Supplementary Materials for:

Food procurement of staple cereals for world major cities in 2050

Toshichika Iizumi [1, *], Takahiro Takimoto [1], Michiya Hayashi [2], Hideo Shiogama [2], Shinichiro Fujimori [3], Tomoko Hasegawa [4]

[1] National Agriculture and Food Research Organization, Tsukuba, Japan
[2] National Institute for Environmental Studies, Tsukuba, Japan
[3] Graduate School of Engineering, Kyoto University, Kyoto, Japan
[4] Research Organization of Science and Technology, Ritsumeikan University, Kusatsu, Japan

The followings accompany this paper:

- Supplementary Data 1
- Supplementary Text 1
- Supplementary Table 1
- Supplementary Figures 1 to 11

Supplementary text 1.

Overview of the crop transport calculation. The procedure of calculating global crop transports consists of three components: the initial crop balance, domestic transport, and international transport. Each component is elaborated below.

Initial crop balance. The initial crop balance condition provides the starting point for the domestic transport. The crop balance is the difference between the production and consumption of the crop for food. On the one hand, the production of the crop for food consumption in the grid cell, $\mathrm{prod.food}_{g,c}$ (t), is calculated as:

$$\mathrm{prod.food}_{g,c} = \mathrm{yld}_{g,c} \times \mathrm{area}_{g,c} \times \mathrm{fr.food}_{i,c}$$

where the suffix *g*, *c* and *i* indicate the grid cell, the crop and the country, respectively, and $\mathrm{yld}_{g,c}$ is the yield of the crop in the grid cell (t/ha), $\mathrm{area}_{g,c}$ is the harvested area of the crop in the grid cell (ha), and $\mathrm{fr.food}_{i,c}$ is the crop's production share for food consumption in the country (fraction). On the other hand, the consumption of the crop for food in the grid cell, $\mathrm{cons}_{g,c}$ (t), is calculated as:

$$\mathrm{cons}_{g,c} = \mathrm{pop}_{g} \times \mathrm{cons.pc}_{i,c} / 1000$$

where pop_{g} is the population in the grid cell (persons) and $\mathrm{cons.pc}_{i,c}$ is the annual per capita consumption of the crop for food in the country (kg/person). The country annual per capita consumption of the crop for food, $\mathrm{cons.pc}_{i,c}$ (kg/person), is calculated as:

$$\mathrm{cons.pc}_{i,c} = [\ (\ \mathrm{yld}_{i,c} \times \mathrm{area}_{i,c} + \mathrm{impt}_{i,c} - \mathrm{expt}_{i,c}\ ) \times \mathrm{fr.food}_{i,c}\ ] / \mathrm{pop}_{i} \times 1000$$

where $\mathrm{yld}_{i,c}$ is the average yield of the crop in the country (t/ha), $\mathrm{area}_{i,c}$ is the total harvested area of the crop in the country (ha), $\mathrm{impt}_{i,c}$ is the annual mass of the crop imported by the country (t), $\mathrm{expt}_{i,c}$ is the annual mass of the crop exported by the country (t), $\mathrm{fr.food}_{i,c}$ is the crop's production share in the country for food consumption (fraction), and pop_{i} is the total population in the country (persons).

The balance of the crop between the production and consumption for food in the grid cell, $\mathrm{spdf}_{g,c}$ (t), is calculated as:

$$\mathrm{spdf}_{g,c} = \mathrm{prod.food}_{g,c} - \mathrm{cons}_{g,c}$$

A positive and a negative $\mathrm{spdf}_{g,c}$ value are referred to as the surplus and deficit of the crop for food consumption, respectively. The local crop transport within the grid cell is then calculated, assuming that the transported distance is the half of the grid interval (~28 km):

$$\mathrm{tp}_{gs\rightarrow gd,c} = \min(\ \mathrm{prod}_{g,c},\ \mathrm{cons}_{g,c}\ )$$

where the suffix *gs* and *gd* are the surplus and deficit grid cells, respectively, and $\mathrm{tp}_{gs\rightarrow gd,c}$ is the crop transported locally from the surplus grid cell to the deficit grid cell (t). For the local transport, the surplus and deficit grid cells are the same (gs=gd).

Domestic transport. After the local transport, the domestic transport begins to fill the crop deficits for food consumption with the surpluses in the same country. For each country, the crop is transported from a surplus grid cell to the nearest deficit grid cell with a maximum transport mass per step of 1,000 tons:

$$\mathrm{tp}_{gs\rightarrow gd,c} = \min(\ \mathrm{spdf}_{gs,c},\ |\mathrm{spdf}_{gd,c}|,\ 1000\ )$$

where $\mathrm{tp}_{gs\rightarrow gd,c}$ is the mass of the crop transported domestically (t), $\mathrm{spdf}_{gs,c}$ is the surplus in the grid cell where the crop is produced (t) and $|\mathrm{spdf}_{gd,c}|$ is the absolute value of the deficit in the grid cell where the crop is transported domestically (t). An absolute value of the deficit is used here because the transport mass is always positive or zero. The above equation leads to one of the following results. If both the surplus ($spdf_{gs,c}$) and the deficit ($|spdf_{gd,c}|$) are greater (>1000), then a maximum mass of the crop transported per step is set as the crop transported, i.e., $tp_{gs \rightarrow gd,c} = 1000$. If both the surplus ($spdf_{gs,c}$) and the deficit ($|spdf_{gd,c}|$) are smaller (≤1000), then the following rules apply – if the surplus is smaller than the absolute value of the deficit ($spdf_{gs,c} < |spdf_{gd,c}|$), then the crop transported is calculated as $tp_{gs \rightarrow gd,c} = spdf_{gs,c}$ and if the surplus is greater than or equal to the deficit ($spdf_{gs,c} \geq |spdf_{gd,c}|$), then the crop transported is calculated as $tp_{gs \rightarrow gd,c} = |spdf_{gd,c}|$. After determining the transported mass of the crop, the crop balance conditions for a pair of the surplus and deficit grid cells are updated:

$$spdf_{gs,c} = spdf_{gs,c} - tp_{gs \rightarrow gd,c} \text{ and } spdf_{gd,c} = spdf_{gd,c} + tp_{gs \rightarrow gd,c}.$$

The crop transport calculation described above for the country *i* is repeated until the sum of the national sum of the deficits or surpluses reached zero, or the national sum of the deficits remains unchanged between the current and the previous steps. This calculation is repeated for all countries.

International transport. After calculating the domestic transport, the surplus of the crop in the grid cells is considered as the stock in the country and eliminated from the international transport. In the international transport, for each country, the production of the crop for export in the grid cell, $prod.expt_{g,c}$ (t), is calculated as:

$$prod.expt_{g,c} = yld_{g,c} \times area_{g,c} \times fr.expt_{i,c}$$

where $yld_{g,c}$ is the yield of the crop in the grid cell (t/ha), $area_{g,c}$ is the harvested area of the crop in the grid cell (ha), and $fr.expt_{i,c}$ is the crop's production share for export in the country (fraction). The surplus of the crop in the grid cell is replaced with the production of the crop for export:

$$spdf_{g,c} = prod.expot_{g,c} \quad \text{if } spdf_{g,c} \geq 0.$$

The deficit of the crop in the grid cell remains the same:

$$spdf_{g,c} = spdf_{g,c} \quad \text{if } spdf_{g,c} < 0.$$

The crop transported from the surplus grid cell in an exporting country to a deficit grid cell in the importing country, $tp_{gs \rightarrow gd}$ (t), is calculated in the similar way as for the domestic transport calculation:

$$tp_{gs \rightarrow gd,c} = \min(spdf_{gs,c} \times fr.trade_{i,j}, |spdf_{gd,c}|, 1000).$$

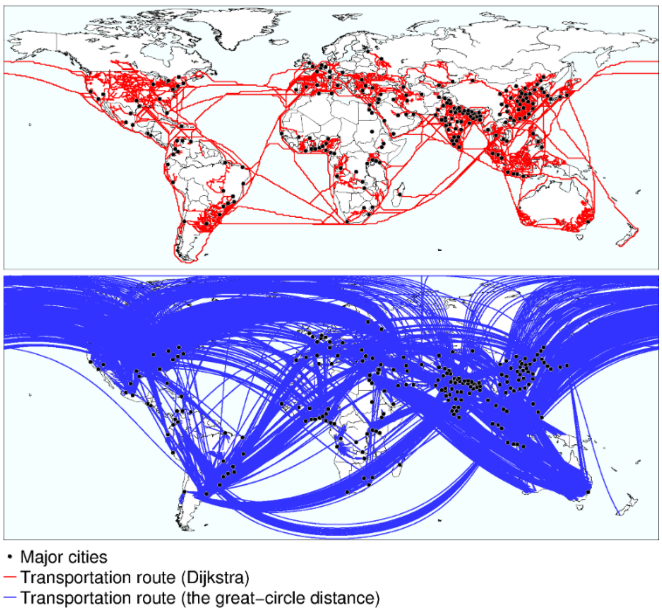
The only difference is that the export share of the exporting country *i* to the importing country *j*, $fr.trade_{i,j}$ (fraction), is taken into account by multiplying it by the surplus of the crop in the grid cell of the exporting country. Once the mass of the crop transported internationally is determined, the crop balance conditions are updated for the surplus in the grid cell of the exporting country and the deficit in the grid cell of the importing country, as in the domestic transport calculation:

$$spdf_{gs,c} = spdf_{gs,c} - tp_{gs \rightarrow gd,c} \text{ and } spdf_{gd,c} = spdf_{gd,c} + tp_{gs \rightarrow gd,c}.$$

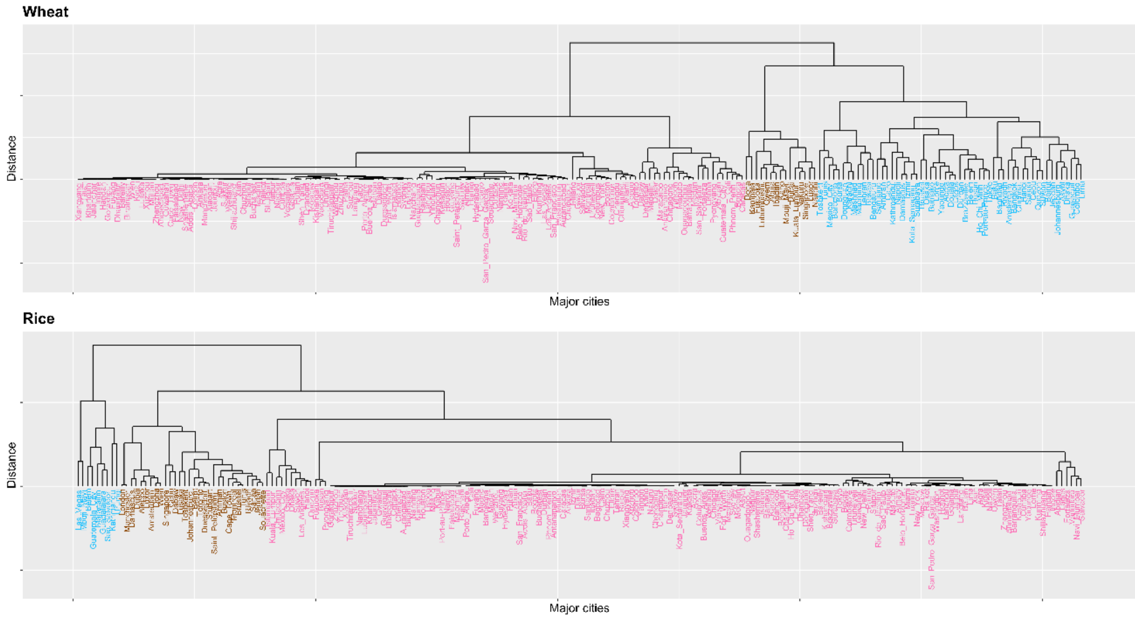
The crop balance condition at the global level is then calculated. The global sum of the crop surpluses, $sum.sp_c$ (t), and the global sum of the crop deficits, $sum.df_c$ (t), are calculated. The international transport calculation is terminated when $sum.sp_c$ or $sum.df_c$ becomes zero, or when $sum.df_c$ remains unchanged between the current and the previous steps.

Supplementary Table 1. The settings related to distance used in the calculation of Dijkstra algorithm,

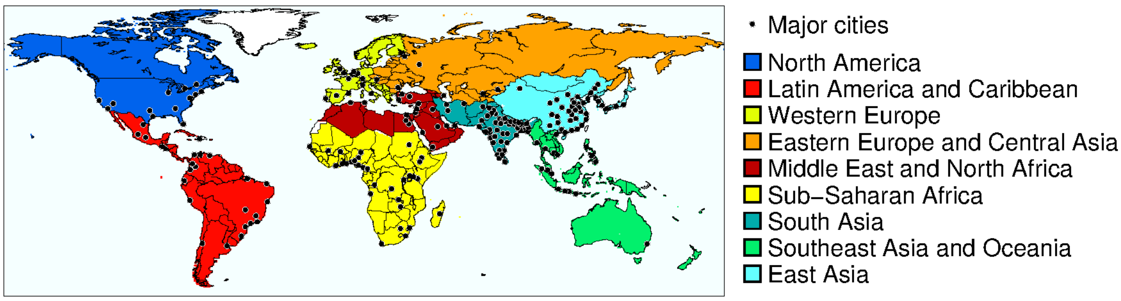
Road and shipping routes category	Average speed (km/h)	Average cargo capacity (t)	Distance used in Dijkstra algorithm (h/t/km)
Primary sea route	40	100	2.5×10^{-4}
Secondary sea route	40	50	5.0×10^{-4}
Highways	80	10	12.5×10^{-4}
Primary roads	50	5	40×10^{-4}
Secondary roads	30	2	167×10^{-4}
National or land-sea borders	5	10	200×10^{-4}
No road or shipping route is available	–	–	–



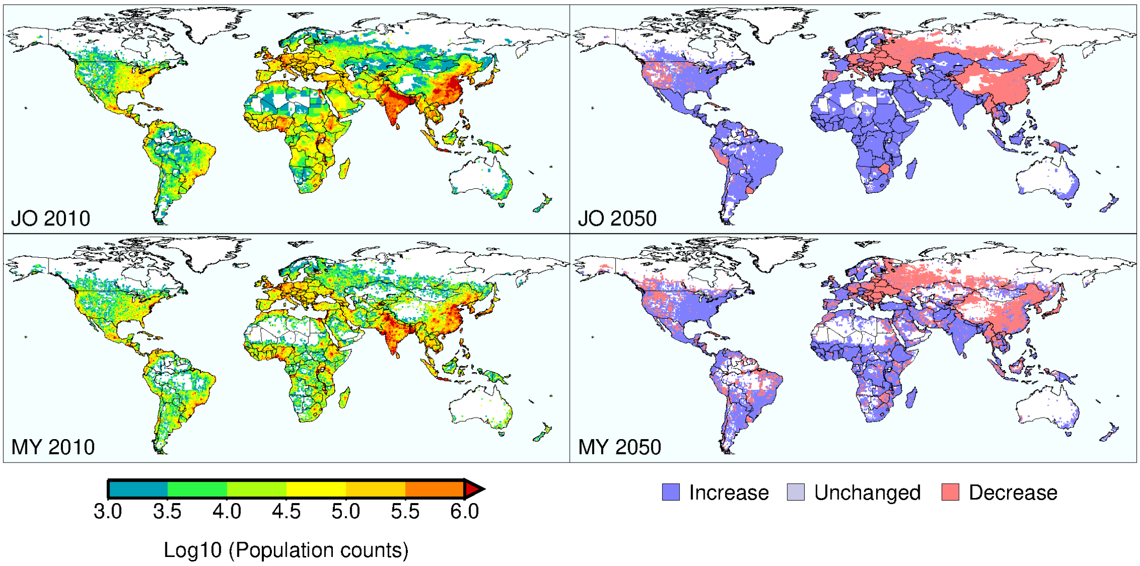
Supplementary Fig. 1. The shortest routes to the major cities estimated using the Dijkstra algorithm and great-circle distance algorithm.



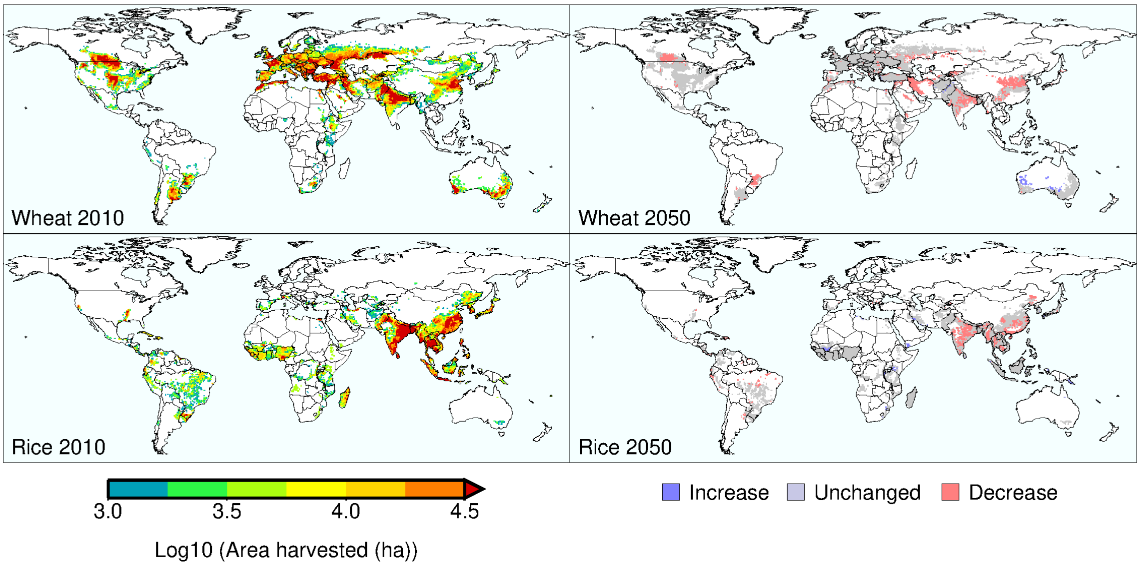
Supplementary Fig. 2. Dendrogram illustrating the clustering result. The 208 major cities are classified to three groups based on the current distance-sufficiency curves using the complete linkage clustering method in R.



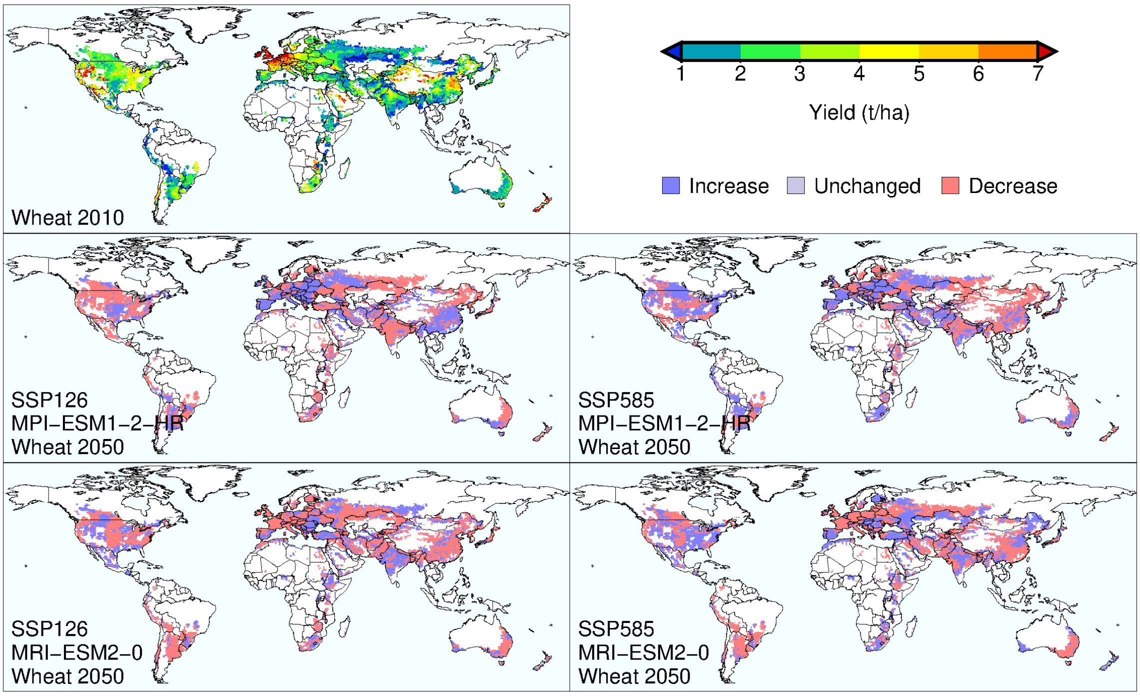
Supplementary Fig. 3. The 208 major cities of the world studied in this study. Colors indicate the classification by geographic region.



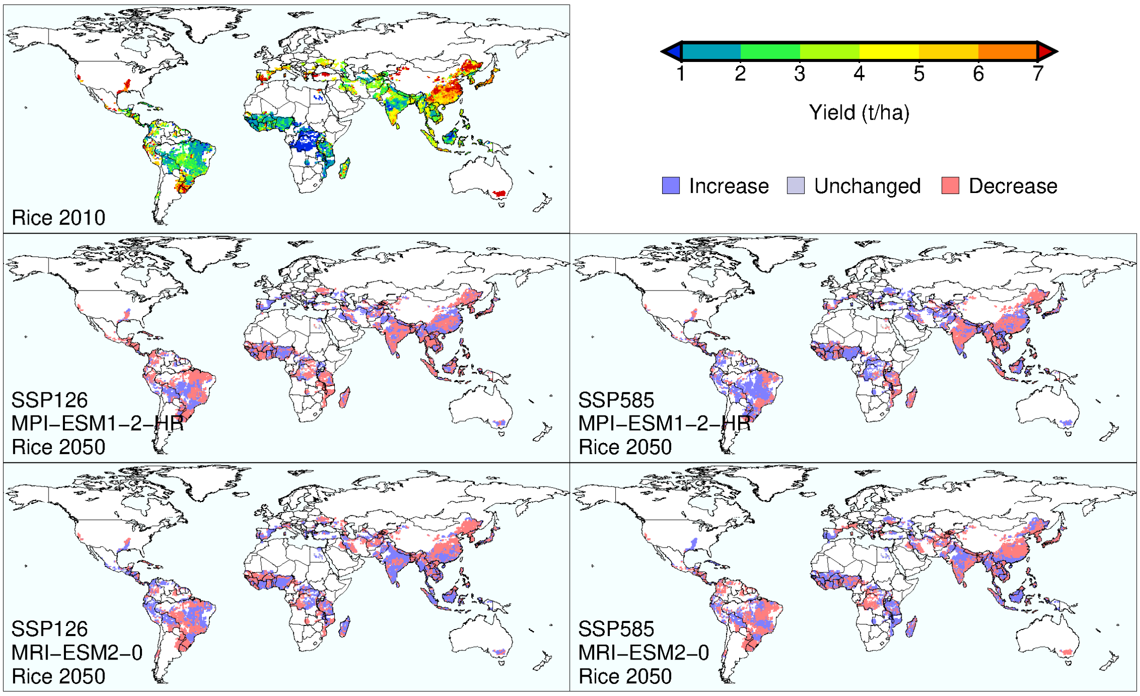
Supplementary Fig. 4. Geographic distribution of population in 2010 and projected change in 2050. The data presented here are obtained from two sources: Jones and O'Neill (2016) (JO) and Murakami and Yamagata (2019) (MY).



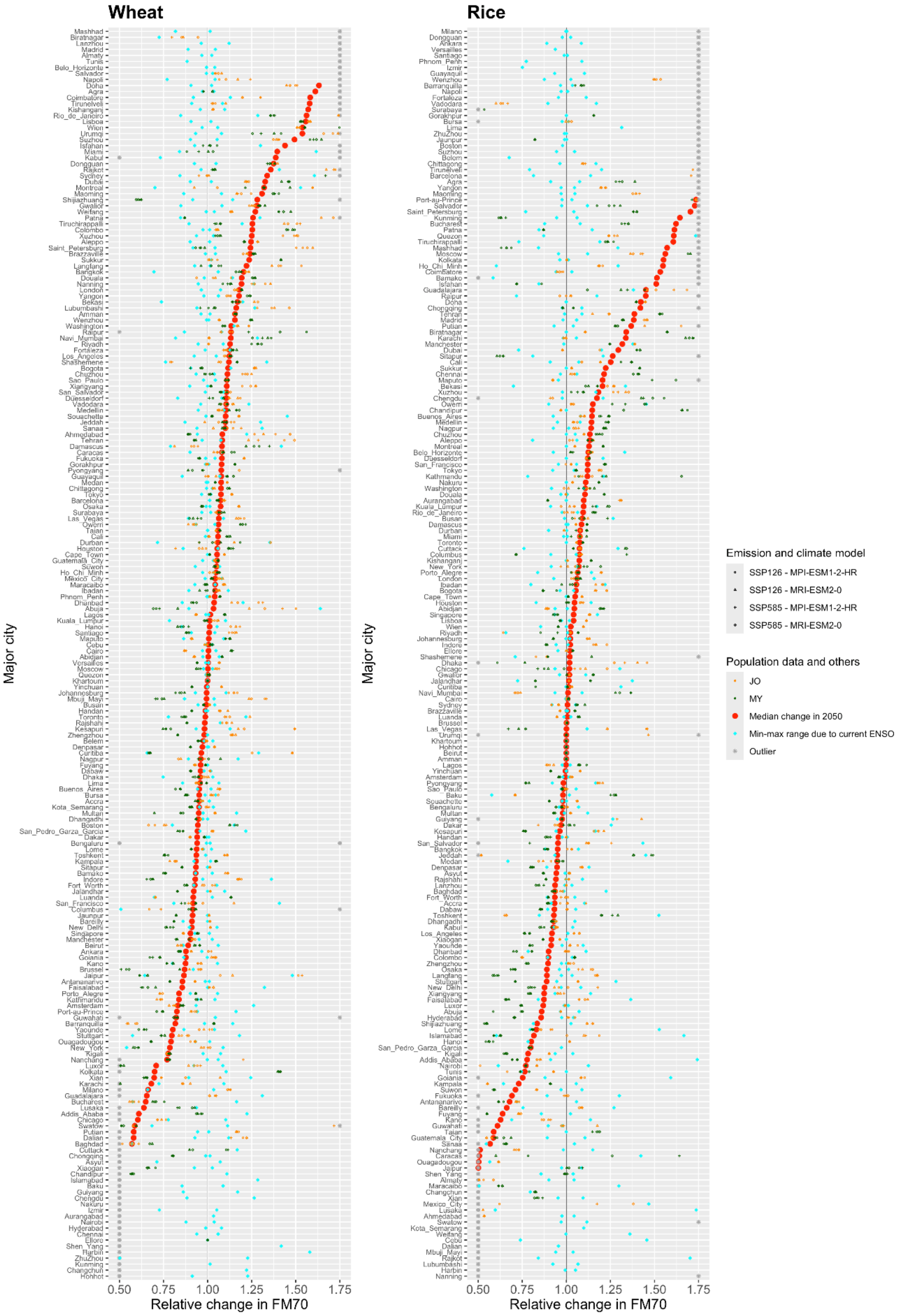
Supplementary Fig. 5. Geographic distribution of harvested area in 2010 and projected change in 2050 for wheat and rice. The projected data are based on the socioeconomic pathways SSP2 and obtained from NIES (2018).



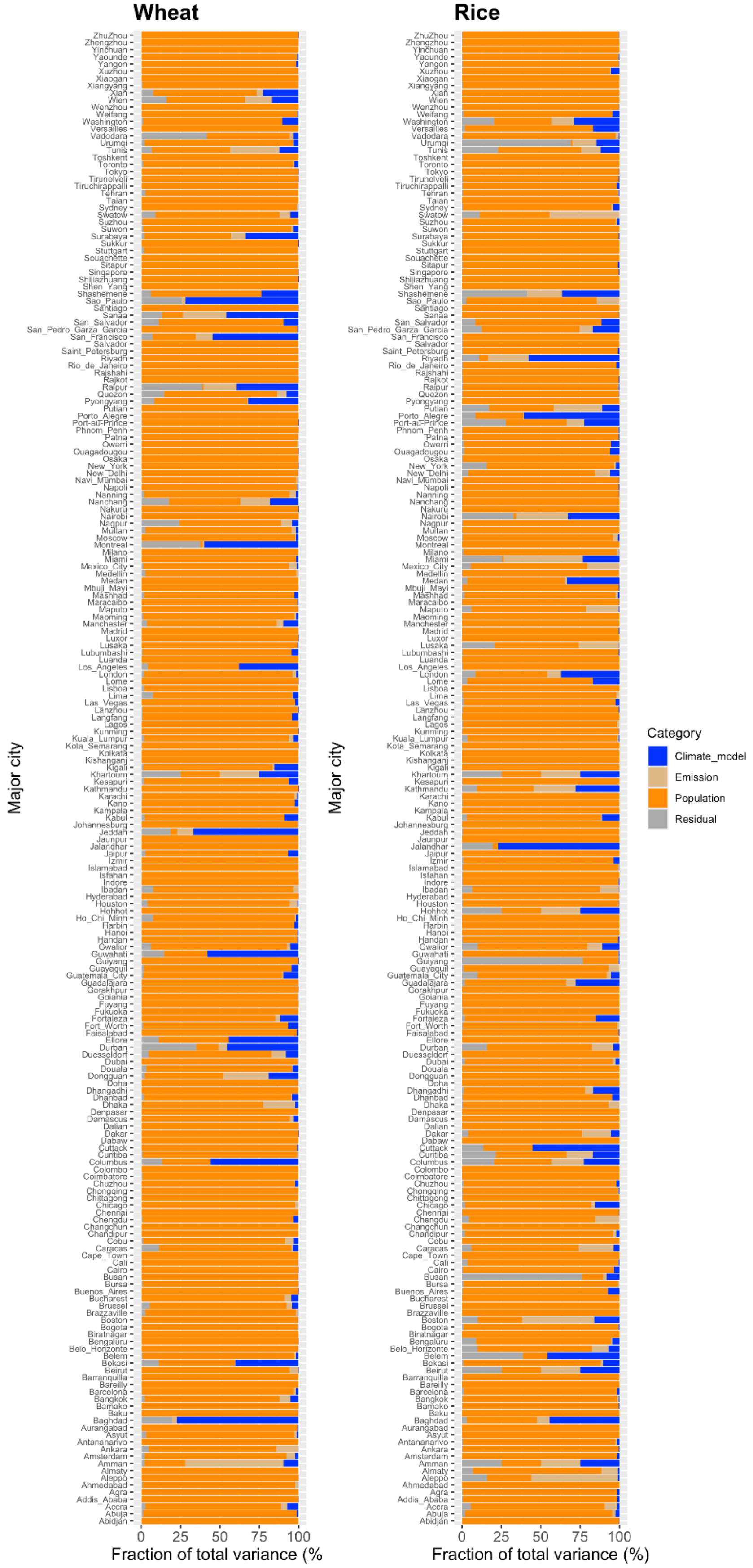
Supplementary Fig. 6. Geographic distribution of yield in 2010 and projected change in 2050 for wheat. The projected data are for ENSO neutral years and sourced from Jägermeyr et al. (2024) and Harrington-Tsunogai et al. (2025).



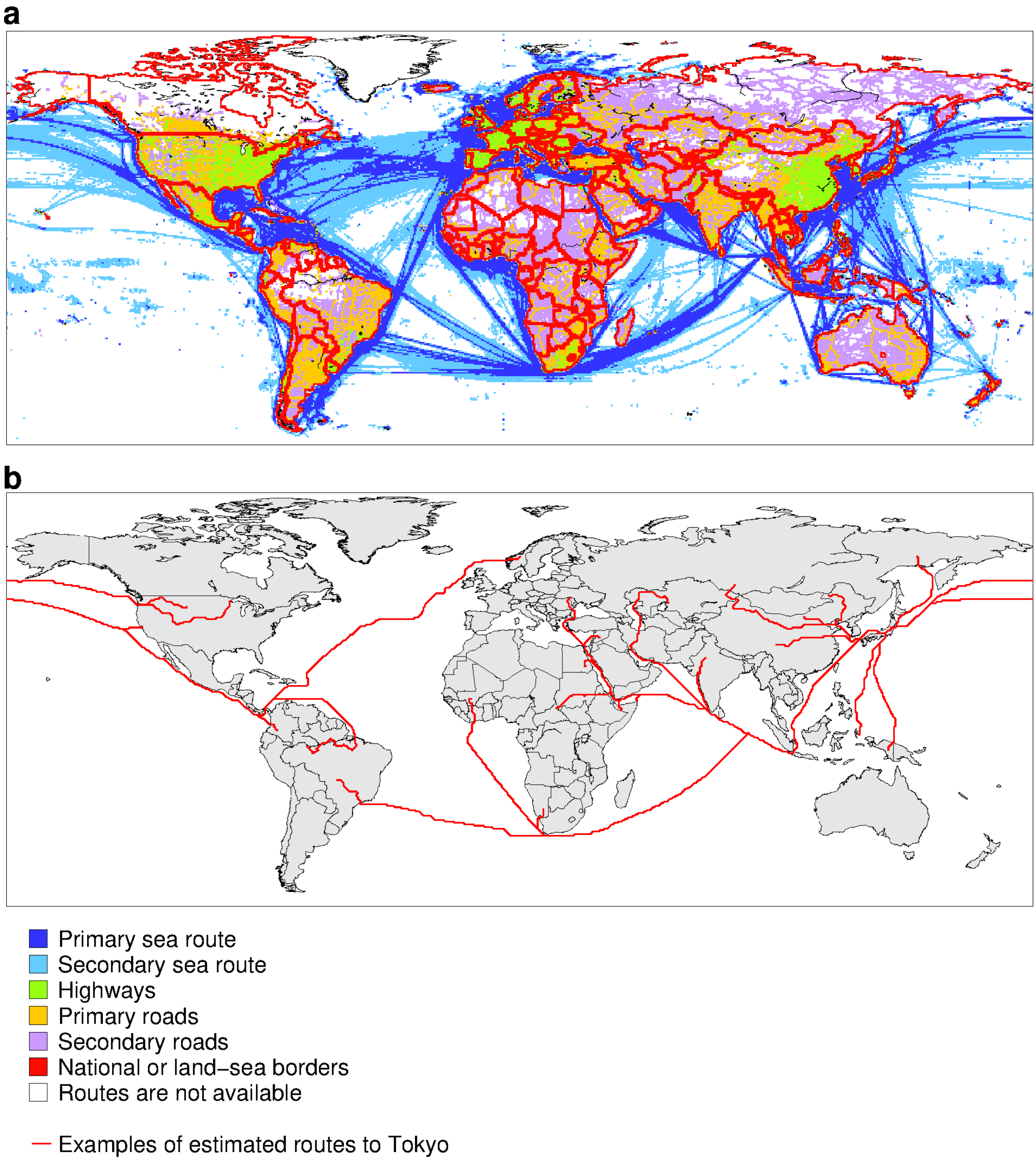
Supplementary Fig. 7. Same as Supplementary Fig. 6, but for rice.



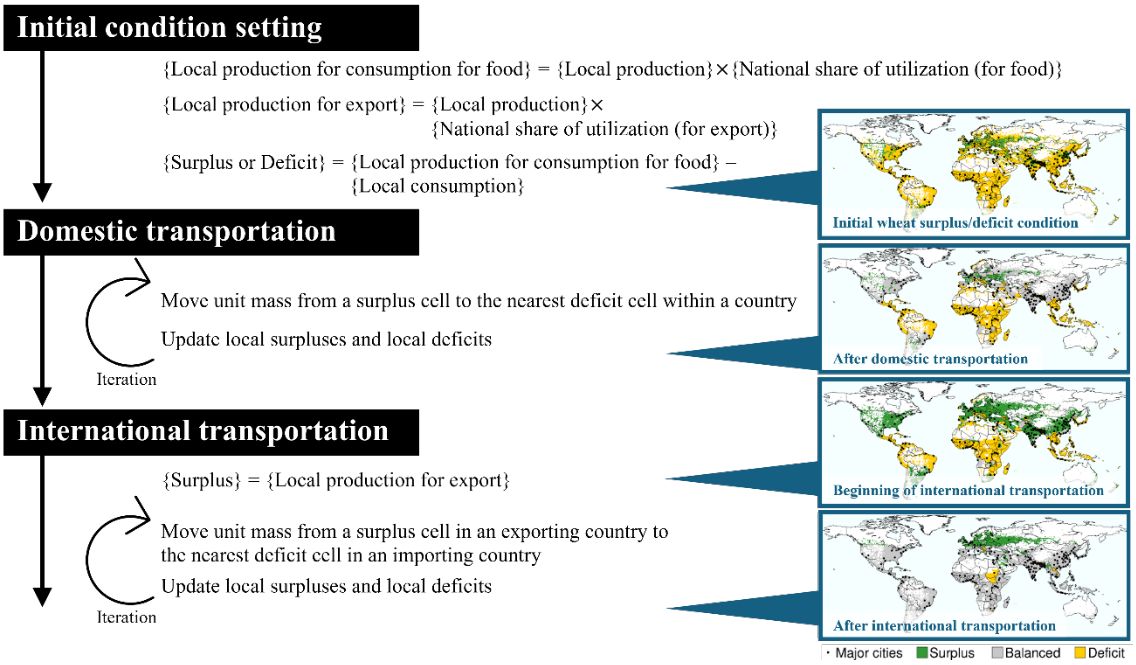
Supplementary Fig. 8. Projected changes in crop-specific FM70 for wheat and rice in 2050. The projected changes in FM70 are relative to the average FM70 over the ENSO neutral years in the current climate. Six projections are considered, consisting of two emission scenarios (SSP126 and SSP585), two climate models (MPI-ESM1-2-HR and MRI-ESM2-0) and two representations of the future population scenario (the JO and MY datasets). Only the data in the ENSO neutral years are used for the future climate. The ENSO-induced min-max range represents the variation in historical FM70 and relative to the average over the current ENSO neutral years.


Wheat
Rice
Major city
Major city
0
25
50
75
100
Fraction of total variance (%
Fraction of total variance (%)
Category
Climate_model
Emission
Population
Residual

Supplementary Fig. 9. The relative contribution of each source of uncertainty in the projected change in FM70 for the 208 major cities in 2050. The fraction of total variance in the projected change in FM70 is explained by use of different population datasets, emission scenarios (RCP) and climate models (GCM). The residual indicates the remaining uncertainty which is not explained by the three sources of uncertainty.



Supplementary Fig. 10. Global map of freight transport route categories. **a**. Freight transport route categories derived from the combined road and vessel density map. National borders and land-sea borders are also shown. **b**. Some of the estimated freight transport routes to Tokyo for explanatory purposes.



Supplementary Fig. 11. Schematic illustrating the procedure to estimate food-miles.