Supplementary Information

Future food sufficiency in the face of climate and societal changes

Contents

Text S1a: Caloric yields modeling: model performance

In order to assess the quality of projections from our model, we put aside 10% of the data during the training process, which is then used to evaluate its performance. To do that, we use two different metrics, the RMSE (Root Mean Square Error) that allows us to have a quantitative measure of the standard deviation of the residuals and the coefficient of determination R-squared that gives us an idea on how well the model replicates observed outcomes based on the ability to explain their variation. We find, for the 10% of data kept aside, a R-squared value of 0.95 and a RMSE of 1.06e+9 calories per hectare (the average calories produced per hectare is around 7e+9). Moreover, with our convex-hull analysis, we ensured that all the future projected points lied, for most of them, in the subspace spanned by the 2000 variables, strengthening our intuitions about the model robustness. We also used an early stopping criterion on a testing set error to prevent overfitting, but considering the large amount of training data used in our model, it was never activated.

Text S1b: List of nutritionally relevant crops

As named by Monfreda et al.[1], these 100 crops were considered as nutritionally relevant. Forage crops, cash crops, spices and oils were excluded. Data in these columns is relative to total production of all crops. Cropland harvested area and yield were derived from Monfreda et al. [1] which combines sub-national agricultural statistics from ~12,500 political units and satellite data from 1997-2004. Calorie conversions were based on Tilman et al.[2].

Crop List:
almond, apple, apricot, artichoke, asparagus, avocado, banana, barley, bean, berrynes, blueberry, brazil, broadbean, buckwheat, cabbage, carob, carrot, cashew, cassava, cauliflower, cherry, chestnut, chickpea, chicory, chilleetc, cocoa, coconut, cowpea, cranberry, cucumberetc, currant, date, eggplant, fig, fruitnes, garlic, ginger, gooseberry, grape, grapefruitetc, greenbroadbean, greencorn, greenonion, greenpea, groundnut, hazelnut, kiwi, lemon, lime, lentil, lettuce, lupin, maize, mango, melonetc, millet, mushroom, nutnes, oats, okra, olive, onion, orange, papaya, pea, peachetc, pear, persimmon, pigeonpea, pineapple, pistachio, plantain, plum, potato, pulsenes, pumpkin etc, quince, quinoa, rapeseed, rasberry, rice, rye, sesame, sorghum, sourcherry, soybean, spinach, strawberry, stringbean, sunflower, sweetpotato, tang, taro, tomato, triticale, tropicalnes, walnut, watermelon, wheat, yam, yautia

Fig S1: Validity of the aggregation assumption

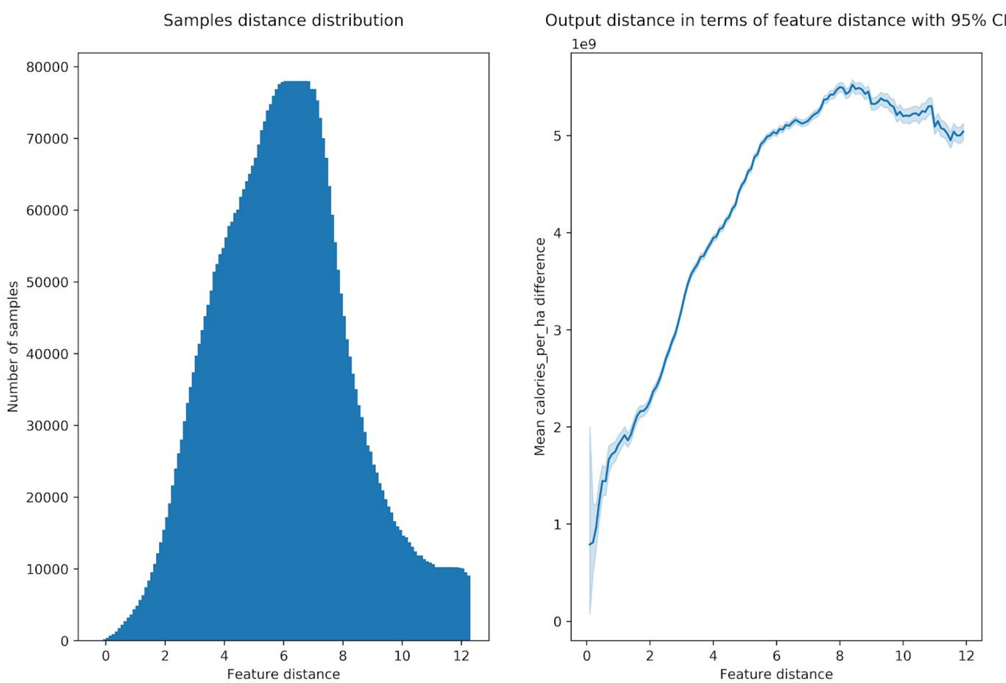


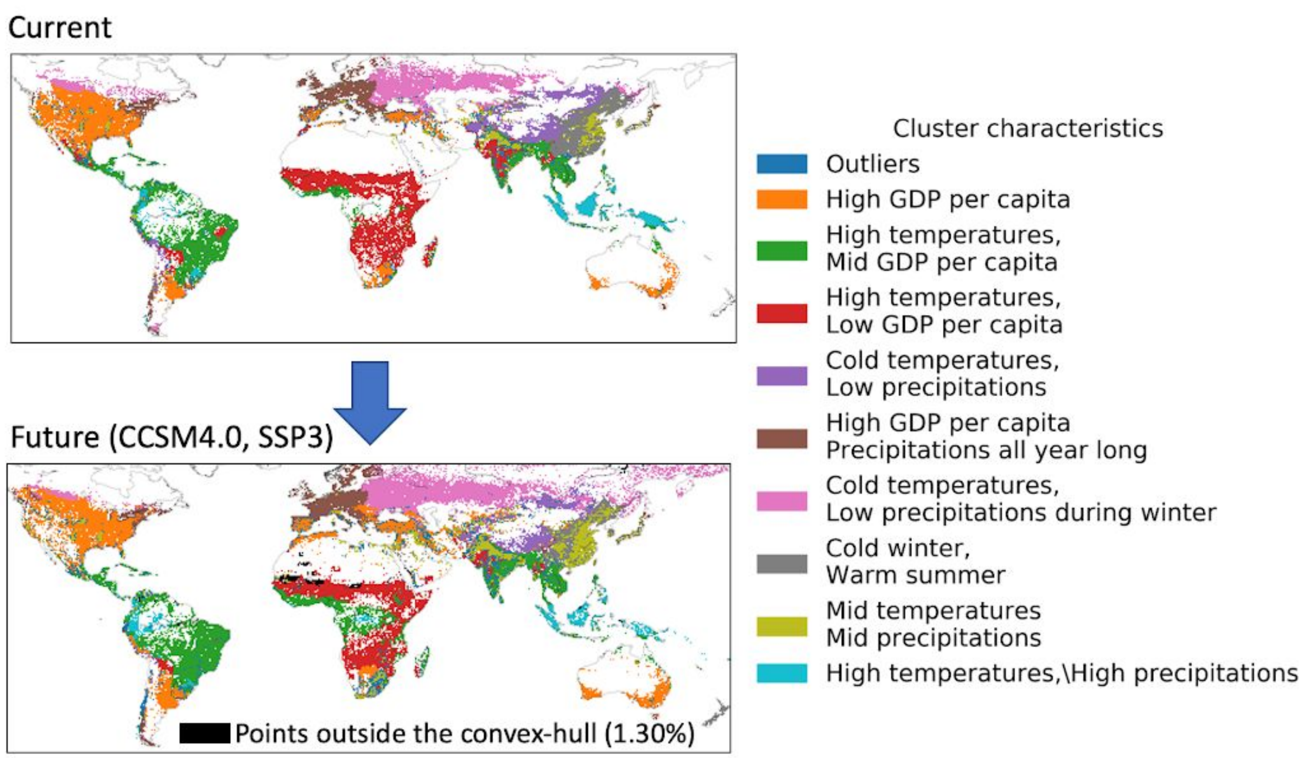
Figure S1 - Plot of the difference in the caloric yields in terms of the feature distance, giving us a definition of similarity between two data points (the more two points will be similar, the smaller will be their Euclidean distance). The increasing curve shows that the higher the Euclidean distance (the less similar are the points), the higher is the difference in terms of caloric yields, i.e similar points have similar aggregated caloric yields. Taking all the points until quantile (0.95) of the euclidean distances (really high values being *outliers* with little to no information of the general trend) we find a pearson correlation coefficient of 0.91 and a p-value of 2.02e-43. Then if we assume measuring the similarity of the points has less relevance when the Euclidean distance is too big and limit us to the points that have a distance < 6.3 (average distance and median are around 6.1), we find a pearson correlation coefficient of 0.995 and a p-value of 7.19e-63. This result shows again that the more similar points are, the closer are their caloric yields.

Fig S2 (a-e): Change in distributions from 2000 to 2050: Clusters and points outside of convex hull, for 4 GCMs.

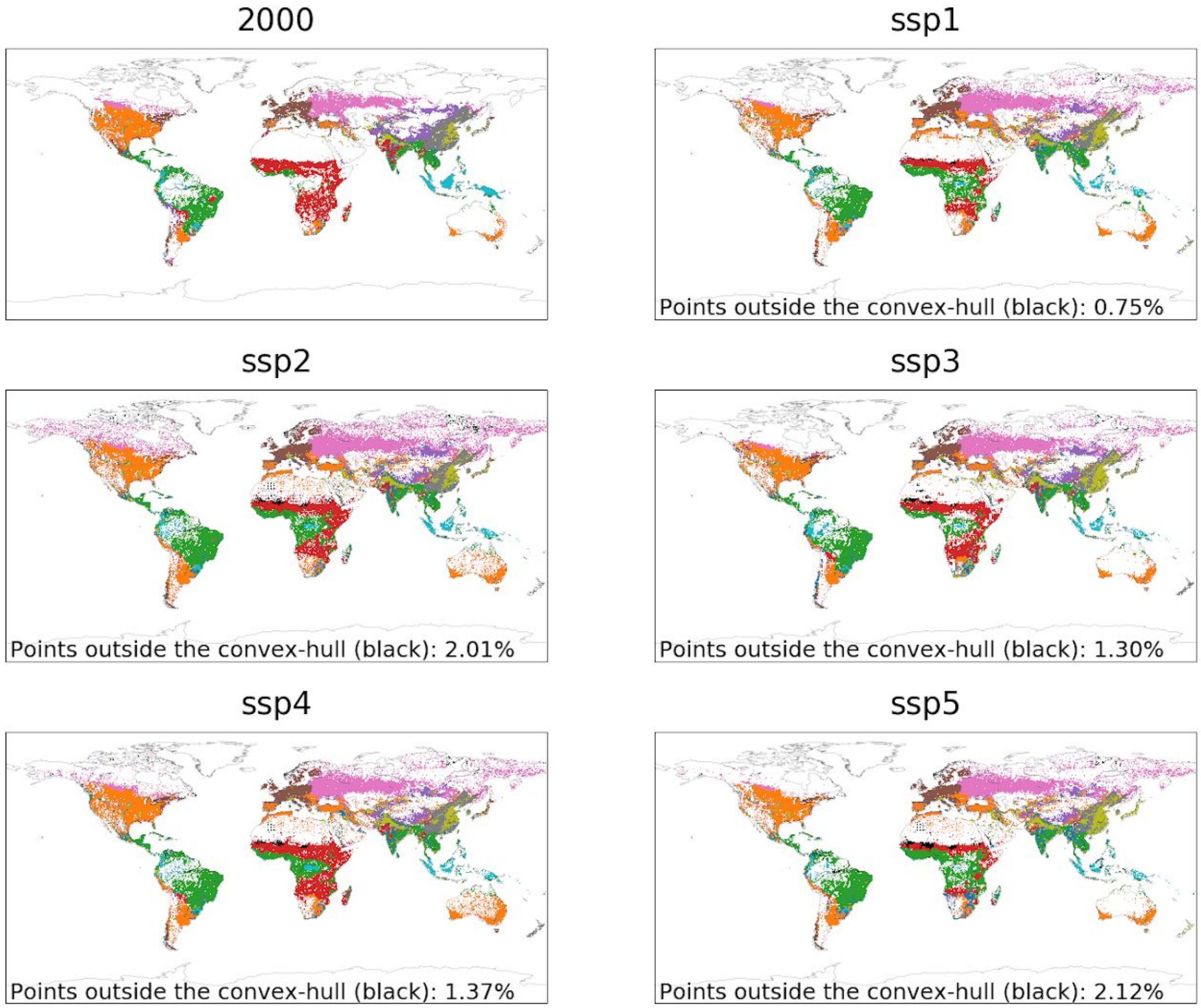
Figure S2a provides an example (for the model CCSM4.0 and scenario SSP3) of the change in distribution of the points, grouped in 10 clusters based on the variables inputs to the yields model. The main characteristics of each cluster are detailed in the legend.

Figures S2b-c-d-e detail the clusters for each of the 20 scenarios. The legend of clusters from fig. S2a applies to all. Points outside of the convex hull of the training dataset represent only < 3% of the points in 18 out of the 20 scenarios (and < 2% in 12 scenarios). Only under HadGem climate model do 3.2% fall outside of the convex hull in SSP 2, and 5.7% in SSP 5. Points outside of the convex hull are mostly located in South Sahara due to an increase in temperatures (Annual mean temperature feature).

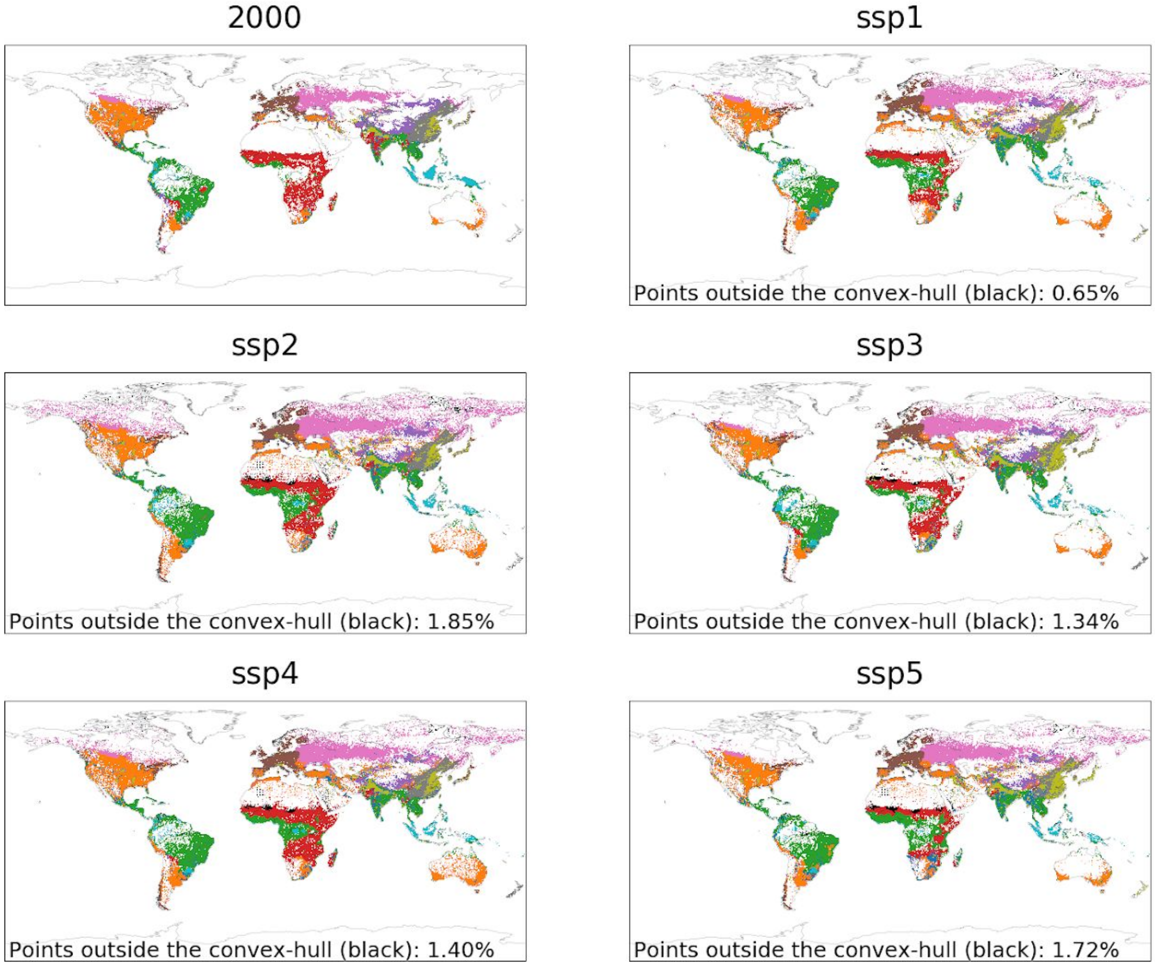
a) Clusters legend



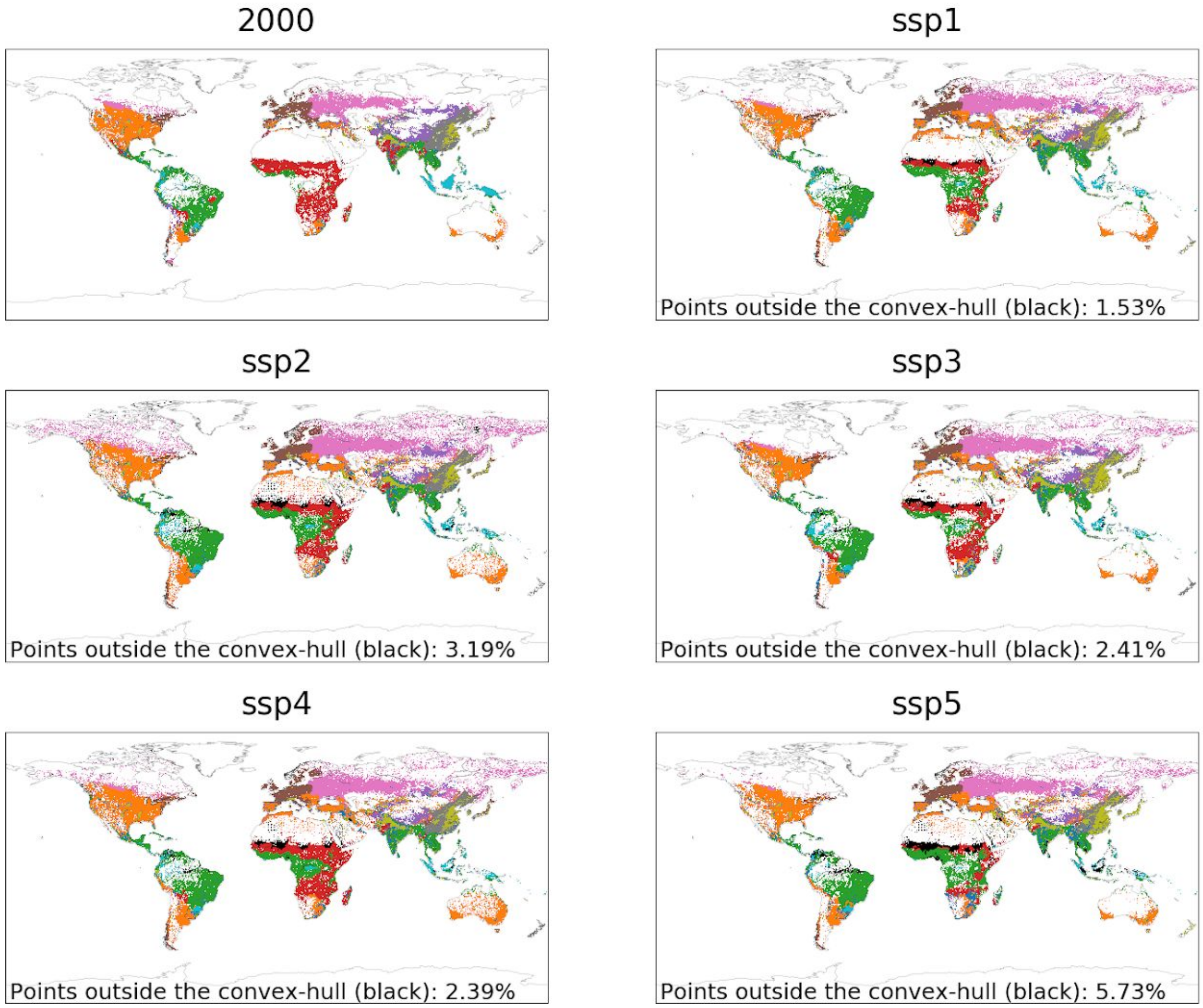
b) With global circulation model (GCM) CCSM4.0



c) With global circulation model (GCM) GISS-E2-R



d) With global circulation model (GCM) HadGEM2 ES



e) With global circulation model (GCM) MIROC-ESM

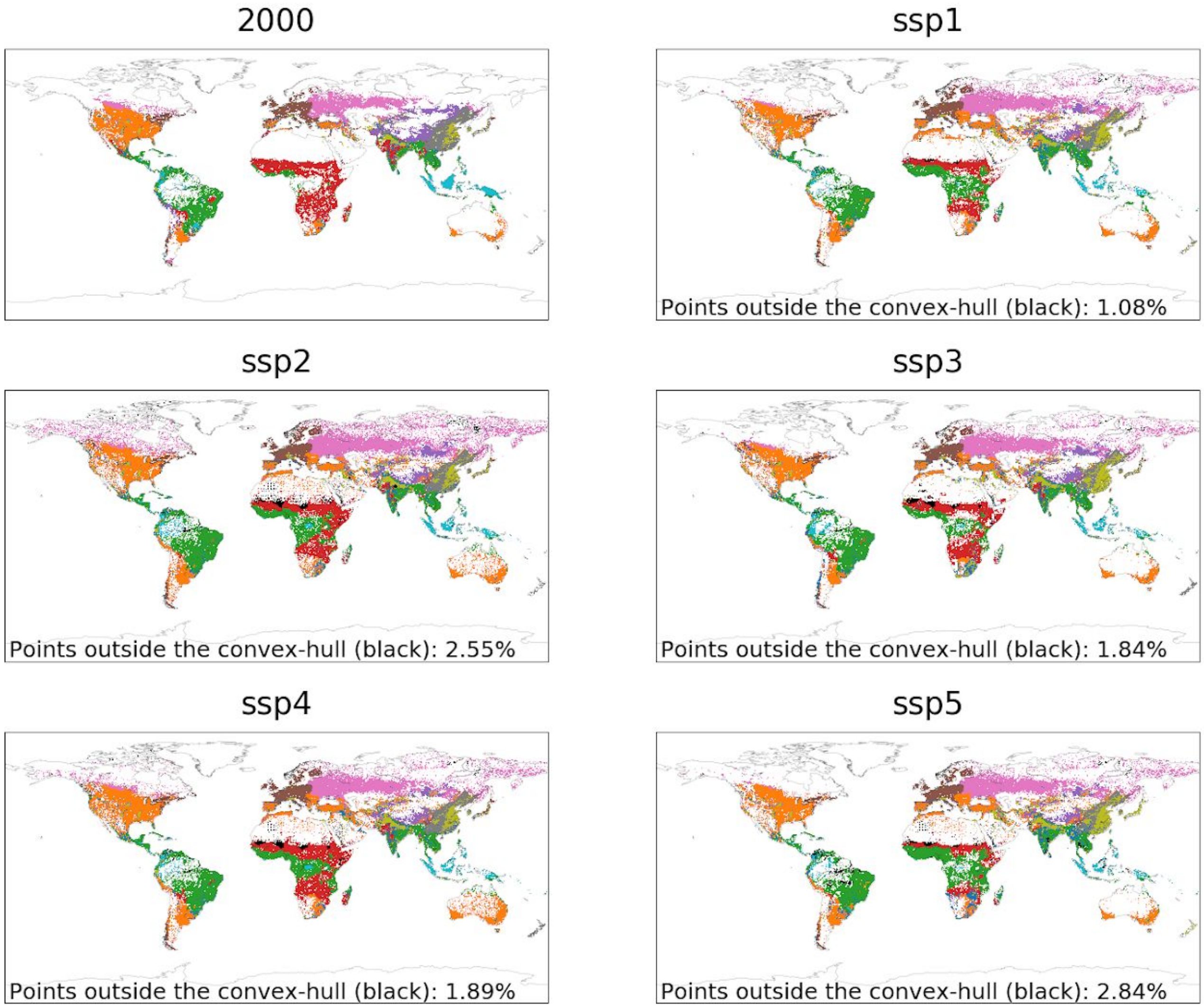


Fig S3: Changes in main drivers

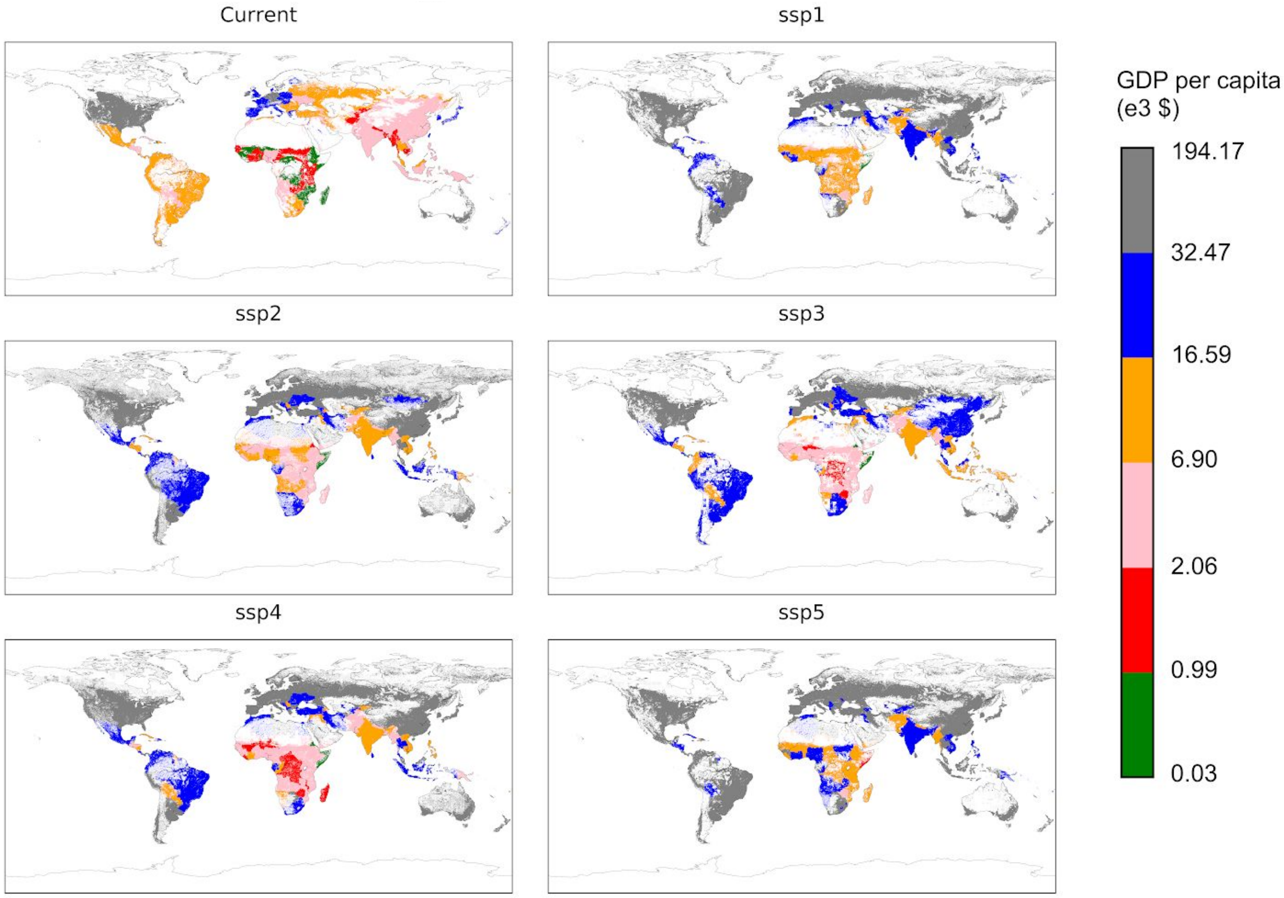
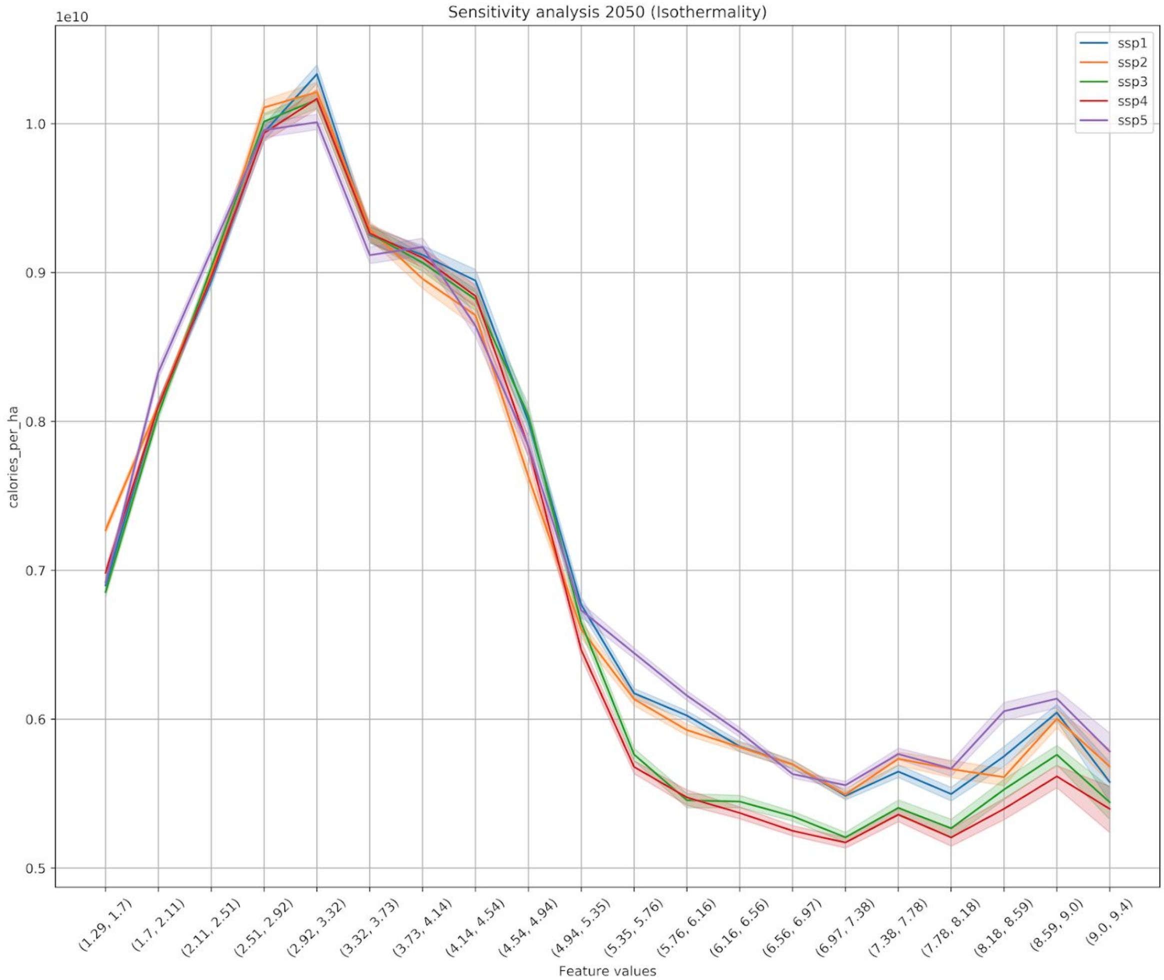
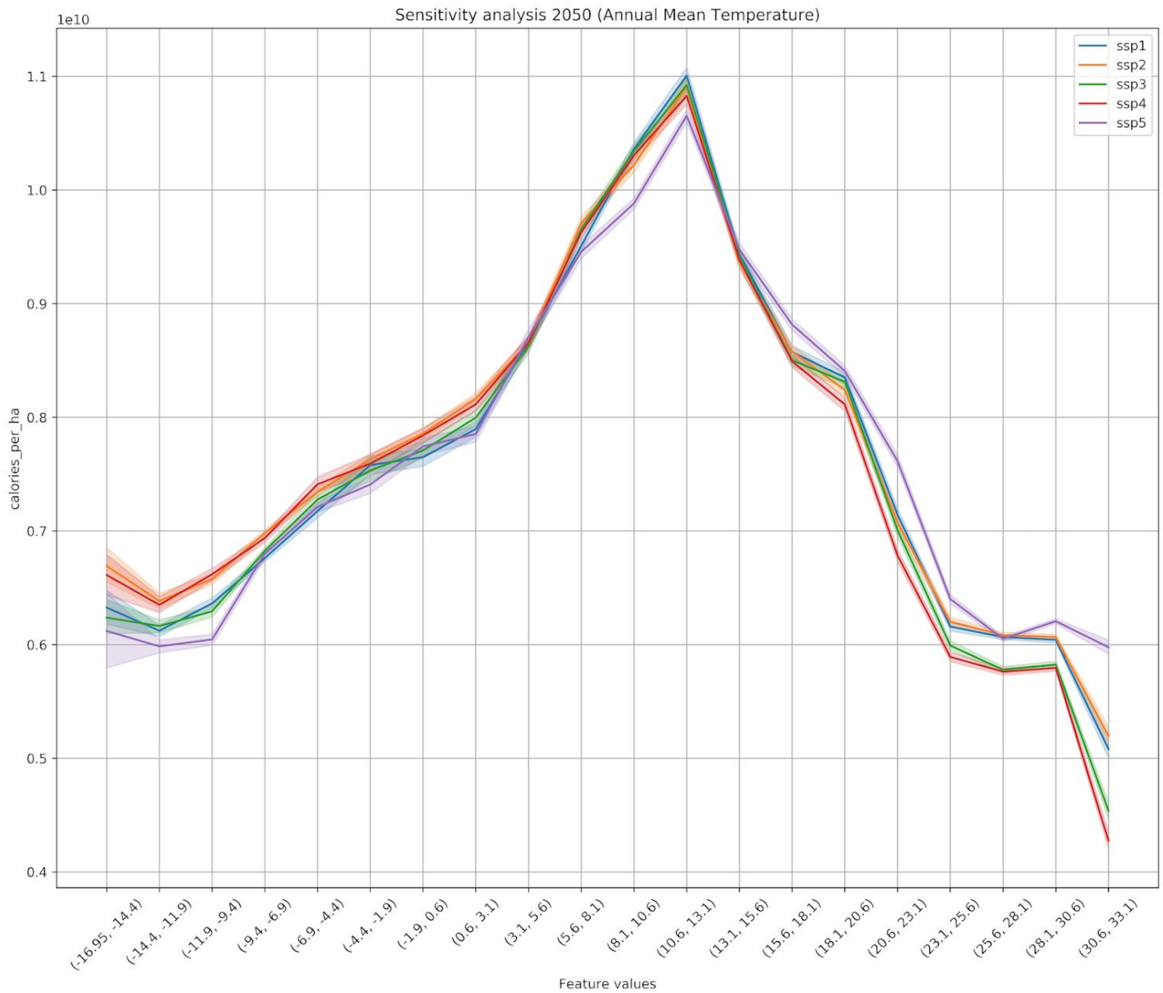


Fig S4 (a-e): Sensitivity Analysis to main drivers

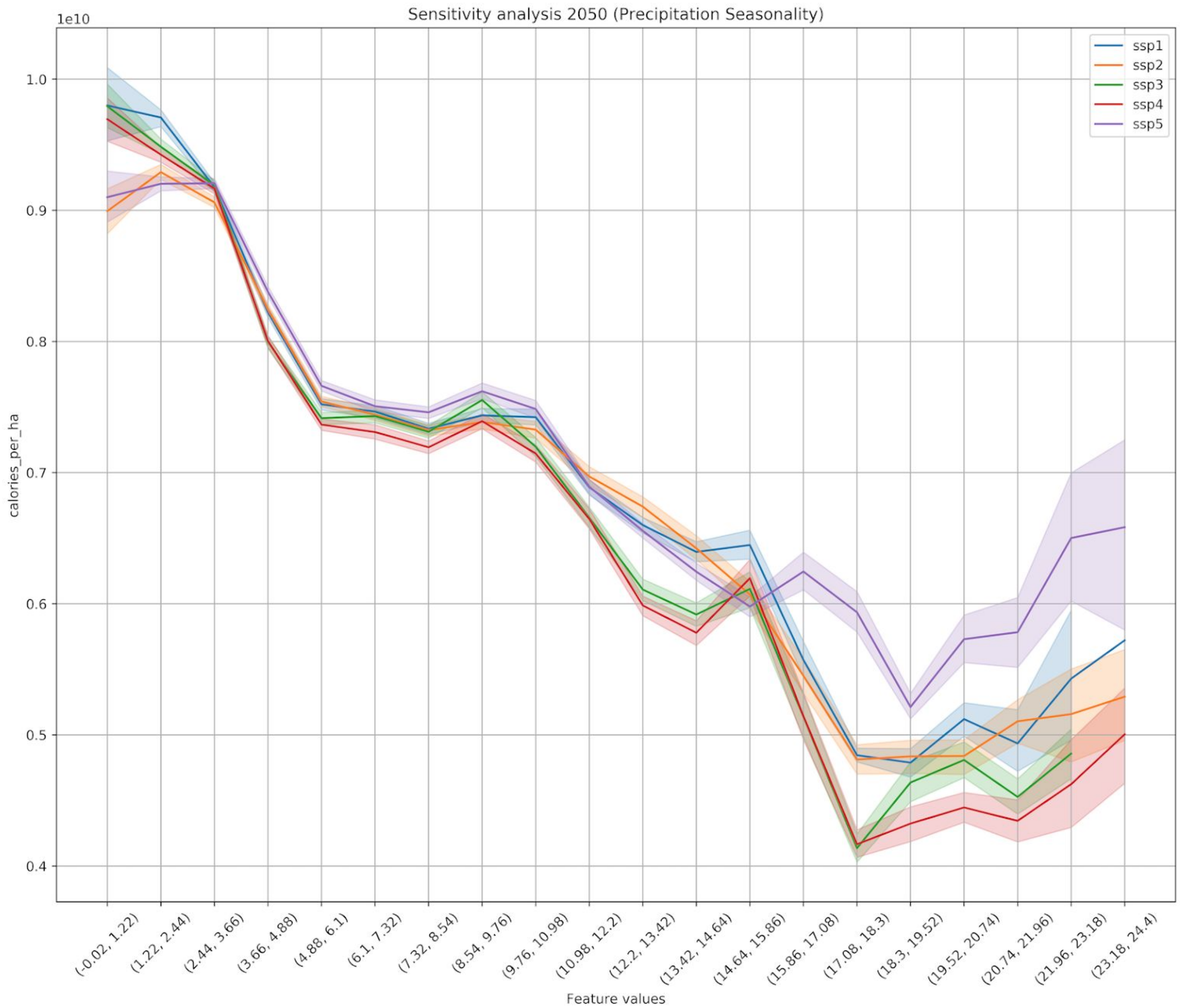
We plot the average yields in terms of the feature values of the 5 features that have the most importance in our model to see how yields react to changes in the feature values.



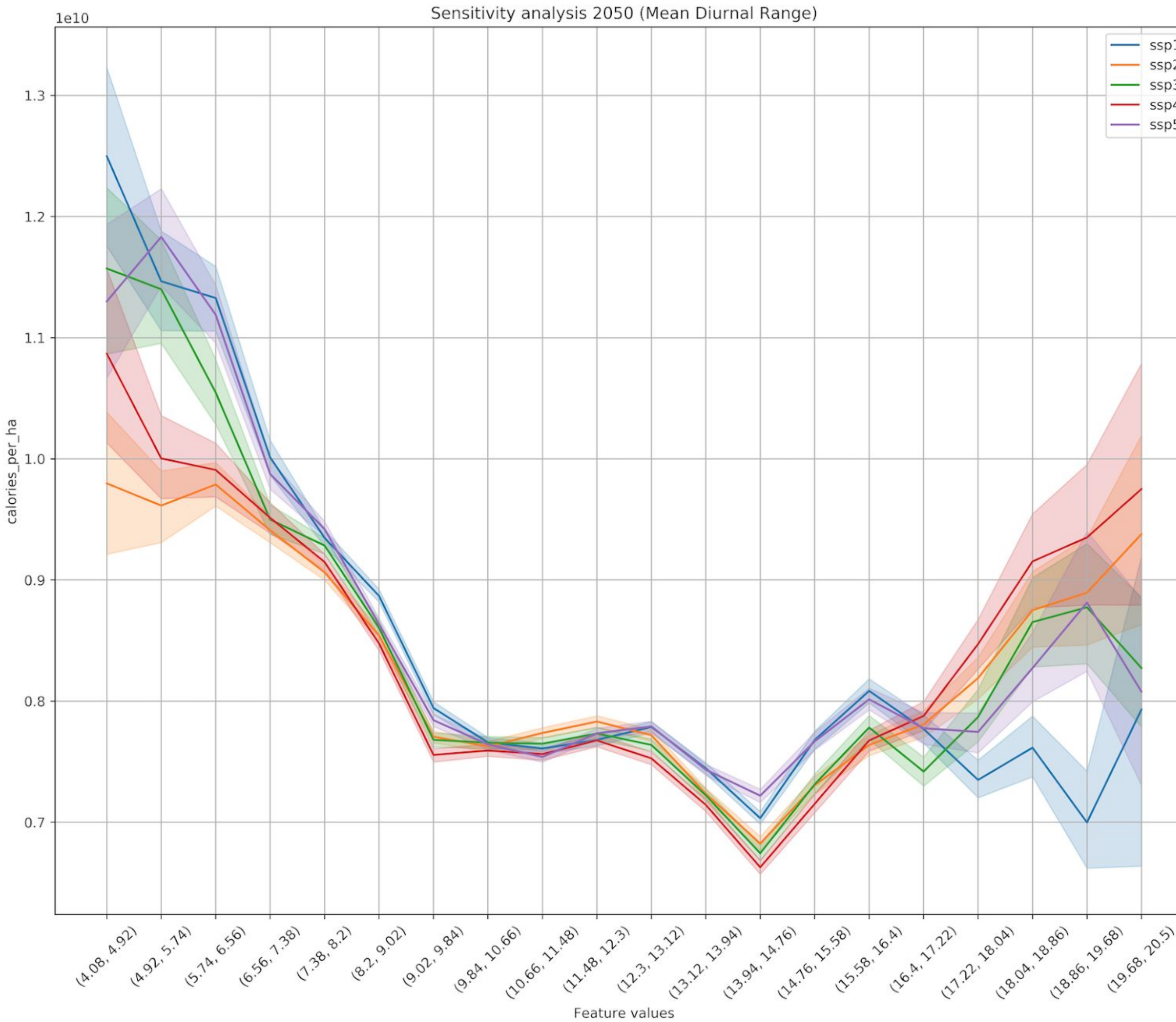
a) Bioclimatic variable BIO3: Isothermality is a quantification of how large the day-to-night temperature oscillation is in comparison to the summer-to-winter oscillation, can be interpreted as temperature "even-ness" on a daily scale. Yields are higher for smaller Isothermality values ([2 to 4]) and drop where it's >5.



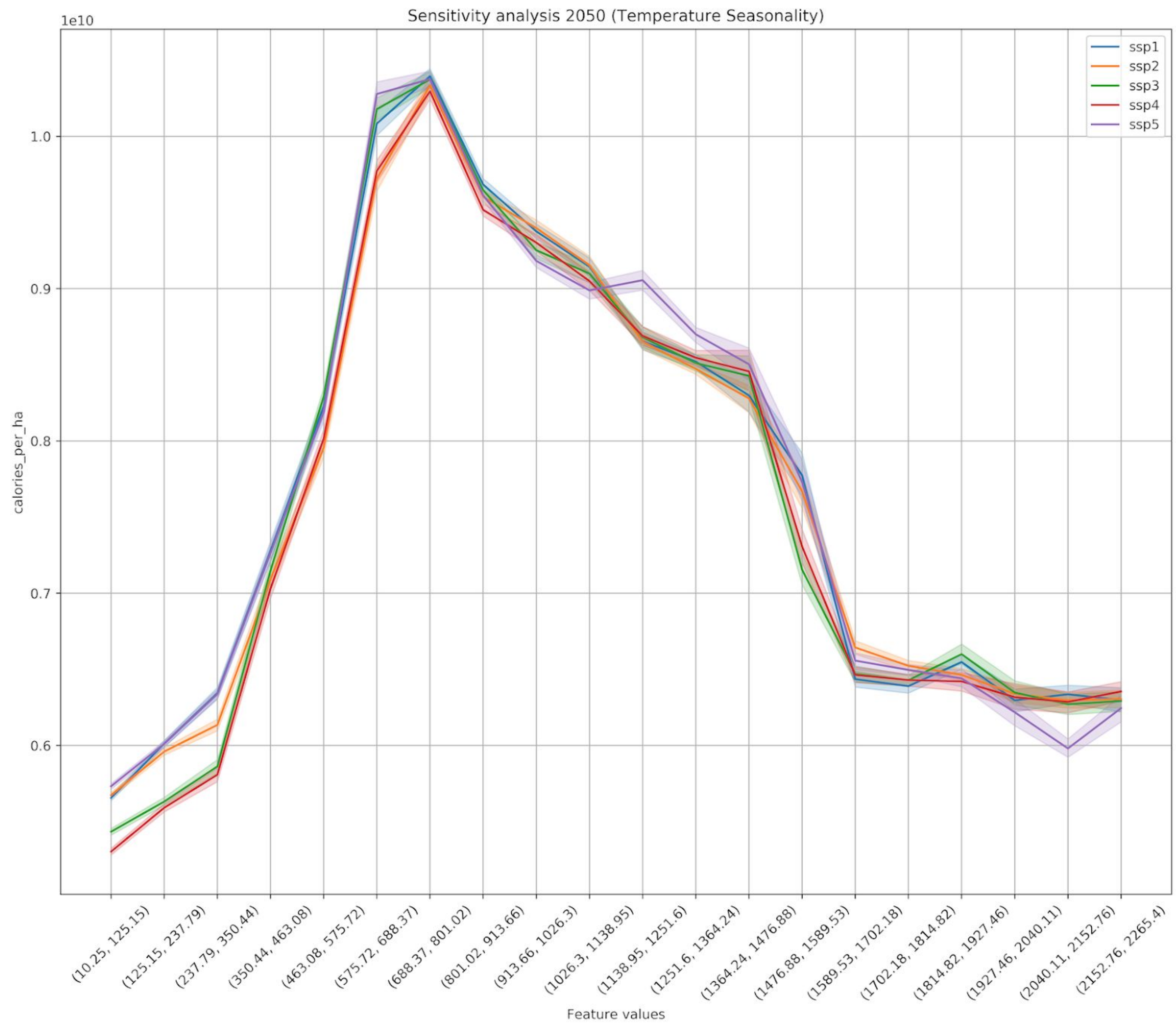
b) Bioclimatic variable BIO1: Annual mean temperature is the average of the temperature during the year. Yields are higher for mid mean temperature values ([7 to 15°C]) and drop where values < 5°C or > 20°C.



c) Bioclimatic variable BIO15: Precipitation seasonality (coefficient of variation) is a measure of how the precipitation varies during the year, low values mean that it stays approximately constant whereas high values imply fluctuations during the year. Yields are higher for smaller precipitation seasonality, when the precipitation is constant throughout the year.



d) Bioclimatic variable BIO2: Mean diurnal range represents the variation of temperatures during a month (max temperature - min temperature) that is then averaged over all months to have a coefficient on a year scale. Yields are higher for smaller values (<7), when the temperature stays around a constant value during the year.



e) Bioclimatic variable BIO4: Temperature seasonality is the standard deviation of temperature values during a year multiplied by 100, this represents the variation of temperatures during the year. Yields are higher for values in range [500, 900] and drop for values < 500 or > 1250.

Fig S5: Change in cropland between 2000 and the 5 scenarios (SSPs)

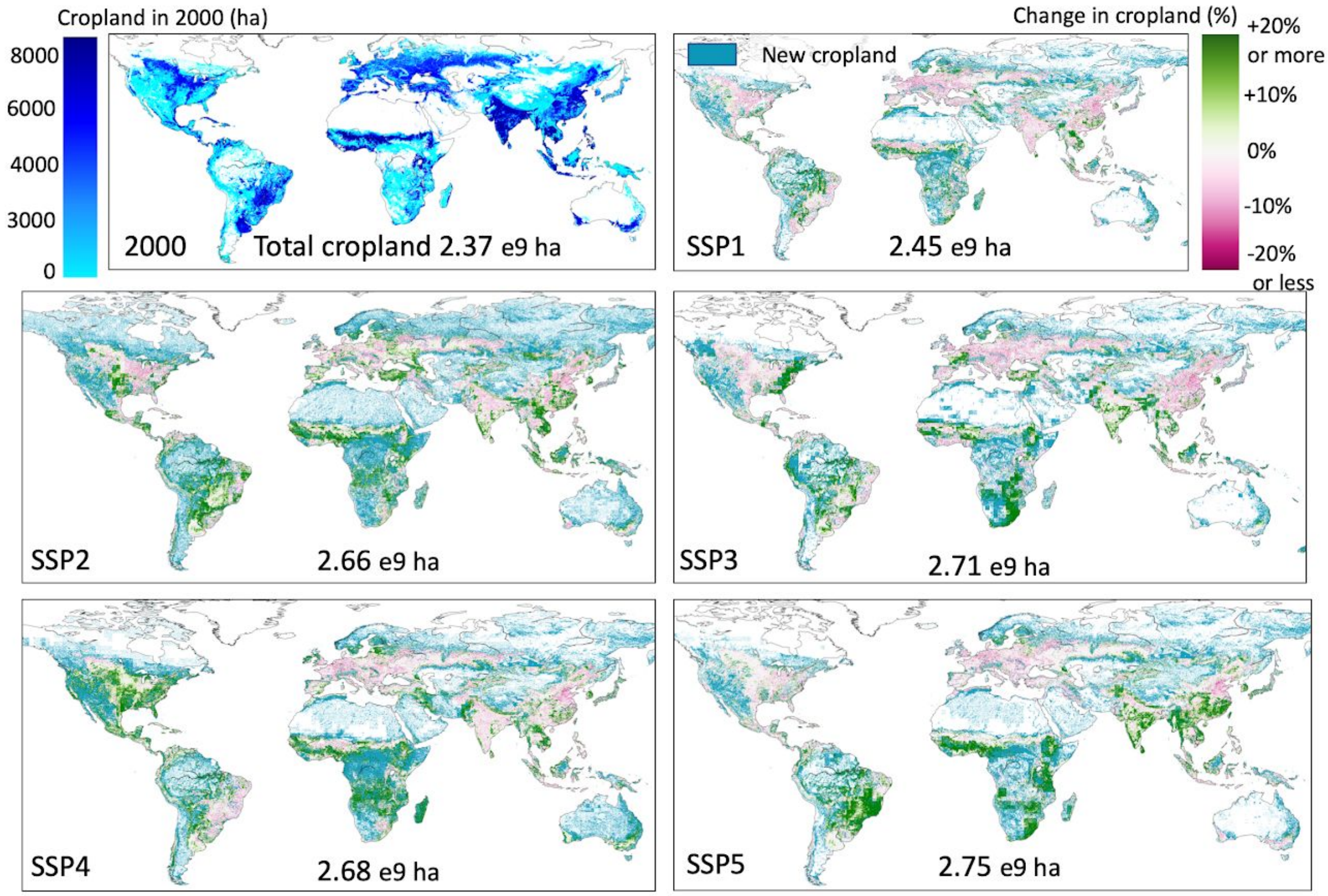
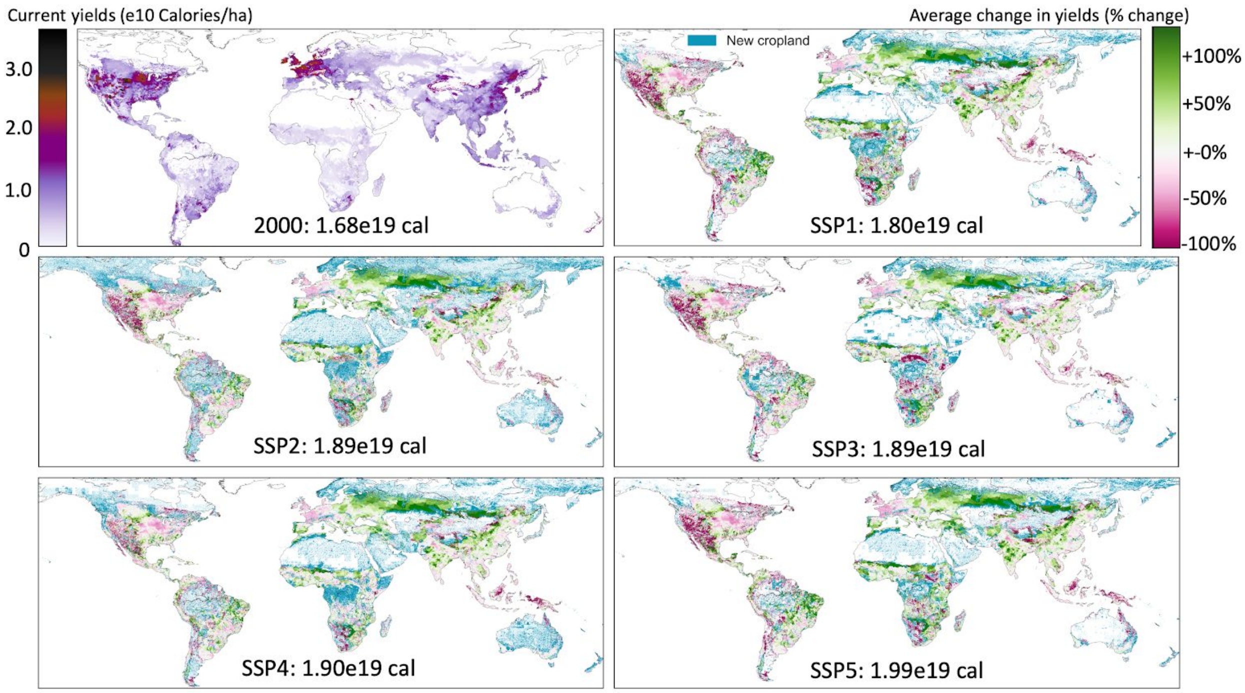


Fig S6: Change in caloric yields and total productions for the 5 SSPs



Left upmost map shows current aggregated yields (in 2000). Aggregated yields (calories per hectare) decrease in the regions most productive today, including Europe and the US Midwest due to an increase in isothermality and mean annual temperature (see sensitivity analysis to main drivers in SI). Despite yield declines in these regions, overall production (calories) increases by about a tenth in all scenarios, thanks to cropland expansion and agriculture intensification.

Text S2: SSPs yields projections, and motivation for a novel modeling approach

Though existing crop models were used by SSPs framework, (a) projected yields are often (at least partly) based on demand, and (b) at a much coarser scale. We developed a new approach consistent across scenarios, with fine scale climate data, and embedding the adaptation assumption.

(a) Several of the SSPs IAMs (Integrated Assessment Models, namely IMAGE [3], used by SSP1, GCAM [4] used by SSP4 and MAgPIE [5] used by SSP5) rely on projected demands to infer their yields, while we are interested in assessing the biophysical capacity of land to produce sufficient food. In the GCAM models, the regional allocation of crops is considered optimal in terms of maximizing global profits, thus it does not model the optimal attainable yields for each region. The IMAGE model uses MAGNET [6] as agricultural economy model where the production increases in response to the increase in demand in agricultural commodities due to demographic changes and increasing income[1]. MAgPIE uses an interplay of demand and intensification costs for its projections.

(b) Furthermore, these projected productions are also modeled at a much coarser scale, from only 11 geopolitical regions in MESSAGE-GLOBIUM [7] and REMIND [8] to around 300 agricultural land-use regions in GCAM.

Global process-based crop models, in addition to the limitations of the ones used by the IAMs in the SSPs, are more challenging to parameterize and run than the statistical models and may be challenging to apply to alternate future scenarios or changed management practice. Statistical models, conversely, can readily be created based on globally available remote sensing data (as in Luderer et al. [9]). As a result, many analyses of global sustainability rely on statistical crop modelling approaches [10–12].

Text S3: Population

Population change for the SSP scenarios was calculated in Jones et al. [10], at 0.125 degree resolution (~13 km). Rather than use the population densities directly from these datasets, we scaled them to most recent population density from the Gridded Population of the World dataset GPWv4[11] . To do so, we took the ratio of future to current population in the scenarios, and multiplied by the GPWv4 population to scale the coarser (0.125 degree) scenario population to that more accurate and finer resolution (30 arc second) current dataset.

We also explored the sensitivity of our results to the choice of population projection, by replicating our results with the UN population projections. To this end, we mapped the following SSPs with UN population projections, based on SSP population narratives and assumptions in terms of fertility, mortalility and migration ([Samir, 2014]), the population data we used ([Jones, 2016]), and the [UN population projections]. It results in 17 scenarios:

SSP1 - Low fertility, SSP4 - Low fertility, SSP2 - Medium fertility, SSP4 - High fertility, SSP3 - High fertility, SSP2- Constant fertility, SSP3- Constant fertility, SSP4- Constant fertility, SSP5- Constant fertility, SSP2- Instant replacement fertility, SSP5- Instant replacement fertility, SSP2 - Momentum, SSP2 - Constant mortality, SSP1 - No change, SSP4h - No change, SSP2 - No change, SSP3- Zero migration.

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[1] Quotes from MAGNET/IMAGE documentation:
"Demographic changes and rising incomes are the primary driving factors of the MAGNET model, and lead to increasing and changing demand for all commodities including agricultural commodities. In response to changing demand, agricultural production is increasing"
"Household demand for agricultural products is calculated based on changes in income, income elasticities, preference shift, price elasticities, cross-price elasticities, and the commodity prices arising from changes in the supply side. Demand and supply are balanced via prices to reach equilibrium.

Text S4: Caloric Sufficiency Calculation

$$\text{Caloric Sufficiency} = \frac{\text{Production}}{\text{Demand}} \overset{\text{(available)}}{=} \frac{\text{Food from crops + Livestock}}{\text{ADER}_{\text{Except Fish}} * \text{Population}}$$

Equation 1: Caloric sufficiency uses SSP assumptions of population and diet changes, assumes constant system losses and relative amount of fish in diets (1.5%), and accounts for changing feed/food split. Our approach does not account for changes in age/gender/cultural dietary requirements (More in Methods).

Detailed Equations (FAO data) *Everything is in calories (or calories ratios)*

(1) PRODUCTION (NUMERATOR)

% of Production that becomes consumed feed or food (accounts for all system losses here) in 2000.

$\%_{Prod}$feed = Consumption_Feed_2000 / Production_Crops_2000 (29%)

$\%_{Prod}$food = Consumption_Food_2000 / Production_Crops_2000 (52%)

Feed Conversion factor

feed_conversion_factor = Consumption_Feed_2000 / Consumption_LS_2000 (=2.3)

% of Livestock products (LS) in diets

$\%_{Diet}$LS_2000 = Consumption_LS_2000 **/** Consumption_Total_2000 (19%)

$\%_{Diet}$LS_2050 = Defined for each SSP (Diet projections from Bodirsky, 2015)

Calculate actual Consumption LS_2050 from this $\%_{Diet}$LS_2050

LS_2050 = $\%_{Diet}$LS_2050*Consumption_Total_2050

with:

Consumption_Total_2050 = LS_2050 + Production*($\%_{Prod}$food) + feed_now_food

with:

feed_now_food = feed_conversion_factor * (LS_2000 - LS_2050)

Thus isolating the unknown:

LS_2050 = $\%_{Diet}$LS2050 * (Production*$\%_{Prod}$food + feed_conversion_factor*LS_2000) / [1 + $\%_{Diet}$LS2050(feed_conversion_factor-1)]

Then calculate:

feed_now_food = feed_conversion_factor * (LS_2000 - LS_2050)

(2) DEMAND (DENOMINATOR)

$\text{ADER}_{\text{w/o fish}}$ = Daily_nutritional_req *(1- $\%_{Diet}$fish)

= 2355 kcal/pers/yr (2016) * (1 - 1.5%) = 2320 kcal

Variables definitions & input data sources

Variable	Meaning	Value	Source
$\%_{Prod}$FEED	Caloric percentage of feed from production at baseline year (2000)	29%	*For 2000:* FAOSTAT Food Balance Sheet, 2016[12] (accessed in November 2018) *For 2050:* Calculated from above data
$\%_{Prod}$FOOD	Caloric percentage of food from production at baseline year (2000)	52%	
$\%_{Diet}$FISH	Caloric percentage of fish in diet (consumption)	2000: 1.5% 2050: cst	
$\%_{Diet}$LS_YEAR	Caloric percentage of livestock products in diet (consumption)	2000: 19% 2050: BODIRSKY	
Consumption_Total_year	Total calories in diet (consumed) in year	-	
Consumption_LS_year (simplified LS_year)	Caloric consumption of Livestock products in year	2000: 1.1483e18	
FEED_CONVERSION_FACTOR	Caloric feed conversion factor	2.3	Calculated from above data.
FEED_NOW_FOOD	Calories that used as feed in 2000, but used at food in 2050 (vice versa if <0)		
ADER	Average Dietary Energy Requirement	2355 kcal/ cap/ d (2016)	FAO
ADER$_{w/o\ fish}$	Average Terrestrial Dietary Energy Requirement (ADER except the part met by fish)	2320 kcal/ cap/ day	Calculated from above data.

Table S1:Changes (in Caloric Sufficiency and its drivers)

Changes in caloric sufficiency and its drivers, for all countries are available. Here we show a representative country of each of the eight category below.

Most vulnerable

Niger	Caloric Sufficiency	Production	Population	Cropland	Livestock
2000	0.69	1,09E+16	1126264729.62	977561611.12	0.10
ssp1	0.25	+77.97%	+293.48%	-13.83%	0.23
ssp2	0.34	+152.83%	+324.08%	+19.52%	0.16
ssp3	0.34	+244.66%	+458.14%	+40.92%	0.14
ssp4	0.30	+190.21%	+461.00%	+26.95%	0.13
ssp5	0.51	+178.36%	+189.65%	+4.39%	0.21

Newly vulnerable

Sudan	Caloric Sufficiency	Production	Population	Cropland	Livestock
2000	1.67	6,58E+16	2797099903.96	3416239894.67	0.23
ssp1	0.75	+66.46%	+156.09%	+15.70%	0.40
ssp2	0.83	+73.91%	+156.74%	+19.05%	0.33
ssp3	0.70	+27.29%	+152.80%	+9.94%	0.25
ssp4	0.71	+30.77%	+156.77%	+11.78%	0.24
ssp5	0.75	+54.20%	+156.15%	+11.31%	0.34

Exporter

Australia	Caloric Sufficiency	Production	Population	Cropland	Livestock
2000	11.09	3,1E+17	1787150042.22	5214676801.65	0.32
ssp1	5.15	+24.32%	+125.79%	+23.13%	0.17
ssp2	5.07	+24.12%	+124.44%	+22.81%	0.19
ssp3	8.80	+21.34%	+15.63%	+20.44%	0.28
ssp4	6.66	+46.90%	+105.84%	+46.41%	0.16
ssp5	4.11	+15.43%	+130.72%	+12.45%	0.31

Importer

South Korea	Caloric Sufficiency	Production	Population	Cropland	Livestock
2000	0.85	4,41E+16	4341673328.70	344499060.38	0.12
ssp1	0.92	+5.19%	+6.38%	+8.48%	0.16
ssp2	0.97	+15.94%	+6.36%	+21.59%	0.16
ssp3	0.97	+18.83%	+6.02%	+23.50%	0.18
ssp4	0.95	+10.84%	+6.29%	+14.83%	0.15
ssp5	0.89	+7.34%	+6.40%	+13.39%	0.20

Vulnerable but improving

Morocco	Caloric Sufficiency	Production	Population	Cropland	Livestock
2000	0.57	2,21E+16	2831905507.80	735527202.74	0.07
ssp1	0.96	+133.14%	+11.38%	+57.21%	0.19
ssp2	0.80	+82.07%	+11.38%	+28.32%	0.18
ssp3	0.77	+64.18%	+11.47%	+22.30%	0.14
ssp4	0.78	+75.48%	+11.38%	+23.52%	0.17
ssp5	0.74	+63.06%	+11.38%	-19.11%	0.17

Decreasing but not as vulnerable

Germany	Caloric Sufficiency	Production	Population	Cropland	Livestock
2000	2.78	3,11E+17	8165178227.48	1664588126.95	0.29
ssp1	2.24	-22.34%	-1.75%	-11.44%	0.22
ssp2	2.38	-14.18%	-1.74%	-0.16%	0.22
ssp3	2.26	-17.63%	-1.74%	-3.68%	0.25
ssp4	2.32	-18.86%	-1.74%	-5.24%	0.21
ssp5	2.11	-23.26%	-1.65%	-5.56%	0.27

Increasing sufficiency

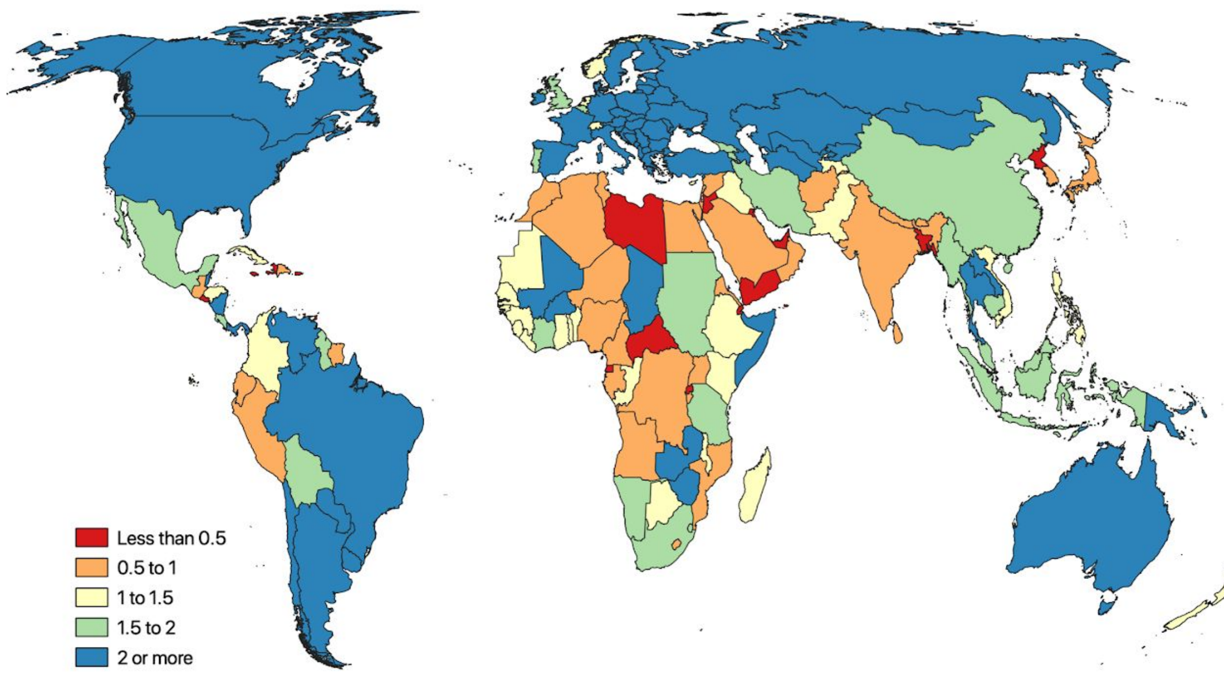
Botswana	Caloric Sufficiency	Production	Population	Cropland	Livestock
2000	1.00	2,36E+15	170326922.62	231606162.36	0.16
ssp1	4.16	+596.07%	+17.05%	+49.15%	0.22
ssp2	2.57	+314.49%	+17.68%	+52.46%	0.21
ssp3	15.82	+2564.38%	+17.86%	+825.45%	0.18
ssp4	5.08	+750.48%	+16.58%	+85.19%	0.21
ssp5	5.26	+793.81%	+18.98%	+83.73%	0.21

Highly variable

Switzerland	Caloric Sufficiency	Production	Population	Cropland	Livestock
2000	1.40	1,06E+16	714553143.26	60322758.60	0.32
ssp1	1.39	-29.00%	+9.24%	-19.35%	0.13
ssp2	1.46	-16.09%	+9.24%	-3.27%	0.14
ssp3	1.37	+1.80%	+9.24%	+16.62%	0.29
ssp4	1.53	-9.39%	+9.24%	+3.86%	0.13
ssp5	0.86	-15.96%	+56.53%	+0.52%	0.32

Fig S7: Caloric Sufficiency Maps by country

A) Current Countries caloric sufficiency



B) Consistency in direction of changes in caloric sufficiency, across 5 SSPs *(consider only changes>0.1)*

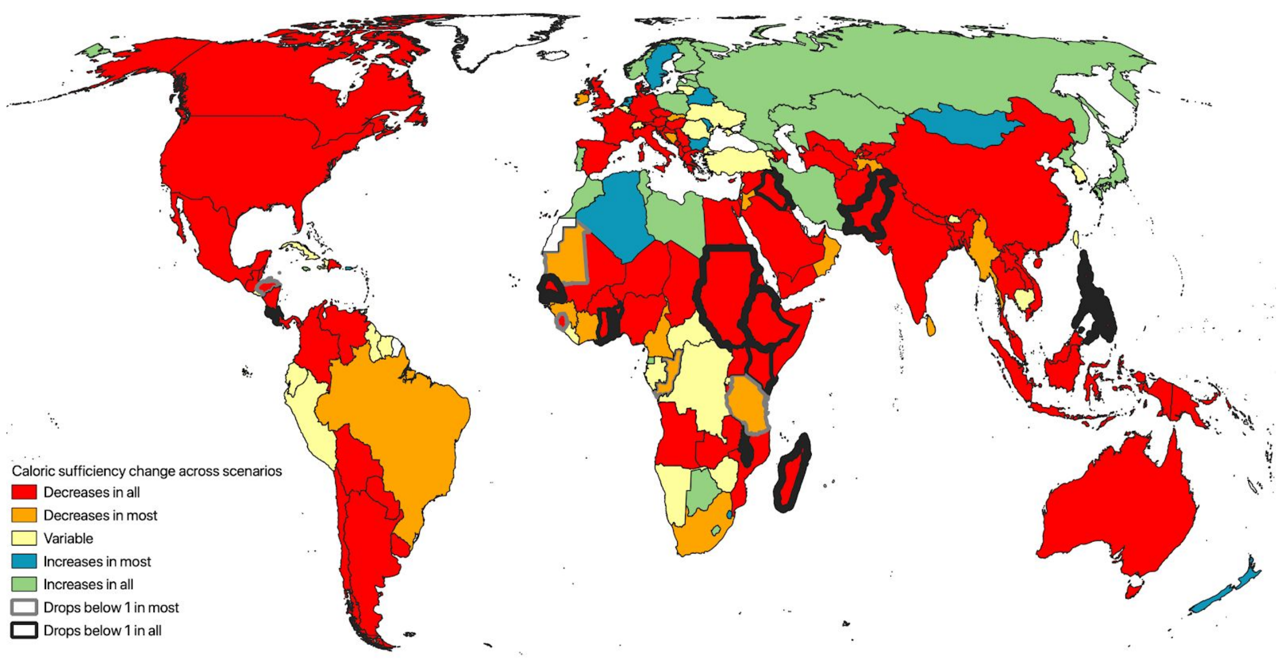
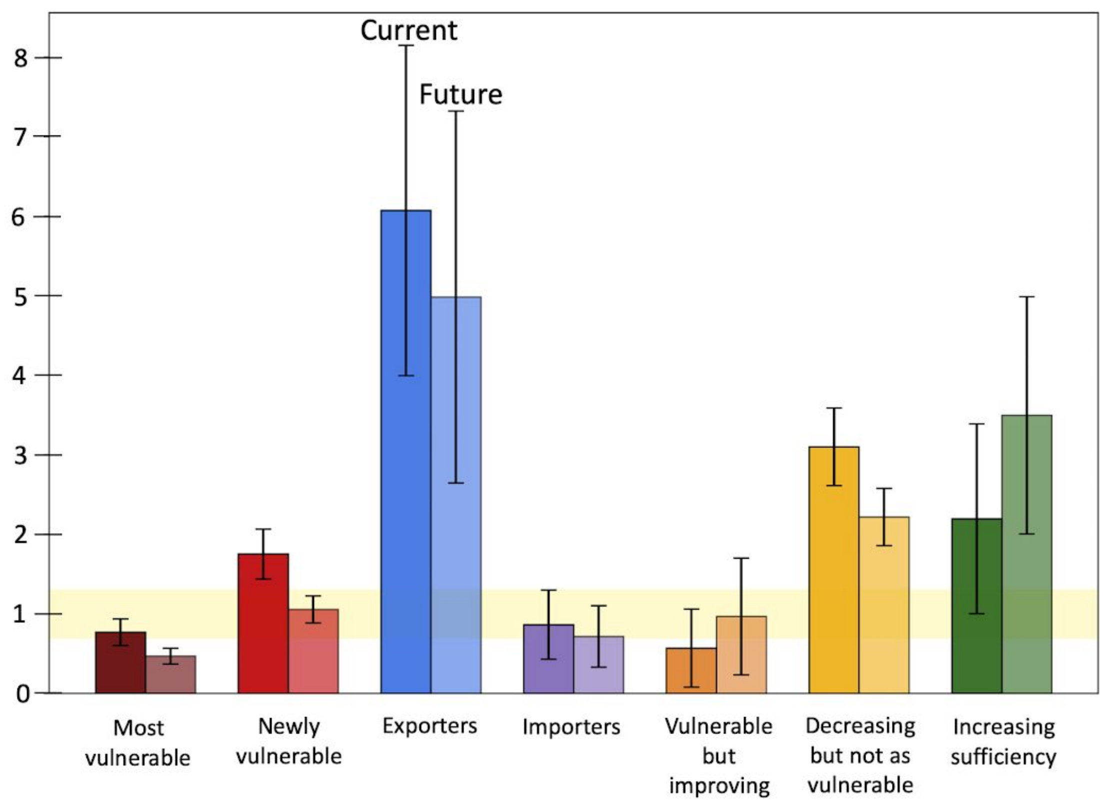
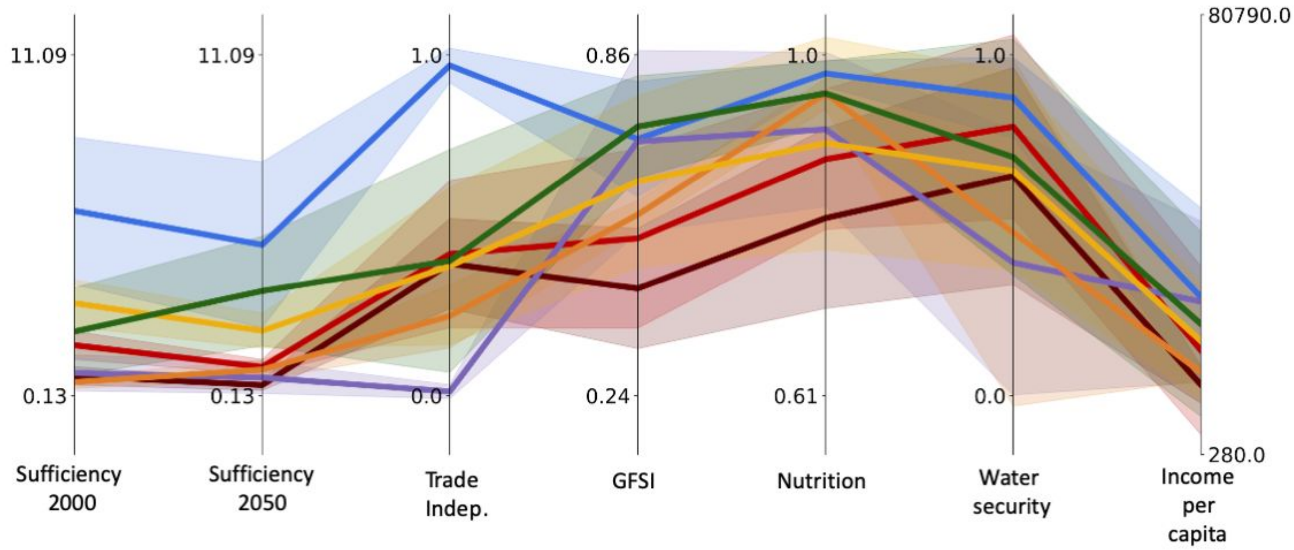


Fig S8: Details on the additional food security datasets, and their links to national caloric sufficiency.

A) Trends in caloric sufficiency per category with 90% confidence interval.



B) Parallel coordinates plot of the sufficiency in 2000 and 2050 with standard deviation of all countries (137) averaged across all scenarios and grouped by category.



C) National Caloric Sufficiency in 2000 vs. Trade independency, Water security, Nutrition, GFSI and income per capita, by countries, for most groups.

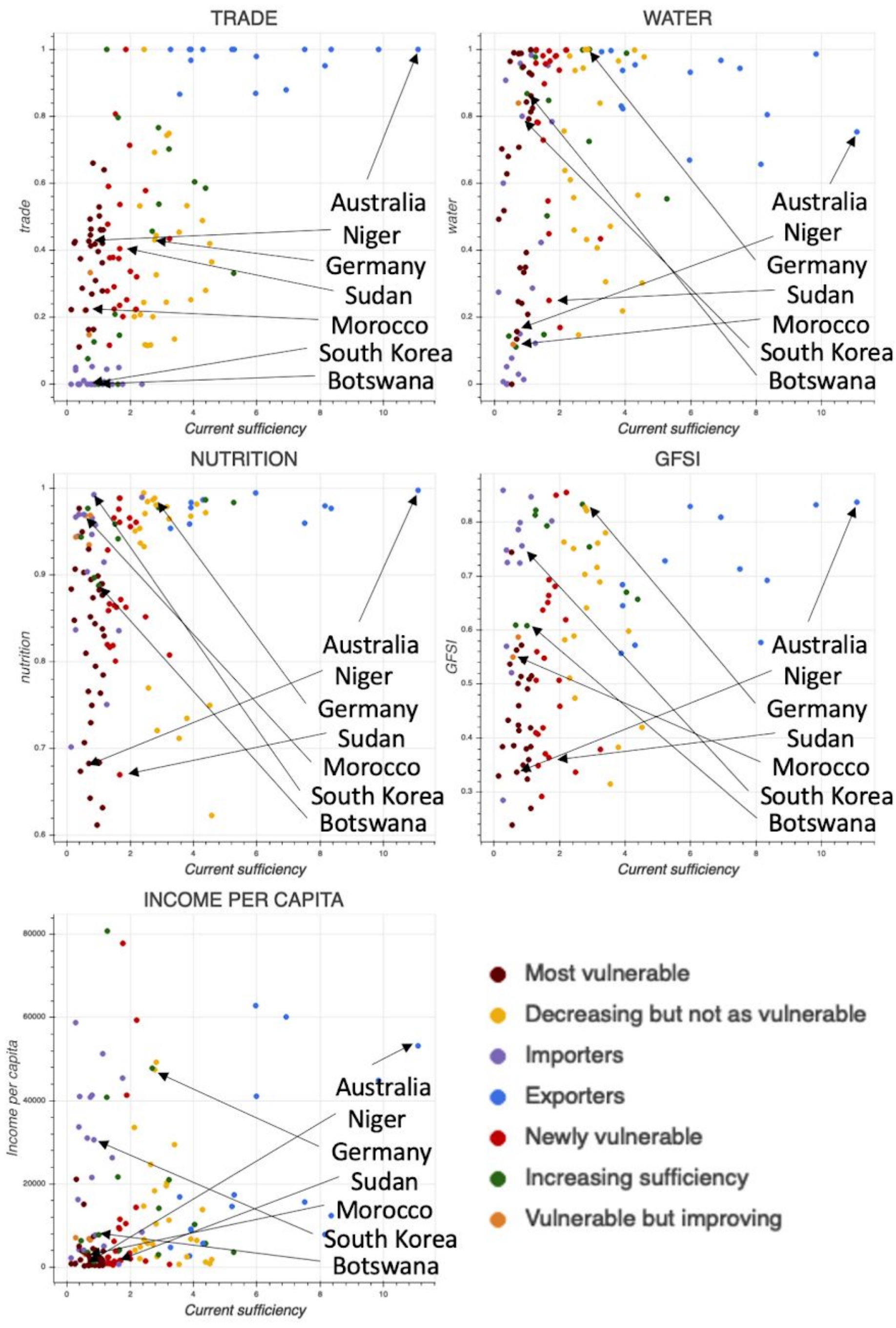


Table S2: Categorization of countries per storylines

Category	*Low Income*	*Medium Income*	*High Income*	**Number of Countries**	**Conditions**	**Full country list** (Categorization based on Jones' SSPs population projections, for the 5 SSPs)
Exporters	0	7	9	**16**	Current sufficiency > 3 and trade independency > 0.8	'Argentina', 'Australia', 'Bulgaria', 'Belize', 'Brazil', 'Canada', 'Denmark', 'France', 'Hungary', 'Kazakhstan', 'Lithuania', 'Latvia', 'Paraguay', 'Ukraine', 'Uruguay', 'United States of America'
Increasing sufficiency	0	11	6	**17**	Sufficiency increases in most scenarios and of at least 0.6 on average or current sufficiency already > 1.2 and increases in most scenarios of more than 0.2	'Belarus', 'Botswana', 'Estonia', 'Finland', 'Georgia', 'Iran', 'Libya', 'Lesotho', 'Moldova', 'Mongolia', 'Norway', 'New Zealand', 'Poland', 'Portugal', 'Russia', 'Swaziland', 'Tunisia'
Importers	2	7	12	**21**	Trade independency < 0.1	'United Arab Emirates', 'Belgium', 'Brunei', 'Cyprus', 'Djibouti', 'Algeria', 'Gambia', 'Iraq', 'Israel', 'Jordan', 'Japan', 'South Korea', 'Kuwait', 'Lebanon', 'Montenegro', 'Mauritania', 'Netherlands', 'Saudi Arabia', 'Singapore', 'Trinidad and Tobago', 'Yemen'
Most vulnerable	17	16	2	**35**	Current sufficiency < 1.2 and (the highest future sufficiency < 0.9 or the sufficiency decreases in most scenarios)	'Afghanistan', 'Angola', 'Burundi', 'Bangladesh', 'Cameroon', 'Democratic Republic of the Congo', 'Republic of Congo', 'Dominican Republic', 'Egypt', 'Eritrea', 'Ethiopia', 'Ghana', 'Guinea Bissau', 'Guatemala', 'Haiti', 'India', 'Jamaica', 'Kenya', 'Sri Lanka', 'Madagascar', 'Mozambique', 'Malawi', 'Niger', 'Nigeria', 'Nepal', 'Oman', 'Pakistan', 'Philippines', 'Puerto Rico', 'North Korea', 'Rwanda', 'El Salvador', 'Syria', 'Togo', 'Uganda'

Newly vulnerable	6	14	4	**24**	Sufficiency decreases in most scenarios and on average of more than 0.2 and (the lowest future sufficiency < 1 or the current sufficiency < 2)	'Benin', 'Burkina Faso', 'Bolivia', 'China', 'Ivory Coast', 'Colombia', 'Costa Rica', 'United Kingdom', 'Guinea', 'Honduras', 'Indonesia', 'Ireland', 'Luxembourg', 'Mexico', 'Malaysia', 'Panama', 'Sudan', 'Senegal', 'Sierra Leone', 'Tajikistan', 'Tanzania', 'Uzbekistan', 'Vietnam', 'Zambia'
Vulnerable but improving	0	4	0	**4**	Current sufficiency < 1.2 and lowest future sufficiency > 0.9*current sufficiency and the sufficiency increases in at least some scenarios	'Gabon', 'Equatorial Guinea', 'Morocco', 'Peru'
Decreasing but not as vulnerable	3	15	10	**28**	Current sufficiency > 2 and the sufficiency decreases in at least some scenarios and of more than 0.1 on average	'Albania', 'Austria', 'Azerbaijan', 'Bosnia and Herzegovina', 'Chile', 'Czech Republic', 'Germany', 'Spain', 'Greece', 'Croatia', 'Italy', 'Kyrgyzstan', 'Laos', 'Macedonia', 'Mali', 'Nicaragua', 'Papua New Guinea', 'Romania', 'Somalia', 'Serbia', 'Slovakia', 'Slovenia', 'Chad', 'Thailand', 'Turkmenistan', 'East Timor', 'Turkey', 'Venezuela'
Highly variable	2	11	2	**15**	Direction of change is variable	'Armenia', 'Bhutan', 'Central African Republic', 'Switzerland', 'Cuba', 'Ecuador', 'Guyana', 'Cambodia', 'Liberia', 'Myanmar', 'Namibia', 'Suriname', 'Sweden', 'South Africa', 'Zimbabwe'

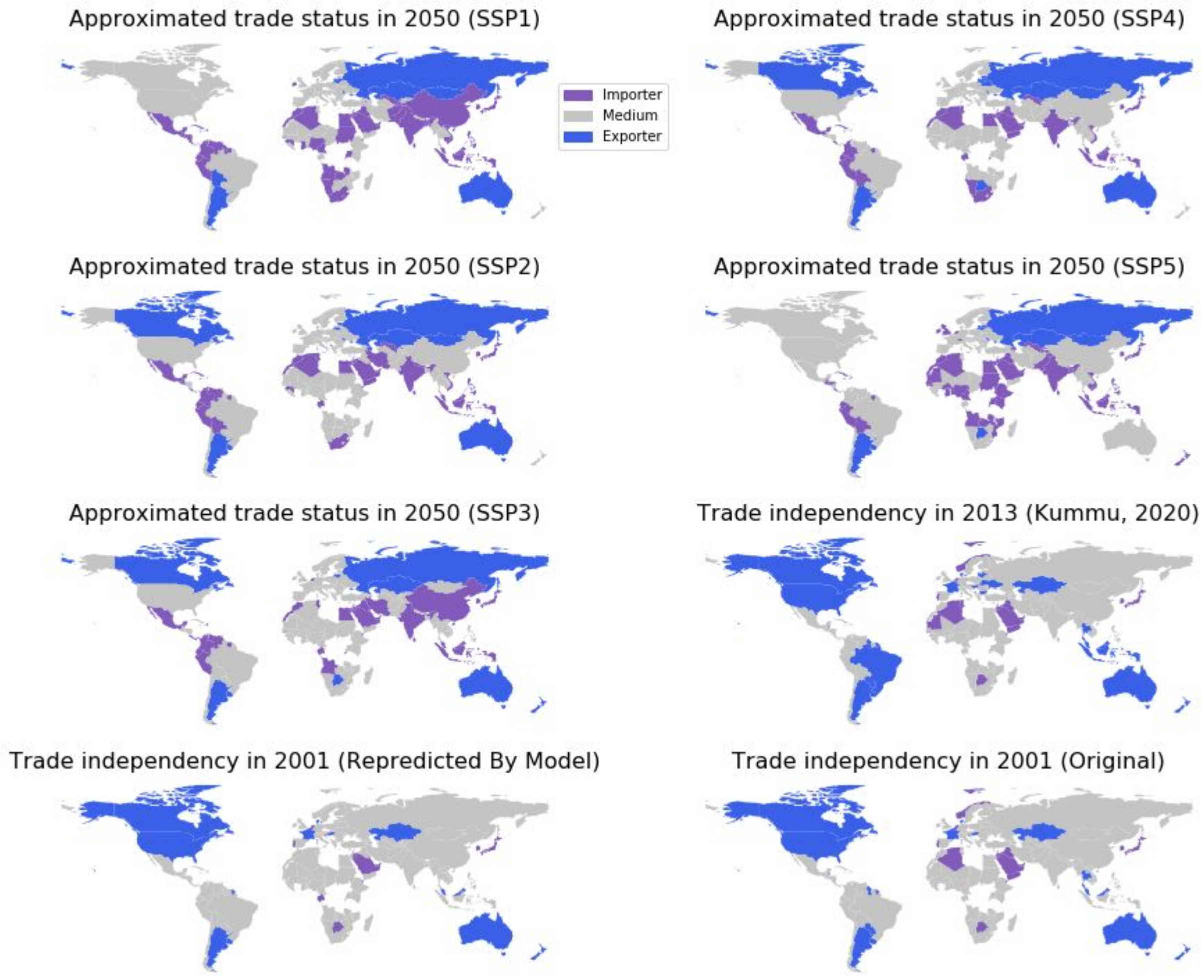
Table S2: Classification tree classifies countries in the order listed in this table, thus, if one country fit two conditions, it will be classified in priority in the row above (e.g Botswana, Norway, Portugal, Tunisia are both importers and increasing sufficiency, but were chosen to give "Increasing sufficiency" priority as they all have sufficient caloric sufficiency).

Table S3: Change in category induced by categorizing with the UN population projections

Category	Countries added	Countries removed
Exporters	--	--
Increasing sufficiency	'Armenia', 'Bosnia and Herzegovina', 'Greece', 'Romania', 'Namibia'	'Iran', 'Lesotho', 'Moldova', 'Mongolia', 'New Zealand', 'Swaziland', 'Tunisia'
Importers	'Tunisia'	'Cyprus', 'Lebanon'
Most vulnerable	'Ecuador', 'Equatorial Guinea', 'Morocco', 'Peru', 'Suriname'	'Eritrea'
Newly vulnerable	'Switzerland', 'Cambodia', 'Mali', 'Myanmar', 'Papua New Guinea', 'Swaziland', 'Chad', 'South Africa', 'Zimbabwe'	'Ireland, 'Sierra Leone'
Vulnerable but improving	'Lesotho'	'Gabon', 'Equatorial Guinea', 'Morocco', 'Peru'
Decreasing but not as vulnerable	'Ireland', 'Mongolia'	'Somalia', 'Albania', 'Bosnia and Herzegovina', 'Greece', 'Croatia', 'Italy', 'Macedonia', 'Mali', 'Papua New Guinea', 'Romania', 'Slovakia', 'Chad'
Highly variable	'Albania', 'Gabon', 'Croatia', 'Iran', 'Italy', 'Moldova', 'Macedonia', 'New Zealand', 'Slovakia', 'Eritrea', 'Somalia', 'Lebanon', 'Sierra Leone', 'Cyprus'	'Armenia', 'Switzerland', 'Ecuador', 'Cambodia', 'Myanmar', 'South Africa', 'Zimbabwe', 'Suriname', 'Namibia'

Table S3: Change in categories when creating them using the UN population projections (17 SSP-UN scenarios).

Fig S9: Future trade: approximating countries' trade status in 2050, based on GDP and Caloric sufficiency.



Though trade patterns result from highly complex interconnected factors, we attempted to roughly approximate future trade status, based on caloric sufficiency and GDP, using their relationship with trade independency in the past (Random forest classifier trained on the GDP, Caloric sufficiency circa 2000 and dependent variable Trade independency[13] in 2001. Accuracy on unseen sample: 82%).

These very approximate projections - too uncertain to be guide country groupings - give us a basis to explore potential future trade statuses: they suggests that over half (13/21) of the current exporters won't remain exporters in any SSPs, while only Russia would be a new country exporter consistenly, due to increased production (3 countries remain exporters in all SSPs, 5 countries remain exporters in some SSPs, and 8 countries become exporters in some SSPs). Meanwhile, the vast majority (16) of the 24 importers remain importers in most scenarios, and an additional 11-63 are expected to become importers! Under SSP1 in particular, 55 countries are expected to become importers!

Fig S10: Sensitivity analysis of Caloric Sufficiency to population, diets, yields, cropland, food waste and feed to food ratio

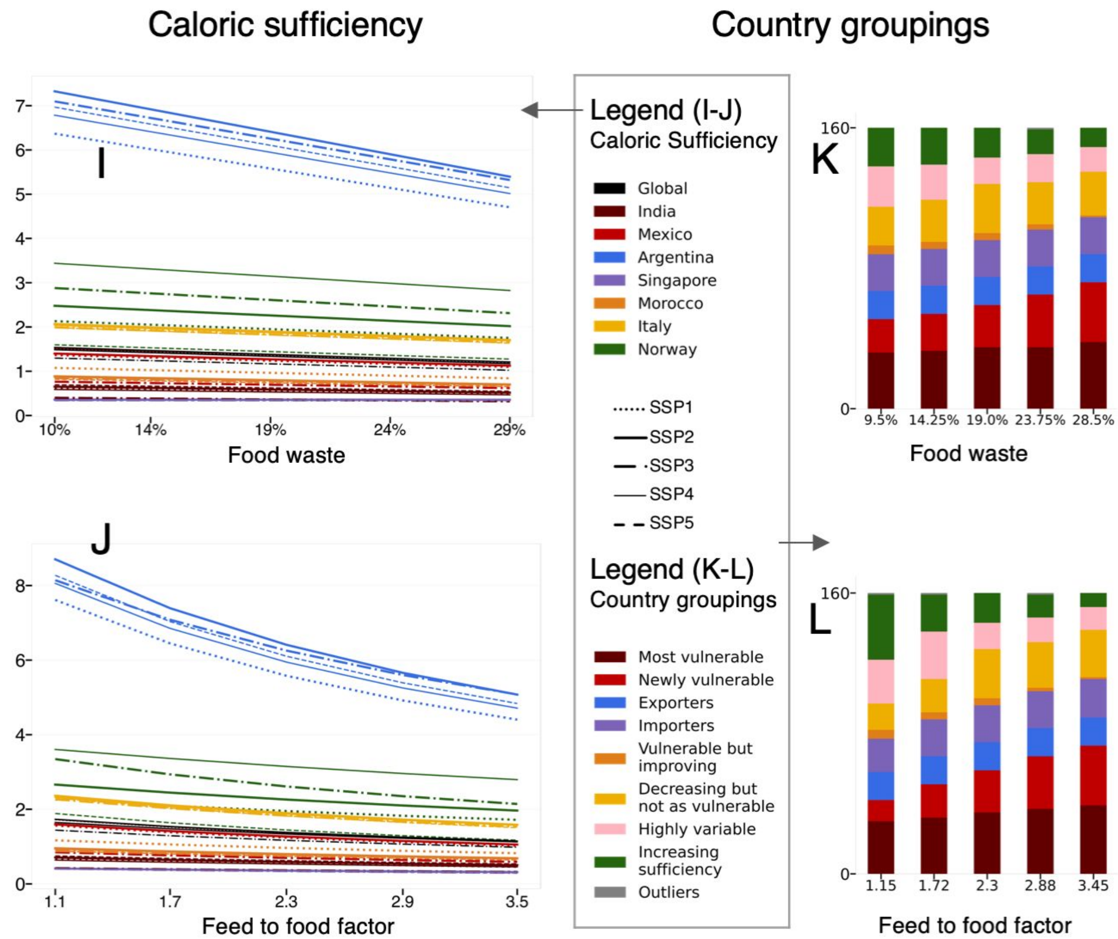


Fig S10 (Figure3 continued): Sensitivity analysis of caloric sufficiency (I-J) and of countries groupings (K-L) to system efficiency drivers : food waste percentage (I,K) and animal products efficiency through the feed to food factor (J,L). See Text S4 for detailed calculation of caloric sufficiency. This figure is obtained from adjusting original feed_conversion_factor (= 2.3) and %Food_waste (=19%) with distortion factors in the [0.5-1.5] range, sampled at .25 increments to investigate impacts on caloric sufficiency and country groupings.–

Table S4: Relative impacts of drivers on global caloric sufficiency

<table>
<tr><td rowspan="2">To increase global caloric sufficiency ...</td><td colspan="2">Increase Production</td><td colspan="2">Improve System Efficiency</td><td colspan="2">Reduce Demand</td></tr>
<tr><td>Cropland</td><td>Yields</td><td>Food waste</td><td>Feed-to-food ratio</td><td>Diets (%Livestock)</td><td>Population</td></tr>
<tr><td>… by +0.1</td><td>+3%
(2.7 to 2.9 bio ha)</td><td>+9%
(6.8 to 7.5 bio cal/ha)</td><td>-30%
(19% to 13%)</td><td>-17%
(2.3 to 1.9)</td><td>- 30%
(23% to 16%)</td><td>~600mio fewer ppl</td></tr>
<tr><td>… by +0.2</td><td>+6.3%
(2.7 to 3.2 bio ha)</td><td>+19%
(6.8 to 8.1 bio cal/ha)</td><td>-60%
(19% to 7.4%)</td><td>-32%
(2.3 to 1.6)</td><td>-56%
(23% to 10%)</td><td>1 bio fewer people</td></tr>
<tr><td>… to its current value (+0.6)</td><td>+19%
(2.7 to 4.1 bio ha)</td><td>+53% (6.8 to 10.6 bio cal/ha)</td><td colspan="3">Impossible acting on any of these driver alone, but could combine -19% food waste (to 6.2%), -67% livestock in diets (to 7.6%) and improving and feed-to-food ratio -22% (to 1.8).</td><td>2.4 bio fewer people</td></tr>
</table>

Changes needed for each driver, to increase Global Caloric sufficiency, in the *middle of the road* scenario (SSP2). The absolute values are presented in parenthesis, (from the projected value in SSP2, to the value needed to increase global caloric sufficiency)

Table S5: Sensitivity Analysis of Caloric Sufficiency to caloric requirements precision

Based on the UN population projections detailed by demographics[14], we replicated caloric sufficiency calculations with age and gender-specific caloric requirements (ADERs from FAO[15]), under SSP2 assumptions and using UN medium fertility population projections for 2050. Caloric sufficiency calculated with this detailed demand (hereafter Cal_Suff_D) is compared to caloric sufficiency calculated with the constant ADER used in this work (hereafter Cal_Suff_0 see Text S4), both globally and nationally.

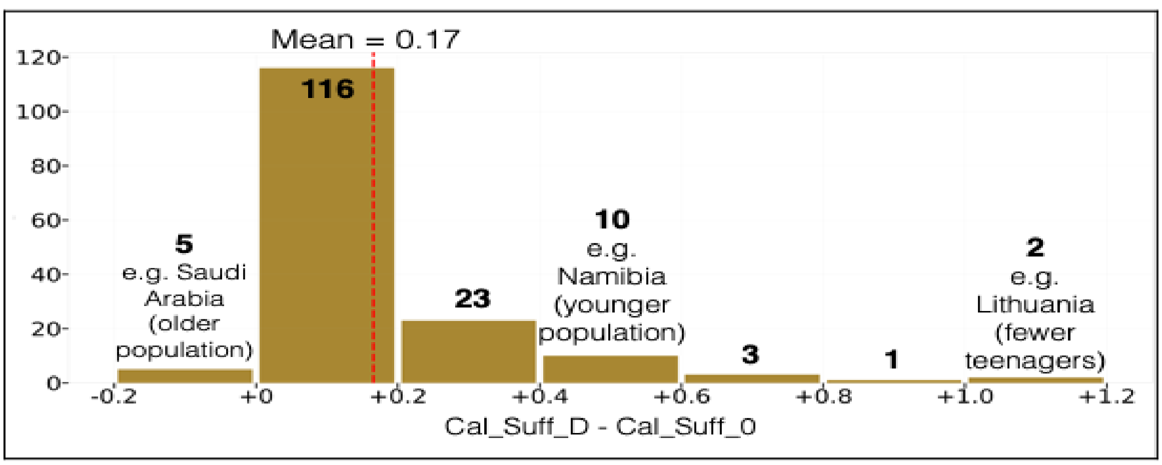
	Cal_Suff_0	Cal_Suff_D							
	Averaged / All pop	toddler (<4y) F	toddler (<4y) M	child (<10y) F	child (<10y) M	teen (<18y) F	teen (<18y) M	adult F	adult M
$ADER_{w/o\ fish}$ in kcal/ cap/ day	2320	902	979	1428	1560	2255	2701	1985	2463
Global Caloric Sufficiency (2000)	**1.96**	**2.13**							
Global Caloric Sufficiency (2050, SSP2- Medium Fertility)	**1.16**	**1.27**							
Countries Caloric sufficiency difference									

Table S5: ADERs were taken FAO: for infants from table 3.2 (daily energy requirements column), for 1-18y.o from tables 4.2 and 4.3, for adults from table 5.10. Values per each age groups are calculated averaging each specific age, assuming uniform age distributions within each age groups. Then the proportion of caloric requirement met by fish consumption is subtracted to get $ADER_{w/o\ fish.}$

Global caloric sufficiency (Cal_Suff_0) is 1.16 using our approach: with age and gender-agnostic terrestrial energy requirements ($ADER_{w/o\ fish}$ = 2320 kcal/cap/day. See Text S4). On the other hand, global caloric sufficiency (Cal_Suff_D) is 1.27 when calculated with energy requirements detailed per demographics (Table S5).

For most countries (116/160), the difference between caloric sufficiencies calculated with energy requirements detailed per demographics (Cal_Suff_D) vs. simplified (Cal_Suff_0) is less than <0.2. However countries with more children than the global proportion get a significantly higher caloric sufficiency when calculated with detailed demographics, up to +15% for 12 countries with mostly low caloric sufficiency

Table S6: Method summary with data and code links

Step	Notebook in github	Inputs	Outputs
Data exploration	Final/Data_exploration.ipynb	The baseline files	The baseline files normalized and clustered with the gdp categorized
Train model	Final/Model_training.ipynb	The baseline files with pixel related information	The trained model
Run model	Final/Model_training.ipynb	The trained model and data to predict	Files with predicted yields and pixel information about land use, population, etc. associated with their counterpart in 2000
Compute first global results: change in yield, cropland, production, livestock	Final/Model_results.ipynb	The current and predicted yields in addition to the data needed to compute each results	Values, figures and maps showing results
Compute global and country sufficiency	Final/sufficiency.ipynb	The files with predicted yields and pixel population in addition to the diet data	Country sufficiencies
Put sufficiency in perspective with added datasets	Final/CtryCalSuff_in_perspective.ipynb	The country sufficiency table and the additional datasets	Information about each country and categorization
Sensitivity analysis to new population data	Revision/New_population.ipynb	Predicted yields, diets, Jones and UN population datasets.	Values and figures to show the results

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