SUPPLEMENTARY DATA
Embodied crop calories in animal products

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Supplementary Text

Text S1. Data harmonization and aggregation

Normally data on feed, crop production and animal production are provided in mass units (see Table 1 main text). For example, FAOSTAT provides data on country-wise animal products production and feed in ton/yr (FAO 2012) and the Global Agro-ecological Zones (GAEZv3.0) provides downscaled data on crop yield for the year 2000 in ton/ha (IIASA/FAO 2012). Using nutritive factors (nf^i, i: the item representing crop or animal product for all of the equations below) from FAO (2001), we converted the data from mass units into calorie units to be able to compare and aggregate these values (see Table S1). We derived the country-wise feed calories (FC_c, c: the country for all of the equations below) based on the FAOSTAT Commodity Balances (FAO 2012). The Commodity Balances present balances of food and agricultural products in the eleven categories: Production Quantity, Import Quantity, Stock Variation, Export Quantity, Domestic supply quantity, Feed, Seed, Waste, Processed, Food and Other Util. The data cover 175 countries for the year 2000. Except for sugar, oils and beverages, the products are listed in their primary equivalents. For examples, soybeans is reported separately for soybeans, soybeans oil and soybeans cakes, whereas, wheat is reported only in terms of wheat equivalent. We used 57 different crop products for which their use as feed is reported to estimate the country-wise feed calories. The crop products include both primary products (e.g. grains) and processed products (e.g. oil cakes). Similarly, we also estimated the country-wise crop mass used as feed (FM_c) aggregating the mass of all the crop products (FAO 2012) weighted respectively for their dry weight and fresh weight (IIASA/FAO 2012).

We calculated the livestock-wise animal calories produced (AP_c^l, l: the livestock type for all of the equations below) on a country scale using the FAOSTAT Livestock Primary Production (FAO 2012) as presented respectively in equation 1 and 2. The production data provides information on the amount of meat, milk and/or eggs produced by country and by livestock types ($AP_c^{(l,i)}$) in tonnes. Since the data on livestock densities is available for six livestock types (Wint & Robinson 2007), we only considered animal calories provided by these livestock types. We use the livestock densities data which are adjusted for the year 2000. The six livestock types, with their associated animal products are: cattle, buffaloes, goats, and sheep, which all provide both milk and meat; pigs which provide meat only and poultry which provide meat and eggs.

$$AP_c = \sum_{l=1}^{n=6} AP_c^l \tag{1}$$

$$AP_c^l = \sum_{i=1}^{n} \left(nf^i \times AP_c^{(l,i)}\right) \tag{2}$$

Gridded total crop calorie production (CP_k, k: the raster cell for all of the equations below) was calculated according to equation 3 below using downscaled data on actual crop yields (cy_k) and area harvested (ha_k) from the GAEZv3.0 (IIASA/FAO 2012) for the year 2000. The GAEZv3.0 estimated crop yields and area harvested on a grid for the year 2000 based on agricultural production statistics from the FAO. The data on crop yields and area harvested are available for 23 major commodities both for rain-fed and irrigated conditions. We considered 19 crop types provided by the GAEZv3.0 excluding non-food crop (e.g. cotton and fodder), stimulant cash crops (e.g. tea, coffee and cacao) and crop commodities under residual section for this analysis. These 19 crop types account for more than 90% of the global crop calories produced in 2000. The global crop calories was estimated using production data reported for 52 different crops in the FAOSTAT Food Balance Sheets (FAO 2012).

$$CP_k = \sum_{i=1}^{n} \left(nf^i \times cy_k^i \times ha_k^i\right) \tag{3}$$

Text S2. Downscaling country data to the 5' grid

Text S2.1. Total production of animal calories

Downscaling of total animal calorie production for the year 2000 to a grid was done based on an adapted methodology reported in FAO (2011*a*) using data on gridded livestock densities and livestock-wise animal calorie production on a country scale. Initially, we derived gridded livestock counts based on gridded livestock densities. We calculated livestock-wise animal calories produced (AP_c^l) on a country scale using the FAOSTAT Livestock Primary Production (FAO 2012) for the year 2000 (see Text S1). We proportionally distributed the livestock-wise calorie production (AP_c^l) of the year 2000 at a country scale across country grids based on livestock counts on the grid (N_k^l) and the country (N_c^l). Finally, summing up calorie produced by the six livestock types on the grid provided the total grid livestock calorie production (AP_k) as presented by equation 4.

$$AP_k = \sum_{l=1}^{n=6} \left(\frac{N_k^l}{N_c^l} \times AP_c^l\right) \tag{4}$$

Text S2.2. Feed calories

Downscaling of country feed calories for the year 2000 to a grid was done in three steps. First, we estimated country-wise feed requirements calculating the feed required per grid cell for each livestock types. Then, we aggregated the gridded feed requirements into two categories: ruminant feed requirements (FR_k^r), and non-ruminant feed requirements (FR_k^{nr}). We considered that non-ruminants are fed on feed whereas ruminants graze in pastures in addition to consuming fodder, forage and/or crop residues (non-crop feed) for rangeland. For non-rangeland, crop products were assumed to be fed to ruminants only when the produced non-crop feed on the grid (symbolized as G_k) was not enough to meet their feed requirements. Using the M3-crop data (Monfreda et al. 2008), we estimated fodder and forage production on a grid. Similarly, crop residues for livestock on a grid was calculated adapting the approach described by Haberl et al. (2007) and based on GAEZv3.0 crop production data (IIASA/FAO 2012). However for non-ruminants, crop products were used as feed regardless of the livestock production systems. Using above assumptions, we estimated the feed requirements for ruminants and non-ruminants on a country scale (FR_c^r and FR_c^{nr} respectively) in ton/yr as presented by equation 5 and 6.

$$FR_c^{nr} = \sum_{k \in c} FR_k^{nr} \tag{5}$$

$$FR_c^r = \sum_{k \in c} (FR_k^r - G_k) \text{ if } G_k < FR_k^r \ \& \ \text{ LPS} \neq \text{rangeland} \tag{6}$$

In the second step, we distributed the derived data on country feed calories (FC_c) from FAOSTAT (FAO 2012) to feed calories for ruminants and non-ruminants based two approaches (I and II). In approach I, we considered whether the total crop mass used as feed in a country (FM_c) is enough to meet the requirement for non-ruminants (FR_c^{nr}). If FM_c is greater than FR_c^{nr}, we divided FC_c into the country feed calories for ruminants (FC_c^r) and non-ruminants (FC_c^{nr}) as presented by equation 7 and 8. However, if FM_c is less than or equal to FR_c^{nr}, FC_c was allocated only to non-ruminants in the country assuming that the ruminants are fed only by fodder and forage. In approach II, we proportionally distributed FC_c into FC_c^{nr} and FC_c^r based on FR_c^{nr} and FR_c^r respectively.

$$FC_c^{nr} = \begin{cases} FC_c \times \dfrac{FR_c^{nr}}{FM_c} & \text{if } \ FM_c > FR_c^{nr} \\ FC_c & \text{if } \ FM_c \leq FR_c^{nr} \end{cases} \tag{7}$$

$$FC_c^{r} = \begin{cases} FC_c \times \dfrac{FM_c - FR_c^{nr}}{FM_c} & \text{if } \ FM_c > FR_c^{nr} \\ 0 & \text{if } \ FM_c \leq FR_c^{nr} \end{cases} \tag{8}$$

In the third and final step, we disaggregated FC_c^r and FC_c^{nr} into grids to obtain data on gridded feed calories based on FR_k^{nr}, FR_c^{nr}, FR_k^r, G_k and FC_c^r as represented by equation 9 and equation 10.

$$FC_k^{nr} = FC_c^{nr} \times \frac{FR_k^{nr}}{FR_c^{nr}} \tag{9}$$

$$FC_k^{r} = \begin{cases} 0 & \text{if LPS = rangeland} \\ 0 & \text{if } G_k \geq FR_k^r \\ FC_c^r \times \dfrac{FR_k^r - G_k}{FR_c^r} & \text{if } G_k < FR_k^r \ \ \& \ \ \text{LPS} \neq \text{rangeland} \end{cases} \tag{10}$$

Text S3. Projection of Feed demand

We derived country scale total animal calorie production (AP_c), animal calorie production (AP'_c) from the six livestock types, animal calories consumed by humans (AC_c) and feed calories (FC_c) for the year 2000 based on the FAOSTAT (FAO 2012). We estimated AP_c using country-wise production data reported for 24 different animal products including marine and aquatic products in the FAOSTAT Food Balance Sheets (FAO 2012). AP'_c was calculated summing up the livestock-wise animal calories produced (AP_c^l) on a country scale (see Text S1) for the six livestock types. On global scale, AP' contributes more than 70% of AP, whereas marine and aquatic products share 13%, animal fats and offals 10% and rest come from other livestock types (FAO 2012). Similarly, AC_c was estimated using data on country scale population and per capita animal product intake from the FAOSTAT Food Balance Sheets (FAO 2012). For, country-wise feed calories (FC_c) see Text S1. All these data cover 175 countries for the year 2000.

We projected the future total animal calorie production AP_c and feed calorie demand FC_c by country based on their relationships with AC_c and AP'_c respectively, as presented by equations 11–14. The future values of the parameters, intercept n^y (y: the year for all of the equations below) and slope m^y, were estimated applying linear extrapolation based on observations over the last decades showing a linear increase in n and linear decrease in m (see Figure 1a′ and 1b′ main text). To take into account country-wise variations from the global linear relation, we also considered residuals ($\varepsilon_{(1,c)}$ and $\varepsilon_{(2,c)}$) for each country. Additionally, we assumed that on a country scale, the share of AP'_c in AP_c will remain constant at the country mean value (f_c) from 1961 to 2007 (see equation 14). Equation 11 is able to reconstruct the past country animal calorie production trends for more than 85% of the countries within the mean absolute error (MEA) as fraction of actual value of 20% (see Figure S5 for some country examples). In contrast, equation 12 is able to reconstruct the past country feed trends only for around 60% of the countries within a MEA as fraction of actual value of 30%. This motivated us also to consider the values of the parameters, n_2 and m_2, based on the observed relation for the recent year i.e. 2007 (see equation 13). Such a method is also used for other studies (e.g. Popp et al. (2011)). Equation 13 that does not consider changes in the parameters across time provided a similar reconstruction error as equation 12. In other words, equation 12 takes into account the future changes in feed conversion efficiency based on the past global trends, whereas, equation 13 keeps it constant.

$$\log(AP_c^y) = m_1^y \times \log(AC_c^y) + n_1^y + \varepsilon_{(1,c)} \tag{11}$$

$$\log(FC_c^y) = m_2^y \times \log(AP_c'^y) + n_2^y + \varepsilon_{(2,c)} \tag{12}$$

$$\log(FC_c^y) = m_2 \times \log(AP_c'^y) + n_2 + \varepsilon_{(2,c)} \tag{13}$$

$$AP_c' = f_c \times AP_c \tag{14}$$

We defined three scenarios to project the feed demand. Scenario A only considers population change for countries based on the mid-range population scenario from United Nations (2011) with the same dietary pattern as in the year 2000. In this baseline scenario, we considered no changes in feed conversion efficiency and thus used equation 13 for estimating the future feed demand. Scenario B takes into account country specific changes in dietary patterns as provided by Pradhan et al. (2013) in addition to population change. However, feed conversion efficiency remains constant. This is an upper bound scenario that considers changes in diet and population but not efficiency. Scenario C represents changes in feed conversion efficiency based on the extrapolated values of n_2^y and m_2^y together with changes in population and dietary patterns as scenario B. Therefore, we used equation 12 to estimate the future feed demand in this scenario resulting in a mid-range scenario. After obtaining country-wise feed demand for all the three scenarios, we proportionally distributed the projected feed calories across the country grids based on grid values for the year 2000.

References

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Supplementary Figures

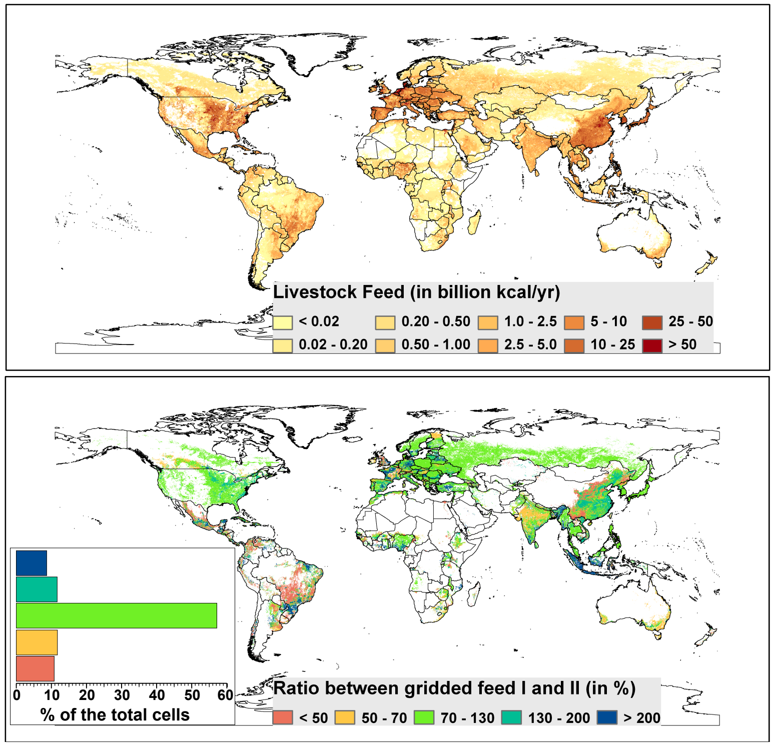

Figure S1. Gridded map showing crop production consumed as livestock feed (FC_k) in billions kcal/yr based on approach II (top) comparing it with the map obtained based on approach I (bottom). Inset presents statistics for ratio between the downscale results obtained from approach I and II for the cells with the feed value larger than 0.2 billion kcal/yr.

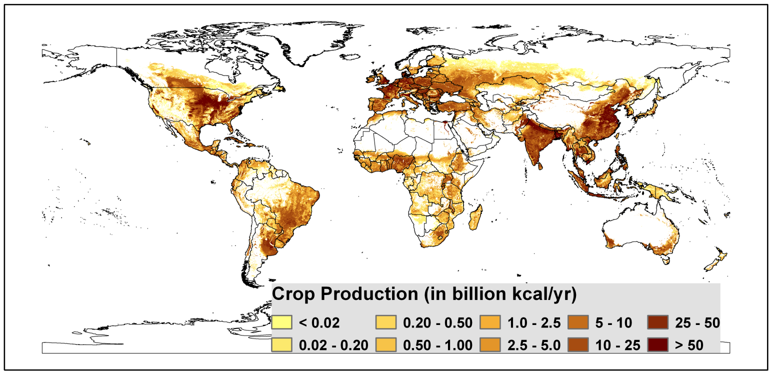

Figure S2. Gridded map of in crop calorie production (CP_k) in billions kcal/yr.

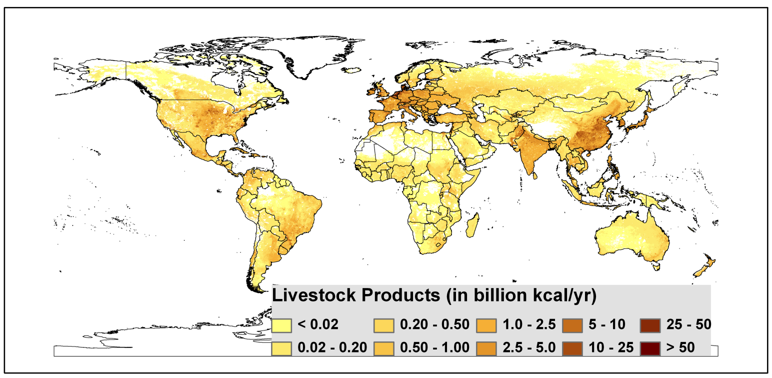

Figure S3. Gridded map of animal calorie production (AP_k) in billions kcal/yr.

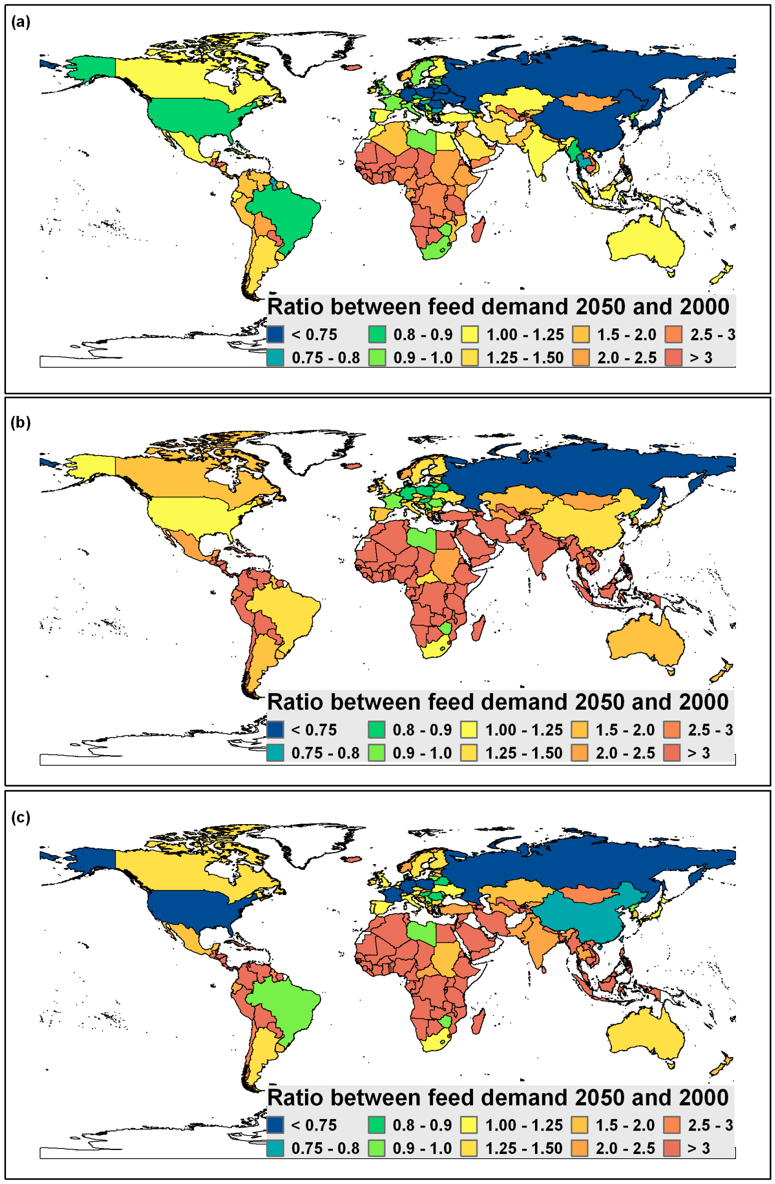

Figure S4. Map of the ratio between the projected feed demand for 2050 and the feed consumed in 2000 for three scenarios. (a) without dietary pattern changes but with population changes (scenario A), (b) with dietary pattern and population changes (scenario B) and (c) with dietary pattern, population and feed conversion efficiency changes (scenario C).

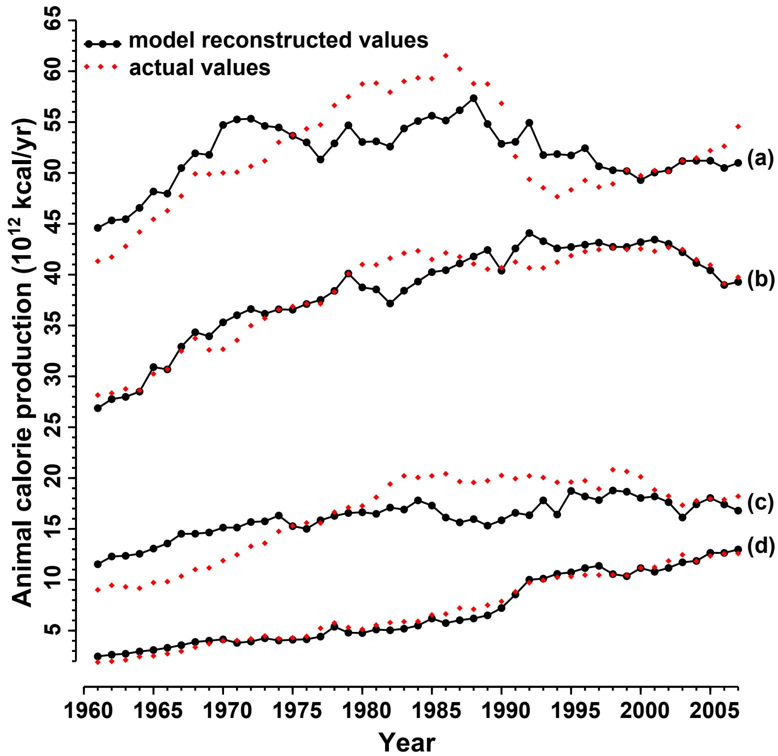

Figure S5. Comparison between country animal calories production trends with reconstructed trends using the global linear regression model: (a) Germany, (b) France, (c) Netherlands and (d) Thailand. Germany and Netherlands are examples of the countries for which reconstructed trends varies the observed one, whereas, France and Thailand are examples of the countries for which the model was almost able to reconstruct the observed trends.

Supplementary Tables

Table S1: List of nutritive factor (nf^i) and conversion factor from fresh weight to dry weight for crop products. The nutritive factors are obtained from FAO (2001) and the conversion factors are adapted from IIASA/FAO (2012).

Crop Product	Nutritive factor (nf^i) (kcal/100gm)	Conversion factor
Apples	48	0.15
Bananas	60	0.35
Barley	332	0.88
Beans	341	1
Brans	244.5	0.9
Cassava	212	0.35
Cereals, Other	340	0.88
Cocoa Beans	414	0.5
Coconuts - Incl Copra	636	0.175
Copra Cake	636	0.9
Cottonseed	253	0.9
Cottonseed Cake	253	0.9
Dates	156	0.15
Fruits, Other	45	0.15
Grapes	53	0.15
Groundnut Cake	363	0.67
Groundnuts (Shelled Eq)	567	0.67
Maize	356	0.87
Millet	340	0.888
Molasses	232	0.8
Oats	385	0.888
Oilcrops Oil, Other	884	1
Oilcrops, Other	387	0.9
Oilseed Cakes, Other	261	0.9
Olive Oil	884	1
Onions	31	0.15
Oranges, Mandarines	34	0.15
Palmkernel Cake	261	0.9
Palmkernels	514	0.9
Peas	346	1
Plantains	75	0.35
Potatoes	67	0.25

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Table S1 – continued from previous page

Crop Product	Nutritive factor (nf^i) (kcal/100gm)	Conversion factor
Pulses, Other	340	1
Rape and Mustard Cake	376	0.9
Rape and Mustard Oil	884	1
Rape and Mustardseed	494	0.9
Rice (Milled Equivalent)	0	0.9
Roots, Other	91	0.3
Rye	319	0.888
Sesameseed	573	0.9
Sesameseed Cake	376	0.9
Sorghum	343	0.88
Soyabean Cake	261	0.9
Soyabean Oil	884	1
Soyabeans	335	0.9
Sugar (Raw Equivalent)	373	1
Sugar Beet	70	0.14
Sugar Cane	30	0.1
Sugar, Non-Centrifugal	351	1
Sunflowerseed	308	0.9
Sunflowerseed Cake	376	0.9
Sweet Potatoes	92	0.3
Sweeteners, Other	310	0.12
Tomatoes	17	0.15
Vegetables, Other	22	0.15
Wheat	334	0.875
Yams	101	0.35

References

FAO 2001 *Food balance sheets: A handbook* FAO Rome.

IIASA/FAO 2012 *Global Agro-ecological Zones (GAEZ v3.0)* IIASA and FAO Laxenburg and Rome.