Supplementary Information Appendix

Data and assumptions

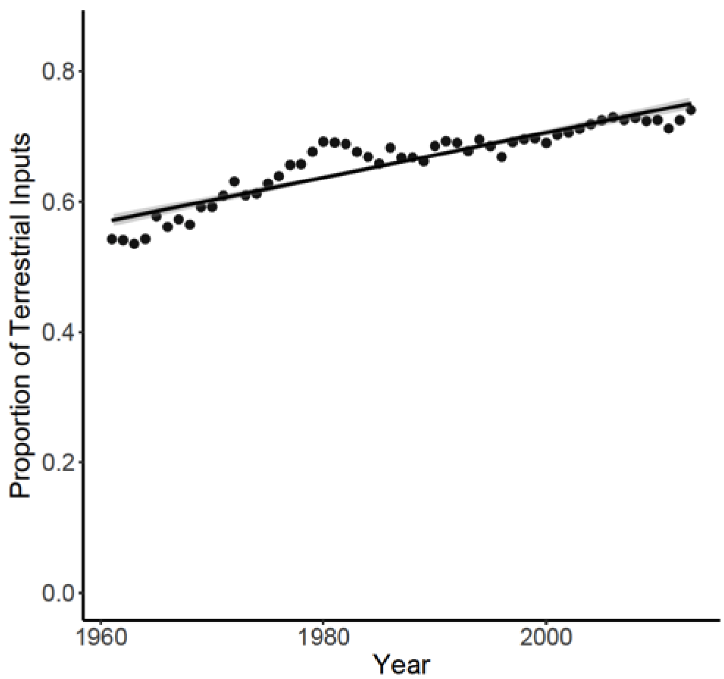

Figure S1. Proportion of inputs from the seven crops (wheat, maize, soy, rapeseed, pulses, barley, and cassava) used for all animal feed relative to other terrestrial feeds from 1961-2013. The increasing trend is statistically significant (F-stat = 287, df = 52, P < 0.001, R_{adj}^2 = 0.85). If this linear trend persists to 2050, these seven crops would contribute to the vast majority of crop inputs (mean ± SE = 0.88 ± 0.01) and thus land-use. Data sourced from Food Balance Sheets from FAOStat (1).

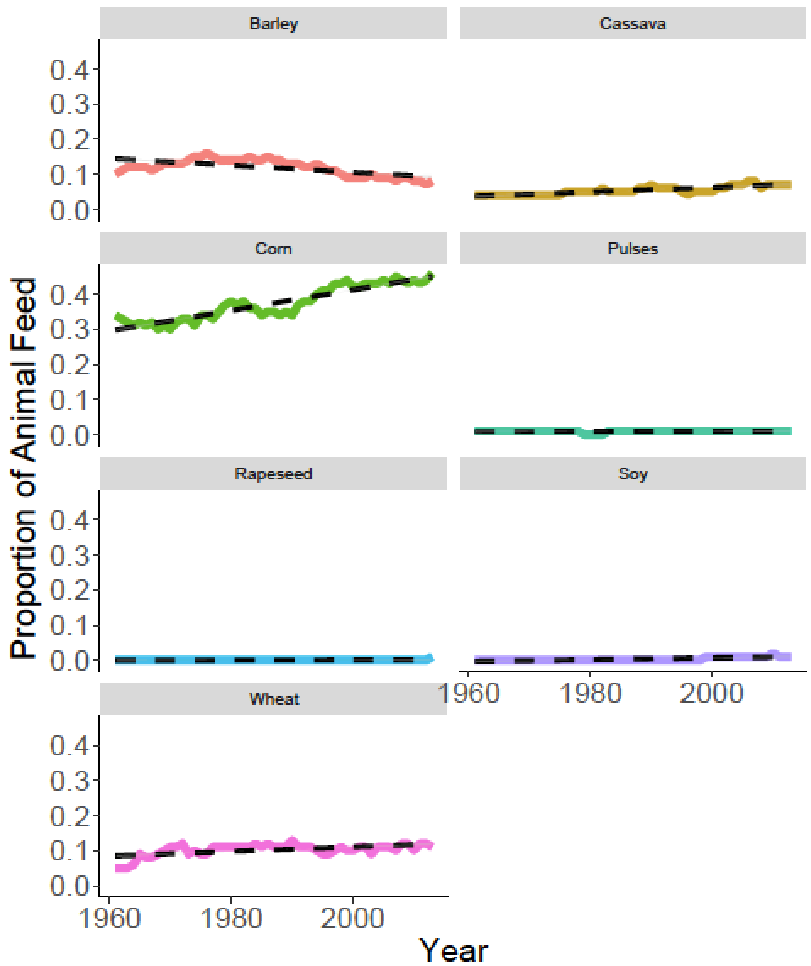

Figure S2. Proportional crop feed inclusion over time estimated by FAO for the seven crops used in this study. *Dash lines* indicate the linear model results for each crop type. Linear trends statistically significant ($p < 0.001$), except for pulses and rapeseed ($p = 0.37$ and $p = 0.09$, respectively), which remain constant.

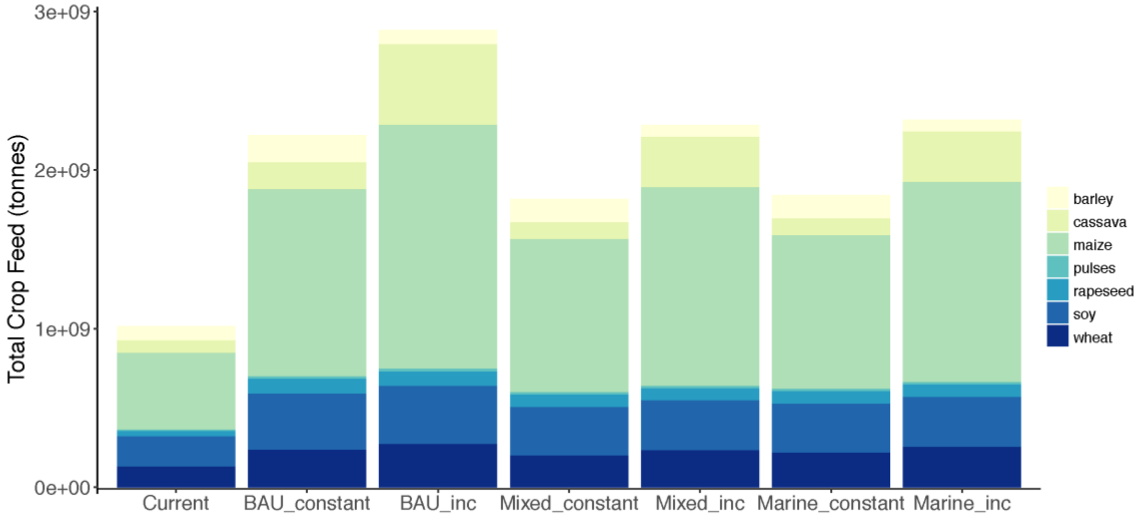

Figure S3. Estimates of animal feed crops with (*inc*) and without (*constant*) greater inclusion and homogenization of the seven crop assessed in this study for each scenario.

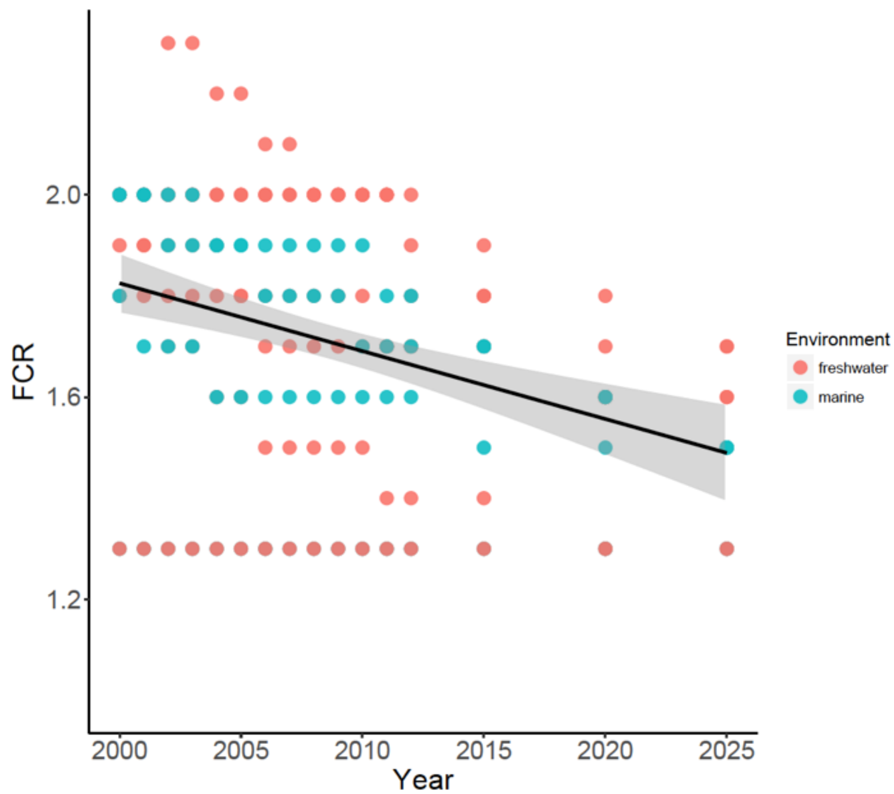

Figure S4. Feed conversation ratios (FCR; F_a parameter in our study) of aquaculture species/groups reported in Tacon and Metian (2). (Linear model: F-stat = 25.6, df =174, $R^2_{adj} = 0.12$, p <0.001).

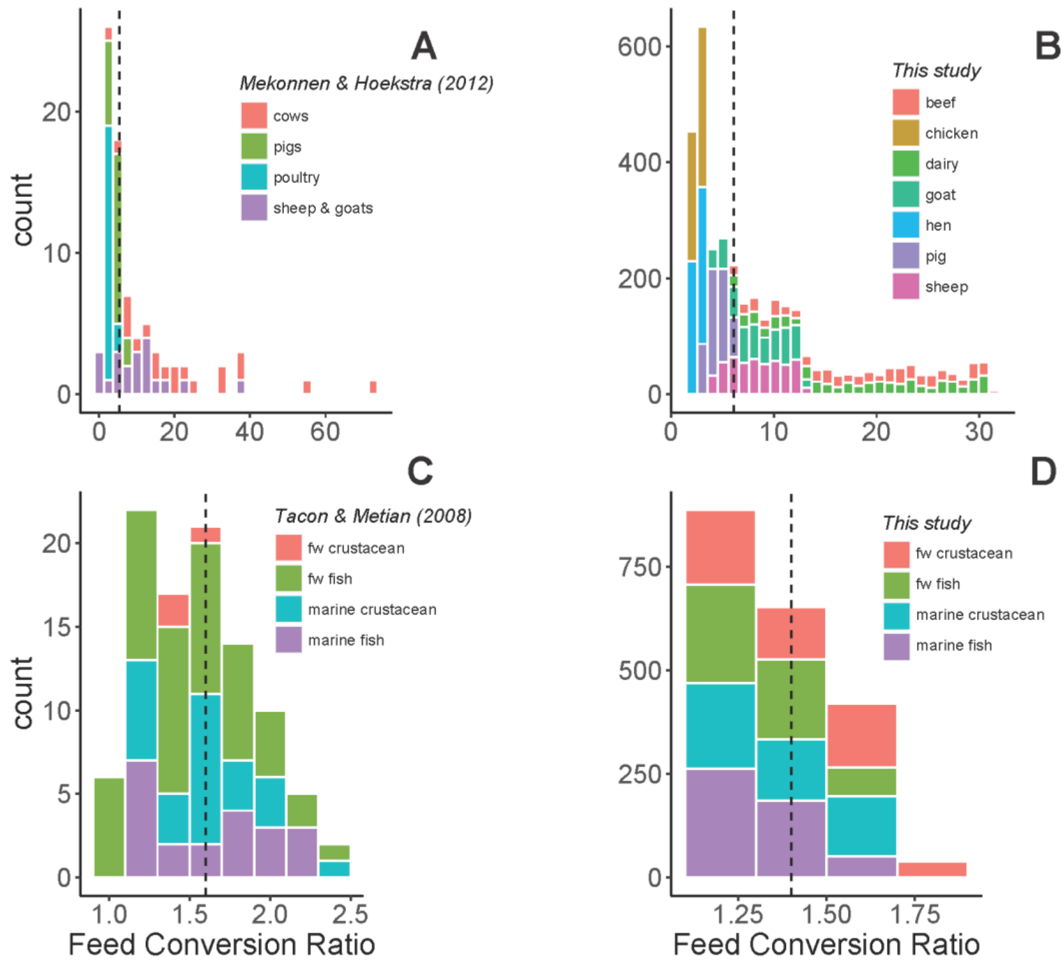

Figure S5. Regional feed conversion ratio distributions for livestock and poultry (*top panels*) and fed aquaculture groups (*bottom panels*) from **(A)** Mekennon and Hoekstra (3) and **(B)** this study ($n_{simulations}$ = 500), and **(C)** Tacon and Metian (4), and, **(D)** this study combined. The median values shown as *dashed lines*. Note, the Tacon and Metian (4) values in *panel C* are self-reported, country values from a 2005/2007 survey. Our values (*panel C*) are based on the average improved efficiencies reported in Tacon and Metian (2), that are not country specific, but result in an average 0.2 global reduction in feed conversion ratios – reflected in the original (2005/2007) median equal to 1.6 and our median of 1.4.

Table S1. Average proportion of edible biomass derived from Bognár and Tilman and Clark (5, 6).

Animal	Edible
Ruminants	0.6
Dairy cow & laying hen*	2.2
Pig	0.5
Broiler chicken	0.6
Fish	0.7
Crustacean	0.3
Mollusc	0.2

**More edible biomass produced from dairy and eggs*

Table S2. Assigned proportion of livestock biomass produced by either feed (P_j) or grazing ($1\text{-}P_j$), for each region. Data source, Mekonnen and Hoekstra (3).

Region	Ruminant Fed (P_j)	Ruminant Grazed ($1\text{-}P_j$)
Australia	0.69	0.31
Canada	0.82	0.18
Caribbean	0.69	0.31
Central America	0.64	0.36
China	0.90	0.10
Eastern Africa	0.44	0.56
Eastern Asia	0.90	0.10
Europe	0.85	0.15
East Europe and CIS	0.63	0.37
Island Nations	0.69	0.31
Central Africa	0.44	0.56
Middle East	0.54	0.46
New Zealand	0.69	0.31
Northern Africa	0.54	0.46
South America	0.64	0.36
Southern Africa	0.44	0.56
Southern Asia	0.91	0.09
USA	0.82	0.18
Western Africa	0.44	0.56
Western Asia	0.54	0.46

Table S3. Ranges of future percent increases in animal production. Uniform ranges sampled for future animal production scenarios derived from Tilman and Clark (6), Bognár (5), FAO (7), and Alexandratos and Bruinsma (8). These ranges represent likely minimum and maximum amounts of respective animal production in 2050, used in our scenario simulations to account for uncertainty in projection estimates. *See Methods for details*.

Nations	Taxa	Range
Developed	beef	11-51%
Developed	goat	0-24%
Developed	sheep	0-26%
Developed	broiler chicken	10-50%
Developed	pig	20-60%
Developed	dairy cow	0-37%
Developed	laying hen	0-37%
Developed	marine fish	80-120%
Developed	marine crustacean	80-120%
Developed	fw fish	80-120%
Developed	fw crustacean	80-120%
Developed	mollusc	80-120%
Developing	beef	31-71%
Developing	goat	4-44%
Developing	sheep	6-46%
Developing	broiler chicken	30-70%
Developing	pig	40-80%
Developing	dairy cow	17-57%
Developing	laying hen	17-57%
Developing	marine fish	100-140%
Developing	marine crustacean	100-140%
Developing	fw fish	100-140%
Developing	fw crustacean	100-140%
Developing	mollusc	100-140%

Table S4. Average 2050 regional diet proportions ($A_{i,a}$) for farmed taxa, by crop. Initial values derived from Tilman and Clark (6), Tacon and Metian (2), and FAO data (1). Proportions that do not add to 1 are assumed to reflect inputs from other sources (e.g., aquatic inputs).

Region	Group	Wheat	Maize	Soy	Rapeseed	Pulses	Barley	Cassava
Australia	freshwater aq.	0.47	0.06	0.22	0.03	0.22	0	0
Canada	freshwater aq.	0.47	0.06	0.22	0.03	0.22	0	0
Caribbean	freshwater aq.	0.37	0.26	0.27	0.01	0.09	0	0
Central Africa	freshwater aq.	0.21	0.4	0.39	0	0	0	0
Central America	freshwater aq.	0.37	0.32	0.31	0	0	0	0
China	freshwater aq.	0.16	0.33	0.51	0	0	0	0
Eastern Africa	freshwater aq.	0.24	0.41	0.35	0	0	0	0
Eastern Asia	freshwater aq.	0.37	0.17	0.31	0.02	0.13	0	0
Europe	freshwater aq.	0.47	0.06	0.22	0.03	0.22	0	0
Middle East	freshwater aq.	0.36	0.28	0.32	0.01	0.03	0	0
New Zealand	freshwater aq.	0.48	0.07	0.21	0.03	0.21	0	0
Northern Africa	freshwater aq.	0.34	0.31	0.31	0.01	0.03	0	0
Other	freshwater aq.	0.35	0.28	0.3	0.01	0.06	0	0
South America	freshwater aq.	0.46	0.19	0.22	0.02	0.11	0	0
Southern Africa	freshwater aq.	0.46	0.29	0.22	0	0.03	0	0
Southern Asia	freshwater aq.	0.33	0.3	0.33	0.01	0.03	0	0
USA	freshwater aq.	0.47	0.06	0.22	0.03	0.22	0	0
Western Africa	freshwater aq.	0.2	0.39	0.41	0	0	0	0
Western Asia	freshwater aq.	0.45	0.22	0.22	0.01	0.1	0	0
Australia	marine aq.	0.47	0.17	0.22	0.03	0	0	0
Canada	marine aq.	0.47	0.17	0.22	0.03	0	0	0
Caribbean	marine aq.	0.37	0.35	0.27	0.01	0	0	0
Central America	marine aq.	0.37	0.32	0.31	0	0	0	0
China	marine aq.	0.16	0.33	0.51	0	0	0	0
Eastern Africa	marine aq.	0.24	0.41	0.35	0	0	0	0
Eastern Asia	marine aq.	0.37	0.28	0.31	0.02	0	0	0
Europe	marine aq.	0.47	0.17	0.22	0.03	0	0	0
Middle East	marine aq.	0.36	0.31	0.32	0.01	0	0	0
New Zealand	marine aq.	0.48	0.18	0.21	0.03	0	0	0
Northern Africa	marine aq.	0.34	0.34	0.31	0.01	0	0	0
Other	marine aq.	0.35	0.34	0.3	0.01	0	0	0
South America	marine aq.	0.46	0.29	0.22	0.02	0	0	0
Southern Africa	marine aq.	0.46	0.32	0.22	0	0	0	0
Southern Asia	marine aq.	0.33	0.33	0.33	0.01	0	0	0
USA	marine aq.	0.47	0.17	0.22	0.03	0	0	0
Western Africa	marine aq.	0.2	0.39	0.41	0	0	0	0

Western Asia	marine aq.	0.45	0.31	0.22	0.01	0	0	0
All regions	beef	0	0.54	0	0.08	0.15	0	0
All regions	chicken	0.11	0.28	0.54	0	0	0	0
All regions	dairy cow	0.05	0.23	0.31	0.28	0.1	0.03	0
All regions	goat	0.15	0.22	0.22	0	0.19	0.13	0
All regions	hen	0.21	0.29	0.42	0	0	0	0
All regions	pig	0.26	0.14	0.4	0.06	0.06	0.05	0.03
All regions	sheep	0.15	0.22	0.22	0	0.19	0.13	0

Table S5. Feed conservation ratio ranges for each animal group (F_a). Assuming a uniform distribution between the maximum and minimum feed conversion ratio, the baseline 'current' model and all future scenarios were calculated 500 times from randomly sampled values of the distributions. Data sources: Brand et al. (9), Hasan and Soto (10), Marine Harvest (11), Mekonnen and Hoestra, Shike (3), Tolkamp (12), Wilkinson (13), Tacon and Metian (2). Tacon and Metian and Mekonnen and Hoestra were used as the primary bounding sources, but values were compared to the other listed articles – particularly for F_{min} and possible improved 2050 efficiencies.

Animal	F_{min}	F_{max}
beef	6.0	31.2
dairy cow	6.0	31.2
pig	3.0	5.9
goat	4.0	12.9
sheep	4.0	12.9
broiler chicken	1.8	3.5
laying hen	1.8	3.5
freshwater finfish	1.1	1.6
freshwater crustacean	1.1	1.8
marine finfish	1.1	1.6
marine crustacean	1.1	1.7

Results and Sensitivity

Table S6. Percent land spared (positive values) or used (negative values) when accounting for feed or feed & grazing land-use requirement under the mixed and marine scenarios.

	Feed Only		***Feed & Grazing***	
Country	*% Mixed Land Used or Spared*	*% Marine Land Used or Spared*	*% Mixed Land Used or Spared*	*% Marine Land Used or Spared*
Afghanistan	9%	9%	7%	7%
Albania	14%	14%	10%	10%
Algeria	15%	15%	19%	19%
American Samoa	60%	60%	22%	22%
Angola	56%	56%	30%	29%
Antigua and Barbuda	38%	38%	4%	4%
Argentina	19%	16%	37%	36%
Armenia	7%	10%	19%	18%
Aruba	0%	0%	0%	0%
Australia	15%	5%	22%	21%
Austria	25%	24%	20%	19%
Azerbaijan	8%	8%	14%	13%
Bahamas	33%	33%	10%	9%
Bahrain	25%	25%	24%	24%
Bangladesh	-5%	0%	9%	9%
Barbados	42%	42%	9%	9%
Belarus	26%	26%	21%	20%
Belgium	24%	18%	21%	20%
Belize	13%	-30%	24%	10%
Benin	32%	33%	18%	18%
Bermuda	0%	0%	7%	6%
Bhutan	5%	5%	6%	5%
Bolivia (Plurinational State of)	24%	22%	37%	37%
Bonaire, Saint Eustatius and Saba	0%	0%	0%	0%
Bosnia and Herzegovina	9%	10%	7%	7%
Botswana	26%	26%	17%	16%
Brazil	26%	24%	29%	28%
British Virgin Islands	0%	0%	39%	39%
Brunei Darussalam	0%	0%	47%	47%
Bulgaria	18%	11%	12%	9%
Burkina Faso	60%	60%	10%	10%
Burundi	25%	25%	12%	11%

Cabo Verde	21%	21%	15%	15%
Cambodia	18%	30%	28%	30%
Cameroon	42%	42%	29%	28%
Canada	21%	15%	23%	21%
Cayman Islands	0%	0%	0%	0%
Central African Republic	0%	0%	25%	25%
Chad	31%	31%	16%	16%
Channel Islands	0%	0%	0%	0%
Chile	3%	-37%	20%	18%
China, Hong Kong SAR	0%	0%	50%	50%
China, Macao SAR	0%	0%	51%	51%
China, mainland	18%	24%	26%	28%
China, Taiwan Province of	16%	3%	14%	12%
Colombia	27%	28%	18%	17%
Comoros	20%	20%	15%	15%
Congo	60%	60%	41%	41%
Cook Islands	60%	60%	38%	38%
Costa Rica	48%	48%	14%	13%
Cote d'Ivoire	36%	35%	15%	15%
Croatia	18%	13%	14%	12%
Cuba	35%	34%	19%	19%
Cyprus	44%	44%	19%	19%
Czech Republic	0%	0%	1%	0%
Czechia	25%	26%	27%	28%
Czechoslovakia	0%	0%	0%	0%
Democratic People's Republic of Korea	22%	23%	27%	27%
Democratic Republic of the Congo	48%	49%	33%	33%
Denmark	30%	28%	18%	17%
Djibouti	0%	0%	22%	22%
Dominica	45%	45%	10%	10%
Dominican Republic	33%	33%	22%	21%
Ecuador	18%	-8%	20%	19%
Egypt	-4%	-40%	23%	20%
El Salvador	20%	19%	10%	10%
Equatorial Guinea	60%	60%	38%	38%
Eritrea	11%	10%	6%	6%
Estonia	17%	17%	12%	11%
Ethiopia	10%	9%	6%	5%
Falkland Islands (Malvinas)	0%	0%	19%	19%
Faroe Islands	0%	0%	15%	15%

Fiji	55%	55%	23%	22%
Finland	20%	14%	17%	15%
France	20%	16%	18%	17%
French Guiana	33%	33%	32%	32%
French Polynesia	60%	60%	24%	24%
Gabon	50%	50%	25%	24%
Gambia	17%	17%	11%	10%
Georgia	11%	11%	6%	5%
Germany	24%	22%	16%	16%
Ghana	25%	31%	15%	16%
Greece	9%	-13%	14%	9%
Greenland	0%	0%	12%	12%
Grenada	20%	20%	22%	21%
Guadeloupe	60%	60%	48%	48%
Guam	2%	-3%	29%	27%
Guatemala	22%	19%	15%	15%
Guinea	18%	18%	13%	12%
Guinea-Bissau	21%	20%	10%	10%
Guyana	26%	25%	10%	9%
Haiti	42%	42%	22%	21%
Honduras	18%	9%	14%	13%
Hungary	22%	19%	17%	15%
Iceland	0%	0%	12%	12%
India	6%	6%	5%	5%
Indonesia	-2%	-13%	23%	18%
Iran (Islamic Republic of)	11%	11%	13%	13%
Iraq	7%	14%	17%	18%
Ireland	13%	10%	19%	18%
Israel	21%	23%	38%	38%
Italy	23%	23%	19%	19%
Jamaica	42%	43%	29%	29%
Japan	26%	15%	31%	31%
Jordan	21%	21%	28%	28%
Kazakhstan	13%	6%	18%	17%
Kenya	16%	16%	11%	10%
Kiribati	0%	0%	0%	0%
Kuwait	18%	17%	25%	25%
Kyrgyzstan	15%	14%	17%	17%
Lao People's Democratic Republic	18%	36%	29%	36%
Latvia	14%	5%	10%	7%
Lebanon	17%	17%	34%	33%
Lesotho	21%	22%	14%	13%

Liberia	30%	30%	21%	20%
Libya	16%	16%	16%	16%
Liechtenstein	0%	0%	1%	0%
Lithuania	15%	11%	11%	10%
Luxembourg	16%	15%	13%	13%
Madagascar	49%	49%	12%	12%
Malawi	41%	42%	27%	27%
Malaysia	15%	3%	18%	18%
Maldives	0%	0%	0%	0%
Mali	19%	19%	12%	12%
Malta	24%	24%	13%	12%
Marshall Islands	0%	0%	0%	0%
Martinique	60%	60%	47%	47%
Mauritania	0%	0%	14%	14%
Mauritius	33%	28%	33%	32%
Mayotte	0%	0%	0%	0%
Mexico	35%	33%	35%	35%
Micronesia (Federated States of)	39%	39%	49%	49%
Mongolia	12%	12%	15%	15%
Montenegro	11%	11%	7%	7%
Montserrat	0%	0%	25%	24%
Morocco	13%	13%	18%	18%
Mozambique	33%	33%	15%	14%
Myanmar	8%	16%	11%	12%
Namibia	27%	27%	18%	18%
Nauru	0%	0%	0%	0%
Nepal	11%	13%	10%	10%
Netherlands	24%	24%	15%	14%
New Caledonia	21%	3%	29%	28%
New Zealand	9%	7%	10%	10%
Nicaragua	25%	19%	14%	14%
Niger	17%	16%	13%	13%
Nigeria	45%	47%	24%	24%
Niue	59%	59%	8%	8%
Norfolk Island	0%	0%	0%	0%
Northern Mariana Is.	0%	0%	0%	0%
Norway	-5%	-41%	16%	11%
Occupied Palestinian Territory	22%	21%	25%	25%
Oman	14%	14%	18%	17%
Pakistan	10%	10%	11%	11%
Palau	0%	0%	0%	0%

Panama	38%	32%	32%	31%
Papua New Guinea	55%	56%	44%	44%
Paraguay	20%	18%	37%	36%
Peru	33%	31%	23%	23%
Philippines	21%	0%	30%	15%
Poland	21%	20%	14%	13%
Portugal	26%	24%	18%	18%
Puerto Rico	60%	60%	13%	12%
Qatar	24%	24%	23%	23%
R'union	60%	60%	13%	12%
Republic of Korea	33%	26%	42%	42%
Republic of Moldova	26%	26%	15%	15%
Romania	16%	13%	12%	10%
Russian Federation	25%	21%	21%	21%
Rwanda	0%	0%	15%	15%
Saint Kitts and Nevis	0%	0%	45%	45%
Saint Lucia	0%	0%	31%	31%
Saint Pierre and Miquelon	0%	0%	0%	0%
Saint Vincent and the Grenadines	55%	55%	21%	21%
Samoa	60%	60%	36%	35%
Sao Tome and Principe	17%	17%	16%	16%
Saudi Arabia	21%	16%	23%	22%
Senegal	26%	26%	12%	12%
Serbia	19%	17%	15%	14%
Serbia and Montenegro	0%	0%	0%	0%
Seychelles	60%	60%	37%	37%
Sierra Leone	58%	58%	16%	15%
Singapore	0%	0%	39%	39%
Slovakia	16%	16%	12%	12%
Slovenia	20%	20%	16%	16%
Solomon Islands	60%	60%	26%	26%
Somalia	15%	14%	10%	10%
South Africa	35%	33%	35%	35%
South Sudan	10%	9%	6%	6%
Spain	31%	29%	23%	22%
Sri Lanka	21%	22%	12%	12%
Sudan	7%	7%	6%	5%
Suriname	31%	30%	37%	36%
Swaziland	24%	24%	15%	14%
Sweden	20%	20%	18%	18%
Switzerland	20%	20%	15%	15%

Syrian Arab Republic	16%	16%	18%	18%
Tajikistan	6%	5%	8%	7%
Thailand	35%	26%	33%	27%
The former Yugoslav Republic of Macedonia	8%	8%	6%	6%
Timor-Leste	47%	47%	43%	43%
Togo	28%	28%	21%	20%
Tokelau	0%	0%	0%	0%
Tonga	60%	60%	41%	41%
Trinidad and Tobago	35%	35%	11%	11%
Tunisia	10%	8%	14%	14%
Turkey	12%	9%	18%	17%
Turkmenistan	11%	11%	18%	18%
Turks and Caicos Islands	0%	0%	0%	0%
Tuvalu	0%	0%	0%	0%
Uganda	14%	17%	9%	8%
Ukraine	21%	18%	19%	18%
United Arab Emirates	0%	0%	26%	26%
United Kingdom	12%	-2%	18%	16%
United Republic of Tanzania	21%	20%	7%	7%
United States of America	22%	20%	25%	24%
United States Virgin Islands	0%	0%	34%	34%
Uruguay	15%	11%	33%	32%
US Virgin Islands	0%	0%	0%	0%
Uzbekistan	4%	5%	20%	20%
Vanuatu	31%	30%	21%	20%
Venezuela (Bolivarian Republic of)	34%	33%	22%	22%
Viet Nam	15%	7%	30%	26%
Wallis and Futuna Islands	60%	60%	23%	23%
Western Sahara	0%	0%	24%	24%
Yemen	24%	24%	24%	24%
Yugoslavia	0%	0%	0%	0%
Zambia	33%	36%	34%	34%
Zanzibar	0%	0%	0%	0%
Zimbabwe	15%	16%	14%	14%

Comparisons to other studies

We took several steps to test the overall performance and sensitivity of our model given our assumptions. First, we examined the general patterns of feed, paying particular attention to aquaculture model outputs due to the limited amount of data at the country level (Table S7). It has been estimated ca. 55 – 70 million tonnes of total feed (compound and farm-made, of which contain crop inputs) is used for aquaculture (2, 14, 15). Our values are based on (harmonized) FAO commodity balance data (i.e., crop primary equivalence). Troell et al. (15) estimate crop equivalences for aquaculture compound feed at ca. 30 million tonnes. We simplified the number of crops and based our values on Tilman and Clark (6) regional percentages, which produces 40 million tonnes of crop equivalence (Table S7), or 4% of total crops used for feed in our analysis. Our model likely produces a higher value, but equivalent crop percentage, since we account for, but do not differentiate between, compound and farm-made crop use, as well as the calculations are based on more recent FAO (2014) aquaculture production estimates (7).

In another benchmark, FAO estimates that globally approximately one-third of crops are destine for feed (16). The total crop production in 2013 (FAOSTAT (1)) of wheat, maize, soy, rapeseed, pulses, barley, and cassava products was 2.7 billion tonnes; our 'current' global livestock and poultry-only estimate (meat plus dairy and eggs; 980 million tonnes) results in 36% of that total. Accounting for aquaculture increases that to 38%.

Table S7. Model outputs of total animal crop feed (tonnes) for the four scenarios.

Group	Current (baseline)	BAU 2050	Mixed 2050	Marine 2050
Dairy & eggs	2.7E+08	6.2E+08	6.2E+08	6.2E+08
Meat	7.1E+08	2.2E+09	1.5E+09	1.5E+09
Seafood	4.0E+07	9.1E+07	1.8E+08	2.1E+08
Total	***1.0E+09***	***2.9E+09***	***2.3E+09***	***2.3E+09***

In addition to evaluating crop-use metrics, we assessed the efficacy of the model by quantifying the model overestimation of cropland compared with FAO estimates (1). This is somewhat challenging, as multiple crops can be cultivated in any given location, either through ‘multiple cropping’ or ‘crop rotation’ (17). In addition, surveyed and ground-truthed estimates of the area of each crop are not currently collected in many nations (18). As such, we assessed measures of error of our model relative to current values with three different scenarios. First, we ran the baseline (current) scenario (the assumptions used and presented in the main text) and quantified how often the model overestimated the area of each crop. We calculated overestimates based on both FAO values for a specific crop and total reported area across these crops. The latter portion was important since, as we mentioned, multiple crops can be grown on same land and thus total cropped area may be a more representative threshold than specific FAO crop estimates. No error estimates are available around the FAO values, so we set our limit of an ‘overestimate’ at 1,000ha in order to detect the most aberrant values. We then tabulated the number of regions that went over for each crop, the relative error rate of the 1,610 values (7 crops for 230 regions), the number of regions that went over the summation of total land of those seven crops, and the average hectares overestimated for the total cropland (± standard error) (Table S8 and S9). For context and comparison, we ran the model and calculated the same overestimation metrics for two other scenarios: (1) feed requirements only being met by domestic production and (2) feed requirements met by imports only (i.e., by exporting countries).

Table S8. Number of FAO regions that overestimated area for each crop (of a total 230 regions) by more than 1,000ha and the overestimation rate of the three test scenarios.

Scenario	Wheat	Maize	Soy	Rapeseed	Pulses	Barley	Cassava	Total	Error Rate
Current	0	6	5	6	34	14	3	68	0.04
All domestic	20	58	63	19	30	26	4	220	0.14
All imports	0	1	1	13	10	14	1	40	0.02

Table S9. Number of regions, average, and standard error (SE) of hectares overestimated (> 1,000ha) when compared to the total seven-crop area of each country.

Scenario	No. Regions	Average ha overestimate	SE
Current	10	435,177	228,437
All domestic	60	418,616	148,546
All imports	15	1,819,267	621,472

We find our 'current' simulation model used in the study performs relatively well compared to the extremes (all imports or domestic). Importantly, we also compared our values of area required for feed-crops to the estimated total area of land that is currently cultivated for all crops (not just crops evaluated in this study) in each country. We found our model outputs are within the bounds of cultivated FAO land estimates (mean ± SE = 14% ± 1.3%). It should also be noted, there are no values available for how much cropland each country uses for feed, so underestimates cannot be assessed, nor can the degree to which they balance out overestimates. Encouraging the gathering of such data should be, and currently is, a priority of global organizations including the World Bank and FAO.

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