate the livestock transition towards to large-scale, standard and industrial livestock production.
Economic incentives (subsidies)	Green Channeling policy (绿色通道)	Since 1995, trucks with fresh food products do not have to pay toll at the highway toll stations. And reduce the time for transportation to avoid of food spoilage.
	Abolish the slaughter and livestock tax since (全面取消牧业和农业税)	The slaughter tax was abolished in 2000, and the livestock tax was abolished in 2005 in the pilot area, and all the agricultural tax was abolished in 2006. In 2000, the slaughter tax and livestock was amount to 3176 million and 272 million RMB.
	Policies for land, water and electricity use (畜牧业农业用地、水和电政策)	Land use is classified to agricultural use, do not need to apply permit for the construction. Livestock producers do not have to pay fees for groundwater, while the price of electricity is 43% cheaper than the commercial electricity price.

	Subsidies for high performance breeds (畜禽良种和冻精补贴)	Since 2005, the central government provided 0.5 -1.3 billion RMB per year for the import of high performance breeds and semen.
	Subsidies for the sows and related insurance (能繁母猪补贴政策)	Since 2007, farmers can get 50 RMB per sow. This subsidies increase to 100 RMB per sow in 2008.
	Farm construction subsidies (标准化养殖场建设补贴)	Since 2007, the government subsidized 10 billion RMB per year to livestock production. In 2008 and 2009, the central government invested 0.2 and 0.5 billion RMB in the modernization of dairy feedlots. Only large size industrial farms can apply for the subsidy.
	Animal epidemic prevention subsidies (畜禽防疫补贴)	Livestock farmers do not have to pay for forced vaccination campaigns. Farms with more than 50 pigs can receive 80 RMB per cadaver for central destruction.
	Subsidies for machinery (畜牧业机械购置补贴政策)	Subsidies for milking machine, manure cleaning machine
	Bonus for the large pig, cattle and sheep production counties (生猪调出大县补贴)	Since 2007, the top 500 pig production and top 100 cattle and sheep production counties receive bonuses with a total value of 3.5 billion RMB per year
Environmental restrict policies	Technical standard of preventing pollution for livestock and breeding (畜禽养殖业污染防治技术规范)	Since 2002, this technical standard define the requirement of location of animal farms, structure of the farms, the type of manure clean technology, manure storage technology, sewage water treatment technology, solid manure recycle technology etc.
	Technical requirement for non-hazardous treatment of animal manure (畜禽粪便无害化处理技术规范)	Since 2006, this technical standard defines the technology for the harmless treatment of solid and liquid manure.
	Technical Specifications for Pollution Treatment Projects of Livestock and Poultry Farms (畜禽养殖业污染治理工程技术规范)	Since 2009, this technical standard defines the requirement for the standard design, construction, check and accept, and operation and maintenance of waste from livestock production. And applied to the new build livestock farms.

Table S3a. Domestic consumption of animal products (in Tg) in 2010 and 2050 (according to the SSP2 scenario), and the import of animal products by China in 2010. For comparison, the total global export of animal products in 2010 is also shown.

Tg	Consumption in 2010	Demand in 2050 (SSP2)	China import	Global export
Pork	50	75	0.9	14
Chicken meat	18	36	1.9	15
Eggs	26	46	0.1	2.4
Beef	6.8	12	0.4	11
Mutton	4.0	6.9	0.1	1.0
Milk	43	116	3.2	104

Table S3b. Domestic production of animal feed (in Tg) in 2010, and the demand for animal feed in 2050 (according to the SSP2 scenario). Also shown are the import of animal feed by China in 2010, and the total global export of animal feed in 2010.

Tg	Production in 2010	Demand in 2050 (SSP2)	China import	Global export
Corn	101	207	6.8	113
Soybean	40	77	57	97
By-products of food processing	234	359		90
Grass	307	454		5.7
Other feeds	985	1097		
Total	1668	2194		

Appendix

Detailed information about the livestock production, feed composition and prediction of future animal products consumption.

Table S4. The egg yield of layers production systems at different growing stages in 1980, 1990, 2000, and 2010. (kg.head^{-1}). (*13*, *47-51*)

		New hen Starter	New hen	Hen	Mother hen
1980	Traditional		2.4	6.0	10.0
	Medium size		2.8	8.0	14.5
	Industrial		11.9	18.0	18.0
1990	Traditional		4.8	7.8	10.0
	Medium size		10.0	16.0	14.5
	Industrial		11.9	18.0	18.0
2000	Traditional		4.8	7.8	10.0
	Medium size		10.6	16.3	14.5
	Industrial		12.0	18.0	18.0
2010	Traditional		3.1	5.1	10.0
	Medium size		6.9	10.6	14.5
	Industrial		12.0	18.0	18.0

Table S5. The LWG and metabolic weight (MW) of broiler production systems at different growing stages in 1980, 1990, 2000, and 2010. (kg head^{-1}). (*13, 52-53*)

			Starter	Grower	Finisher	Mother hen
LWG	1980	Traditional	0.25	0.61	0.79	0
		Medium size	0.29	0.70	0.91	0
		Industrial	0.29	0.69	0.89	0
	1990	Traditional	0.27	0.67	0.86	0
		Medium size	0.35	0.84	1.09	0
		Industrial	0.35	0.75	0.90	0
	2000	Traditional	0.30	0.74	0.96	0
		Medium size	0.34	0.83	1.08	0
		Industrial	0.35	0.75	0.90	0
	2010	Traditional	0.27	0.67	0.86	0
		Medium size	0.31	0.74	0.97	0
		Industrial	0.32	0.68	0.81	0
			Starter	Grower	Finisher	Mother hen
MW	1980	Traditional	0.21	0.64	1.18	0.00
		Medium size	0.23	0.71	1.32	1.93
		Industrial	0.23	0.71	1.30	1.87
	1990	Traditional	0.22	0.69	1.27	0.00
		Medium size	0.27	0.82	1.51	1.93
		Industrial	0.27	0.79	1.39	1.87
	2000	Traditional	0.24	0.74	1.37	0.00
		Medium size	0.27	0.81	1.49	1.93
		Industrial	0.27	0.79	1.39	1.87
	2010	Traditional	0.22	0.69	1.27	0.00
		Medium size	0.24	0.75	1.38	1.93
		Industrial	0.25	0.73	1.28	1.87

Table S6. The LWG and MW of beef and draught, and sheep and goat production systems in 1980, 1990, 2000, and 2010. (kg head^{-1}). (*13*, *54-56*)

			1980	1990	2000	2010
Beef and draught	LWG	Traditional	5.5	20	65	64
		Grassland	7.0	23	75	74
		Industrial	300	35	113	111
	MW	Traditional	106	98	89	81
		Grassland	98	89	81	72
		Industrial	89	81	72	63
			1980	1990	2000	2010
Sheep and goat	LWG	Traditional	4.0	7.5	15	15
		Grassland	6.0	13	24	25
		Industrial	49	18.75	37	38
	MW	Traditional	18.8	17.4	15.9	14.4
		Grassland	17.4	15.9	14.4	12.8
		Industrial	15.9	14.4	12.8	11.2

Table S7. Feed compositions used in layer production systems at different growing stages (%). (*47-50*)

	Traditional			Medium size				Industrial size			
	New hen Starter	New hen	Hen	New hen Starter	New hen	Hen	Breed hen	New hen Starter	New hen	Hen	Breed hen
Corn	5.0	5.0	5.0	28.0	24.0	20.0	17.0	36.0	34.0	34.0	21.0
Soybean	2.0	1.5	1.5	16.0	13.0	9.0	11.0	22.0	22.0	22.0	15.0
Rice	0.7	0.7	0.7	4.1	3.5	2.9	2.5	5.2	4.9	4.9	3.0
Wheat	0.6	0.6	0.6	3.3	2.8	2.4	2.0	4.2	4.0	4.0	2.5
Vegetables	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
By-products	30.0	30.0	30.0	40.0	50.0	60.0	60.0	28.0	30.0	30.0	50.0
Animal product	0.0	0.0	0.0	2.1	0.9	1.1	1.1	2.1	1.1	1.2	1.2
Residue of vegetables	25.0	25.0	25.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
P additives	0.0	0.0	0.0	0.9	1.0	0.9	0.9	1.5	1.5	1.3	1.3
Other	36.7	37.2	27.7	5.6	4.8	3.8	5.6	1.0	2.5	2.6	6.0

Table S8. Feed compositions used in broiler production systems at different growing stages (%). (*51-53*)

	Traditional			Medium size				Industrial size			
	New hen Starter	New hen	Hen	New hen Starter	New hen	Hen	Breed hen	New hen Starter	New hen	Hen	Breed hen
Corn	5.0	5.0	5.0	38.4	30.0	20.8	17.0	40.0	35.0	28.0	21.0
Soybean	3.0	3.0	3.0	19.0	13.0	9.0	8.5	25.0	20.0	19.0	15.0
Rice	0.7	0.7	0.7	5.6	4.3	3.0	2.5	5.8	5.1	4.1	3.0
Wheat	0.6	0.6	0.6	4.5	3.5	2.4	2.0	4.7	4.1	3.3	2.5
Vegetables							0.0				0.0
By-products	30.0	30.0	30.0	25.0	40.0	55.0	60.0	15.0	30.0	40.0	50.0
Animal product	0.0	0.0	0.0	1.9	1.1	1.0	1.1	2.0	1.4	1.1	1.2
Residue of vegetables	20.0	20.0	20.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
P additives	0.0	0.0	0.0	2.2	1.0	1.0	0.9	1.5	1.3	1.1	1.3
Other	40.7	40.7	40.7	3.4	7.0	7.7	8.1	6.0	3.1	3.4	6.0

Table S9. Feed compositions used in beef and draught production systems and sheep and goat production systems (%). (*54-65*)

	Beef and draught cattle			Sheep and goat		
	Traditional	Grassland	Industrial	Traditional	Grassland	Industrial
Corn	0.8	0.0	17.7	1.9	0.0	9.5
Soybean	0.3	0.0	5.9	0.5	0.0	4.8
Rice	0.1	0.0	2.6	0.3	0.0	1.4
Wheat	0.1	0.0	2.1	0.2	0.0	1.1
Vegetables	0.0	0.0	0.0	0.0	0.0	0.0
By-products	2.6	0.0	9.4	4.8	0.0	9.5
Straw	18.4	0.0	5.9	14.3	0.0	4.8
Grass	15.8	100	40.1	14.3	100	52.3
Tubers	10.5	0.0	0.0	0.0	0.0	0.0
Animal product	0.0	0.0	0.0	0.0	0.0	0.0
Kitchen waste	0.0	0.0	0.0	0.0	0.0	0.0
Leafs and green straw	23.7	0.0	0.0	4.8	0.0	0.0
Residue of vegetables	18.4	0.0	0.0	4.8	0.0	0.0
P additives	0.0	0.0	0.0	0.0	0.0	0.0
Other	9.2	0.0	16.4	54.4	0.0	16.6

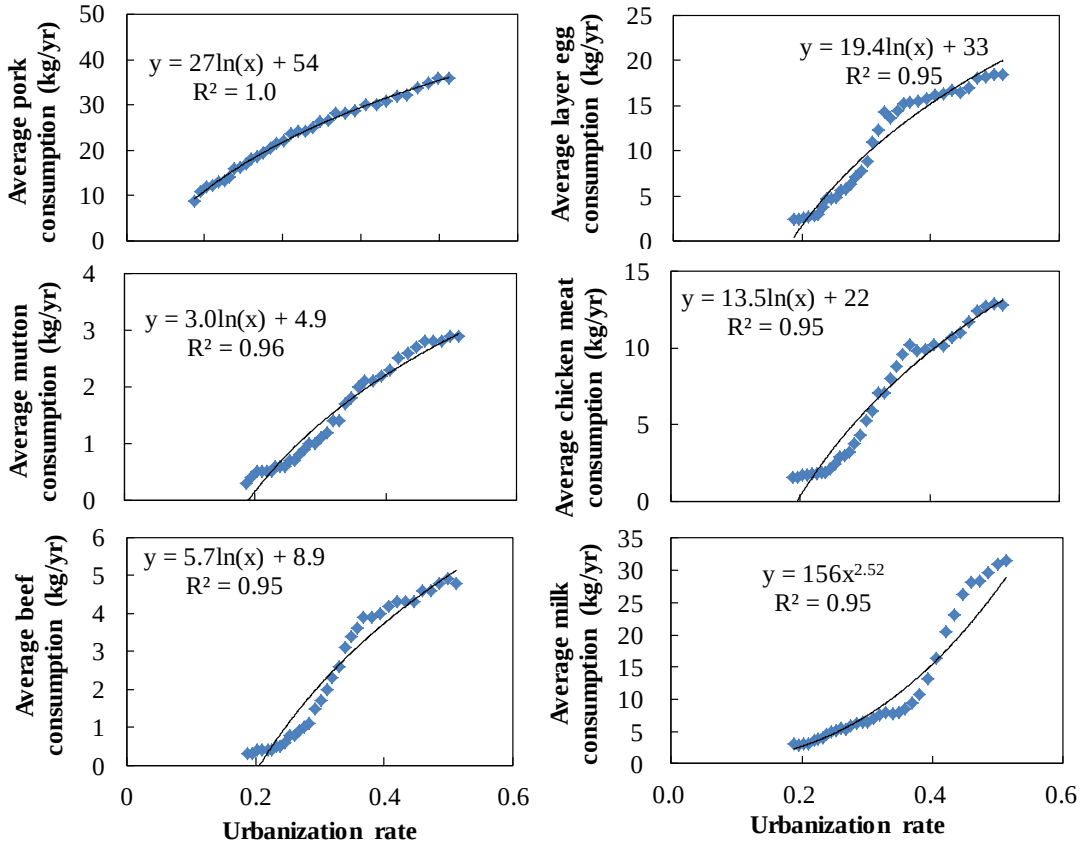

Fig. S8. Relationships between urbanization and livestock product consumption per capita in China. (*13*)

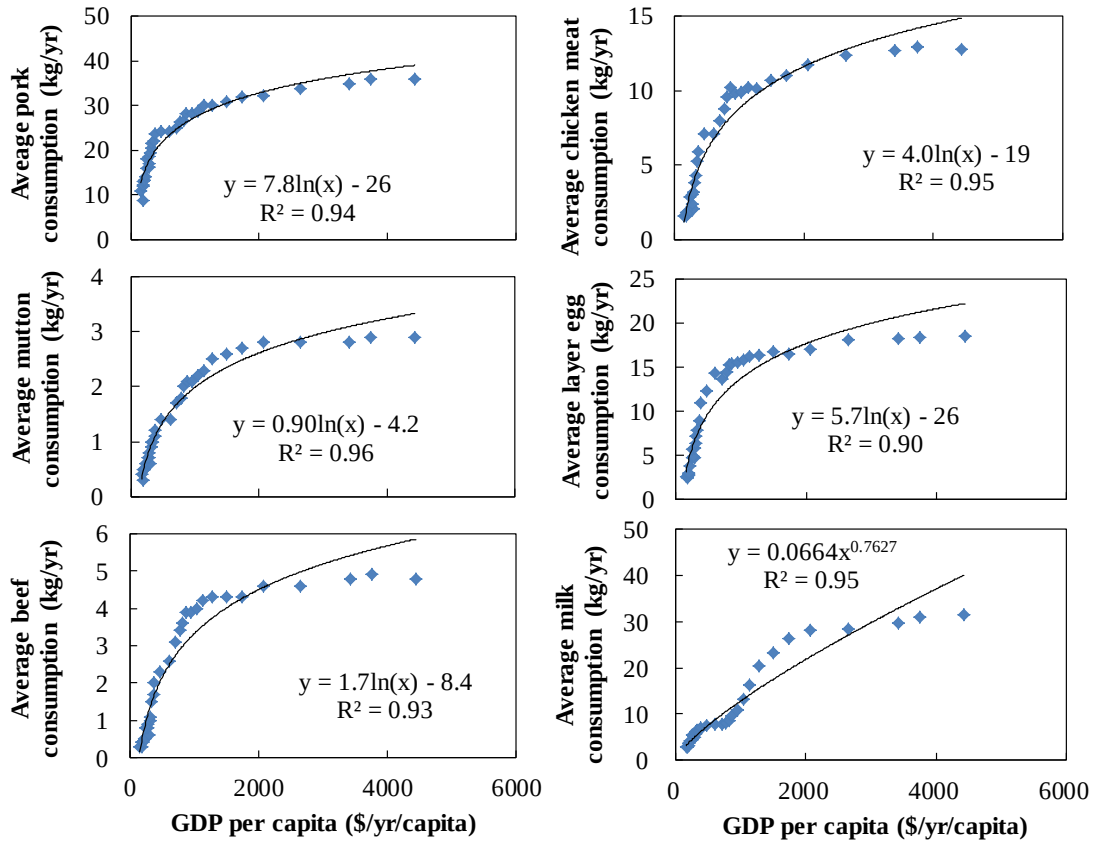

Fig. S9. Relationship between per capita GDP and livestock product consumption per capita in China. (*13*)

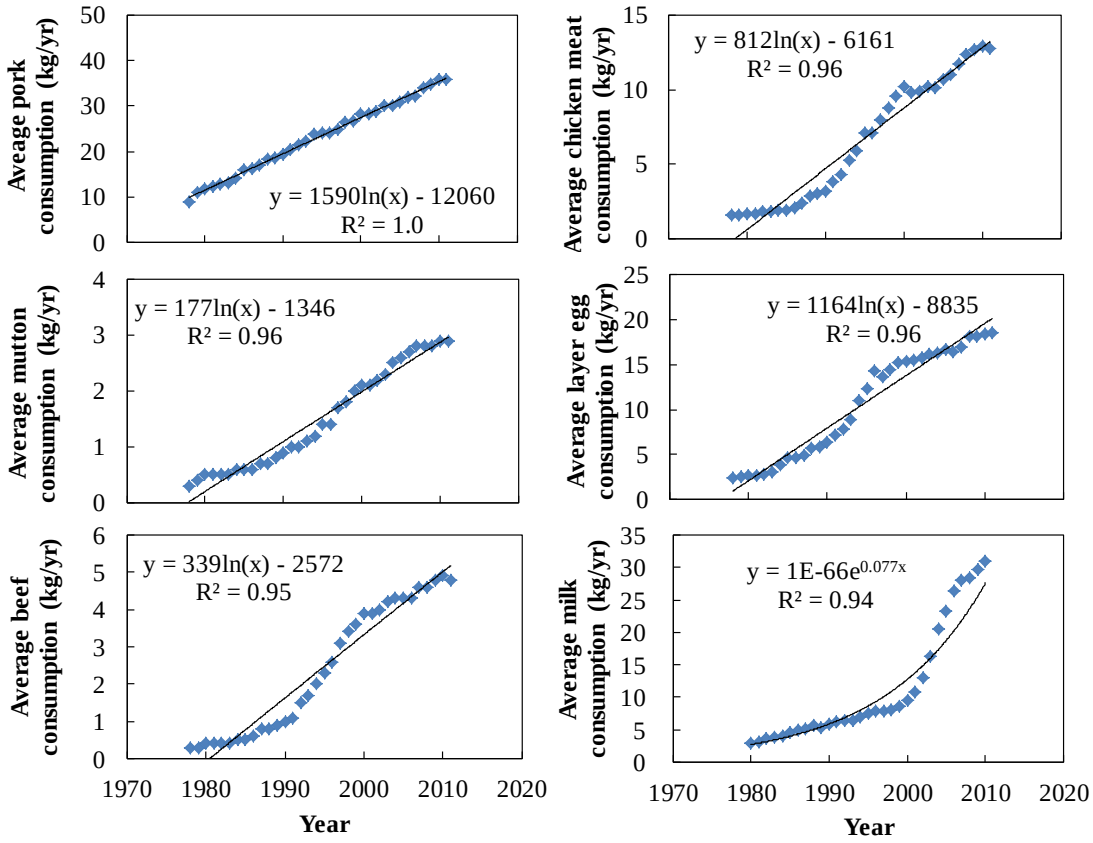

Fig. S10. Changes over time in livestock product consumption per capita in China. (*13*)