SI methods material

LandSyMM modules

PLUM

PLUM is a global land-use and food-system model that combines spatially-explicit, biophysically-derived crop yield with socio-economic scenario data to project future demand, land use, and management inputs[44]. For each country and timestep, the land under cultivation and level of agricultural imports or exports is determined through a least-cost optimisation that meets the demand for food and bioenergy commodities in each country. The demand for food is calculated for eight commodity groups: cereals, oilcrops, pulses, starchy roots, sugar, fruit and vegetables, ruminant products, and monogastric products. Demand is calculated by the modified, implicit, directly additive demand system (MAIDADS)[20,21]. MAIDADS system uses per-capita income levels, food prices and price elasticities to estimate subsistence and discretionary consumption levels and captures the nonlinearity of the relationship between food demand and income. Subsistence and discretionary consumption levels within a country are influenced by income via the utility level, which is indirectly determined by the income level. Discretionary consumption levels respond to price however subsistence consumption is unaffected by price. The demand system gives rise to a relationship between income and food products such that calories are consumed in the form of staple foods (cereals, oilcrops and pulses) at low income levels but this shifts to meat, milk, fruit and vegetables as incomes rise (Figure S1). Conversely, as prices increase, consumption shifts away from 'luxury' goods—such as meat and fruit and vegetables—back towards staple crops. If a country can't afford subsistence levels of consumption then demand for food products is calculated by scaling desired subsistence consumption by the ratio between income available for food expenditure and the desired subsistence consumption.

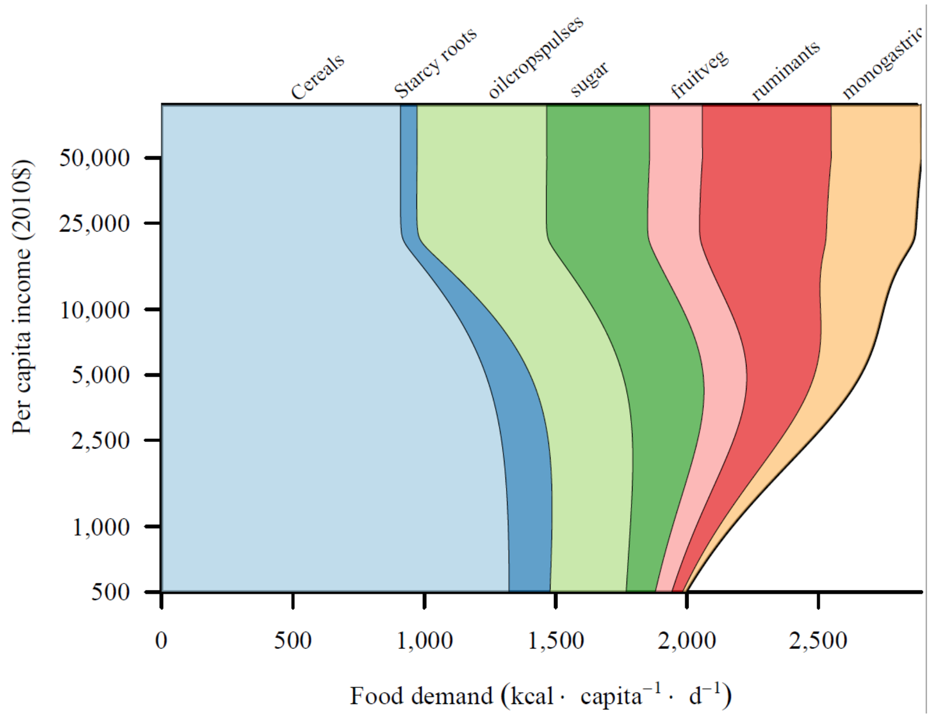

Figure S1: Relationship between per capita income and food demand in PLUM for the seven commodity groups.

Demand for commodities is met by in-country agricultural expansion and/or intensification or from imports from the global market. Commodities produced in excess of a country's domestic demand are exported to the global market. The global market is not constrained to be in equilibrium, instead allowing over- or undersupply of commodities buffered through modelled stocks. Prices are updated for the next year based on global stock levels. For example, oversupply of a commodity on the global market decreases the price as stocks rise, which in return reduces the benefits from its export and reduces the cost of importing it. For each commodity a single tariff free price exists in each time step, which is adjusted for transport costs and other trade barriers, e.g. tariffs, to obtain country specific prices. PLUM determines optimal land-use allocation on a 0.5° grid to meet country level demand. Within the land-use optimisation, PLUM uses spatially specific crop yield responses to intensity inputs, various land-use costs (such as land conversion costs and input costs), protected area constraints and trade costs (see Alexander et al., 2018 for more details on the land-use optimisation).

Land-use optimization also happens at a finer grain in LandSyMM (about 3400 grid cell clusters) than in other similar model systems (tens to hundreds of clusters).

Spatial constraints

The proportion of protected land within a grid cell is calculated using data from the WDPA database[45]. This equates to 1978 Mha or 6.7% of the modelled land surface. Within each grid cell, natural land designated as protected is prevented from conversion to any form of agricultural use; thus, we assume the strictest IUCN classification. In cells where agricultural land already exceeds the area specified as protected, agricultural land is not converted to natural land however no further agricultural expansion can occur. Slope constraints[46] also prevent agricultural use. The slope mask gives the fraction of land allowed for cropland, based on the area in different slope classes from the Harmonized World Soil Database. Cropland is allowed on up to 80% of the second-steepest class (30–45% grade, 27–40.5°) and therefore prevented on steeper slopes which includes land in the steepest class (> 45% grade, 40.5°).

Spatial distribution of protection

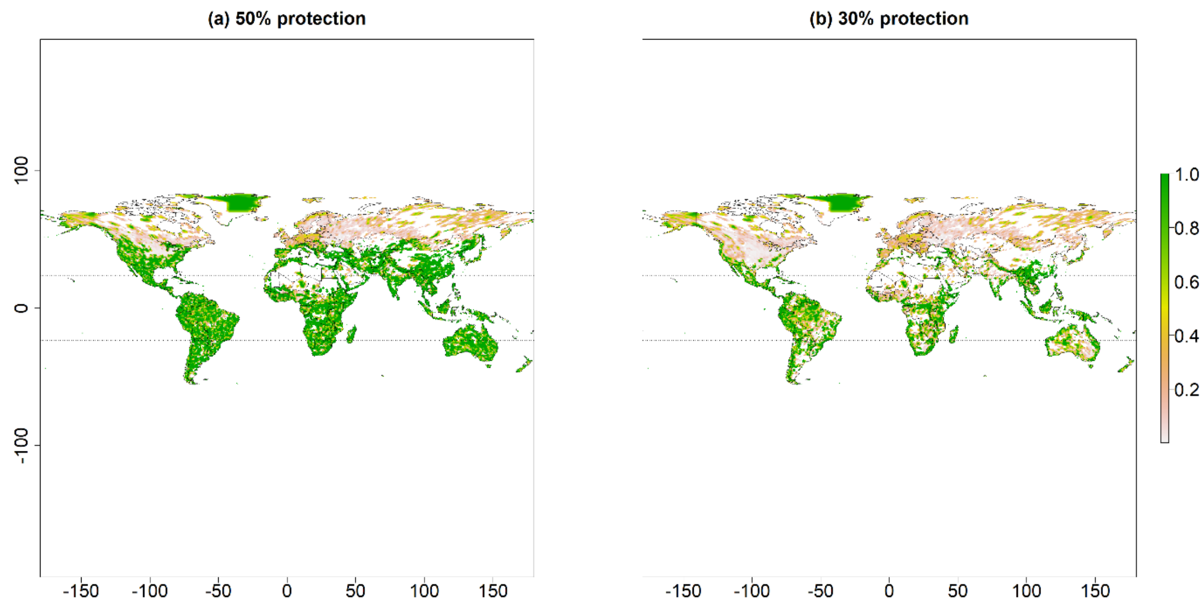

Figure S2: *The proportion of the grid cells protected is shown for the (a) 30% protection scenario and (b) 50% protection scenario. Dotted lines show the subtropical belt (-23.5° to 23.5°).*

Parameter	**Central value**
Irrigation cost, *w_cost* ($\$/m^2$)	0.5
Fertiliser cost, *f_cost* ($/t)	1800
Other intensity cost, *m_cost* ($ at max management input)	600
Land cover change cost, *lc_change*: Natural to agricultural ($/ha)	60
Land cover change cost, *lc_change*: Managed forest to agricultural ($/ha)	160
Land cover change cost, *lc_change*: Agricultural land to natural ($/ha)	200
Land cover change cost, *lc_change*: Pasture to cropland ($/ha)	220
Land cover change cost, *lc_change*: Cropland to pasture ($/ha)	370
Minimum natural or managed forest cover	10%
Pasture harvest fraction	50%
Seed and waste rate	10%
Technology yield change rate, , above that from intensification of production	0.2%
Initial price shift factor	1.0
International market price sensitivity,	0.3
International import tariff, *i_tariff*	20%
Transport costs, *t_cost* ($/t)	50
Transportation losses, *t_loss*	5%
Proportion of animal product substituted by cereals	0.3
Proportion of animal product substituted by pulses	0.35
Proportion of animal product substituted by starchy roots	0.3
Proportion of animal product substituted by oilcrops	0.05

Table S1: *LandSyMM model parameters used. A uniform distribution was sampled across a range 50% either side of the central values.*

Indicators

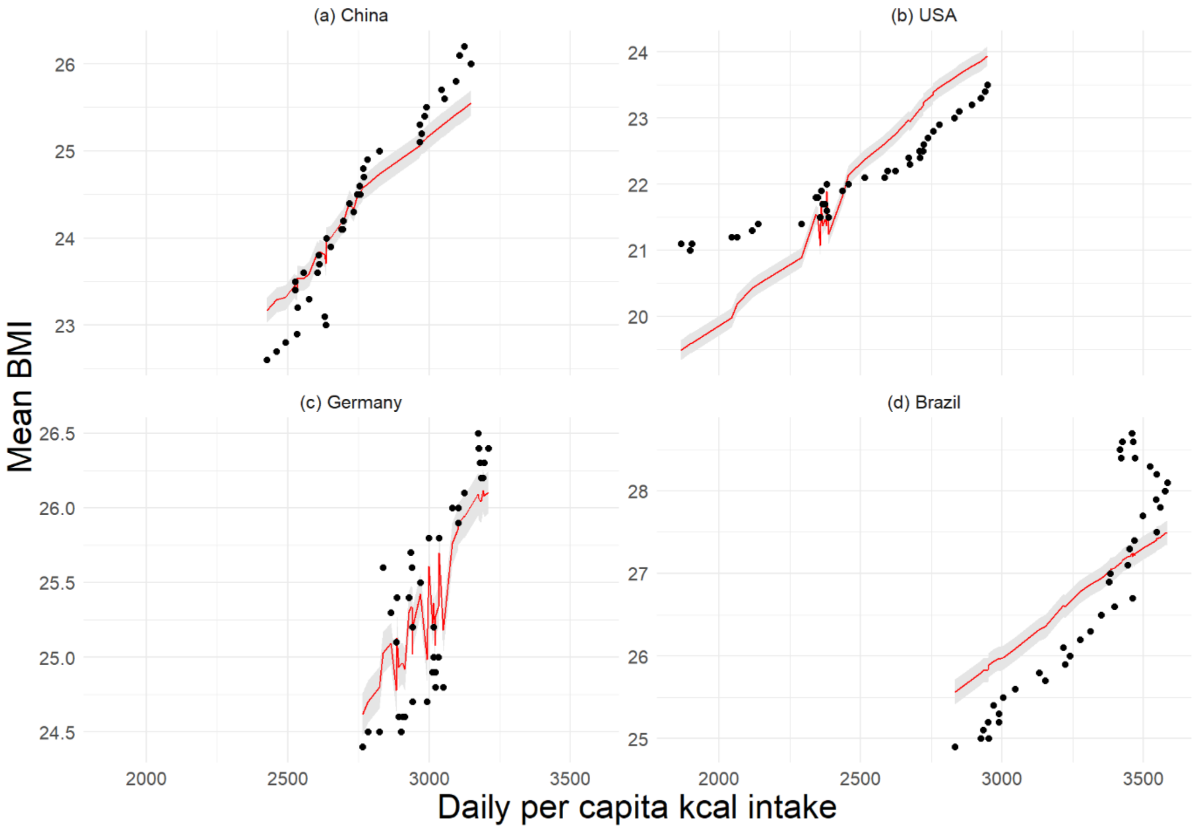

Figure S3: Relationship between daily per person calorie intake and mean BMI based on data from FAO and WHO for the years 2000 – 2017. Data for China, United States of America, Germany and Brazil are shown as examples. The points represent the historic data and the red line represents the fitted model with standard error shown as grey shading.

Risk factor	**Relative risk per cause of death**					
	Coronary heart disease	Stroke	All cancers	Colorectal cancer	Type-II diabetes	Other causes
Fruit consumption	0.95	0.77	0.94			
Vegetable consumption	0.87	0.95	0.94			
Red meat consumption		1.10		1.15	1.14	
Underweight	0.68	1.03	1.11			1.75
Normal weight						
Overweight	1.31	1.07	1.10		1.54	0.96
Obese	1.78	1.55	1.40		7.37	1.33

Table S2: Relative risk parameters taken from Springmann et al.[36] supplementary table 9. Blank spaces indicate an absence of evidence to support a relationship between a risk factor and disease endpoint and therefore those pairwise interactions are not included in the analysis.

Modelled food category	*FAO food category*
Red meat	*Bovine Meat, Meat Other, Mutton & Goat Meat*
Fruit	*Apples, Bananas, Citrus Other, Coconut Oil,Coconuts - Incl Copra, Dates, Fruits Other, Grapefruit,Grapes (excl wine), Lemons, Limes,Oranges, Mandarines, Pineapples*
Vegetables	*Onions, Pepper, Pimento, Plantains, Tomatoes, Vegetables Other*

Table S3: Modelled food categories and FAO commodities included.

Region	Countries
East Asia & Pacific	Australia, Brunei Darussalam, Cambodia, Fiji, Indonesia, Japan, Lao People's Democratic Republic, Malaysia, Mongolia, Myanmar, New Zealand, Philippines, Republic of Korea, Solomon Islands, Vanuatu, Viet Nam
Europe & Central Asia	Albania, Armenia, Austria, Azerbaijan, Belarus, Belgium, Bosnia and Herzegovina, Bulgaria, Croatia, Cyprus, Czechia, Denmark, Estonia, Finland, France, Georgia, Germany, Greece, Hungary, Iceland, Ireland, Italy, Kazakhstan, Kyrgyzstan, Latvia, Lithuania, Luxembourg, Malta, Montenegro, Netherlands, Norway, Poland, Portugal, Republic of Moldova, Romania, Russian Federation, Serbia, Slovakia, Slovenia, Spain, Sweden, Switzerland, Tajikistan, The former Yugoslav Republic of Macedonia, Turkey, Turkmenistan, Ukraine, United Kingdom, Uzbekistan
Latin America & Caribbean	Argentina, Bahamas, Barbados, Belize, Bolivia, Brazil, Chile, Colombia, Costa Rica, Cuba, Dominican Republic, Ecuador, El Salvador, Guatemala, Guyana, Haiti, Honduras, Jamaica, Mexico, Nicaragua, Panama, Paraguay, Peru, Saint Lucia, Vincent and the Grenadines, Suriname, Trinidad and Tobago, Uruguay, Venezuela
Middle East & North Africa	Algeria, Egypt, Iran, Iraq, Israel, Kuwait, Lebanon, Libya, Morocco, Oman, Saudi Arabia, Tunisia, United Arab Emirates, Yemen
North America	Canada, United States of America
South Asia	Afghanistan, Bangladesh, India, Maldives, Nepal, Pakistan, Sri Lanka
Sub-Saharan Africa	Angola, Benin, Botswana, Burkina Faso, Cabo Verde, Cameroon, Central African Republic, Chad, Congo, Cote d'Ivoire Democratic Republic of the Congo, Djibouti, Ethiopia, Gabon, Gambia, Ghana, Guinea, Guinea-Bissau, Kenya, Lesotho, Liberia, Madagascar, Malawi, Mali, Mauritius, Mozambique, Namibia, Niger, Nigeria,

	Rwanda, Sao Tome and Principe, Senegal, Sierra Leone, Somalia, South Africa, South Sudan, Sudan, Swaziland, Togo, Uganda, United Republic of Tanzania, Zambia, Zimbabwe

Table S4: Regional groupings.

SI results material

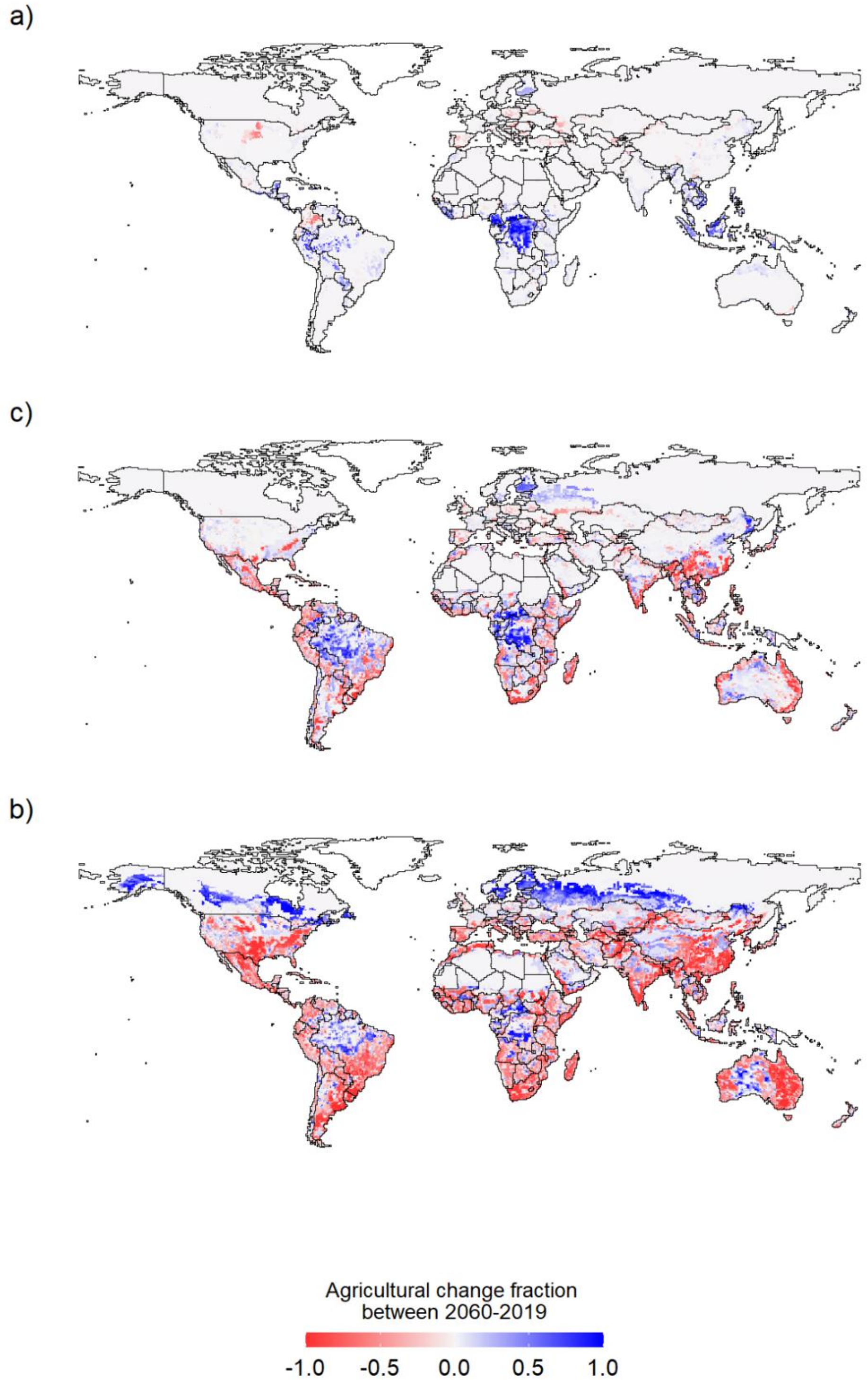

Figure S4: Agricultural land use fraction change between 2019 and 2060 in (a) the Reference scenario (b) the 30% protection scenario (c) the 50% protection scenario. The results of the median parameter run are shown.

Food type	Scenario 2019	Reference	30% protection	50% protection
East Asia & Pacific				
Meat	1.202	1.508	1.494	1.469
Fruit	2.404	2.180	2.168	2.153
Veg	6.400	5.168	5.147	5.116
Europe & Central Asia				
Meat	1.404	1.479	1.474	1.460
Fruit	3.115	3.118	3.107	3.085
Veg	3.520	3.489	3.475	3.447
Latin America & Caribbean				
Meat	1.129	1.391	1.383	1.368
Fruit	2.872	2.901	2.873	2.843
Veg	1.835	1.844	1.827	1.807
Middle East & North Africa				
Meat	0.376	0.655	0.647	0.624
Fruit	2.631	2.528	2.513	2.494
Veg	4.451	3.972	3.950	3.916
North America				
Meat	1.760	1.746	1.738	1.721
Fruit	3.210	3.224	3.208	3.179
Veg	3.041	3.048	3.033	3.005
South Asia				
Meat	0.112	0.222	0.215	0.200
Fruit	1.593	1.958	1.897	1.887
Veg	2.133	2.544	2.460	2.446
Sub-Saharan Africa				
Meat	0.370	1.074	1.050	0.981
Fruit	1.257	1.750	1.739	1.728
Veg	1.773	2.447	2.432	2.411

Table S5: Average number of 100g servings of red meat, fruit and vegetables in the seven world regions in the base period of 2019 and in the three scenarios in 2060. N=30.

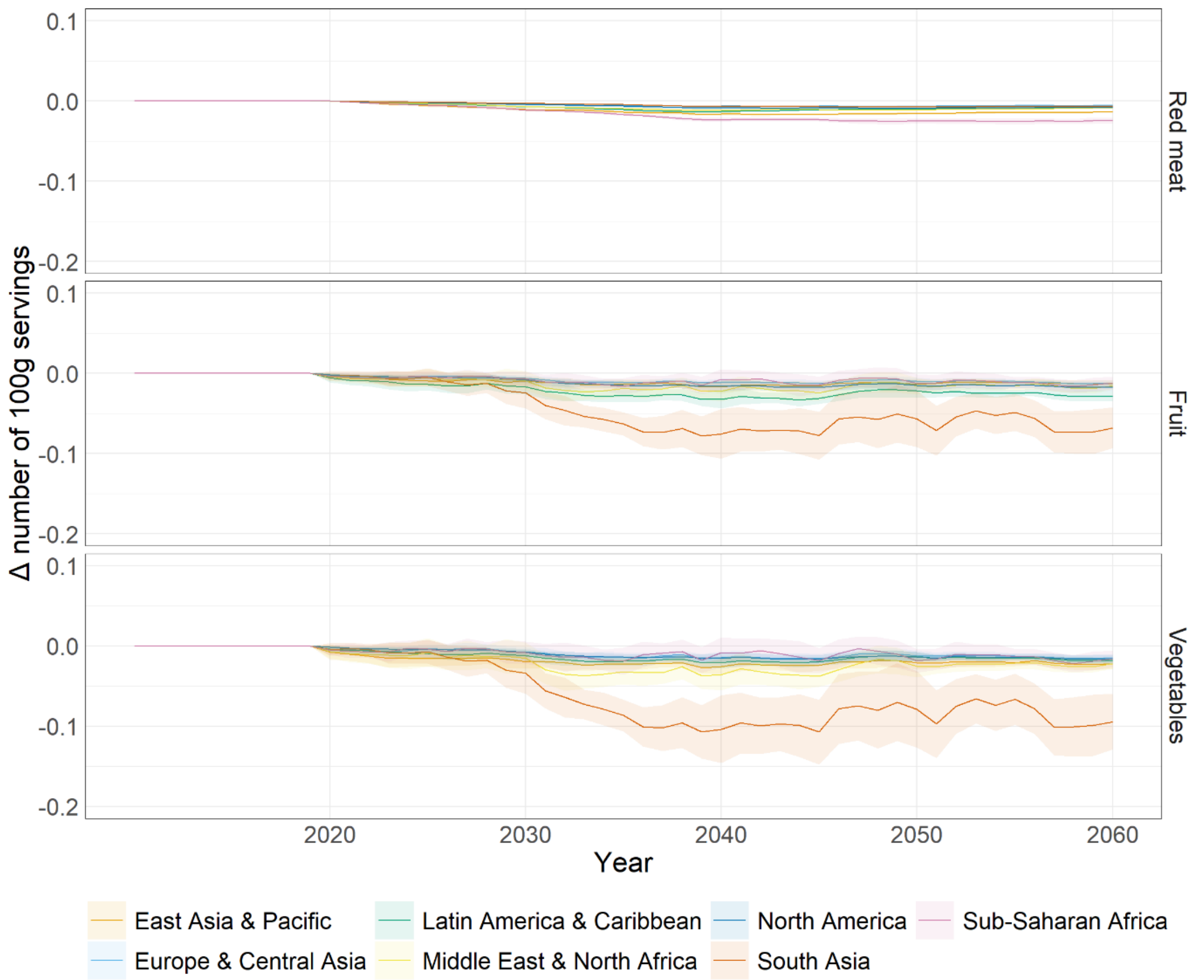

Figure S5: Difference in the number of 100g servings of red meat, fruit and vegetables between the 30% protection scenario and the Reference scenario. Changes in the y-axis value indicate a change as a result of the 30% protection scenario. The median and standard deviation as shown as line and shading respectively. N=30.

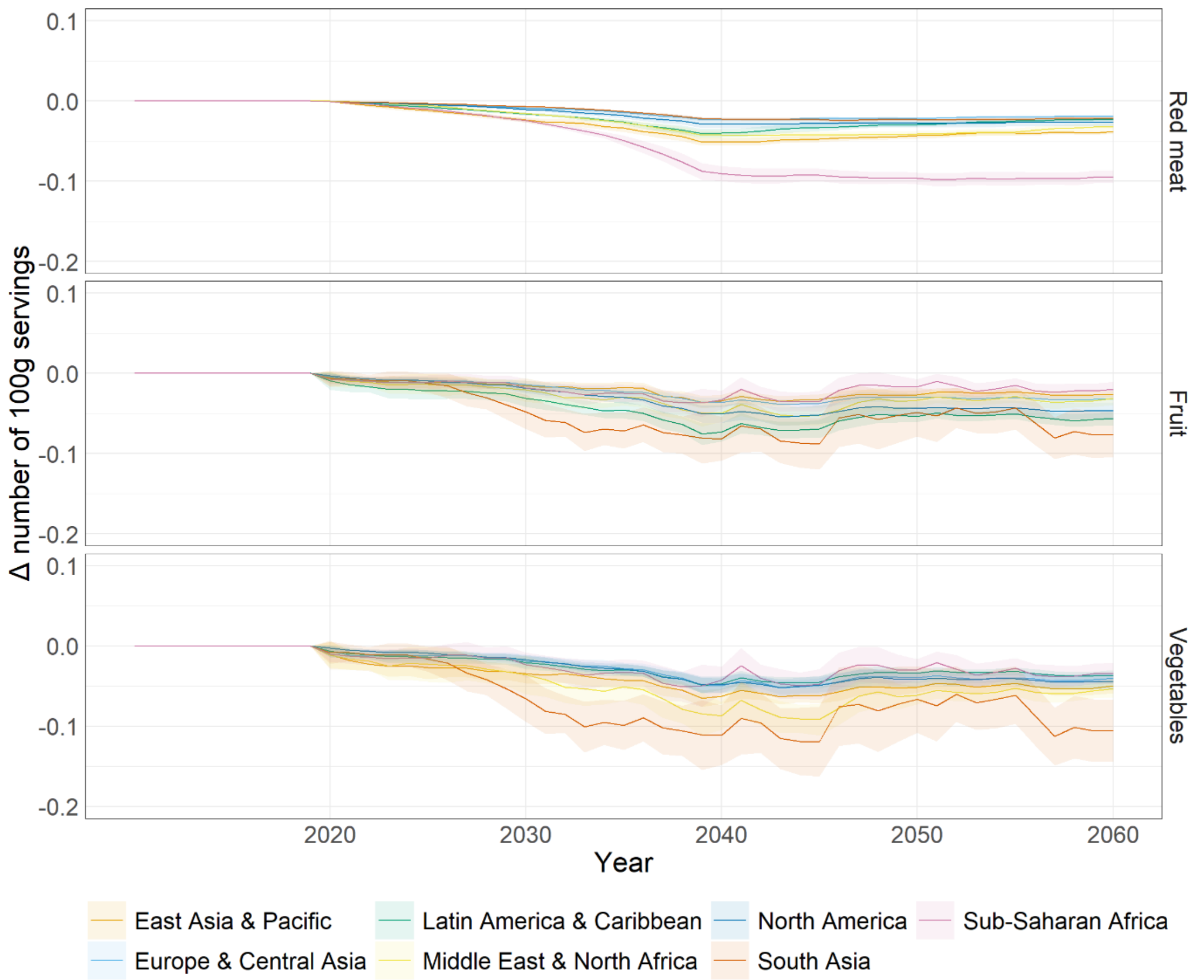

Figure S6: Difference in the number of 100g servings of red meat, fruit and vegetables between the 50% protection scenario and the Reference scenario. Changes in the y-axis value indicate a change as a result of the 50% protection scenario. The median and standard deviation as shown as line and shading respectively. N=30.

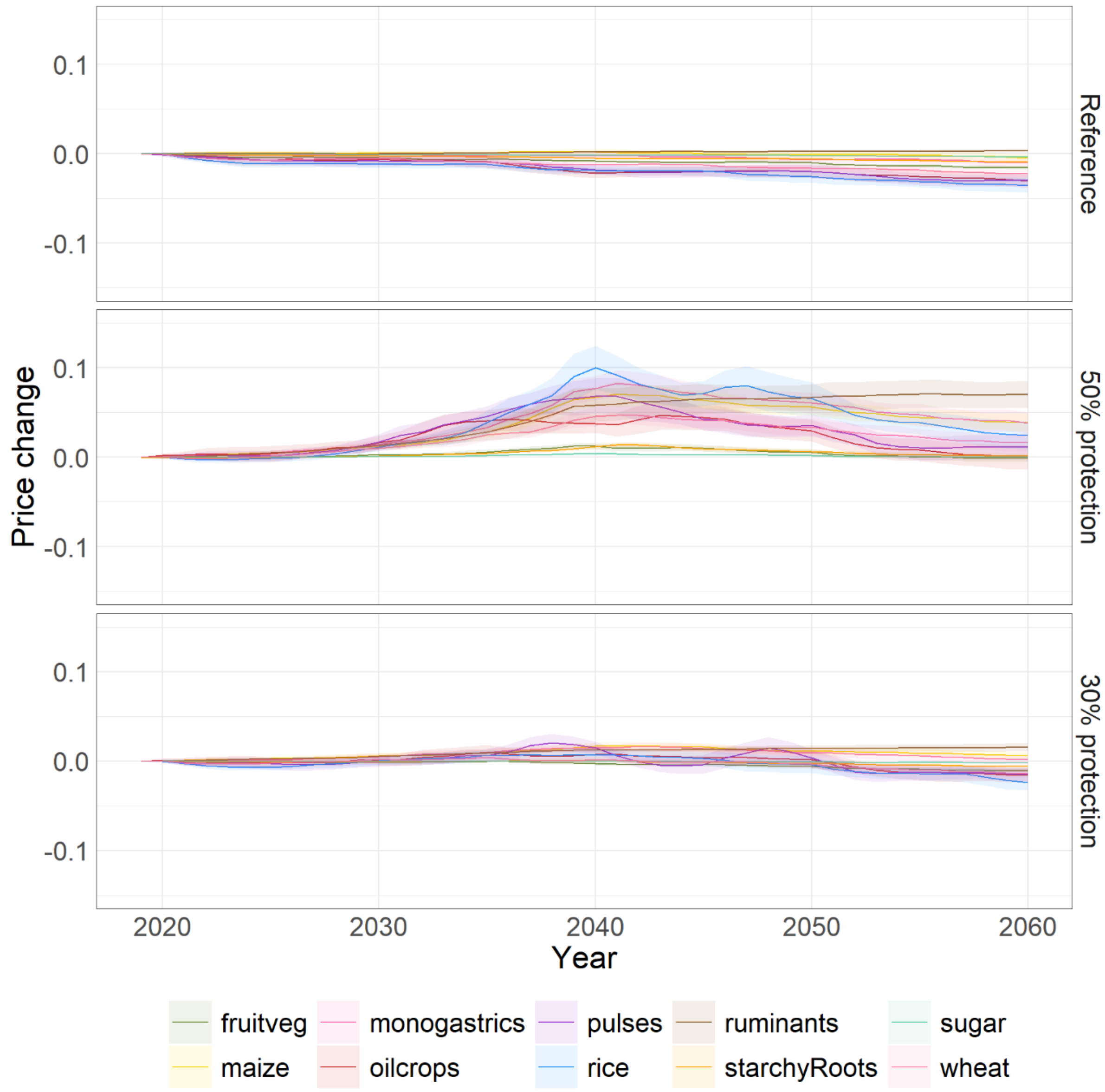

Figure S7: Global price change in the 3 different scenarios for the 8 different commodity types. The median and standard deviation are as shown as line and shading, respectively. N=30.