**Supplementary Material**

**Supplementary Text**

Processing of LPJmL harvest outputs for the calorie calculation scheme

LPJmL (here, version 3.5) dynamically simulates growth and harvest of 14 Crop Functional Types (CFTs). Thereof, CFT1-12 are parametrized as specific food crops (see columns in Tab S5), CFT13 collectively represents other crops and CFT14 managed grasslands. Assuming a dry matter (DM) carbon content of plant biomass of 0.45 (Schlesinger & Bernhardt, 2013), all simulated carbon yields were converted to DM for our analysis of calorie supply. To take into account pasture management practices not directly modelled in LPJmL, a scaling factor was applied to CFT14 grass harvest as to represent observed grazing data for the year 2000 for 29 world regions (Herrero et al., 2013; see Gerten et al., 2020). This factor was also applied to the roughage share of CFT13: While CFT1-12 are human edible, CFT13 includes next to other perennial and annual crops such as potatoes, oil palm, grapes/vine or coffee also forage crops. Based on the global harvested area share of fodder grasses in this CFT according to the MIRCA2000 land use input (Fader et al., 2010; Portmann et al., 2010), 27.4% of CFT13 was subtracted from human edible crop production and allocated to grass and roughage production (see Fig. S1).

Whereas grass and roughage production was kept in terms of dry matter, edible harvest quantities were converted to fresh matter (FM) by applying CFT-specific global conversion factors (Wirsenius, 2000, p. 274). For CFT13 (“others”) a conversion based on simple plant specific water content estimations is not possible since the composition of CFT13 greatly varies between regions. Therefore, country-specific conversion factors were used that adjust LPJmL DM production from the baseline scenario to reported FM production from the FAO Food Balance Sheets (FBS; FAOSTAT, 2017) for 2005.

Calculation of FBS derived input factors

Most input factors to translate LPJmL harvest quantities to calorie supply from both livestock and crop production were derived from FBS data (FAOSTAT, 2017) and Commodity Balance Sheet (CBS) data (FAOSTAT, 2018) for 2005. These input factors are estimated similar to Gerten et al. (2020) and were used in the calorie calculation scheme as described in the methods of the main text and visualized in Fig. S1. The FBS provide production quantities as well as domestic supply divided into different utilization accounts (Food, Feed, Other uses, Seed, Processed, Losses (after production)) and per capita food supply quantities in terms of weight, energy and protein content for most countries and almost 100 food items (FAOSTAT, 2017). Edible food processing by-products used as feed, such as oilseed cakes, molasses and brans, are not included in the FBS, but their accounts were taken from the CBS and complemented the FBS feed utilization accounts of the respective plants they were produced of. As the accounts of molasses and brans are not differentiated according to their original plant, the quantities were allocated to the original plants based on their relative production ratios (sugar cane and sugar beet for molasses; wheat, barley, rye, oat, sorghum, millet and other cereals for brans). The FBS food items were allocated to the 13 CFTs implemented in LPJmL, not considering seafood, alcoholic beverages, non-edible products such as cotton, fibers and rubber, tobacco, honey and infant food. For sugar (produced from both sugar cane (CFT12) and sugar beet (CFT6)), the quantities were allocated to the two CFTs by taking into account the relative production ratio of sugar beet and sugar cane respectively. In the following, the specific calculations of the different FAOSTAT derived input factors needed for the translation of LPJmL crop yields to calorie supply (Fig. S1) are introduced. All FBS feed data refer to the adapted data (see above) which include food processing by-products from the CBS.

*Roughage Requirement per Livestock Product:*

The roughage requirement per unit of an average regional livestock product (RReq) for 12 worlds regions (reg, visualized in Fig. S2) was calculated by dividing the simulated and scaled pasture and roughage production (P&R production) from LPJmL by total FBS livestock production. All countries which are covered by FBS data within the respective world region were considered (for FBS data) and all grid cells belonging to these countries respectively (for LPJmL P&R production):

Total livestock production was calculated by including the following FBS food items: Bovine, mutton, goat, pig, poultry and other meat; edible offal, animal fats, eggs, butter, cream and milk. The obtained regional roughage requirements are provided in Table S4.

*Feed Requirement per Livestock Product:*

FBS Production and FBS utilization accounts were aggregated for each world region (reg) and CFT. The FBS Feed quantities were divided by total FBS livestock production (total\_FBS\_LP) to obtain the regional CFT feed requirement per unit of livestock product (FReq). In order to adjust these “feed baskets” to LPJmL harvest amounts they were scaled by a factor which divides simulated LPJmL production by FBS production:

Total CFT Feed requirements per livestock product for 12 world regions are provided in Table S4; the shares of single CFTs contributing to total CFT Feed requirements are provided in Table S5. For the implementation of dietary change scenarios and a sensitivity analysis exploring the effects of including or excluding by-products as potential food source, these feed requirements were additionally calculated without including food processing by-products as well as only considering food processing by-products. This is important as calorie and protein content of the by-products differ from the average regional CFT energy and protein content for food items (see below).

*Other uses:*

FBS utilization accounts, aggregated for CFTs and world regions, for “Other uses” and “Seed” were divided by the utilization accounts for “Other uses”, “Seed”, “Feed”, “Food” and “Losses”, thereby determining the share of other uses for each region and CFT:

Crop quantities for food processing were not included as they were indirectly accounted for by including by-products from the CBS in the feed account (see above) and processed oils and sugar in the Food and Feed accounts. Calculated regionally and CFT-specific factors are provided in Table S6.

*Dietary energy and protein content of an average livestock product:*

We determined the dietary energy content per weight (e\_per\_fm) for each livestock product (l) and country (c) by dividing FBS Food supply in terms of calorie by Food supply in terms of weight. The regional average dietary energy content per unit of livestock product (e\_LSreg) was calculated through weighting by country-specific FBS livestock production (FBS\_LP) considering all listed countries belonging to the respective region (reg) and all livestock products (ls).

*Dietary energy and protein content of 13 CFTs:*

We calculated the dietary energy content per weight (e\_per\_fm) for each food item (f) and country (c) by dividing FBS Food supply quantities in terms of dietary energy by Food supply quantities in terms of weight. In countries where data for specific food items was missing, we used the global average dietary energy content of the respective food item. Regional (reg) averages for each CFT (e\_Cropsreg,cft) were obtained through weighting by production quantities (FBS\_P):

The same procedure was used to calculate regional average protein content for each CFT based on FBS food supply quantities in terms of protein weight. Both calorie and protein content for each region and CFT are provided in Table S7.

*Dietary energy and protein content of by-products used as feed:*

We obtained regional average energy and protein content for food processing by-products, allocated to the respective CFTs, based on energy and protein data for brans, molasses and oilseed cakes provided in the FAO Food Balance Sheet Handbook (FAO, 2001)*.* For all by-products with missing data, we interpolated protein and energy content based on the values of similar products. Regional and CFT-specific dietary energy and protein content was then obtained as described above.

In our dietary change scenarios towards less livestock products, the amount of CFT harvest allocated to feed decreases and more harvest is available for direct human consumption. This implies a reallocation of feed to direct consumption. For this, we differentiate between “normal” crop feed and food-processing by-products used as feed, with specific dietary energy and protein content as described above.

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**Fig. S1:** Detailed calorie calculation scheme. Details on the different calculation steps are provided in the Supplementary Text. Adapted after Gerten et al. (2020).

|  |
| --- |
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| C:\Users\jobraun\Nextcloud\WiMi PIK 2020\4 publication of thesis\r_out\plots\!rel_EFR_deficit_baseline.tiff |

F**ig. S2:** Global distribution of current EFR transgressions (i.e. simulated discharge < EFR) in the baseline scenario. (a) Number of months with EFR transgressions > 5% of pristine river discharge. (b) Monthly EFR deficit divided by pristine river discharge, averaged over all months of a year. All results are averaged for 1980–2009 climate with constant land use for 2005 and calculations omitted in grid cells with pristine river discharge < 1m3s-1 (white color).

**Table S1:** Changes in calorie supply of various scenarios in comparison to the baseline scenario (current irrigation practices, diets as derived from the Food Balance Sheets for 2005) resulting from the three dietary change scenarios. *LS* refers to calorie from livestock production only, *total* refers to changes in combined calorie supply from animal and plant-based products. The three columns for each category show the results of a sensitivity analysis regarding the edibility of manufacture by-products used as feed: all BP = all by-products such as molasses and protein cakes from oil production are edible; some BP = some by-products are human edible (see methods; this scenario provided the basis for the result’s section, see Fig. 3); no BP = by-products are not edible at all.

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| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | **calorie supply baseline scenario** | | | | **Rel. change in kcal supply in DC25 scenario** [%] | | | | | | | | | | | | **Rel. change in kcal supply in DC12.5 scenario** [%] | | | | | | **Rel. change in kcal supply – DC0** [%] | | | |
|  | [1013 kcal] | | | | LS | | | | | | total | | | | | | LS | | | total | | | LS | total | | |
|  | total | crops | LS | | no BP | | some BP | | all BP | | no BP | | some BP | | all BP | | no BP | some BP | all BP | no BP | some BP | all BP | all scenarios | no BP | some BP | all BP |
| East Asia | 121.1 | 94.8 | 26.4 | | -31.6 | | **-29.6** | | -28.3 | | 1.0 | | **2.1** | | 2.5 | | -67.6 | **-64.1** | -62.9 | 2.1 | **5.1** | 6.0 | -100.0 | 3.1 | **8.4** | 10.1 |
| South Asia | 93.2 | 82.5 | 10.7 | | 0.0 | | **0.0** | | 0.0 | | 0.0 | | **0.0** | | 0.0 | | -49.8 | **-46.4** | -44.0 | -4.2 | **-1.7** | -0.6 | -100.0 | -8.4 | **-3.7** | -1.5 |
| North America | 73.5 | 59.0 | 14.5 | | -14.5 | | **-10.6** | | -10.3 | | 5.3 | | **5.1** | | 5.1 | | -56.7 | **-47.8** | -47.0 | 20.9 | **23.0** | 23.3 | -100.0 | 36.9 | **48.2** | 49.7 |
| Southeast Asia | 67.0 | 63.5 | 3.6 | | 0.0 | | **0.0** | | 0.0 | | 0.0 | | **0.0** | | 0.0 | | -42.0 | **-36.9** | -36.0 | 2.8 | **4.8** | 5.1 | -100.0 | 6.7 | **13.3** | 14.3 |
| Eastern Europe and Central Asia | 48.0 | 38.0 | 10.1 | | -27.7 | | **-26.3** | | -25.6 | | 9.2 | | **10.0** | | 10.1 | | -62.5 | **-60.8** | -60.0 | 20.8 | **23.1** | 23.6 | -100.0 | 33.1 | **38.0** | 39.4 |
| Western Europe | 47.7 | 30.4 | 17.3 | | -50.7 | | **-48.6** | | -46.2 | | 20.5 | | **23.1** | | 24.8 | | -74.7 | **-73.1** | -71.1 | 30.4 | **35.0** | 38.3 | -100.0 | 40.7 | **48.3** | 54.3 |
| South America | 47.6 | 38.5 | 9.2 | | -13.5 | | **-11.3** | | -11.1 | | 0.8 | | **1.5** | | 1.6 | | -59.8 | **-55.0** | -54.4 | 3.7 | **7.3** | 7.7 | -100.0 | 6.2 | **13.2** | 14.2 |
| Southern Africa | 41.5 | 38.1 | 3.4 | | 0.0 | | **0.0** | | 0.0 | | 0.0 | | **0.0** | | 0.0 | | -46.5 | **-42.6** | -41.6 | 5.5 | **7.3** | 7.8 | -100.0 | 11.9 | **17.2** | 18.7 |
| Middle East | 15.6 | 12.8 | 2.8 | | -32.6 | | **-30.9** | | -28.8 | | 3.8 | | **5.2** | | 5.6 | | -66.9 | **-65.1** | -63.2 | 9.8 | **12.9** | 13.9 | -100.0 | 15.6 | **20.9** | 22.9 |
| Central America | 14.0 | 11.5 | 2.5 | | -48.4 | | **-45.6** | | -44.6 | | 5.3 | | **8.5** | | 8.7 | | -75.1 | **-72.9** | -72.1 | 9.2 | **14.3** | 14.8 | -100.0 | 12.9 | **20.3** | 21.2 |
| North Africa | 8.3 | 6.5 | 1.8 | | -49.3 | | **-42.8** | | -40.6 | | -1.9 | | **2.6** | | 3.3 | | -76.3 | **-71.6** | -70.3 | -1.1 | **6.2** | 7.2 | -100.0 | -0.4 | **9.8** | 11.2 |
| Australia and Oceania | 8.2 | 5.1 | 3.0 | | -55.1 | | **-54.2** | | -52.2 | | -8.9 | | **-7.7** | | -5.9 | | -79.3 | **-78.7** | -77.3 | -12.8 | **-11.1** | -8.7 | -100.0 | -16.1 | **-14.0** | -11.2 |
| **GLOBAL** | **585.8** | **480.5** | | **105.2** | | **-26.5** | | **-24.6** | | **-23.5** | | **3.4** | | **4.2** | | **4.5** | **-63.4** | **-59.6** | **-58.3** | **7.9** | **10.7** | **11.6** | **-100.0** | **12.6** | **19.0** | **21.0** |

**Table S2:** Evaluation of global estimates of simulated key variables against independent datasets.

|  |  |  |
| --- | --- | --- |
| Variable | Estimates from this study (2005 land use; climate input for 1980-2009) | Range of other estimates [year] |
| Irrigation water withdrawals | 2498 km3yr-1 | 2158–3185 km3 yr–1 [various recent periods] (Droppers et al., 2020 and references therein) |
| crop production contributed from irrigated agriculture | 33.5% (referring to calories) 36.4% (referring to fresh matter) | 31% [2000] (referring to calories)  (Rosa et al., 2018)  33% [2000] (referring to weight)  (Siebert & Döll, 2010) |
| Total crop production (incl. losses for animal feed and food waste, and other uses such as biofuels and seed production) | 8.9 \* 1015 kcal1 | 9.46\*1015 [2000]2 (Cassidy et al., 2013)  ~9.5 \* 1015 kcal [2006] (Searchinger et al., 2013, p.18,24)  1.31 \* 1016 [2010]  (Searchinger et al., 2018)(Searchinger et al., 2018) |
| Vegetal supply (excl. post-production losses, animal feed and other uses such as bioenergy) | 4.81\* 1015 kcal | 5.06 \* 1015 kcal [2005]3 (FAOSTAT, 2017) |
| Livestock kcal supply | 1.05 \* 1015 kcal4 | 1.02 \* 1015kcal [2005] 4 (FAOSTAT, 2017) |
| Animal kcal share | 18.0 %4 | 17.0% [2005] (FAOSTAT, 2017) |
| Animal feed share (kcal);  referring to total crop kcal production | 29.5%5 | 36% [2000]  (Cassidy et al., 2013)  40% [2000]  (Pradhan et al., 2013)  34% [2013] (Berners-Lee et al., 2018) |

1based on kcal conversion factors for the 13 CFTs which were calculated as described in the supplementary text but excluding processed items like oils and sugar; slight underestimation mostly because multi-cropping systems are not yet implemented in LPJmL  
2including 41 crops accounting for over 90% of total calorie production   
3excluding alcoholic beverages, up-scaled from FBS food supply quantities in terms of calories per capita and year by multiplication with FBS population data and 365 days.   
4without seafood  
5including processing by-products such as molasses, oilseed cakes and brans

**Table S3:** Energy (kcal) provided by proteins in % of total supply in the baseline and dietary change scenarios. Coloring refers to the recommended protein energy share between 10 and 15 % as stated by the WHO (2003). Red: below 10, yellow: between 10 and 12.5, light green: between 12.5 and 15, dark green: >15%. Calorie and protein supply from fish and seafood is not included, which would likely augment all values, especially in Southeast Asia, where fish consumption is high (FAO, 2018). Results are based on the regional protein content per kg of an average livestock product and CFT calculated as described in the supplementary text. It was assumed that 1 gram of protein provides 4 kcal.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | baseline | DC25 | DC12.5 | DC0 |
| Australia and Oceania | 15.6 | 14.8 | 13.8 | 12.9 |
| Central America | 10 | 9.2 | 9.2 | 9.3 |
| East Asia | 11.5 | 11.6 | 12 | 11.9 |
| Eastern Europe and Central Asia | 13 | 12.5 | 13.3 | 14.2 |
| South Asia | 10.4 | 10.3 | 10.1 | 9.7 |
| South America | 16.6 | 16.4 | 16.7 | 17 |
| Southern Africa | 9.9 | 9.9 | 10.2 | 10.8 |
| Middle East | 13.2 | 12.6 | 12.8 | 12.9 |
| North Africa | 12.6 | 11.9 | 11.8 | 11.8 |
| North America | 14.2 | 14.2 | 16.6 | 20 |
| Southeast Asia | 5.1 | 5.1 | 5.7 | 6.5 |
| Western Europe | 14.3 | 13.1 | 13.7 | 14.5 |
| GLOBAL | 11.7 | 11.5 | 12.1 | 12.7 |

**Table S4:** Regional feed requirements and dietary energy and protein content for an average livestock product. Data was calculated as described in the supplementary text. Crop Feed Requirements refer to total crop feed from CFT1-13, including molasses and oilseed cakes. Values slightly differ from Gerten et al. (2020) as more livestock products (LPs) were included in this study.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Region** | **Roughage Requirement  (kg roughage DM / kg LP)** | **Crop Feed Requirement (kg crop FM / kg LP)** | **Dietary Energy Content (Kcal / kg LP)** | **Protein Content (g protein / kg LP)** |
| Australia & Oceania | 5.04 | 0.28 | 984.31 | 49.03 |
| Central America | 2.78 | 1.03 | 1080.20 | 68.09 |
| East Asia | 1.77 | 1.52 | 1993.20 | 91.89 |
| East. Eur. & Central Asia | 1.82 | 1.35 | 912.15 | 50.18 |
| South Asia | 5.55 | 0.33 | 846.26 | 42.95 |
| South America | 4.32 | 0.87 | 1181.40 | 72.16 |
| Southern Africa | 10.26 | 2.30 | 1088.26 | 73.44 |
| Middle East | 2.83 | 0.94 | 900.48 | 59.39 |
| North Africa | 4.20 | 0.61 | 922.46 | 57.77 |
| North America | 1.80 | 1.46 | 1162.12 | 61.44 |
| Southeast Asia | 13.33 | 2.94 | 2071.87 | 105.53 |
| Western Europe | 1.17 | 1.05 | 999.98 | 52.62 |

**Table S5:** Regional composition of crop feed requirements for an average regional LP. The table displays relative shares (%) of different CFTs in total crop feed requirements (referring to FM; second column in Table S4).

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | **Crop functional type (CFT)** | | | | | | | | | | | | |
| **Region** | Temperate  Cereals | Rice | Maize | Tropical  Cereals | Pulses | Temperate  Roots | Tropical  Roots | Sun flower | Soy bean | Ground nuts | Rape seed | Sugar cane | Others |
| Australia & Oceania | 38.5 | 1.5 | 1.7 | 7.7 | 10.9 | 0.0 | 0.0 | 0.3 | 3.6 | 0.0 | 2.1 | 1.1 | 32.5 |
| Central America | 4.9 | 2.4 | 50.0 | 11.7 | 0.2 | 0.0 | 1.7 | 0.0 | 5.8 | 0.1 | 0.0 | 8.2 | 15.0 |
| East Asia | 4.1 | 7.3 | 35.3 | 1.4 | 0.8 | 0.1 | 2.1 | 0.2 | 7.7 | 1.1 | 1.3 | 0.4 | 38.2 |
| East. Eur. & Central Asia | 39.0 | 0.1 | 19.8 | 0.6 | 1.2 | 4.8 | 0.0 | 1.1 | 1.2 | 0.0 | 0.3 | 0.0 | 32.0 |
| South Asia | 15.2 | 22.8 | 8.7 | 3.1 | 3.5 | 0.0 | 0.1 | 0.6 | 2.3 | 4.1 | 4.4 | 11.0 | 24.3 |
| South America | 2.1 | 2.2 | 48.8 | 3.5 | 0.1 | 0.1 | 22.2 | 0.8 | 10.0 | 0.2 | 0.0 | 4.8 | 5.2 |
| Southern Africa | 0.5 | 1.2 | 14.4 | 8.6 | 1.5 | 0.0 | 50.5 | 0.4 | 1.1 | 1.6 | 0.0 | 0.4 | 19.7 |
| Middle East | 56.8 | 1.7 | 16.4 | 0.7 | 1.1 | 1.8 | 0.0 | 1.6 | 1.4 | 0.0 | 0.0 | 0.0 | 18.5 |
| North Africa | 46.4 | 3.4 | 31.8 | 3.9 | 1.1 | 1.1 | 0.0 | 0.8 | 0.5 | 1.2 | 0.1 | 5.5 | 4.3 |
| North America | 7.9 | 0.1 | 70.8 | 0.9 | 0.3 | 0.5 | 0.0 | 0.3 | 12.8 | 0.1 | 0.8 | 0.4 | 5.1 |
| Southeast Asia | 1.8 | 39.1 | 25.5 | 0.4 | 1.1 | 0.0 | 10.2 | 0.1 | 8.0 | 0.5 | 0.1 | 5.3 | 7.9 |
| Western Europe | 48.1 | 0.2 | 28.8 | 0.1 | 2.1 | 1.3 | 0.0 | 1.4 | 4.5 | 0.0 | 2.3 | 0.0 | 11.1 |

**Table S6**: Regional share of crop production (%) used for other purposes than food and feed for each CFT. Shares were calculated based on FBS utilization accounts for 2005 as described in the supplementary text.

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | **Crop functional type (CFT)** | | | | | | | | | | | | |
| **Region** | Temperate Cereals | Rice | Maize | Tropical Cereals | Pulses | Temperate Roots | Tropical Roots | Sunflower | Soybean | Ground nuts | Rapeseed | Sugarcane | Others |
| Australia & Oceania | 13.6 | 14.7 | 5.1 | 0.4 | 7.3 | 0.0 | 51.0 | 7.6 | 0.3 | 0.0 | 16.2 | 36.8 | 8.5 |
| Central America | 16.8 | 1.4 | 1.8 | 0.3 | 7.7 | 0.0 | 1.3 | 3.4 | 8.8 | 3.0 | 30.1 | 10.9 | 11.4 |
| East Asia | 5.5 | 4.6 | 13.2 | 1.2 | 5.8 | 0.0 | 22.2 | 22.1 | 10.8 | 14.3 | 18.9 | 2.4 | 1.2 |
| East. Eur. & Central Asia | 13.9 | 3.5 | 2.6 | 3.4 | 10.1 | 0.3 | 100.0 | 12.1 | 4.4 | 0.4 | 25.2 | 3.8 | 13.0 |
| South Asia | 5.4 | 2.6 | 6.9 | 3.2 | 5.0 | 0.0 | 1.4 | 4.2 | 20.3 | 6.0 | 4.3 | 25.6 | 3.4 |
| South America | 4.3 | 5.5 | 3.5 | 0.7 | 6.0 | 0.2 | 5.8 | 3.1 | 13.5 | 6.3 | 24.3 | 89.7 | 3.4 |
| Southern Africa | 2.2 | 5.3 | 2.3 | 2.6 | 9.5 | 0.0 | 1.4 | 8.4 | 2.7 | 22.9 | 18.5 | 19.2 | 13.2 |
| Middle East | 7.8 | 5.3 | 4.3 | 6.7 | 8.2 | 1.0 | 35.0 | 9.5 | 2.8 | 2.4 | 19.7 | 24.7 | 3.2 |
| North Africa | 3.1 | 5.8 | 1.6 | 28.2 | 3.9 | 6.4 | 0.0 | 7.7 | 9.8 | 29.6 | 8.0 | 7.6 | 3.0 |
| North America | 7.4 | 7.9 | 22.1 | 0.5 | 13.7 | 0.9 | 34.4 | 10.8 | 7.4 | 5.7 | 6.5 | 17.7 | 3.3 |
| Southeast Asia | 1.0 | 8.3 | 9.1 | 2.5 | 10.9 | 0.0 | 27.3 | 27.0 | 5.2 | 13.7 | 3.8 | 15.3 | 10.4 |
| Western Europe | 6.5 | 3.5 | 6.2 | 1.0 | 4.5 | 25.1 | 6.5 | 10.8 | 1.7 | 0.2 | 21.0 | 5.7 | 7.9 |

**Table S7**: Regional average dietary energy (kcal; in kcal per kg FM) and protein (prot; in g Protein per kg FM) for 13 CFTs, as calculated based on FBS data for 2005 and described in the supplementary text.

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | **Temperate  Cereals** | | **Rice** | | **Maize** | | **Tropical  Cereals** | | **Pulses** | | **Temperate  Roots** | | **Tropical  Roots** | | **Sunflower** | | **Soybean** | | **Groundnuts** | | **Rapeseed** | | **Sugarcane** | | **Others** | |
| **Region** | kcal | prot | kcal | prot | kcal | prot | kcal | prot | kcal | prot | kcal | prot | kcal | prot | kcal | prot | kcal | prot | kcal | prot | kcal | prot | kcal | prot | kcal | prot | |
| Australia & Oceania | 2871 | 103 | 3361 | 64 | 2972 | 66 | 3011 | 87 | 3406 | 205 | NA | NA | 948 | 7 | 4820 | 89 | 3541 | 147 | 5664 | 234 | 3710 | 320 | 689 | 2 | 942 | 22 | |
| Central America | 2730 | 74 | 3565 | 70 | 3149 | 81 | 3029 | 87 | 3441 | 214 | NA | NA | 971 | 5 | 8878 | 3 | 6897 | 128 | 5944 | 232 | 8852 | 9 | 600 | 2 | 599 | 10 | |
| East Asia | 3147 | 100 | 3805 | 70 | 2936 | 63 | 2862 | 78 | 3601 | 220 | 1199 | 12 | 1081 | 8 | 4676 | 98 | 4929 | 232 | 5806 | 182 | 4712 | 257 | 587 | 2 | 475 | 13 | |
| East. Eur. & Central Asia | 2717 | 79 | 3595 | 68 | 2860 | 67 | 2934 | 82 | 3376 | 229 | 898 | 14 | NA | NA | 4883 | 94 | 3771 | 210 | 6853 | 164 | 4082 | 301 | 3466 | 0 | 759 | 20 | |
| South Asia | 3053 | 87 | 3655 | 68 | 3025 | 77 | 3171 | 92 | 3478 | 205 | 1066 | 13 | 834 | 4 | 4964 | 93 | 4090 | 315 | 6301 | 165 | 4462 | 273 | 485 | 1 | 654 | 16 | |
| South America | 3077 | 82 | 3713 | 73 | 3092 | 69 | 3011 | 87 | 3391 | 221 | 900 | 14 | 876 | 6 | 5127 | 88 | 3215 | 233 | 5975 | 214 | 4533 | 279 | 521 | 1 | 677 | 13 | |
| Southern Africa | 3033 | 89 | 3657 | 75 | 3183 | 80 | 2898 | 80 | 3373 | 220 | NA | NA | 920 | 6 | 4933 | 84 | 4102 | 330 | 6064 | 199 | 4600 | 278 | 601 | 2 | 1082 | 18 | |
| Middle East | 2855 | 88 | 3494 | 66 | 3039 | 71 | 3133 | 89 | 3481 | 207 | 979 | 13 | NA | NA | 5466 | 80 | 7033 | 80 | 6095 | 208 | 4972 | 246 | 1425 | 1 | 513 | 11 | |
| North Africa | 2842 | 85 | 3827 | 74 | 3486 | 92 | 3125 | 89 | 3478 | 242 | 1154 | 13 | 1365 | 13 | 5397 | 83 | 7972 | 84 | 6052 | 207 | 4753 | 245 | 562 | 2 | 581 | 12 | |
| North America | 2602 | 88 | 3822 | 71 | 2749 | 49 | 3310 | 99 | 3464 | 237 | 1199 | 12 | NA | NA | 3788 | 108 | 3859 | 170 | 6185 | 262 | 5457 | 314 | 670 | 2 | 598 | 17 | |
| Southeast Asia | 2744 | 69 | 3548 | 69 | 2681 | 66 | 3323 | 93 | 3421 | 213 | NA | NA | 1050 | 5 | 4393 | 69 | 5182 | 242 | 5448 | 200 | 4245 | 297 | 526 | 2 | 2470 | 12 | |
| Western Europe | 2598 | 85 | 3748 | 73 | 2770 | 63 | 3013 | 87 | 3252 | 222 | 924 | 14 | NA | NA | 5508 | 79 | 7124 | 90 | 8845 | 7 | 4630 | 263 | 3555 | 0 | 777 | 16 | |

**Calculation of livestock calorie and protein supply from 100% grass-fed livestock**

In the implemented diet change scenarios, we assume that all livestock products are reduced equally, not differentiating between primarily crop-based systems and grazing systems. This is (a) due to the the FBS and CBS data based calculation (FBS and CBS data provide aggregate amounts of feed not differentiating between different animal species or products) and (b) avoids additional assumptions on shifts in relative contributions of specific livestock products and livestock production systems. Yet, livestock systems uniquely fed on rainfed pasture areas would allow for livestock production without contributing to EFR transgressions and could even allow to sustain a higher calorie supply within limited water resources. For contextualization of our results, we therefore roughly estimated the potential global calorie and protein supply from 100% grass-fed livestock for the DC0 scenario by adapting the calculation from Van Zanten et al. (2016). As outlined in Van Zanten et al. (2016), a grazing intensity of 0.5 Tropical Livestock Units (TLU = 250 kg live weight) per ha is assumed on all global pasture areas (Pasturearea = 2961 Mha according to our land use input (Portman et al. 2010)), as this is the average livestock density on marginal pasture areas derived from Herrero et al. (2013) and should avoid overgrazing according to Smil (2014). Global meat and milk supply in terms of weight is then calculated as follows, by accounting for dairy cattle (d), beef cattle (b) and sheep and goat (sg):

TLUshare specifies the relative share of dairy cattle, beef cattle as well as sheep and goat per ha referring to TLUs for 100% grass-based systems on worldwide grasslands derived from Herrero et al. 2013 (taken from Van Zanten et al. (2016), see Table S8). FM (see Table S8) refers to the related average milk and meat fresh matter production per TLU (based on the protein production per TLU provided in Van Zanten et al. (2016), back-calculated to fresh matter based on conversion factors provided within the Supplementary (ibid., p.6)).

**Table S8**: Data for the calculation of potential grass-fed livestock production, derived from Van Zanten et al. (2016) (Supplementary Table S7). TLUshare = relative contribution of dairy cattle, beef cattle and sheep and goat per ha for 100% grass-based systems referring to Tropical Livestock Units (TLU). FMmilk/FMmeat = average milk/meat fresh matter production per TLU and year.

|  |  |  |  |
| --- | --- | --- | --- |
|  | **share of TLU** *TLUshare* | **milk** (kg TLU-1year-1) *FMmilk* | **meat** (kg TLU-1year-1) *FMmeat* |
| **Dairy cattle** (*d*) | 0.05 | 1260.3 | 38.9 |
| **Beef cattle** (*b*) | 0.86 | - | 57.4 |
| **Sheep and goat** (*sg*) | 0.09 | 449.5 | 70.9 |

**Table S9:** Global supply of animal products in terms of weight, calories and proteins according to three studies onsustainable livestock production uniquely based on food processing by-products, food waste, crop residues and grass from pasture areas (non-food-competing feedstuffs). Included studies were taken from Van Zanten et al. (2018), only considering global studies. One global study (Smil, 2014) was excluded, because of the rule of thumb approach without references. To increase comparability between studies and eliminate uncertainties due to differences in calorie and protein conversion factors, the total global weight of the respective animal commodities were either directly retrieved or recalculated based on numbers provided within the papers (see details below). For conversion to calorie and protein supply, the conversion factors from Van Zanten et al. (2018) (Table S2) were then applied to all studies. For non-ruminant meat, the conversion factors for pig and chicken meat were averaged.

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | **Van Zanten et al. (2016)**\* | | | **Schader et al. (2015)**\*\* | | | **Röös et al. (2017)**\*\*\* | | |
| **Included feedstuff** | Food by-products, food waste, grass from pasture areas | | | Crop residues, food by-products, grass from pasture areas | | | Food by-products, food waste, grass from pasture areas | | |
| **Diet** | Healthy vegan (2050 population) | | | Projected (2050 population) | | | Projected (2050 population) | | |
|  | **Weight** (kg) | **Calories** (kcal) | **Protein** (kg) | **Weight** (kg) | **Calories** (kcal) | **Protein** (kg) | **Weight** (kg) | **Calories** (kcal) | **Protein** (kg]) |
| milk ruminants | 1.73E+11 | 1.05E+14 | 5.44E+09 | 4.67E+11 | 2.85E+14 | 1.47E+10 | 9.59E+11 | 5.85E+14 | 3.02E+10 |
| meat ruminants | 9.63E+10 | 1.79E+14 | 1.82E+10 | 6.67E+10 | 1.24E+14 | 1.26E+10 | 1.78E+11 | 3.31E+14 | 3.36E+10 |
| meat pig | 2.52E+11 | 6.91E+14 | 4.16E+10 |  | 0 | 0 | 9.06E+10 | 2.49E+14 | 1.5E+10 |
| non-ruminant meat | 0 | 0 | 0 | 2.67E+10 | 6.53E+13 | 4.68E+09 | 0 | 0 | 0 |
| Eggs | 0 | 0 | 0 | 1.00E+10 | 1.43E+13 | 1.26E+09 | 0 | 0 | 0 |
| **total** |  | **9.75E+14** | **6.52E+10** |  | **4.89E+14** | **3.33E+10** |  | **1.16E+15** | **7.87E+10** |

\*Total global ruminant meat and milk based on 100% grass-based systems was calculated as outlined in the Supplementary of Van Zanten et al. (2016) (p.6) and recapitulated on page 12, with the difference that the global pasture area is assumed to be 3340 Mha according to Van Zanten et al. (2016). Global pork production from food by-products and waste was recalculated based on available energy from by-products and waste as well as feed energy requirements for a 116 kg pig as described in the Supplementary in Van Zanten et al. (2016, p. 3-6) with a world population of 9.7 billion people by 2050.

\*\*Total global provision of animal products in terms of fresh matter was taken from Table S28 for the scenario with 0% food competing feedstuffs fed to livestock (scenario assumptions: no climate change impacts on yields; 20% reduction in livestock productivity due to reduction in food-competing feedstuffs; 2005-2009 pasture area extent and projected cropland area for 2050). The values per capita were converted to total global weight with the assumed world population of 9.14 billion people by 2050.

\*\*\*Global mean animal product provision from Röös et al. (2017) was taken from Van Zanten et al. (2018) (Table 1) as no global data was available directly in Röös et al. (2017). The animal product weight per capita was converted to total global weight with the assumed world population of 9.55 billion by 2050.

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