Embodied crop calories in animal products

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Abstract

Increases in animal products consumption and the associated environmental consequences have been a matter of scientific debate for decades. Consequences of such increases include rises in greenhouse gas emissions, growth of consumptive water use, and perturbation of global nutrients cycles. These consequences vary spatially depending on livestock types, their densities and their production sy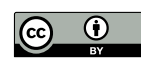stem. In this letter, we investigate the spatial distribution of embodied crop calories in animal products. On a global scale, about 40% of the global crop calories are used as livestock feed (we refer to this ratio as *crop balance for livestock*) and about 4 kcal of crop products are used to generate 1 kcal of animal products (*embodied crop calories* of around 4). However, these values vary greatly around the world. In some regions, more than 100% of the crops produced is required to feed livestock requiring national or international trade to meet the deficit in livestock feed. Embodied crop calories vary between less than 1 for 20% of the livestock raising areas worldwide and greater than 10 for another 20% of the regions. Low values of embodied crop calories are related to production systems for ruminants based on fodder and forage, while large values are usually associated with production systems for non-ruminants fed on crop products. Additionally, we project the future feed demand considering three scenarios: (a) population growth, (b) population growth and changes in human dietary patterns and (c) changes in population, dietary patterns and feed conversion efficiency. When considering dietary changes, we project the global feed demand to be almost doubled (1.8–2.3 times) by 2050 compared to 2000, which would force us to produce almost equal or even more crops to raise our livestock than to directly nourish ourselves in the future. Feed demand is expected to increase over proportionally in Africa, South-Eastern Asia and Southern Asia, putting additional stress on these regions.

1. Introduction

Globally, human diets are changing in terms of the amount and composition of food (Alexandratos 2006, Kearney 2010).

Most of the changes are towards higher calorie dietary patterns consisting of a larger share of animal products, vegetable oils, and sugar and sweeteners (Pradhan *et al* 2013). Dietary patterns play an important role in shaping various aspects of the agricultural sector. An increase in intake of animal products exacerbates environmental consequences induced by agriculture (Steinfeld *et al* 2006). For example, it leads to increases in agricultural greenhouse gas (GHG) emissions (Eshel and Martin 2006, Reay *et al* 2012) and

Table 1. List of data used for the study.

Data	Resolution	Unit	Source
Food supply	Country	kcal/cap/day	FAO (2012)
Feed use	Country	ton yr^{-1}	FAO (2012)
Animal products	Country	ton yr^{-1}	FAO (2012)
Population projection	Country	count	United Nations (2011)
Dietary patterns projection	Country	kcal/cap/day	Pradhan *et al* (2013)
Livestock feed requirement	Region	DM kg/head/day	Haberl *et al* (2007)
Crop yield	5′	ton ha^{-1}	IIASA/FAO (2012)
Crop harvest area	5′	ha^{-1}	IIASA/FAO (2012)
Fodder yield	5′	ton ha^{-1}	Monfreda *et al* (2008)
Fodder harvest area	5′	ha^{-1}	Monfreda *et al* (2008)
Livestock density	3′	counts km^{-2}	Wint and Robinson (2007)
Livestock production system	3′	—	Robinson *et al* (2011)
Nutritive factors	Items	kcal/100 g	FAO (2001)

growth in demand for anthropogenic inputs such as fertilizer (Metson *et al* 2012). The livestock sector uses about 26% of global land area directly as pastures and meadows (FAO 2012). Livestock is a major emitter of GHGs, e.g. CH$_4$ emission from enteric fermentation accounts for 32% of the total agricultural non-CO$_2$ GHG emissions in 2005 (Metz *et al* 2007). However, the livestock sector plays an important role in global food security (Wint and Robinson 2007) and livelihood conditions as animal products provide high-quality protein to consumers. Livestock generates regular income, draft animal power and manure for producers and plays critical role as an asset depending on the livestock production system (FAO 2011b).

The total global crop calorie demand, including the demand for humans and livestock, is projected to double by 2050 compared to 2005 as per capita crop calorie demands will likely increase with per capita income (Tilman *et al* 2011). Meeting this projected dietary change would aggravate agriculture induced environmental impacts. For example, expected higher calorie dietary patterns by 2050 would increase agricultural GHG emissions by more than 60% compared to 1995 (Popp *et al* 2011) and demand more than 1.8 times the present agricultural water use (Hanjra and Qureshi 2010). This also leads to a large increase in major fluxes of the nitrogen cycle (Smil 2002, Bodirsky *et al* 2012), for which we have already transgressed the planetary boundary (Rockström *et al* 2009). The livestock sector will increasingly play a major role in contributing agricultural GHG emissions (Pradhan *et al* 2013) and in perturbation of global nutrients cycles (Bouwman *et al* 2011). However, the crop demand and the environmental impacts vary spatially. Although human attribution of net primary production is 22% on a global scale, it exceeds 90% in some regions worldwide (Imhoff *et al* 2004, Haberl *et al* 2007). Similarly, spatial distribution of different types of livestock vary based on various social, cultural and economic factors (Wint and Robinson 2007). Climatic factors and the mode of agricultural practices influence the geography of livestock production systems (Robinson *et al* 2011, IPCC 2006). Subsequently, we observe geographical variation in animal product production (FAO 2011a) and livestock influences on local nutrient fluxes (Potter *et al* 2010).

Hence, the overarching goal of this study is to investigate the spatial distribution of embodied crop calories in animal products and to project the future feed demand. This involves three main steps. First we downscale country scale feed data (FAO 2012) into a raster grid of five arc-minutes (5′) resolution using data on livestock densities and their production systems (Wint and Robinson 2007, Robinson *et al* 2011). For this study, we defined feed explicitly as the crop products supplied to raise livestock, however, the total feed mix might consist of crop products, crop residues, fodder and forage (non-crop feed). Second, we compare derived gridded feed data with gridded data on the production of crop and animal calories to understand the spatial distribution of crop balance for livestock and embodied crop calories in animal products. We define the crop balance for livestock as the ratio between feed calories used and crop calories produced, and the embodied crop calories as the ratio between feed calories used and animal calories produced. Finally, we estimate the future feed demand considering three scenarios: (a) assuming diets would remain as they were in the year 2000 but the population growth according to United Nations (2011), (b) dietary changes as projected by Pradhan *et al* (2013), with the same population growth considerations and (c) changes in population, dietary patterns and feed conversion efficiency.

2. Materials and methods

2.1. Data harmonization and aggregation

Table 1 presents the overview of data used for this study. Data for feed, crop production and animal production are normally provided in mass units. Using nutritive factors from FAO (2001), we converted the data from mass units into calorie units to be able to compare and aggregate these values (see text S1 and table S1 available at stacks.iop.org/ ERL/8/044044/mmedia). We derived the country-wise crop calories and crop mass used as feed based on the FAOSTAT Commodity Balances (FAO 2012). Similarly, we calculated livestock-wise animal calories produced on a country using the FAOSTAT Livestock Primary Production (FAO 2012). Since the data on livestock densities adjusted for the year

2000 is available for six livestock types (Wint and Robinson 2007), we only considered animal calories provided by these livestock types. 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.

Gridded total crop calorie production was calculated using downscaled data on crop yields and area harvested from the GAEZv3.0 (IIASA/FAO 2012) for the year 2000 (see text S1 available at stacks.iop.org/ERL/8/044044/mmedia). 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. These 19 crop types account for more than 90% of the global crop calories produced in 2000 (FAO 2012). Gridded livestock density data (Wint and Robinson 2007) and gridded livestock production system data (Robinson *et al* 2011) on 3′ resolution were harmonized to the 5′ resolution of the crop data with the *Bilinear Resampling Technique* in ArcMap 10.

2.2. Downscaling country data to the 5′ grid

We obtained the total animal calorie production for the year 2000 to a grid by adapting methodology reported in FAO (2011a) (see text S2.1 available at stacks.iop.org/ERL/8/044044/mmedia). We proportionally distributed livestock-wise calorie production based on gridded livestock density data.

Downscaling of country-wise feed calories for the year 2000 to a grid was done in three steps (see text S2.2 available at stacks.iop.org/ERL/8/044044/mmedia). First, we estimated country-wise feed requirements. We calculated feed required per grid cell for each livestock types in ton per year multiplying regional and livestock-wise daily feed requirements (Haberl *et al* 2007) with the gridded livestock counts. Then, we aggregated the gridded feed requirements into two categories: ruminant feed requirements for cattle, buffaloes, goats, and sheep, and non-ruminant feed requirements for pigs and poultry. Depending on the livestock production system (LPS), the feed requirements are met by a mix of fodder, forage, crop residues and crop products. To simplify the analysis, we grouped the 14 LPSs provided by Robinson *et al* (2011) into two categories: rangeland consists of rangeland-based LPSs and non-rangeland consists of mixed rain-fed and irrigated LPSs including classes urban and other. Adapting the methods of European Commission (2009), we considered that non-ruminants are provided with feed whereas ruminants graze in pastures in addition to consuming non-crop feed (e.g. fodder, forage and/or crop residues) for rangeland LPS. For non-rangeland, crop products were assumed to be fed to ruminants only when the produced non-crop feed on the grid was not enough to meet their feed requirements. However for non-ruminants, crop products were used as feed regardless of the LPSs.

In the second step, we distributed the derived data on country feed calories from FAOSTAT (FAO 2012) to ruminants and non-ruminants. Since FAOSTAT does not distinguish feed share for ruminants and non-ruminants, we used two approaches (I and II) for this (see text S2.2 available at stacks.iop.org/ERL/8/044044/mmedia). In approach I, we prioritized non-ruminants for obtaining feed calories because globally around 80% of the total livestock feed is supplied to non-ruminants (Erb *et al* 2012). This is a close to reality approach that provides a low bound for ruminant feed calories but a high bound for non-ruminants. For this, we first allocated the country feed calories to non-ruminants based on the crop mass used as feed and the non-ruminant feed requirement. Then the remaining feed calories were assigned to ruminants if the crop mass used as feed is larger than the non-ruminant feed requirement. But if that is not the case, we assumed that ruminants are supplied only with non-crop feed. However, farming systems exist around the world where similar amount of feed is used for ruminants and non-ruminants, e.g. in Denmark (Dalgaard *et al* 2006). Taking this into account, we assumed a second approach. In approach II, we proportionally distributed country feed calories to non-ruminants and ruminants based on their respective feed requirements. We considered this as an extreme case that provides a high bound for ruminant feed calories but a low bound for non-ruminants.

In the third and final step, we disaggregated the country scale ruminant and non-ruminant feed calories into grids to obtain gridded feed calories (see text S2.2 available at stacks.iop.org/ERL/8/044044/mmedia). For this, we proportionally distributed the country scale non-ruminant feed calories across the country grids based on the grid and the country scale non-ruminant feed requirements. In case of ruminants, we estimated the crop products required as feed on a grid based on the difference between the ruminant feed requirement and the production of non-crop feed. Afterwards, we proportionally distributed the ruminant feed calories based on the difference, assuming that ruminants are fed only on non-crop feed in rangeland and in the grids where enough non-crop feed are produced to meet the requirements. Finally, we obtained the grid feed by summing up ruminants and non-ruminants feed calories.

2.3. Projection of feed demand

We assumed that the demand for animal calories drives their production and that the production drives feed demand. Country-wise total animal calorie production (AP) and animal calories consumed by humans (AC) demonstrate a linear relation in a log–log plot (figure 1(a)). Additionally, country scale animal calorie production (AP′) from the six livestock types and feed calories (FC) demonstrate a similar relation (figure 1(b)). We derived AP, AP′, AC and FC from the FAOSTAT (FAO 2012) (see text S3 available at stacks.iop.org/ERL/8/044044/mmedia). The parameters, slope (*m*) and intercept (*n*), of these relations changed across time showing a complex behavior (figures 1(a′) and (b′)). We simplified the complex behavior to linear trends in the parameters overtime based on observation over the last decades showing a linear increase in *n* and decrease in *m*. Biases for these fits are discussed in text S3 (available at stacks.iop.org/ERL/8/
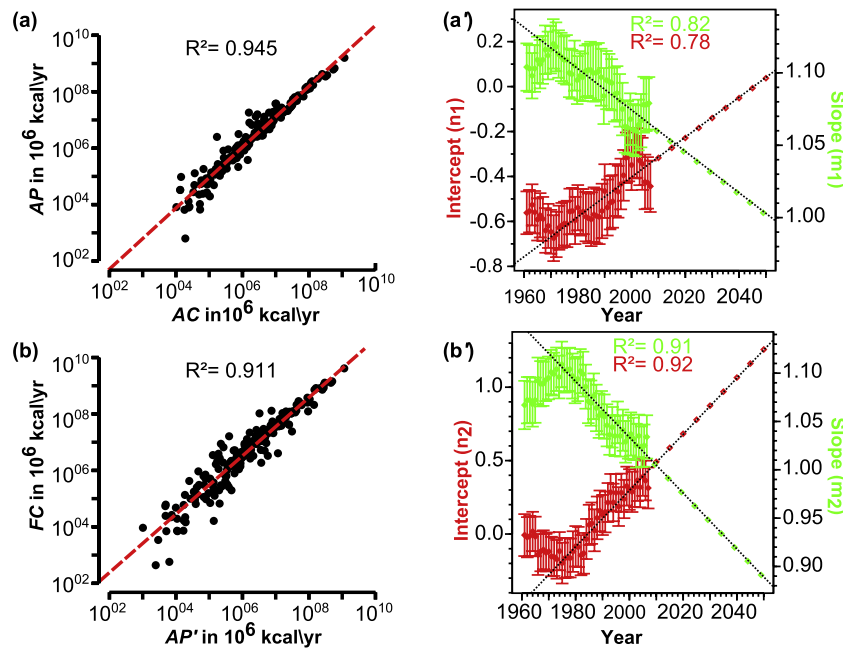
Figure 1. Relations among animal calorie consumed, animal calorie produced and feed used, and trends of slope (*m*) and intercept (*n*) observed between 1961 and 2007. (a) Correlation between country-wise animal calorie consumed (AC) and produced (AP—total animal calories) for 2007 on a log–log plot. (b) Correlation between country-wise animal calorie produced (AP′—animal calories obtained from the six livestock species) and crop calories used as feed (FC) for 2007 on a log–log plot. The red dashed lines show their linear relations. Trends of slope (*m*) and intercept (*n*) observed between 1961 and 2007 for (a′) correlation between AC and AP, and (b′) correlation between AP′ and FC. The error bars represent the standard errors. We observe linear increase in *n* and linear decrease in *m* over the last decades for both relationships, shown by dotted lines.

044044/mmedia) and section 4. Applying linear extrapolation, we estimated the future values of n^y (y: the year) and m^y. The extrapolated values of n^y and m^y across time implicitly represent changes in the future role of international trade to meet country-wise animal product demand (figure 1(a′)) and changes in feed conversion efficiencies (figure 1(b′)). We then 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 (see text S3 available at stacks.iop.org/ERL/8/044044/mmedia).

We defined three scenarios to project the feed demand. The first one (scenario A) is a baseline scenario where the dietary pattern of a country stays the same as in the year 2000 and hence, per capita animal product consumption. Scenario A only considers population change for countries based on the mid-range population scenario from United Nations (2011) that estimates around 9 billion people globally by 2050. We considered this scenario as a low bound. In addition to population change, the second one (scenario B) takes into account country specific changes in dietary patterns as provided by Pradhan *et al* (2013). Pradhan *et al* (2013) estimated the future per capita animal product demand by country till 2050 based on observed exponential relationship between per capita animal product intake and the Human Development Index (HDI), using the HDI extrapolation from Costa *et al* (2011) based on logistic regression. The data for per capita animal product demand cover 148 countries. We considered this scenario as an upper bound based on changes in animal products demand and population. Additional to

changes in population and dietary patterns, the third one (scenario C) considers changes in feed conversion efficiency based on the extrapolated values of n_2^y and m_2^y (see text S3 available at stacks.iop.org/ERL/8/044044/mmedia). This is a mid-range scenario.

3. Results

3.1. Spatial patterns of feed calories

Figure 2 presents a gridded map of feed calories for the year 2000 based on approach I (see figure S1 available at stacks.iop.org/ERL/8/044044/mmedia for approach II). The map presents embodied feed used for livestock in billions of kilo-calories per 5 arc-minutes grid. For about 60% cells with the feed value larger than 0.2 billion kcal yr^{-1}, grid feed estimation based on approach I is within ±30% range of the result obtained from approach II (figure S1 available at stacks.iop.org/ERL/8/044044/mmedia). We observed more than double overestimation or underestimation for around 20% of the cell while comparing results from approach I and II. That means the 'close to reality' approach I represents the 'extreme case' approach II in about 60% of the cells within ±30% range. The underestimation is due to ruminants getting equal priority as non-ruminants for crop-based feed in approach II (see Brazil and India in figure S1 available at stacks.iop.org/ERL/8/044044/mmedia), whereas the overestimation is due to non-ruminants getting the first priority in approach I.
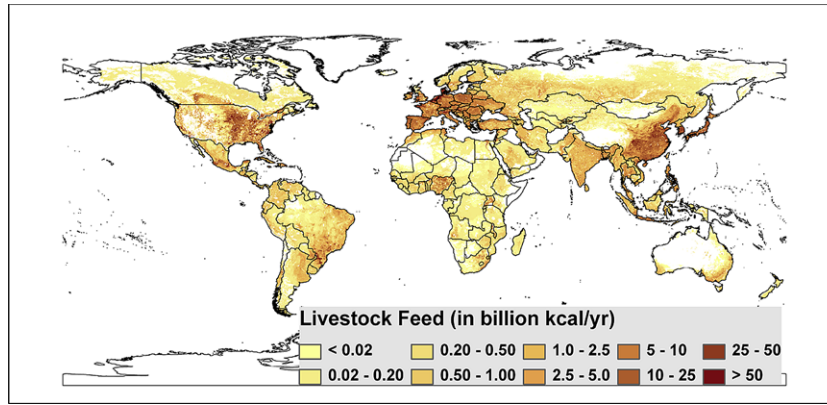
Figure 2. Gridded map showing crop production consumed as livestock feed (FC_k) in billions kcal yr^{-1} based on approach I. Livestock in these grid cells are fed on crops regardless of where the crops were produced. Cattle, buffaloes, goats, sheep, pigs and poultry are livestock considered in this investigation. Missing and zero values are represented by white color in the map.

Table 2. Regional overview on crop calories, animal calories and feed. The columns present regional breakdown of crop calorie production (CP), animal calorie production (AP), feed calories for 2000 (FC) and feed demand for 2050 without dietary changes (FC_5), with dietary changes (FC_5^d), and also including changes in feed conversion efficiency ($FC_5^{d,f}$) in 10^{12} kcal yr^{-1}. Additionally, they provide regional values of crop balance for livestock (FC/CP) and embodied crop calories (FC/AP) along with the ratios between projected feed demand for 2050 and feed consumed in 2000 without dietary changes (FC_5/FC), with dietary changes (FC_5^d/FC) and also including changes in feed conversion efficiency ($FC_5^{d,f}$/FC).

Regions	CP	AP	FC	FC_5	FC_5^d	$FC_5^{d,f}$	$\dfrac{FC}{CP}$	$\dfrac{FC}{AP}$	$\dfrac{FC_5}{FC}$	$\dfrac{FC_5^d}{FC}$	$\dfrac{FC_5^{d,f}}{FC}$
			(10^{12} kcal yr^{-1})								
Africa											
East Africa	165	9	29	88	467	422	0.18	3.21	3.00	15.98	14.44
Middle Africa	58	2	10	74	272	271	0.17	6.53	7.57	27.73	27.68
North Africa	126	16	65	92	335	243	0.52	4.21	1.41	5.13	3.73
South Africa	57	6	21	23	25	25	0.37	3.76	1.10	1.22	1.21
West Africa	271	6	79	245	1121	931	0.29	14.05	3.11	14.24	11.83
America											
Caribbean	23	3	11	13	40	42	0.48	3.47	1.14	3.60	3.78
Central America	149	22	88	117	272	220	0.59	4.05	1.33	3.10	2.51
North America	1704	146	816	692	953	593	0.48	5.57	0.85	1.17	0.73
South America	771	81	252	290	527	408	0.33	3.12	1.15	2.09	1.62
Asia											
Central Asia	78	9	24	38	66	65	0.31	2.77	1.59	2.76	2.72
East Asia	1774	236	803	551	1203	695	0.45	3.40	0.69	1.50	0.87
South Asia	1264	111	166	202	867	550	0.13	1.50	1.22	5.23	3.32
South-East Asia	756	28	150	180	819	629	0.20	5.32	1.20	5.46	4.19
West Asia	173	21	101	150	408	360	0.59	4.90	1.48	4.02	3.55
Europe											
East Europe	731	84	374	240	327	287	0.51	4.46	0.64	0.87	0.77
North Europe	192	42	129	129	164	149	0.67	3.12	0.99	1.27	1.15
South Europe	264	49	226	228	333	280	0.86	4.62	1.01	1.47	1.24
West Europe	532	98	303	260	300	239	0.57	3.10	0.86	0.99	0.79
Oceania											
Australia and New Zealand	149	22	38	42	61	49	0.26	1.69	1.11	1.61	1.29
World	9235	988	3685	3653	8558	6457	0.40	3.73	0.99	2.32	1.75

On continental scale, North America, Europe (excluding North Europe and Russia) and East Asia are regions that use a very high amount of crop-based feed. Table 2 displays information on continental scale and highlights that in these regions (all Europe excluding North Europe) feed consumption is larger than 800×10^{12} (or eight hundreds thousands billions) kcal yr^{-1}. One billion kilo-calories of food is enough to sustain about 1000 persons for a year with a daily diet of 2800 kcal/cap/day. Thus, the crop calories used as feed in these regions is enough to nourish ≈800 million people, which is about the number of people (≈900 million) estimated to be undernourished in 2010 (FAO 2010). Central America, South and South-East Asia, and South America also use a high amount of crop-based feed. Overall, on a continental scale, feed calorie consumed is the lowest in Africa (≈200×10^{12} kcal yr^{-1}). However, some regions in Africa e.g. Nigeria, Nile valley and South Africa, the values are comparatively high.
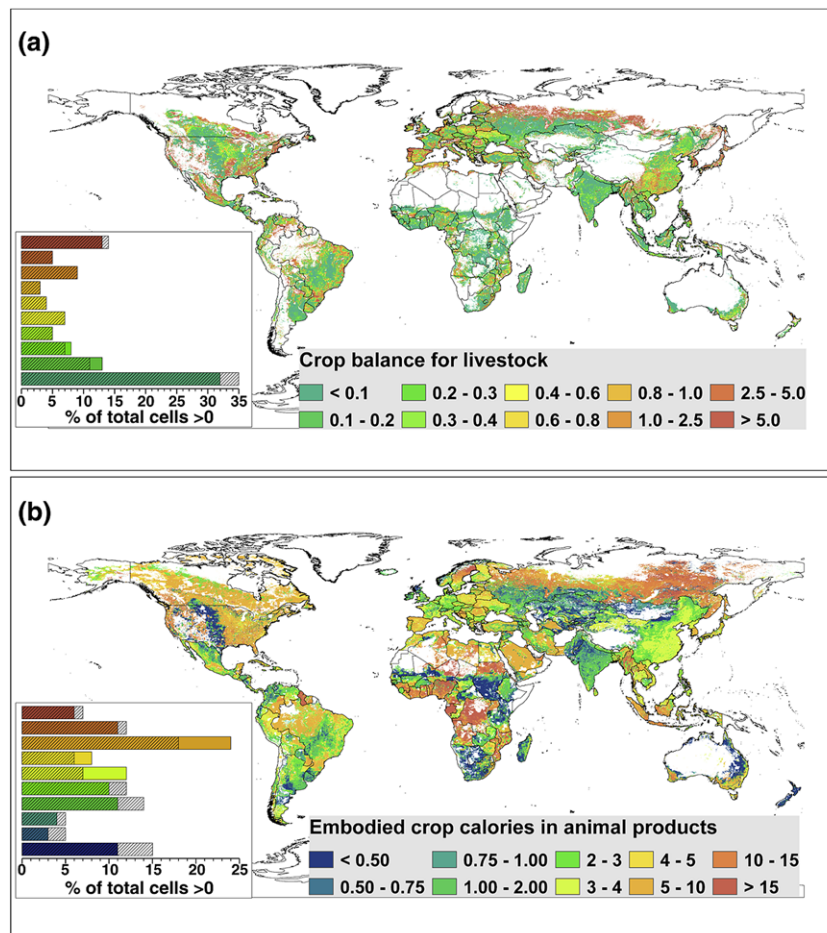
Figure 3. Maps showing the ratios among crop calories produced, animal calories produced and feed consumed for year 2000 based on approach I. (a) Crop balance for livestock, and (b) embodied crop calories in animal products. Insets present statistics for both maps with hatched bar showing statistics for the results based on approach II. The estimated global average values of the crop balance and the embodied crop calories are ≈ 0.4 and ≈ 4 respectively for the year 2000.

3.2. Feed, crops and livestock calories

Figure 3(a) shows a gridded map of the crop balance for livestock. Similarly, figure 3(b) presents a gridded map of the embodied crop calories in animal products. Maps of crop calorie production and livestock calorie production are presented in figures S2 and S3 (available at stacks.iop.org/ERL/8/044044/mmedia).

Looking at the first indicator used in our study, the crop balance for livestock, we see it is around 0.40 on a global scale (table 2). That means 40% of the global crop calories are fed to livestock. The balance is greater than 1 for around 30% of grid cells for the both approaches I and II (figure 3(a)—inset), i.e. the feed used in these areas is greater than the crop calories produced. Accordingly, these areas need national or international trade to meet their feed consumption. Identifying the regions where trade is a necessity is an important result of our analysis. This result also highlights the role of livestock production systems in spatial flow of biomass and nutrient (Erb *et al* 2009, Billen *et al* 2010). For around 30–35% of grid cells, we observed a crop balance of less that 10%. These are regions producing a high amount of crop calories (figure S2 available at stacks.

iop.org/ERL/8/044044/mmedia) and/or using a low amount of feed (figure 2). However, the lower values of crop balance do not rule out the possible use of crop calorie produced on the cell as feed on other cells worldwide. In addition to the feed, crop products are also needed to meet the dietary demand of people living in those regions. Spatially, we observed a high number of cells with values exceeding the global average of 0.4 or the threshold of self-sufficiency of 1 across the Americas, Europe, Northern Africa, Western Asia and Eastern Asia (figure 3(a)). These regions consist of areas producing a comparatively high amount of animal calories (figure S3 available at stacks.iop.org/ERL/8/044044/mmedia) with high densities of pigs and poultry (Wint and Robinson 2007). Moreover, the crop balance is also higher in regions producing a lower amount of crop calories (figure S2 available at stacks.iop.org/ERL/8/044044/mmedia), but raising non-ruminants (pigs and poultry), e.g. high values appearing as a band in Russia (figure 3(a)). The balance is comparatively low (below the global average) in regions producing a lower amount of animal calories (figure S3 available at stacks.iop.org/ERL/8/044044/mmedia), but a higher amount of crop calories (figure S2 available at stacks.iop.org/ERL/8/044044/mmedia), as in

Australia, New Zealand, South Asia, South-East Asia, Middle Africa and East Africa.

The second indicator, the embodied crop calories in animal products, is 3.7 on a global scale (table 2). That means global average crop-based feed consumed to produce 1 kcal of animal products is ≈4 kcal. We found that the value of embodied crop calories is smaller than the global average for about 40–50% of the cells including about 20–25% of the cells with values less than 1 (figure 3(b)—inset). The lower embodied calories mostly refer to either rangeland livestock production systems or other production systems mainly raising ruminants (cattle, buffaloes, goats and sheep) fed on non-crop feed. Although these livestock production systems have lower embodied crop calories, the amount of non-crop calories is normally higher and other environmental stress generated by these livestock systems may be of a higher value, e.g. use of land and energy, and emission of greenhouse gases (De Vries and De Boer 2010, Zervas and Tsiplakou 2012). We observed the cells with the embodied crop calories of less than 1 widely across these regions including East and South Africa, United States, and Argentina (table 2). Additionally, we figured out that more than 5 kcal of crop products are used to generate 1 kcal of animal products in about 40% of the cells for the both approaches I and II, including about 20% of the cells with values greater than 10. A high number of cells with embodied crop calories greater than 5 are mostly distributed across South-East Asia, North America, Middle Africa and West Africa (figure 3(b)). Additionally, countries like Russia, Suriname and Guyana also consist of a larger number of cells with high values. The high values are associated with livestock production systems other than rangeland, mainly involving non-ruminants fed on crop products. Additionally, the values are higher for less intensive production systems than for intensive ones. For example, non-ruminants have shares of more than 60% of animal calorie produced in China and Nigeria (FAO 2012), however, the embodied crop calories is lower for China than for Nigeria. One explanation for this is the less intensive production system in Nigeria compared to that of China (Robinson *et al* 2011).

3.3. Feed demand for 2050

Figure 4 presents a trend and projection of the global feed and food demand until 2050. On a global scale, we can see a trend of increased use of crop-based feed. In 1961, ≈1.3 × 10¹⁵ kcal of feed were used, which has increased by ≈1.9 times to ≈3.7 × 10¹⁵ kcal in 2000. However, the ratio of crop calories used as feed and consumed directly by human remained between 0.7 and 0.8 from 1961 to 2000.

We found that the global feed demand would more than double (2.3 times) in 2050 compared to 2000 while considering the changes in dietary patterns and population (scenario B), and 1.8 times if changes in feed efficiency are also considered (scenario C) (table 2). The changes in dietary patterns consist of a high intake of total calories, animal products, sugar–sweeteners, oils and vegetables with increased in countries' HDI (Pradhan *et al* 2013). Therefore,
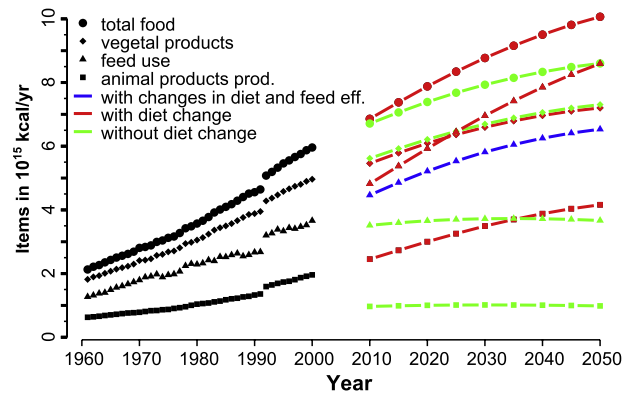

Figure 4. Global feed use projection until 2050. The figure also shows total supply of food calories, vegetal calories and animal calories for human consumption and crop calories used as feed on the global scale from 1961 to 2000. The sharp rise in the values for 1992 is caused by inclusion of the countries from the former Soviet Union in the analysis from 1992 onwards. Projection of the demand of food calories, vegetal calories and animal calories for human consumption and the feed demand until 2050 are presented 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). Since feed conversion efficiency do not affect food demand, scenario B and C overlap for food calories, vegetal calories and animal calories for human consumption.

the high feed demand we estimated, is related to increase in animal product consumption and an expected global population of 9 billion by 2050. We figured out that the ratio of crop calories demand for feeding livestock and for direct human consumption will increase between 0.9 and 1.2 by 2050 due to dietary pattern changes, in contrast to the ratio varying between 0.7 and 0.8 for the last 5 decades. This results increases in the share of the global crop calories used as feed from 40% in 2000 between 48% and 55% by 2050. Thus, changes in population, animal product consumption and feed demand lead society to produce equal or even more crops to raise livestock than to nourish mankind directly in the future. Overall, we calculated a need of 60%–80% increase in crop calorie production by 2050 compared to 2000.

The ratio between feed used in 2000 and feed demand in 2050 varies across regions and in the three scenarios (figures 5 and S4 available at stacks.iop.org/ERL/8/044044/mmedia). In scenario A, we see the feed demand increases by more than 50% for most African countries and less than 25% for most South-East and South Asian countries (figures 5(a) and S4(a) available at stacks.iop.org/ERL/8/044044/mmedia). This is due to an expected increase in population in these regions (United Nations 2011). For regions like Europe and East Asia, and countries like United States, Brazil and South Africa, feed demand decreases under scenario A, because of the projected decrease in population in these regions by 2050 (United Nations 2011). Additionally, this decrease in feed demand might also be due to changes in feed conversion efficiency in these regions between 2000 and 2007 (deduced from decrease in slope across time in figure 1(b′)). Overall feed demand is nonetheless comparatively larger in these
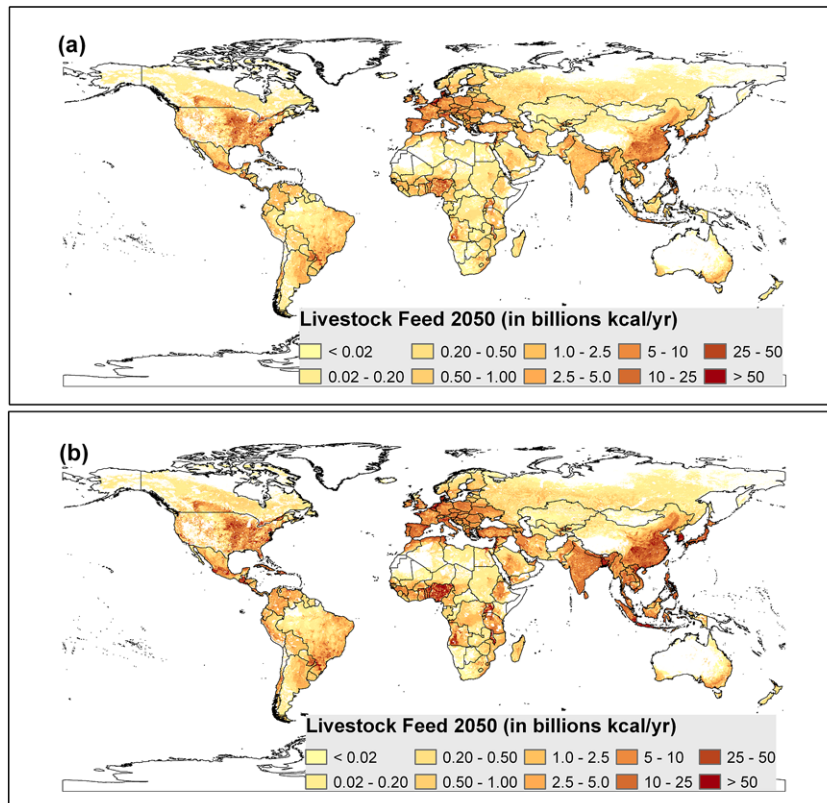
Figure 5. Gridded map of projected feed calorie demand presented in billions kcal yr^{-1} for year 2050 for two scenarios. (a) Low bound scenario A without dietary pattern changes but with population changes and (b) upper bound scenario B with dietary pattern and population changes. Both maps are based on the results from approach I.

regions for all scenarios (figure 5). In scenario B, we see increases in the feed demand for most of the regions. We estimated that the feed demand will be more than tripled by 2050 for most of African, South-East and South Asian countries (figure S4(b) available at stacks.iop.org/ERL/8/ 044044/mmedia). Additionally, we found that regions in Africa (besides South Africa), South-East Asia and West Asia will not be able to meet their feed demand by 2050 based on their present total crop production (table 2). This indicates that these continents are potential feed-limited regions, and thus they need to increase their crop production and/or be dependent on international trade even to feed their livestock in the future. Presently, these countries' dietary patterns have a small share of animal products (FAO 2012) that is projected to increase in the future with development (Pradhan *et al* 2013). In scenario C, we observe increases in the feed demand for most countries as in scenario B. However, the increases in demand are lower than that for scenario B in most of the regions due to changes in feed conversion efficiency. Overall, changes in dietary pattern towards more animal product consumption increase crop-based feed demand. This demand could be reduced by increasing feed conversion efficiency.

4. Discussion

In this study, we present global maps with crop calories used as feed and their inter-relations with crop and animal

calorie production, and project the feed demand until 2050. In the past, crop products have been increasingly used to feed livestock with an growth of ≈1.9 times from 1961 to 2000. This trend will continue more rapidly in the future resulting in around double (1.8–2.3 times) the feed demand by 2050 compared to 2000 due to an increase in population and dietary pattern shifts towards higher intake of animal products, mainly in developing countries. However, the increase in feed demand varies geographically. Compared to the developed world, the feed demand growth rate will be larger in developing countries.

With our approach we present several innovations for assessing roles of dietary patterns in shaping various aspects of the agricultural sector. The first novelty lies in aggregating information on crop and animal products in a single comparable calorific unit. A limited number of studies try to present this information in units other than mass units (Foley *et al* 2011, Cassidy *et al* 2013). This is important because human dietary requirements are generally measured in calorific values (FAO/WHO/UNU 2004). Moreover, our analysis presenting 40% of crop calories used as feed is similar to that of 36% provided by Cassidy *et al* (2013).

Second, information we uniquely deduced on gridded feed calories is a consumption rather than production perspective. This gridded feed data complements existing gridded livestock data sets, such as livestock density (Wint and Robinson 2007), livestock production systems (Robinson

et al 2011), animal products (FAO 2011a) and livestock manure (Potter *et al* 2010). Such information can be used for a holistic assessment of food security and food self-sufficiency on local, regional and global scales, considering both crop and animal calorie production, and crop calories use for direct human consumption and for livestock feed. Additionally, our study highlights variability between global and gridded analysis presenting that ≈4 kcal of crop products are embodied in 1 kcal of animal products on a global scale, however, there are regions even within a country with values less than 1 or more than 10. Similarly, we identified regions using more crop calories to feed their livestock than crop calories they produced, showing a necessity of within-country transfers and/or international trade to meet the shortfalls. This is more important when larger regions/countries become more trade dependent. For example, regions in Africa (besides South Africa), South-East Asia and West Asia would not be able even to meet their feed demand by 2050 without increasing their present crop production.

Third, we are able to project the future crop-based feed demand making use of existing relationships between animal calorie production, animal calorie consumption and feed consumption at a national scale. This adds to existing studies that focus on projections of crop demand (Alexandratos 2006). Our results project 60%–80% increases in global crop calorie demand by 2050 compared to 2000, differ from the projected ≈100% increases in the demand by 2050 compared to 2005 (Tilman *et al* 2011). However, our results are closer to the projected 60% higher food demand than that of 2005 (Alexandratos and Bruinsma 2012). The discrepancy might be due to the explicit consideration of livestock feed demand which other studies (e.g. Tilman *et al* 2011) consider only implicitly.

Although this study produced clear findings as mentioned above, interpretation of the results also require an understanding of its limitations. One of the limitations lies in our assumption that non-crop feed is not explicitly transferred among grid cells. This overestimates country scale ruminant crop-based feed by more than 20% for about 30% of the countries. However, we distributed feed calorie used in a country to ruminants only after fulfilling non-ruminant feed requirements in approach I, which reduces the overestimation. Moreover, on a global scale only around 12% of cells produce more non-crop feed than needed to meet ruminants' requirements. Additionally, our assumption that crop-based feed is supplied to ruminants only if produced non-crop feed is not enough, slightly underestimates crop-based feed used for ruminants. However, we used this simple approach due to underlying complexity in identifying cells where crop-based feed might be supplied to ruminants although enough non-crop feed could be produced. Moreover, globally only around 20% of the total feed is supplied to ruminants (Erb *et al* 2012).

The second limitation is that the actual feed composition affects the mass of required feed. Here, we used a single value for feed requirement regional and livestock-wise due to data constraints. This might be a reason for observing few cases of greater country-wise feed mass requirement for non-ruminants than country-wise feed mass used. Due to data unavailability, we did not take into account intensive and/or landless livestock production system while downscaling feed calorie used, which is another limitation of this study. Additionally, our future projection is based on global relations instead of country trends which may exhibit some limitations due to variations between global and country trends. However, we tried to represent this by considering country specific residuals during the projections. Moreover, our models are 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 available at stacks.iop.org/ERL/8/044044/mmedia) and the past country feed trends for more than 60% of the countries within a MEA as fraction of actual value of 30%.

Our study highlights an important implication of the ongoing dietary pattern changes towards a large share of animal products. The study explicitly indicates a need to grow equal or even more crops to feed livestock than for direct human consumption by 2050. However, whether the feed demand could be met or not will depend on the future crop price volatility (Wright 2011) and the future increases in crop yields (Edgerton 2009). Moreover, the current crop yield trends are insufficient to double crop production by 2050 (Ray *et al* 2013) showing a need to explore ways for sustainable agricultural intensification (Mueller *et al* 2012) and/or to expand cultivated land. Biofuel as a climate change mitigation option is also a competitor for limited suitable land for cultivation (Fargione *et al* 2008). Moreover, the feed demand will increase by more than 2 times mainly in developing countries in Asia and Africa, where people are presently suffering from undernourishment (FAO 2010). Additionally, crop production in these regions will very likely suffer from the negative impacts of climate change if sufficient adaptation measures are not implemented (Lobell *et al* 2008). Summing up, we ask an important question regarding the approach to meeting future animal product demand: is it possible to make livestock production systems more efficient, therefore enabling these systems to meet the animal product demand in a sustainable way taking into account the environmental impacts of different kinds of livestock-rearing systems (Pretty *et al* 2010) or do we need a shift to dietary composition with small share of animal products, reversing current trends?

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