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## Going global to local: achieving agri-food sustainability from a spatially explicit input-output analysis perspective

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## **Appendix**

## 8 Appendix

### 8.1 Supporting information to chapter 2

#### 8.1.1 Critical review methodology – selection of the literature

We searched all papers using spatially-explicit input-output (SIO) approaches published before March, 2018 and analyzed their spatial scale, method, and environmental impacts.

We use Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines to search for articles using SIO approaches, on March, 2018 (Figure S 8.1) <sup>424</sup>. PRISMA aims to be a standard operating procedure for systematic reviews, in order give a more reliable and less biased result <sup>425</sup>. The systematic and explicit methods for this systematic review reduces issues with identifying, selecting, synthesizing, summarizing, collecting and analyzing data <sup>425</sup>. It also allows for reproducibility by providing all the information required to perform the review. We searched three scientific catalogues: Web of Science, ScienceDirect and the Leiden University Catalogue. There is a large diversity of terms in the literature describing the same, spatially-explicit concept, including “map”, “mapping”, and “hotspots”. Of course, not all of these are synonyms, and not all of these studies are in fact spatially-explicit. In order to restrict the search further we included terms including “input-output” and “MRIO (Multi-Regional Input Output)”, For example, we use the combination of (“spatial\*” or “map\*” or “hotspot\*”) and (“input output analysis” or “input output model” or “input output table” or “MRIO”) in for the research topic in Web of Science. For the detailed protocol please see the Supporting Information.

The search criteria are: (1) that all papers are in English; (2) that all papers are in peer-reviewed; (3) that all papers use input-output method; (4) that all papers have spatially distributed results at a resolution higher than regional. A flow diagram of the search methodology is shown in Table S 8.1. After using search protocols, we find another 15 papers using Google Scholar, and then perform a snowball sampling of these papers, finding a further 14 eligible papers.

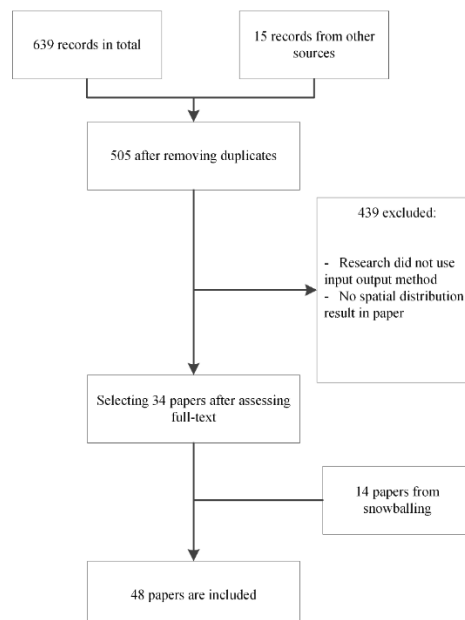


**Figure S 8.1** Flow diagram of the search methodology used. After a large number of initial studies were found, these were filtered on the criteria described above to 48 analyses.



### 8.1.2 Methodological approaches in the literature

#### Method 1: mapping between MRIO model and hydrological model—WaterGAP

Lutter et al. and Holland et al. combined an MRIO model (EXIOBASE in the case of Lutter et al. and GTAP8 in the case of Holland et al.), with WaterGAP model to research fresh water consumption embodied in trade almost at the same time<sup>50,113</sup>. Their core work is to build up mapping relationship between MRIO table and water consumption data from WaterGAP model by production sector, particularly different agricultural sectors (Table S 8.2). The difference was that Lutter et al mapped MRIO data into watershed scale, but Holland et al. mapped MRIO data into original resolution—0.5°×0.5° grid cell—of WaterGAP<sup>113</sup>.

**Table S 8.2** Example of disaggregation matrix, indicating which share of water consumption in a specific industry-region combination is originating from which watershed.

|             | Region 1 |     |       | ... | Region n |     |       |
|-------------|----------|-----|-------|-----|----------|-----|-------|
|             | Ind 1    | ... | Ind n | ... | Ind 1    | ... | Ind n |
| Watershed 1 | 0        | ... | 0.95  | ... | 0.57     | ... | 0.3   |
| ...         | ...      | ... | ...   | ... | ...      | ... | ...   |
| Watershed m | 1        | ... | 0.05  | ... | 0.43     | ... | 0.7   |

Source: from Lutter et al.<sup>50</sup>

#### Method 2: identifying hotspots from supply chains

Kanemoto et al. developed a spatially-explicit MRIO method to identify spatially-explicit environmental impacts hotspots embodied in supply chain<sup>95</sup>. The core of this method is to nest spatial distribution map (R) into traditional multi-regional input-output model.

$$H_{(m)s} = \sum_r R^r \frac{\sum_i f_i^r \sum_{jt \neq s} L_{ij}^{rt} y_j^{ts}}{\sum_i d_i^r} \quad (S1)$$

$$H^{(c)s} = \sum_r R^r \frac{\sum_i f_i^r \sum_{jt} L_{ij}^{rt} y_j^{ts}}{\sum_i d_i^r} \quad (S2)$$

**Table S 8.3** Variables and description of hotspots method.

| Variables  | Description                                                                              |
|------------|------------------------------------------------------------------------------------------|
| $H_{(m)s}$ | the PM <sub>2.5</sub> emission hotspots H driven by imports (m) into country s           |
| $H^{(c)s}$ | the PM <sub>2.5</sub> emission hotspots H driven by total consumption (c) into country s |
| $R$        | PM <sub>2.5</sub> emission maps term (R) are in absolute values                          |
| $d$        | total emissions                                                                          |
| $f$        | intensity of PM <sub>2.5</sub>                                                           |

|     |                                                           |
|-----|-----------------------------------------------------------|
| $L$ | Leontief inverse                                          |
| $y$ | final demand                                              |
| $i$ | sector of origin and destination                          |
| $j$ | sector of destination                                     |
| $r$ | exporting country                                         |
| $s$ | importing country                                         |
| $t$ | country of last sale in the consumption and imports terms |

### Method 3: integrating process-based model with input-output model

Wang et al. developed hybrid method that integrated process-based model with input-output model to analyze global water scarcity at basin level <sup>97</sup>. The most pivotal part of this method is

$$WSI_i^{BAU} = \frac{WW_i^{BAU}}{BA_i} \quad (S3)$$

$$WSI_i^{NT} = \frac{WW_i^{NT}}{BA_i} \quad (S4)$$

**Table S 8.4** Variables and description of integrating process-based model with input-output model.

| Variables     | Description                                                 |
|---------------|-------------------------------------------------------------|
| $WSI_i^{BAU}$ | Water stress index with international trade at basin $i$    |
| $WSI_i^{NT}$  | Water stress index without international trade at basin $i$ |
| $WW_i^{BAU}$  | Water withdraw at basin $i$ with international trade        |
| $WW_i^{NT}$   | Water withdraw at basin $i$ without international trade     |
| $BA_i$        | Blue water availability annually at basin $i$               |

$WW_i^{BAU}$  was calculated by downscaling production-based national water withdraws into basins based on water withdraw estimated Aqueduct Global Maps in 2010.

$WW_i^{NT}$  was calculated by downscaling consumption-based national water withdraws, which got from MRIO model, into basins based on the same proportion of  $WW_i^{BAU}$

### Method 4: Integrating MRIO model with production-side location information.

Cazcarro et al. integrated input-output model with spatial location information to downscale grey water footprints into business level <sup>116</sup>. There were three steps to downscaling grey water footprints as following figure (Figure S 8.2): (1) estimating direct intensities of grey water footprints; (2) calculating grey water footprints with multi-regional input-output model; (3) downscaling grey water footprints into business level.

Mekonnen et al. estimated global agricultural grey water footprints driven by EU27 consumption with similar method of agricultural part in Cazcarro et al <sup>115</sup>.

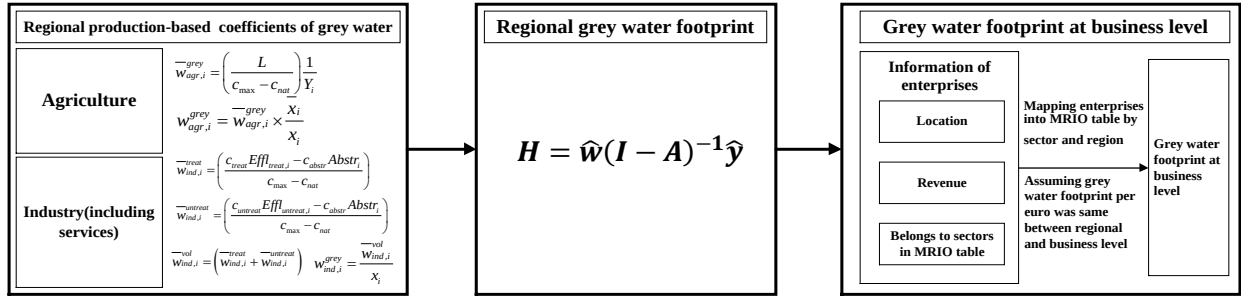


**Figure S 8.2** Process of downscaling grey water footprints into business level.

**Table S 8.5** Variables and description of method that downscales grey water footprints.

| Variables                   | Description                                                                          |
|-----------------------------|--------------------------------------------------------------------------------------|
| $\bar{w}_{agr,i}^{grey}$    | Agricultural physical grey water coefficient (m <sup>3</sup> /ton) for $i^{th}$ crop |
| $L$                         | Excess of nitrogen (kg/ha per year)                                                  |
| $c_{max}$                   | Maximum acceptable concentration                                                     |
| $c_{nat}$                   | Natural concentration                                                                |
| $Y_i$                       | Crop yield for $i^{th}$ crop                                                         |
| $w_{agr,i}^{grey}$          | Agricultural direct grey water coefficient (m <sup>3</sup> /euro) for $i^{th}$ crop  |
| $x_i$                       | Agricultural output (euro) for $i^{th}$ crop                                         |
| $\bar{X}_i$                 | Agricultural production (ton) for $i^{th}$ crop                                      |
| $\bar{w}_{ind,i}^{treat}$   | Amount of grey water from treated water(m <sup>3</sup> ) for sector $i$              |
| $\bar{w}_{ind,i}^{untreat}$ | Amount of grey water from untreated water(m <sup>3</sup> ) for sector $i$            |
| $c_{treat}$                 | Concentration of treated effluent(mg/l)                                              |
| $c_{abstr}$                 | Actual concentration(mg/l)                                                           |
| $Effl_{treat,i}$            | Volume of treated effluent for sector $i$                                            |
| $Abstr_i$                   | Water volume(m <sup>3</sup> ) for sector $i$                                         |
| $c_{untreat}$               | Concentration of untreated effluent(mg/l)                                            |
| $Effl_{untreat,i}$          | Volume of untreated effluent for sector $i$                                          |
| $\bar{w}_{ind,i}^{vol}$     | Total amount of grey water(m <sup>3</sup> ) for sector $i$                           |

---

|                    |                                                     |
|--------------------|-----------------------------------------------------|
| $w_{ind,i}^{grey}$ | Direct grey water coefficient for sector $i$        |
| $H$                | Grey water footprint matrix                         |
| $\hat{w}$          | Grey water coefficient matrix                       |
| $I$                | Identify matrix                                     |
| $A$                | Technical coefficient matrix for input-output table |
| $\hat{y}$          | Final demand vector                                 |

---

### Method 5: dynamic inoperability input-output model (DIIM)

Inoperability input-output model is a good tool to assess risk, and McDonald et al. integrated dynamic inoperability input-output model with volcanic locations to estimate economic loss<sup>117</sup>.

Four steps to construct spatial map of risk by DIIM:

- splitting regional output into the finest spatial scale;
- evaluating production inoperability in each finest spatial location;
- estimating total economic impact by DIIM;
- adjusting total economic impacts based on hazard probability.

### Method 6: combining data from MRIO table and demand-side subnational information.

Several researchers linked subnational information with input-output model to estimate subnational environmental impacts, the details referenced to their papers<sup>105,108,123,126–128</sup>. Maybe some small difference existed in their method, but the core of their method is to combine supply chain information in national input-output database or multi-regional input output database to track upstream environmental impacts with subnational consumption information to calculate subnational environmental impacts, for example consumer expenditure surveys (CESs), to calculate subnational environmental impacts.

For example, Feng et al. combined with geo-demographic data to calculate water footprints at subnational area. The core equations are as follows.

$$w_{Int} = e^{d*}(I - A)^{-1}y + w_{hh} \quad (S10)$$

$$w_{Ext} = e^{i*}(I - A)^{-1}y \quad (S11)$$

$$e^{d*} = [e^d, 0] \quad (S12)$$

$$e^{i*} = [0, e^i] \quad (S13)$$

$$y = \begin{bmatrix} y^d \\ y^i \end{bmatrix} \quad (S14)$$

**Table S 8.6** Variables and description of method that combines with subnational information.

---

| Variables | Description |
|-----------|-------------|
|-----------|-------------|

---

|           |                                                                    |
|-----------|--------------------------------------------------------------------|
| $w_{Int}$ | Water footprint from domestic consumption                          |
| $w_{Ext}$ | Water footprint from other countries                               |
| $w_{hh}$  | Water consumption from direct household consumption                |
| $e^d$     | Water consumption coefficients of domestic commodities             |
| $e^i$     | Water consumption coefficients of commodities from other countries |
| $y^d$     | Final demand from domestic and export commodities                  |
| $y^i$     | Final demand from other countries                                  |
| $I$       | Identify matrix                                                    |
| $A$       | Technological coefficients matrix                                  |

$A$  is from MRIO table at country level, and replace final demand  $y$  at regional level, it would calculate water footprint at local regional scale.

#### Method 7: integrating MRIO with GEOS-Chem model

Lin et al. and Zhang et al. combined multi-regional input-output model with GEOS-Chem to simulate transport of emissions<sup>98,104</sup>. Firstly, calculating environmental impacts (or emissions) embodied in trade at country level, and then using GEOS-Chem model to simulate the spatial distribution of environmental impacts on worldwide (Figure S 8.3). Zhang et al., also link health impacts model, Integrated Exposure-Response (IER), to simulate spatial distribution of premature death driven by consumption

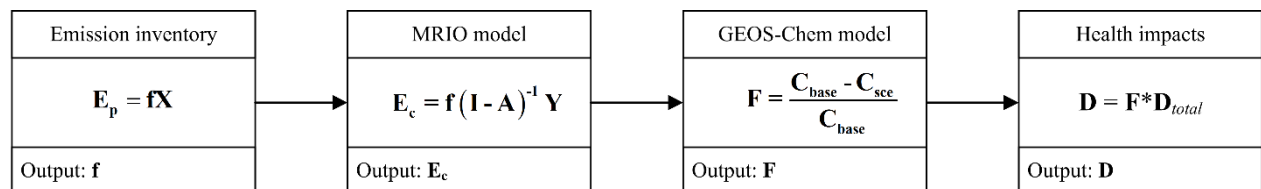


**Figure S 8.3** Process of method that integrated with GEOS-Chem model.

**Table S 8.7** Variables and description of method that integrated with GEOS-Chem model.

| Variables | Description                       |
|-----------|-----------------------------------|
| $E_p$     | Emission matrix from production   |
| $F$       | Emission intensity vector         |
| $X$       | Total output                      |
| $E_c$     | Consumption-based emission matrix |
| $I$       | Identify matrix                   |

|             |                                                                                              |
|-------------|----------------------------------------------------------------------------------------------|
| $A$         | Technological matrix                                                                         |
| $Y$         | Final demand vector                                                                          |
| $F$         | Spatial distribution of fractional contribution of emission derived from different scenarios |
| $C_{base}$  | Emission concentration on base scenarios                                                     |
| $C_{sce}$   | Emission concentration on different scenarios                                                |
| $D$         | Premature death population at grid cell driven by consumption                                |
| $D_{total}$ | Global total premature death population using IER model at grid cell                         |

### Method 8: combining input-output model with air pollution dispersion model.

Firstly, applying regional input-output table and emission inventory data to calculate emission coefficients of different sectors, and then using these coefficients to calculate amount of emission discharging sites<sup>93</sup>. Finally, applying smeared concentration approximation method (SCA) to simulate spatial diffusion of these emissions (Figure S 8.4).

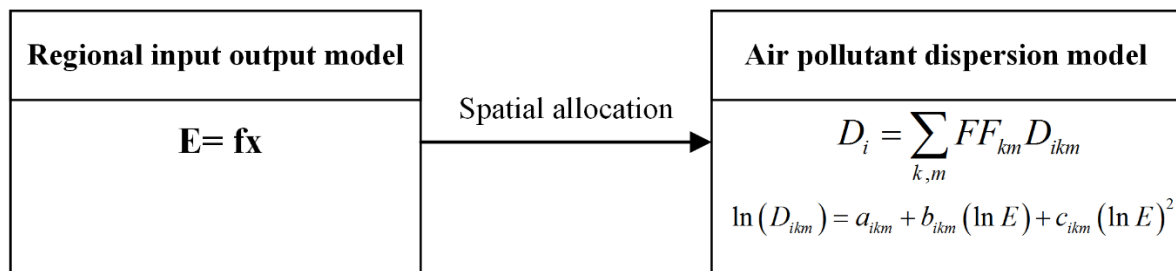


**Figure S 8.4** Process of combining with air pollution dispersion model

| Table S 8.8 Parameters and description of method that combines with air pollution dispersion model |                                                                          |
|----------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------|
| Variables                                                                                          | Description                                                              |
| $E$                                                                                                | Production-based emission                                                |
| $F$                                                                                                | Emission intensity                                                       |
| $X$                                                                                                | total output                                                             |
| $D_i$                                                                                              | Average concentration of emission between source and receiver            |
| $FF_{km}$                                                                                          | Frequency of emission occur                                              |
| $D_{ikm}$                                                                                          | Average contribution of concentration of emission at different situation |
| $I$                                                                                                | Emission classes                                                         |
| $K$                                                                                                | Atmospheric stability condition                                          |
| $M$                                                                                                | Windspeed classes                                                        |

### **Method 9: spatial regional econometric input–output model**

Kim et al. developed spatial regional econometric input-output model through integrating regional econometric input–output model(REIM) with disequilibrium adjustment model, and they used the model to predict population and employment change of 296 municipalities in Chicago, USA <sup>118</sup>. The core of this method included 5 steps:

- Quantifying potential employment growth for year  $t$  based on exogenous national economic growth.
- Estimating information for grid cell in year  $t-1$ .
- Calculating employment and population at local level for year  $t$  based on information: (a) potential employment growth for year  $t-1$  (b) information of grid cell for year  $t-1$  (c) their own information for year  $t-1$  (d) interaction relationship between local-level employment and population.
- Updating macroeconomic variables for year  $t$  based on information of employment and population change with modified REIM formulation.
- Predicting information at grid cell level for year  $t$  via simple logic econometrics model or other more complicated simulation approach.

### **Method 10: Integrating MRIO model with GIS technology.**

Van Der Veen et al. constructed contour map of value added based on employment data from enterprises and spatial interpolation methods with GIS platform, regarding multipliers from input-output model as the weight <sup>121</sup>. Similarly, Zhou et al. estimated spatial flow of chemical oxygen demand (COD) in Changzhou city, China at GIS platform <sup>119,120,122</sup>.

### **Method 11 (in Trase.earth): spatially-explicit information on production to consumption systems(SEI-PCS) model**

In order to trace spatial heterogeneity of environmental impacts related to production consumed by other regions within a country, especially large country, which contributes to global consumption. Godar et al. developed SEI-PCS model <sup>109</sup>, and they used the model to analyse crops and virtual water embedded in farming commodities in Brazil at subnational scale <sup>153,154</sup>. The model downscales production consumed by domestic and other countries into finest scale, the municipality level, in a country. The following graph (Figure S 8.5) describes the core theory of this model, and the detail can reference to Godar et al. 2015 <sup>109</sup>.

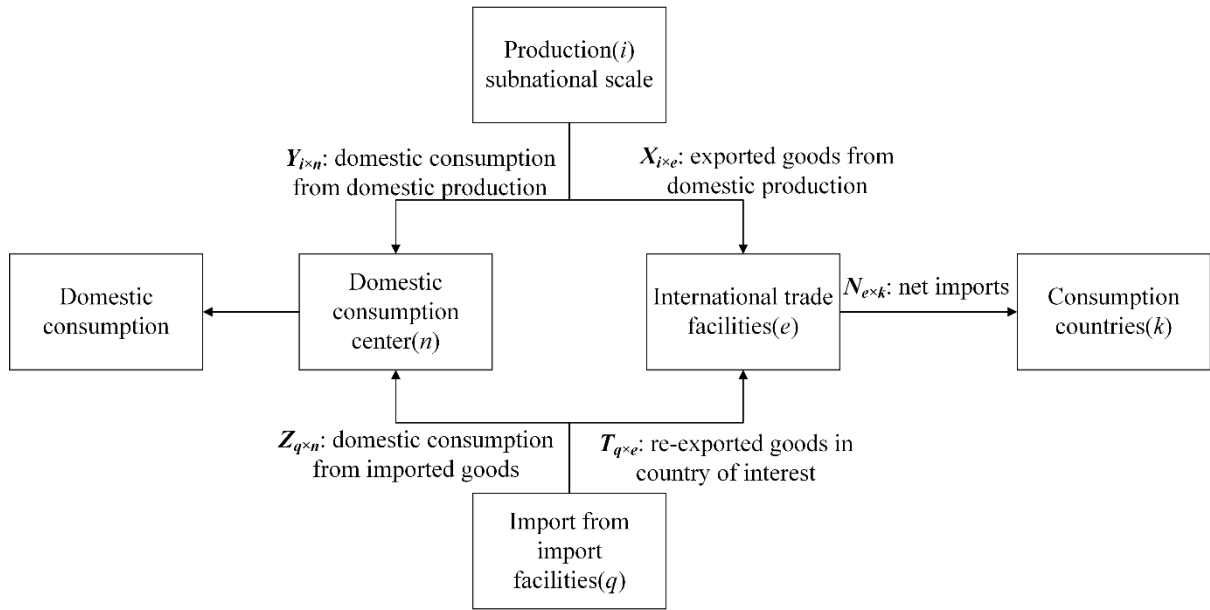


Figure S 8.5 The framework of SEI-PEC.

$$R_{i \times k} = D_{i \times e} \times L_{e \times k} \times B_{k \times k} \quad (S5)$$

$$\bar{r}_{i,k} \begin{cases} r_{i,k} & \text{if } k \neq \text{country of interest} \\ p_i - \sum_j r_{i,j} & \text{if country} = \text{country of interest} \end{cases} \quad (S6)$$

$$EI_k = EII_i \times \bar{R}_{i \times k} \quad (S7)$$

$$d_{i,e} = \frac{x_{i,e}}{\sum_i x_{i,e}} \quad (S8)$$

$$l_{e,k} = \frac{n_{e,k}}{p^k} \quad (S9)$$

Table S 8.9 Variables and description of equation in model SEI-PCS.

| Variables        | description                                                                            |
|------------------|----------------------------------------------------------------------------------------|
| $R_{i \times k}$ | consumption of $k$ countries produced by $i$ domestic producers in country of interest |
| $\bar{R}_{i,k}$  | The revised value of $R_{i \times k}$                                                  |
| $D_{i \times e}$ | Share of commodities from $i$ sub-regional producers to $e$ trade facilities           |
| $L_{e \times k}$ | Ratio between imports from countries $k$ and production of that country                |
| $B_{k \times k}$ | Bilateral trade flow between $k$ countries                                             |
| $EI_k$           | Environmental impacts in $k$ countries                                                 |
| $EII_i$          | Environmental impacts intensity in subnational regions $i$                             |
| $X_{i \times e}$ | Exported commodities produced in subnational regions                                   |

---

|                           |                                                           |
|---------------------------|-----------------------------------------------------------|
| $\mathbf{Y}_{i \times n}$ | Domestic production produced in subnational regions       |
| $\mathbf{T}_{q \times e}$ | Re-exported commodities in country of interest            |
| $\mathbf{Z}_{q \times n}$ | Imported commodities were consumed in country of interest |
| $\mathbf{P}^k$            | Production of consumption countries $k$                   |
| $\mathbf{x}_{i,e}$        | The elements of $\mathbf{X}_{i \times e}$                 |
| $\mathbf{d}_{i,e}$        | The elements of $\mathbf{D}_{i \times e}$                 |
| $\mathbf{l}_{e,k}$        | The elements of $\mathbf{L}_{e \times k}$                 |
| $\mathbf{n}_{e,k}$        | The elements of $\mathbf{N}_{e \times k}$                 |
| $\mathbf{r}_{i,k}$        | The elements of $\mathbf{R}_{i \times k}$                 |
| $\bar{\mathbf{r}}_{i,k}$  | The elements of $\bar{\mathbf{R}}_{i,k}$                  |

---

## 8.2 Supporting information to chapter 3

### 8.2.1 Explanatory note 1

#### 8.2.1.1 Methods for aggregating Millet and Coffee

In the SPAM databases, there are *Millet Pearl* and *Millet Small*, and *Coffee Arabica* and *Coffee Robusta*. But there are only *Millet* and *Coffee* in FAOSTAT and so EXIOBASE as well. In order to match SPAM databases with EXIOBASE, we aggregate *Millet Pearl* and *Millet Small* into *Millet*, and aggregate *Coffee Arabica* and *Coffee Robusta* into *Coffee*. Because we use total production of primary crops in SPAM, namely a value in grid cell stands for its production quantity in metric tons, we use Raster Calculator tools in ArcGIS 10.2.2 to add two raster databases of production of *Millet Pearl* and *Millet Small* as the spatial distribution of total production of *Millet*. And the similar way for calculation for *Coffee*.

#### 8.2.1.2 Special solution for Canada

Canada is a special case for the spatial distribution of some livestock. There is no major road further north than a latitude of 70° N; yet ducks and sheep are in relative abundance north of that. Therefore, we regard the region below 70° N within a concave hull based on a 1-degree buffer around all roads as the first-priority region for export and the second-priority region for domestic consumption, and the rest as the first-priority region for second-priority region for export and the first-priority region for domestic consumption.

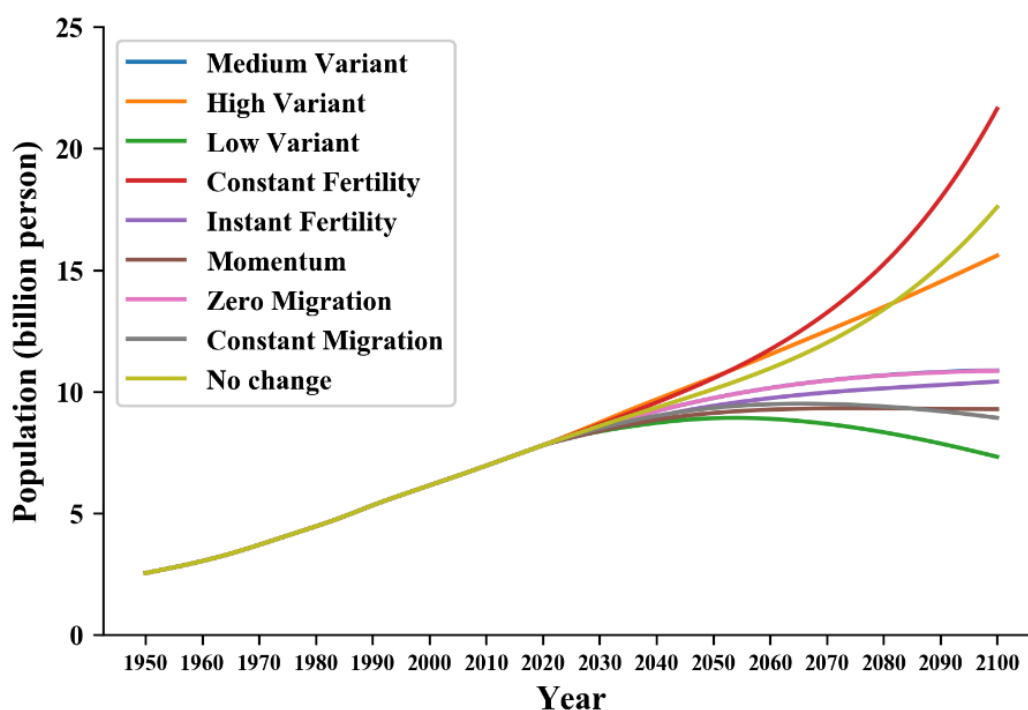


Figure S 8.6. World Population from 1950 to 2100. Source: World Population Prospects: The 2019 Revision.

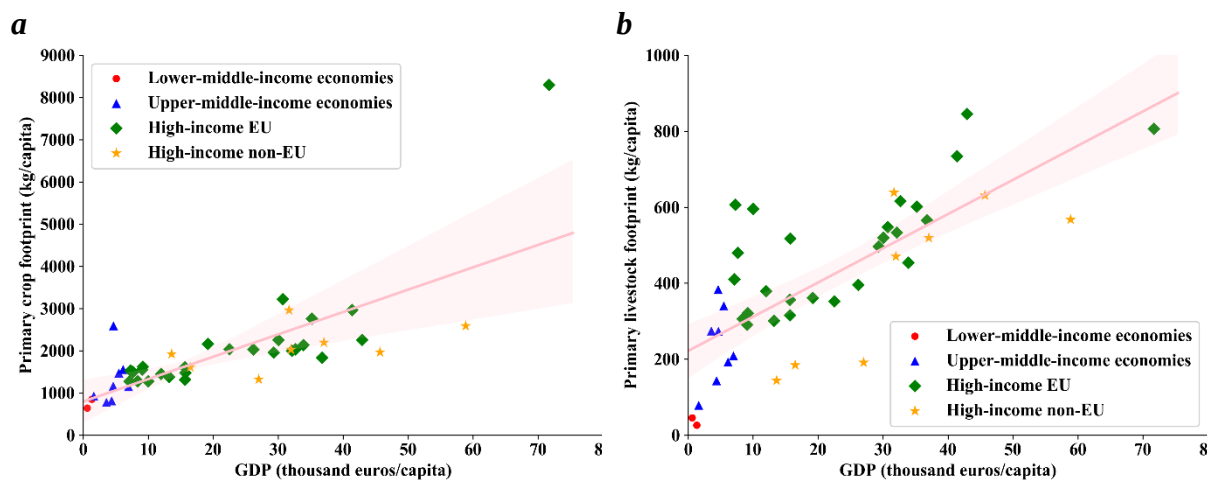


**Figure S 8.7.** Per-capita embodied primary crop (a) and livestock (b) consumption and per-capita GDP for 44 countries in EXIOBASE.

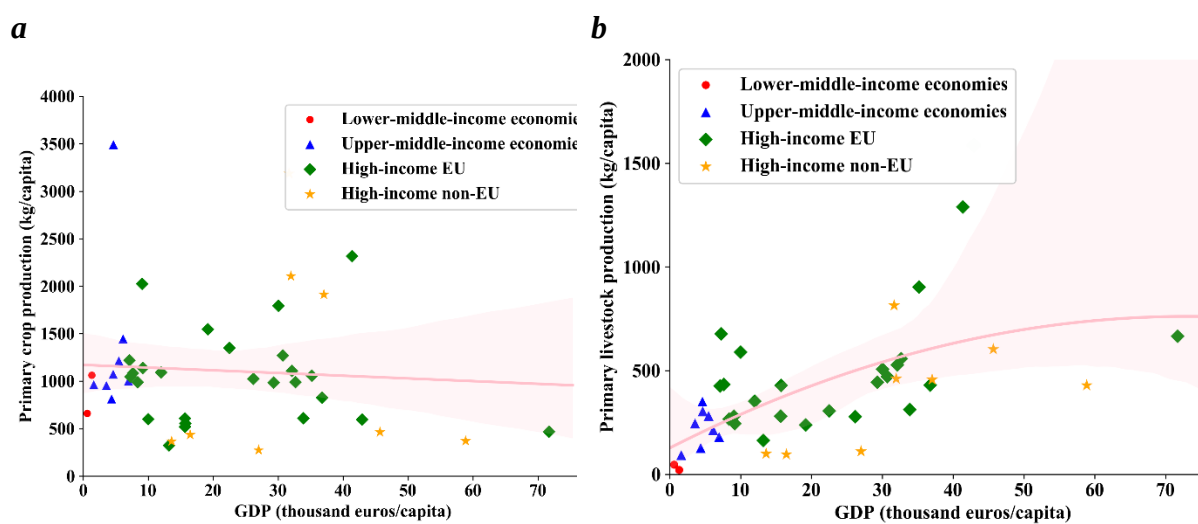


**Figure S 8.8.** Per-capita primary crop (a) and livestock (b) production and per-capita GDP for 44 countries in EXIOBASE.

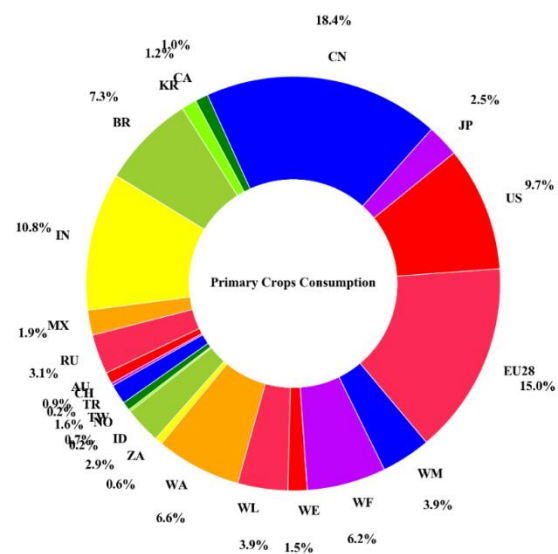


**Figure S 8.9.** Embodied primary crop consumption for each region in EXIOBASE

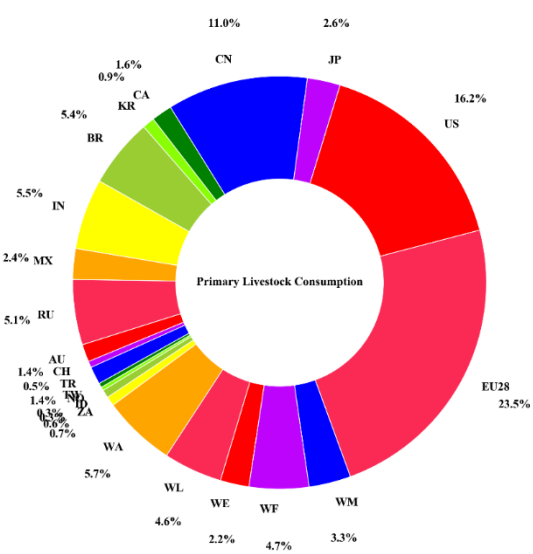


**Figure S 8.10.** Embodied livestock for each region in EXIOBASE

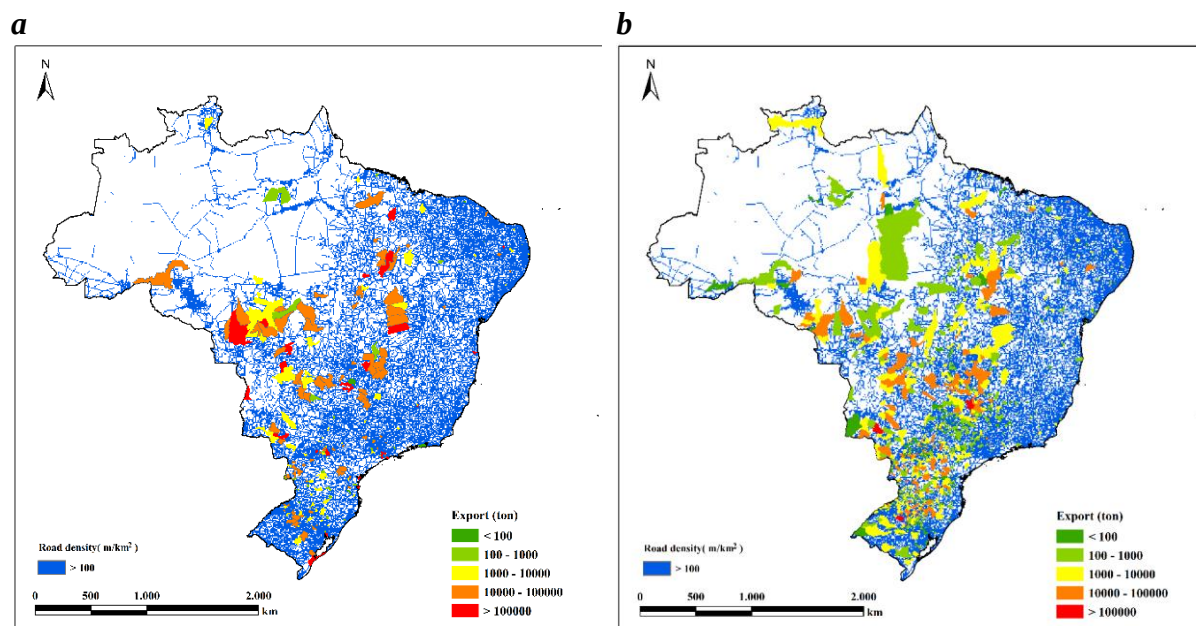


**Figure S 8.11.** Soybean export from official statistics data (a) and Trase.earth calculation (b) in 2006 at municipality level.

**Table S 8.10.** Mapping relationship between resource extensions about crop accounts in EXIOBASE with SPAM

| Extensions in EXIOBASE                                           | unit | SPAM code | name in SPAM      | Sector in EXIOBASE      |
|------------------------------------------------------------------|------|-----------|-------------------|-------------------------|
| Domestic Extraction Used - Primary Crops – Abaca                 | kt   | 31        | other fibre crops | Plant-based fibers      |
| Domestic Extraction Used - Primary Crops - Agave Fibres          | kt   | 31        | other fibre crops | Plant-based fibers      |
| Domestic Extraction Used - Primary Crops – Almonds               | kt   | 42        | rest of crops     | Vegetables, fruit, nuts |
| Domestic Extraction Used - Primary Crops - Anise, Badian, Fennel | kt   | 42        | rest of crops     | Crops nec               |
| Domestic Extraction Used - Primary Crops – Apples                | kt   | 40        | temperate fruit   | Vegetables, fruit, nuts |
| Domestic Extraction Used - Primary Crops – Apricots              | kt   | 40        | temperate fruit   | Vegetables, fruit, nuts |
| Domestic Extraction Used - Primary Crops – Arecanuts             | kt   | 42        | rest of crops     | Vegetables, fruit, nuts |
| Domestic Extraction Used - Primary Crops – Artichokes            | kt   | 41        | vegetables        | Vegetables, fruit, nuts |
| Domestic Extraction Used - Primary Crops – Asparagus             | kt   | 41        | vegetables        | Vegetables, fruit, nuts |
| Domestic Extraction Used - Primary Crops – Avocados              | kt   | 39        | tropical fruit    | Vegetables, fruit, nuts |
| Domestic Extraction Used - Primary Crops - Bambara beans         | kt   | 19        | other pulses      | Vegetables, fruit, nuts |
| Domestic Extraction Used - Primary Crops – Bananas               | kt   | 37        | banana            | Vegetables, fruit, nuts |
| Domestic Extraction Used - Primary Crops – Barley                | kt   | 4         | Barley            | Cereal grains nec       |
| Domestic Extraction Used - Primary Crops - Beans, dry            | kt   | 14        | Bean              | Vegetables, fruit, nuts |
| Domestic Extraction Used - Primary Crops - Beans, green          | kt   | 41        | vegetables        | Vegetables, fruit, nuts |
| Domestic Extraction Used - Primary Crops - Berries nec           | kt   | 40        | temperate fruit   | Vegetables, fruit, nuts |

|                                                                          |    |    |                 |                         |
|--------------------------------------------------------------------------|----|----|-----------------|-------------------------|
| Domestic Extraction Used - Primary Crops – Blueberries                   | kt | 40 | temperate fruit | Vegetables, fruit, nuts |
| Domestic Extraction Used - Primary Crops - Brazil nuts, with shell       | kt | 42 | rest of crops   | Vegetables, fruit, nuts |
| Domestic Extraction Used - Primary Crops - Broad beans, horse beans, dry | kt | 19 | other pulses    | Vegetables, fruit, nuts |
| Domestic Extraction Used - Primary Crops – Buckwheat                     | kt | 8  | other cereals   | Cereal grains nec       |
| Domestic Extraction Used - Primary Crops – Cabbages                      | kt | 41 | vegetables      | Vegetables, fruit, nuts |
| Domestic Extraction Used - Primary Crops - Canary Seed                   | kt | 8  | other cereals   | Cereal grains nec       |
| Domestic Extraction Used - Primary Crops – Carobs                        | kt | 41 | vegetables      | Vegetables, fruit, nuts |
| Domestic Extraction Used - Primary Crops – Carrots                       | kt | 41 | vegetables      | Vegetables, fruit, nuts |
| Domestic Extraction Used - Primary Crops - Cashew nuts, with shell       | kt | 42 | rest of crops   | Vegetables, fruit, nuts |
| Domestic Extraction Used - Primary Crops – Cashewapple                   | kt | 39 | tropical fruit  | Vegetables, fruit, nuts |
| Domestic Extraction Used - Primary Crops – Cassava                       | kt | 12 | cassava         | Vegetables, fruit, nuts |
| Domestic Extraction Used - Primary Crops - Cassava leaves                | kt | 41 | vegetables      | Vegetables, fruit, nuts |
| Domestic Extraction Used - Primary Crops - Castor oil seed               | kt | 27 | other oil crops | Oil seeds               |
| Domestic Extraction Used - Primary Crops – Cauliflower                   | kt | 41 | vegetables      | Vegetables, fruit, nuts |
| Domestic Extraction Used - Primary Crops - Cereals nec                   | kt | 8  | other cereals   | Cereal grains nec       |
| Domestic Extraction Used - Primary Crops – Cherries                      | kt | 40 | temperate fruit | Vegetables, fruit, nuts |
| Domestic Extraction Used - Primary Crops – Chestnuts                     | kt | 42 | rest of crops   | Vegetables, fruit, nuts |
| Domestic Extraction Used - Primary Crops - Chick peas                    | kt | 15 | chickpea        | Vegetables, fruit, nuts |
| Domestic Extraction Used - Primary Crops - Chicory Roots                 | kt | 41 | vegetables      | Vegetables, fruit, nuts |

|                                                                        |    |    |                   |                         |
|------------------------------------------------------------------------|----|----|-------------------|-------------------------|
| Domestic Extraction Used - Primary Crops - Chillies and peppers, dry   | kt | 42 | rest of crops     | Crops nec               |
| Domestic Extraction Used - Primary Crops - Chillies and peppers, green | kt | 41 | vegetables        | Vegetables, fruit, nuts |
| Domestic Extraction Used - Primary Crops – Cinnamon                    | kt | 42 | rest of crops     | Crops nec               |
| Domestic Extraction Used - Primary Crops - Citrus Fruit nec            | kt | 39 | tropical fruit    | Vegetables, fruit, nuts |
| Domestic Extraction Used - Primary Crops – Cloves                      | kt | 42 | rest of crops     | Crops nec               |
| Domestic Extraction Used - Primary Crops - Cocoa Beans                 | kt | 34 | Cocoa             | Crops nec               |
| Domestic Extraction Used - Primary Crops – Coconuts                    | kt | 22 | coconut           | Vegetables, fruit, nuts |
| Domestic Extraction Used - Primary Crops - Coffee, Green               | kt | 32 | arabica coffee    | Crops nec               |
| Domestic Extraction Used - Primary Crops – Coir                        | kt | 31 | other fibre crops | Plant-based fibers      |
| Domestic Extraction Used - Primary Crops - Cotton Lint                 | kt | 30 | Cotton            | Plant-based fibers      |
| Domestic Extraction Used - Primary Crops – Cottonseed                  | kt | 30 | Cotton            | Oil seeds               |
| Domestic Extraction Used - Primary Crops - Cow peas, dry               | kt | 16 | cowpea            | Vegetables, fruit, nuts |
| Domestic Extraction Used - Primary Crops – Cranberries                 | kt | 40 | temperate fruit   | Vegetables, fruit, nuts |
| Domestic Extraction Used - Primary Crops - Cucumbers and Gherkins      | kt | 41 | vegetables        | Vegetables, fruit, nuts |
| Domestic Extraction Used - Primary Crops – Currants                    | kt | 40 | temperate fruit   | Vegetables, fruit, nuts |
| Domestic Extraction Used - Primary Crops – Dates                       | kt | 39 | tropical fruit    | Vegetables, fruit, nuts |
| Domestic Extraction Used - Primary Crops – Eggplants                   | kt | 41 | vegetables        | Vegetables, fruit, nuts |
| Domestic Extraction Used - Primary Crops - Fibre Crops nes             | kt | 31 | other fibre crops | Plant-based fibers      |
| Domestic Extraction Used - Primary Crops – Figs                        | kt | 39 | tropical fruit    | Vegetables, fruit, nuts |

|                                                                      |    |    |                   |                         |
|----------------------------------------------------------------------|----|----|-------------------|-------------------------|
| Domestic Extraction Used - Primary Crops - Flax Fibre and Tow        | kt | 31 | other fibre crops | Plant-based fibers      |
| Domestic Extraction Used - Primary Crops – Fonio                     | kt | 8  | other cereals     | Cereal grains nec       |
| Domestic Extraction Used - Primary Crops - Fruit Fresh Nes           | kt | 40 | temperate fruit   | Vegetables, fruit, nuts |
| Domestic Extraction Used - Primary Crops - Fruit, tropical fresh nes | kt | 39 | tropical fruit    | Vegetables, fruit, nuts |
| Domestic Extraction Used - Primary Crops – Garlic                    | kt | 41 | vegetables        | Vegetables, fruit, nuts |
| Domestic Extraction Used - Primary Crops – Ginger                    | kt | 42 | rest of crops     | Crops nec               |
| Domestic Extraction Used - Primary Crops – Gooseberries              | kt | 40 | temperate fruit   | Vegetables, fruit, nuts |
| Domestic Extraction Used - Primary Crops - Grapefruit and Pomelos    | kt | 39 | tropical fruit    | Vegetables, fruit, nuts |
| Domestic Extraction Used - Primary Crops – Grapes                    | kt | 40 | temperate fruit   | Vegetables, fruit, nuts |
| Domestic Extraction Used - Primary Crops - Groundnuts in Shell       | kt | 21 | groundnut         | Oil seeds               |
| Domestic Extraction Used - Primary Crops – Hazelnuts                 | kt | 42 | rest of crops     | Vegetables, fruit, nuts |
| Domestic Extraction Used - Primary Crops - Hemp Fibre and Tow        | kt | 31 | other fibre crops | Plant-based fibers      |
| Domestic Extraction Used - Primary Crops – Hempseed                  | kt | 27 | other oil crops   | Oil seeds               |
| Domestic Extraction Used - Primary Crops – Hops                      | kt | 42 | rest of crops     | Crops nec               |
| Domestic Extraction Used - Primary Crops - Jojoba Seeds              | kt | 27 | other oil crops   | Oil seeds               |
| Domestic Extraction Used - Primary Crops - Jute and Jute-like Fibres | kt | 31 | other fibre crops | Plant-based fibers      |
| Domestic Extraction Used - Primary Crops - Kapok Fibre               | kt | 31 | other fibre crops | Plant-based fibers      |
| Domestic Extraction Used - Primary Crops - Karite Nuts               | kt | 27 | other oil crops   | Oil seeds               |
| Domestic Extraction Used - Primary Crops - Kiwi Fruit                | kt | 40 | temperate fruit   | Vegetables, fruit, nuts |

|                                                                         |    |    |                 |                         |
|-------------------------------------------------------------------------|----|----|-----------------|-------------------------|
| Domestic Extraction Used - Primary Crops – Kolanuts                     | kt | 42 | rest of crops   | Vegetables, fruit, nuts |
| Domestic Extraction Used - Primary Crops - Leeks and other Alliac. Veg. | kt | 41 | vegetables      | Vegetables, fruit, nuts |
| Domestic Extraction Used - Primary Crops - Leguminous vegetables, nes   | kt | 41 | vegetables      | Vegetables, fruit, nuts |
| Domestic Extraction Used - Primary Crops - Lemons and Limes             | kt | 39 | tropical fruit  | Vegetables, fruit, nuts |
| Domestic Extraction Used - Primary Crops – Lentils                      | kt | 18 | Lentil          | Vegetables, fruit, nuts |
| Domestic Extraction Used - Primary Crops – Lettuce                      | kt | 41 | vegetables      | Vegetables, fruit, nuts |
| Domestic Extraction Used - Primary Crops – Linseed                      | kt | 27 | other oil crops | Oil seeds               |
| Domestic Extraction Used - Primary Crops – Lupins                       | kt | 19 | other pulses    | Vegetables, fruit, nuts |
| Domestic Extraction Used - Primary Crops – Maize                        | kt | 3  | Maize           | Cereal grains nec       |
| Domestic Extraction Used - Primary Crops - Maize, green                 | kt | 41 | vegetables      | Vegetables, fruit, nuts |
| Domestic Extraction Used - Primary Crops - Mangoes, mangosteens, guavas | kt | 39 | tropical fruit  | Vegetables, fruit, nuts |
| Domestic Extraction Used - Primary Crops – Mate                         | kt | 42 | rest of crops   | Crops nec               |
| Domestic Extraction Used - Primary Crops – Melonseed                    | kt | 27 | other oil crops | Oil seeds               |
| Domestic Extraction Used - Primary Crops – Millet                       | kt | 5  | pearl millet    | Cereal grains nec       |
| Domestic Extraction Used - Primary Crops - Mixed Grain                  | kt | 8  | other cereals   | Cereal grains nec       |
| Domestic Extraction Used - Primary Crops – Mushrooms                    | kt | 41 | vegetables      | Vegetables, fruit, nuts |
| Domestic Extraction Used - Primary Crops - Mustard Seed                 | kt | 25 | rapeseed        | Oil seeds               |
| Domestic Extraction Used - Primary Crops - Natural Rubber               | kt | 42 | rest of crops   | Crops nec               |
| Domestic Extraction Used - Primary Crops - Nutmeg, mace and cardamoms   | kt | 42 | rest of crops   | Crops nec               |
| Domestic Extraction Used - Primary Crops - Nuts, nes                    | kt | 42 | rest of crops   | Vegetables, fruit, nuts |

|                                                                   |    |    |                   |                         |
|-------------------------------------------------------------------|----|----|-------------------|-------------------------|
| Domestic Extraction Used - Primary Crops – Oats                   | kt | 8  | other cereals     | Cereal grains nec       |
| Domestic Extraction Used - Primary Crops - Oil Palm Fruit         | kt | 23 | oilpalm           | Oil seeds               |
| Domestic Extraction Used - Primary Crops - Oilseeds nec           | kt | 27 | other oil crops   | Oil seeds               |
| Domestic Extraction Used - Primary Crops – Okra                   | kt | 41 | vegetables        | Vegetables, fruit, nuts |
| Domestic Extraction Used - Primary Crops – Olives                 | kt | 27 | other oil crops   | Oil seeds               |
| Domestic Extraction Used - Primary Crops – Onions                 | kt | 41 | vegetables        | Vegetables, fruit, nuts |
| Domestic Extraction Used - Primary Crops - Onions, dry            | kt | 41 | vegetables        | Vegetables, fruit, nuts |
| Domestic Extraction Used - Primary Crops – Oranges                | kt | 39 | tropical fruit    | Vegetables, fruit, nuts |
| Domestic Extraction Used - Primary Crops - Other Bastfibres       | kt | 31 | other fibre crops | Plant-based fibers      |
| Domestic Extraction Used - Primary Crops - Other melons           | kt | 39 | tropical fruit    | Vegetables, fruit, nuts |
| Domestic Extraction Used - Primary Crops – Papayas                | kt | 39 | tropical fruit    | Vegetables, fruit, nuts |
| Domestic Extraction Used - Primary Crops - Peaches and Nectarines | kt | 40 | temperate fruit   | Vegetables, fruit, nuts |
| Domestic Extraction Used - Primary Crops – Pears                  | kt | 40 | temperate fruit   | Vegetables, fruit, nuts |
| Domestic Extraction Used - Primary Crops - Peas, dry              | kt | 19 | other pulses      | Vegetables, fruit, nuts |
| Domestic Extraction Used - Primary Crops - Peas, Green            | kt | 41 | vegetables        | Vegetables, fruit, nuts |
| Domestic Extraction Used - Primary Crops – Pepper                 | kt | 42 | rest of crops     | Crops nec               |
| Domestic Extraction Used - Primary Crops – Peppermint             | kt | 42 | rest of crops     | Crops nec               |
| Domestic Extraction Used - Primary Crops – Persimmons             | kt | 39 | tropical fruit    | Vegetables, fruit, nuts |
| Domestic Extraction Used - Primary Crops - Pigeon peas            | kt | 17 | pigeonpea         | Vegetables, fruit, nuts |

|                                                                     |    |    |                   |                         |
|---------------------------------------------------------------------|----|----|-------------------|-------------------------|
| Domestic Extraction Used - Primary Crops – Pineapples               | kt | 39 | tropical fruit    | Vegetables, fruit, nuts |
| Domestic Extraction Used - Primary Crops – Pistachios               | kt | 42 | rest of crops     | Vegetables, fruit, nuts |
| Domestic Extraction Used - Primary Crops – Plantains                | kt | 38 | plantain          | Vegetables, fruit, nuts |
| Domestic Extraction Used - Primary Crops – Plums                    | kt | 40 | temperate fruit   | Vegetables, fruit, nuts |
| Domestic Extraction Used - Primary Crops - Pome fruit, nes          | kt | 40 | temperate fruit   | Vegetables, fruit, nuts |
| Domestic Extraction Used - Primary Crops - Poppy Seed               | kt | 27 | other oil crops   | Oil seeds               |
| Domestic Extraction Used - Primary Crops – Potatoes                 | kt | 9  | Potato            | Vegetables, fruit, nuts |
| Domestic Extraction Used - Primary Crops - Pulses nec               | kt | 19 | other pulses      | Vegetables, fruit, nuts |
| Domestic Extraction Used - Primary Crops - Pumpkins, Squash, Gourds | kt | 41 | vegetables        | Vegetables, fruit, nuts |
| Domestic Extraction Used - Primary Crops - Pyrethrum, Dried Flowers | kt | 42 | rest of crops     | Crops nec               |
| Domestic Extraction Used - Primary Crops – Quinces                  | kt | 40 | temperate fruit   | Vegetables, fruit, nuts |
| Domestic Extraction Used - Primary Crops – Quinoa                   | kt | 8  | other cereals     | Cereal grains nec       |
| Domestic Extraction Used - Primary Crops – Ramie                    | kt | 31 | other fibre crops | Plant-based fibers      |
| Domestic Extraction Used - Primary Crops – Rapeseed                 | kt | 25 | rapeseed          | Oil seeds               |
| Domestic Extraction Used - Primary Crops – Raspberries              | kt | 40 | temperate fruit   | Vegetables, fruit, nuts |
| Domestic Extraction Used - Primary Crops – Rice                     | kt | 2  | Rice              | Paddy rice              |
| Domestic Extraction Used - Primary Crops - Roots and Tubers, nes    | kt | 13 | other roots       | Cereal grains nec       |
| Domestic Extraction Used - Primary Crops – Rye                      | kt | 8  | other cereals     | Cereal grains nec       |
| Domestic Extraction Used - Primary Crops - Safflower Seed           | kt | 27 | other oil crops   | Oil seeds               |

|                                                                       |    |    |                   |                         |
|-----------------------------------------------------------------------|----|----|-------------------|-------------------------|
| Domestic Extraction Used - Primary Crops - Sesame Seed                | kt | 26 | sesameseed        | Oil seeds               |
| Domestic Extraction Used - Primary Crops – Sisal                      | kt | 31 | other fibre crops | Plant-based fibers      |
| Domestic Extraction Used - Primary Crops – Sorghum                    | kt | 7  | sorghum           | Cereal grains nec       |
| Domestic Extraction Used - Primary Crops - Sour Cherries              | kt | 40 | temperate fruit   | Vegetables, fruit, nuts |
| Domestic Extraction Used - Primary Crops – Soybeans                   | kt | 20 | soybean           | Oil seeds               |
| Domestic Extraction Used - Primary Crops - Spices nec                 | kt | 42 | rest of crops     | Crops nec               |
| Domestic Extraction Used - Primary Crops – Spinach                    | kt | 41 | vegetables        | Vegetables, fruit, nuts |
| Domestic Extraction Used - Primary Crops - Stone Fruit nec,           | kt | 40 | temperate fruit   | Vegetables, fruit, nuts |
| Domestic Extraction Used - Primary Crops – Strawberries               | kt | 40 | temperate fruit   | Vegetables, fruit, nuts |
| Domestic Extraction Used - Primary Crops - String beans               | kt | 41 | vegetables        | Vegetables, fruit, nuts |
| Domestic Extraction Used - Primary Crops - Sugar Beets                | kt | 29 | sugarbeet         | Sugar cane, sugar beet  |
| Domestic Extraction Used - Primary Crops - Sugar Cane                 | kt | 28 | sugarcane         | Sugar cane, sugar beet  |
| Domestic Extraction Used - Primary Crops - Sugar Crops nes            | kt | 42 | rest of crops     | Sugar cane, sugar beet  |
| Domestic Extraction Used - Primary Crops - Sunflower Seed             | kt | 24 | sunflower         | Oil seeds               |
| Domestic Extraction Used - Primary Crops - Sweet Potatoes             | kt | 10 | sweet potato      | Vegetables, fruit, nuts |
| Domestic Extraction Used - Primary Crops - Tallowtree Seeds           | kt | 27 | other oil crops   | Oil seeds               |
| Domestic Extraction Used - Primary Crops - Tang. Mand Clement. Satsma | kt | 39 | tropical fruit    | Vegetables, fruit, nuts |
| Domestic Extraction Used - Primary Crops – Taro                       | kt | 13 | other roots       | Vegetables, fruit, nuts |
| Domestic Extraction Used - Primary Crops – Tea                        | kt | 35 | Tea               | Crops nec               |
| Domestic Extraction Used - Primary Crops - Tea nes                    | kt | 35 | Tea               | Crops nec               |

|                                                                 |    |    |                 |                         |
|-----------------------------------------------------------------|----|----|-----------------|-------------------------|
| Domestic Extraction Used - Primary Crops - Tobacco Leaves       | kt | 36 | tobacco         | Crops nec               |
| Domestic Extraction Used - Primary Crops – Tomatoes             | kt | 41 | vegetables      | Vegetables, fruit, nuts |
| Domestic Extraction Used - Primary Crops – Triticale            | kt | 8  | other cereals   | Cereal grains nec       |
| Domestic Extraction Used - Primary Crops - Tung Nuts            | kt | 27 | other oil crops | Oil seeds               |
| Domestic Extraction Used - Primary Crops – Vanilla              | kt | 42 | rest of crops   | Crops nec               |
| Domestic Extraction Used - Primary Crops - Vegetables Fresh nec | kt | 41 | vegetables      | Vegetables, fruit, nuts |
| Domestic Extraction Used - Primary Crops – Vetches              | kt | 19 | other pulses    | Vegetables, fruit, nuts |
| Domestic Extraction Used - Primary Crops – Walnuts              | kt | 42 | rest of crops   | Vegetables, fruit, nuts |
| Domestic Extraction Used - Primary Crops – Watermelons          | kt | 39 | tropical fruit  | Vegetables, fruit, nuts |
| Domestic Extraction Used - Primary Crops – Wheat                | kt | 1  | Wheat           | Wheat                   |
| Domestic Extraction Used - Primary Crops – Yams                 | kt | 11 | Yams            | Vegetables, fruit, nuts |
| Domestic Extraction Used - Primary Crops – Yautia               | kt | 13 | other roots     | Vegetables, fruit, nuts |

**Table S 8.11.** Mapping relationship between EXIOABSE account with FAOSTAT product of livestock

| EXIOBASE sector number | EXIOBASE name            | FAOSTAT product names                                                                   |
|------------------------|--------------------------|-----------------------------------------------------------------------------------------|
| 11                     | Poultry                  | Eggs, hen, in shell                                                                     |
| 14                     | Raw milk                 | Milk, whole fresh cow; Milk, whole fresh goat; Milk, whole fresh sheep                  |
| 43                     | Products of meat cattle  | Hides, cattle, fresh; Meat indigenous, cattle                                           |
| 44                     | Products of meat pigs    | Meat indigenous, pig.                                                                   |
| 45                     | Products of meat poultry | Meat indigenous, chicken; Meat indigenous, duck                                         |
| 46                     | Meat products nec        | Meat indigenous, goat; Skins, goat, fresh; Meat indigenous, sheep; Skins, sheep, fresh. |

**Table S 8.12.** Mapping relationship between countries in FAOSTAT with regions in EXIOABSE for livestock

| FAOSTAT countries             | EXIOBASE regions | Region abbreviation in EXIOBASE |
|-------------------------------|------------------|---------------------------------|
| Austria                       | Austria          | AT                              |
| Belgium                       | Belgium          | BE                              |
| Bulgaria                      | Bulgaria         | BG                              |
| Cyprus                        | Cyprus           | CY                              |
| Czechia                       | Czech Republic   | CZ                              |
| Germany                       | Germany          | DE                              |
| Denmark                       | Denmark          | DK                              |
| Estonia                       | Estonia          | EE                              |
| Spain                         | Spain            | ES                              |
| Finland                       | Finland          | FI                              |
| France                        | France           | FR                              |
| Greece                        | Greece           | GR                              |
| Croatia                       | Croatia          | HR                              |
| Hungary                       | Hungary          | HU                              |
| Ireland                       | Ireland          | IE                              |
| Italy                         | Italy            | IT                              |
| Lithuania                     | Lithuania        | LT                              |
| Luxembourg                    | Luxembourg       | LU                              |
| Latvia                        | Latvia           | LV                              |
| Malta                         | Malta            | MT                              |
| Netherlands                   | Netherlands      | NL                              |
| Netherlands Antilles (former) | Netherlands      | NL                              |
| Poland                        | Poland           | PL                              |
| Portugal                      | Portugal         | PT                              |

|                           |                      |    |
|---------------------------|----------------------|----|
| Romania                   | Romania              | RO |
| Sweden                    | Sweden               | SE |
| Slovenia                  | Slovenia             | SI |
| Slovakia                  | Slovakia             | SK |
| United Kingdom            | United Kingdom       | GB |
| United States of America  | United States        | US |
| Japan                     | Japan                | JP |
| China, Hong Kong SAR      | China                | CN |
| China, mainland           | China                | CN |
| Canada                    | Canada               | CA |
| Republic of Korea         | South Korea          | KR |
| Brazil                    | Brazil               | BR |
| India                     | India                | IN |
| Mexico                    | Mexico               | MX |
| Russian Federation        | Russia               | RU |
| Australia                 | Australia            | AU |
| Switzerland               | Switzerland          | CH |
| Turkey                    | Turkey               | TR |
| China, Taiwan Province of | Taiwan               | TW |
| Norway                    | Norway               | NO |
| Indonesia                 | Indonesia            | ID |
| South Africa              | South Africa         | ZA |
| New Caledonia             | RoW Asia and Pacific | WA |
| Afghanistan               | RoW Asia and Pacific | WA |
| American Samoa            | RoW Asia and Pacific | WA |
| Armenia                   | RoW Asia and Pacific | WA |

|                                       |                      |    |
|---------------------------------------|----------------------|----|
| Azerbaijan                            | RoW Asia and Pacific | WA |
| Bangladesh                            | RoW Asia and Pacific | WA |
| Bhutan                                | RoW Asia and Pacific | WA |
| Brunei                                | RoW Asia and Pacific | WA |
| Cambodia                              | RoW Asia and Pacific | WA |
| Cook Islands                          | RoW Asia and Pacific | WA |
| Democratic People's Republic of Korea | RoW Asia and Pacific | WA |
| Fiji                                  | RoW Asia and Pacific | WA |
| French Polynesia                      | RoW Asia and Pacific | WA |
| Georgia                               | RoW Asia and Pacific | WA |
| Guam                                  | RoW Asia and Pacific | WA |
| Kazakhstan                            | RoW Asia and Pacific | WA |
| Kyrgyzstan                            | RoW Asia and Pacific | WA |
| Lao People's Democratic Republic      | RoW Asia and Pacific | WA |
| Malaysia                              | RoW Asia and Pacific | WA |
| Micronesia (Federated States of)      | RoW Asia and Pacific | WA |
| Mongolia                              | RoW Asia and Pacific | WA |
| Myanmar                               | RoW Asia and Pacific | WA |
| Nepal                                 | RoW Asia and Pacific | WA |
| New Zealand                           | RoW Asia and Pacific | WA |
| Niue                                  | RoW Asia and Pacific | WA |
| Norfolk Island                        | RoW Asia and Pacific | WA |
| Pakistan                              | RoW Asia and Pacific | WA |
| Papua New Guinea                      | RoW Asia and Pacific | WA |
| Philippines                           | RoW Asia and Pacific | WA |
| Samoa                                 | RoW Asia and Pacific | WA |

|                           |                      |    |
|---------------------------|----------------------|----|
| Singapore                 | RoW Asia and Pacific | WA |
| Solomon Islands           | RoW Asia and Pacific | WA |
| Sri Lanka                 | RoW Asia and Pacific | WA |
| Tajikistan                | RoW Asia and Pacific | WA |
| Thailand                  | RoW Asia and Pacific | WA |
| Timor-Leste               | RoW Asia and Pacific | WA |
| Tonga                     | RoW Asia and Pacific | WA |
| Turkmenistan              | RoW Asia and Pacific | WA |
| Uzbekistan                | RoW Asia and Pacific | WA |
| Vanuatu                   | RoW Asia and Pacific | WA |
| Viet Nam                  | RoW Asia and Pacific | WA |
| Wallis and Futuna Islands | RoW Asia and Pacific | WA |
| Antigua and Barbuda       | RoW America          | WL |
| Argentina                 | RoW America          | WL |
| Bahamas                   | RoW America          | WL |
| Barbados                  | RoW America          | WL |
| Belize                    | RoW America          | WL |
| Bermuda                   | RoW America          | WL |
| Bolivia                   | RoW America          | WL |
| British Virgin Islands    | RoW America          | WL |
| Cayman Islands            | RoW America          | WL |
| Chile                     | RoW America          | WL |
| Colombia                  | RoW America          | WL |
| Costa Rica                | RoW America          | WL |
| Cuba                      | RoW America          | WL |
| Dominica                  | RoW America          | WL |

|                                  |             |    |
|----------------------------------|-------------|----|
| Dominican Republic               | RoW America | WL |
| Ecuador                          | RoW America | WL |
| El Salvador                      | RoW America | WL |
| Falkland Islands (Malvinas)      | RoW America | WL |
| French Guiana                    | RoW America | WL |
| Greenland                        | RoW America | WL |
| Grenada                          | RoW America | WL |
| Guadeloupe                       | RoW America | WL |
| Guatemala                        | RoW America | WL |
| Guyana                           | RoW America | WL |
| Haiti                            | RoW America | WL |
| Honduras                         | RoW America | WL |
| Jamaica                          | RoW America | WL |
| Martinique                       | RoW America | WL |
| Montserrat                       | RoW America | WL |
| Nicaragua                        | RoW America | WL |
| Panama                           | RoW America | WL |
| Paraguay                         | RoW America | WL |
| Peru                             | RoW America | WL |
| Puerto Rico                      | RoW America | WL |
| Saint Kitts and Nevis            | RoW America | WL |
| Saint Lucia                      | RoW America | WL |
| Saint Pierre and Miquelon        | RoW America | WL |
| Saint Vincent and the Grenadines | RoW America | WL |
| Suriname                         | RoW America | WL |
| Trinidad and Tobago              | RoW America | WL |

|                                           |             |    |
|-------------------------------------------|-------------|----|
| United States Virgin Islands              | RoW America | WL |
| Uruguay                                   | RoW America | WL |
| Venezuela (Bolivarian Republic of)        | RoW America | WL |
| Albania                                   | RoW Europe  | WE |
| Belarus                                   | RoW Europe  | WE |
| Bosnia and Herzegovina                    | RoW Europe  | WE |
| Faroe Islands                             | RoW Europe  | WE |
| Iceland                                   | RoW Europe  | WE |
| Liechtenstein                             | RoW Europe  | WE |
| Montenegro                                | RoW Europe  | WE |
| Republic of Moldova                       | RoW Europe  | WE |
| Serbia                                    | RoW Europe  | WE |
| The former Yugoslav Republic of Macedonia | RoW Europe  | WE |
| Ukraine                                   | RoW Europe  | WE |
| Algeria                                   | RoW Africa  | WF |
| Angola                                    | RoW Africa  | WF |
| Benin                                     | RoW Africa  | WF |
| Botswana                                  | RoW Africa  | WF |
| Burkina Faso                              | RoW Africa  | WF |
| Burundi                                   | RoW Africa  | WF |
| Côte d'Ivoire                             | RoW Africa  | WF |
| Cabo Verde                                | RoW Africa  | WF |
| Cameroon                                  | RoW Africa  | WF |
| Central African Republic                  | RoW Africa  | WF |
| Chad                                      | RoW Africa  | WF |
| Comoros                                   | RoW Africa  | WF |

|                                  |            |    |
|----------------------------------|------------|----|
| Congo                            | RoW Africa | WF |
| Democratic Republic of the Congo | RoW Africa | WF |
| Djibouti                         | RoW Africa | WF |
| Equatorial Guinea                | RoW Africa | WF |
| Eritrea                          | RoW Africa | WF |
| Ethiopia                         | RoW Africa | WF |
| Gabon                            | RoW Africa | WF |
| Gambia                           | RoW Africa | WF |
| Ghana                            | RoW Africa | WF |
| Guinea                           | RoW Africa | WF |
| Guinea-Bissau                    | RoW Africa | WF |
| Kenya                            | RoW Africa | WF |
| Lesotho                          | RoW Africa | WF |
| Liberia                          | RoW Africa | WF |
| Libya                            | RoW Africa | WF |
| Madagascar                       | RoW Africa | WF |
| Malawi                           | RoW Africa | WF |
| Mali                             | RoW Africa | WF |
| Mauritania                       | RoW Africa | WF |
| Mauritius                        | RoW Africa | WF |
| Morocco                          | RoW Africa | WF |
| Mozambique                       | RoW Africa | WF |
| Namibia                          | RoW Africa | WF |
| Niger                            | RoW Africa | WF |
| Nigeria                          | RoW Africa | WF |
| Reunion                          | RoW Africa | WF |

|                                              |                 |    |
|----------------------------------------------|-----------------|----|
| Rwanda                                       | RoW Africa      | WF |
| Saint Helena, Ascension and Tristan da Cunha | RoW Africa      | WF |
| Sao Tome and Principe                        | RoW Africa      | WF |
| Senegal                                      | RoW Africa      | WF |
| Seychelles                                   | RoW Africa      | WF |
| Sierra Leone                                 | RoW Africa      | WF |
| Somalia                                      | RoW Africa      | WF |
| Sudan (former)                               | RoW Africa      | WF |
| Swaziland                                    | RoW Africa      | WF |
| Togo                                         | RoW Africa      | WF |
| Tunisia                                      | RoW Africa      | WF |
| Uganda                                       | RoW Africa      | WF |
| United Republic of Tanzania                  | RoW Africa      | WF |
| Western Sahara                               | RoW Africa      | WF |
| Zambia                                       | RoW Africa      | WF |
| Zimbabwe                                     | RoW Africa      | WF |
| Bahrain                                      | RoW Middle East | WM |
| Egypt                                        | RoW Middle East | WM |
| Iran (Islamic Republic of)                   | RoW Middle East | WM |
| Iraq                                         | RoW Middle East | WM |
| Israel                                       | RoW Middle East | WM |
| Jordan                                       | RoW Middle East | WM |
| Kuwait                                       | RoW Middle East | WM |
| Lebanon                                      | RoW Middle East | WM |
| Occupied Palestinian Territory               | RoW Middle East | WM |
| Oman                                         | RoW Middle East | WM |

|                      |                 |    |
|----------------------|-----------------|----|
| Qatar                | RoW Middle East | WM |
| Saudi Arabia         | RoW Middle East | WM |
| Syrian Arab Republic | RoW Middle East | WM |
| United Arab Emirates | RoW Middle East | WM |
| Yemen                | RoW Middle East | WM |

8.3 Supporting information to chapter 4

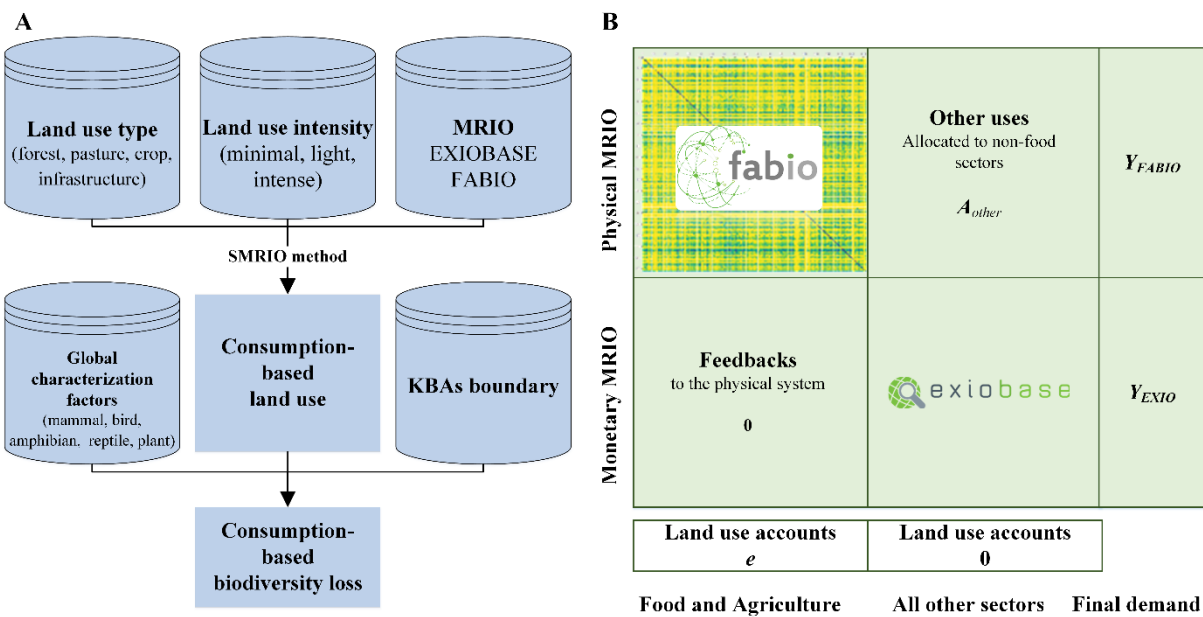


Figure S 8.12. Schematic of the methodology in general (a), and of linking FABIO and EXIOBASE (b).

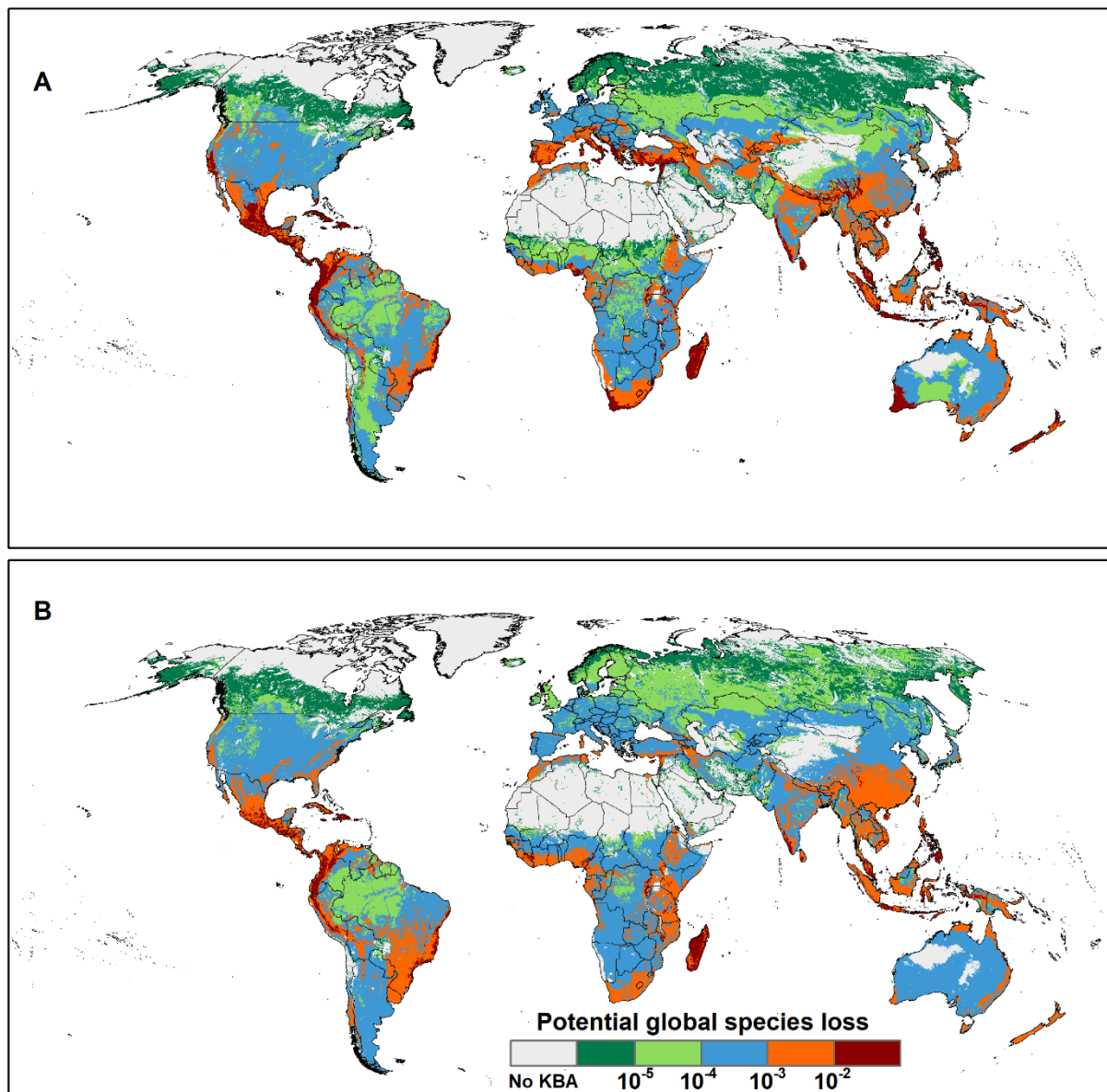


**Figure S 8.13.** Spatial distribution of potential global species loss driven by land use inside and outside KBAs for a) plants, and b) vertebrates (mammals + birds + amphibians + reptiles). The spatial resolution is 5 arc min.

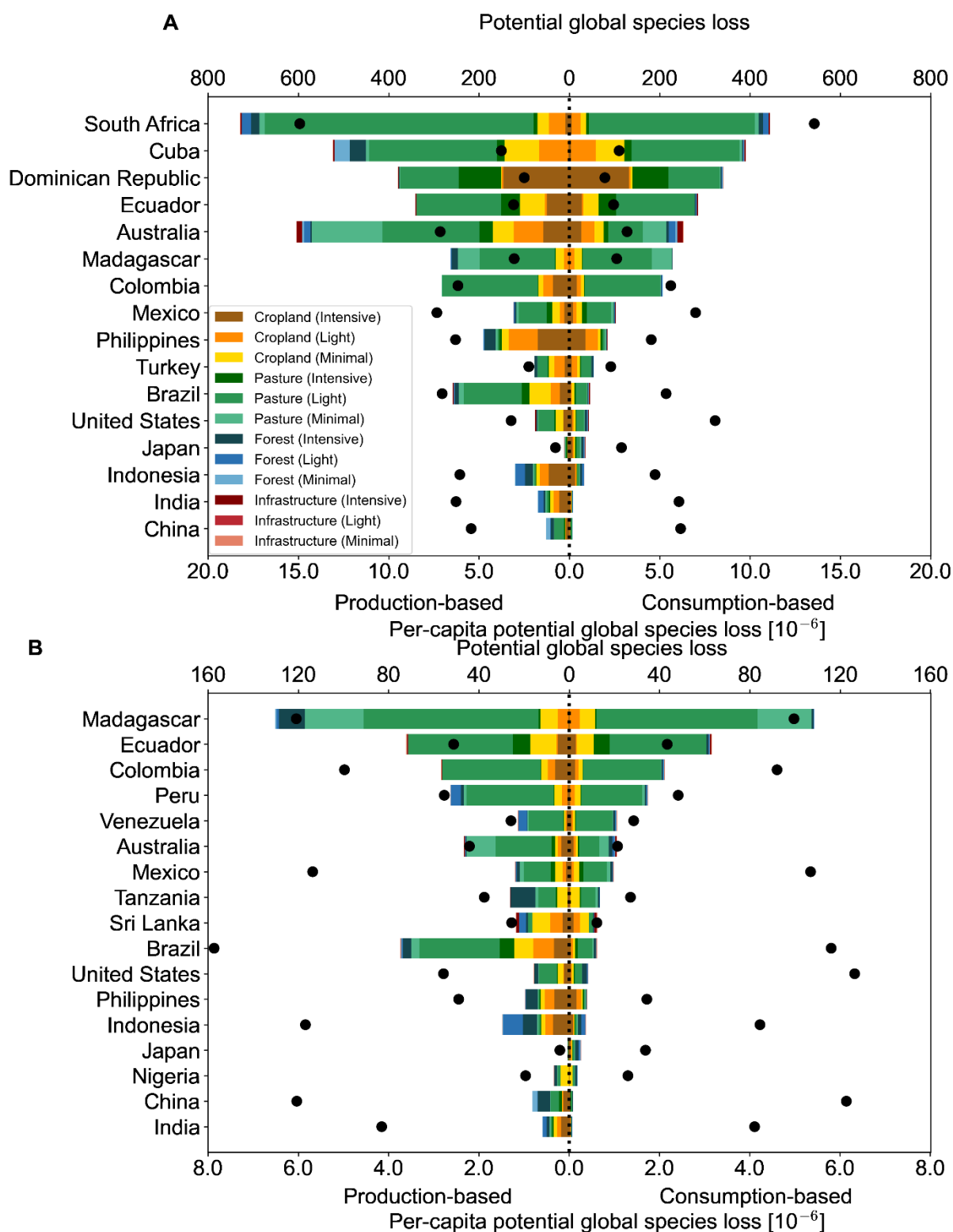


**Figure S 8.14.** The potential global species loss from land use inside and outside KBAs for plants (a) and vertebrates (b) (mammals, birds, amphibians, and reptiles). On each x-axis (bottom and top of figures), the production-based perspective is shown to the left of zero and the consumption-based perspective to the right. The y-axis lists the top 15 countries/regions with the largest consumption-based or production-based biodiversity loss from land use within and outside KBAs at the national level. The bar shows the per-capita value of biodiversity loss per land type and land use intensity. The circles show the total national biodiversity loss with a value shown by the upper x-axes on the top of each plot.

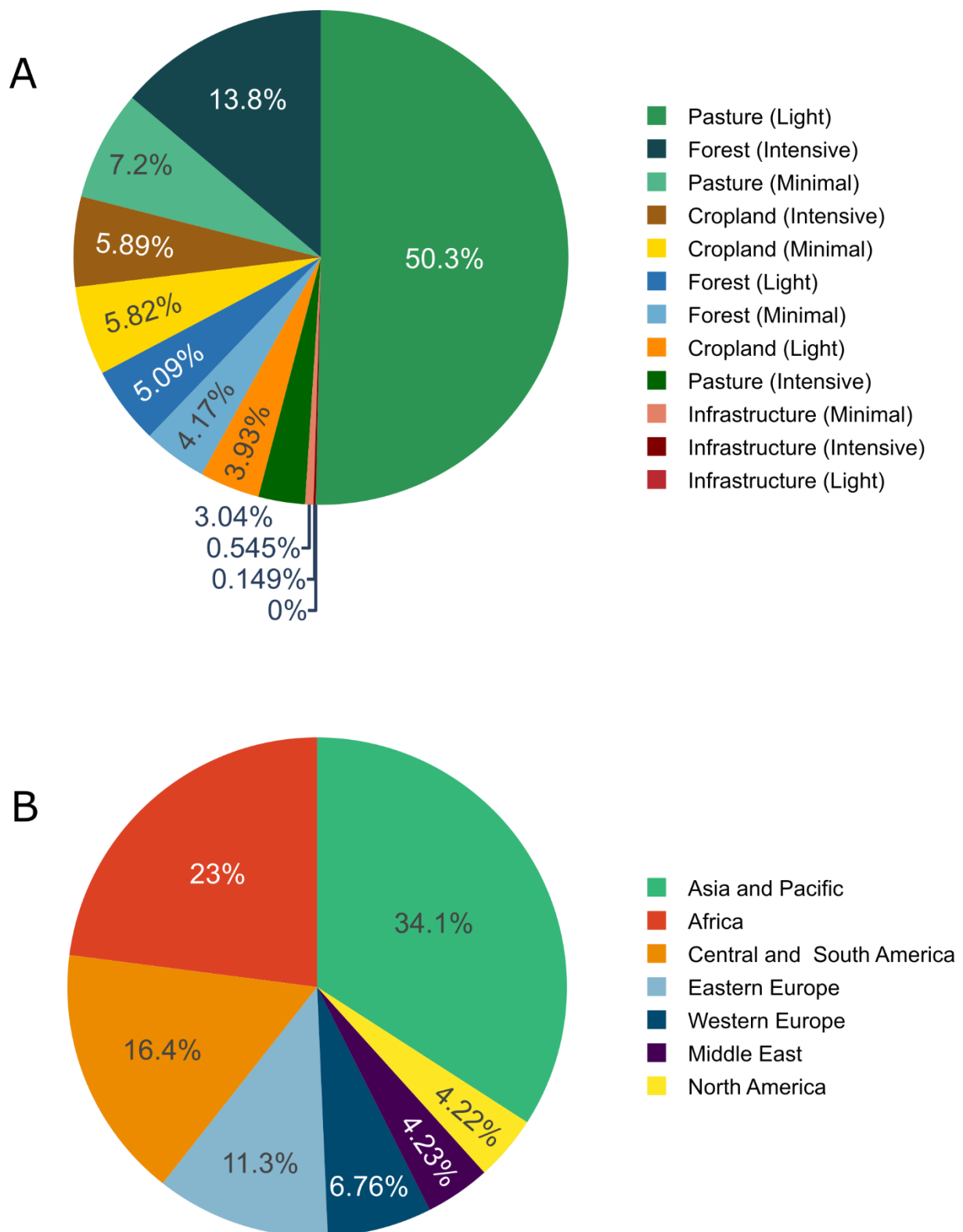


**Figure S 8.15.** Land use within KBAs with different land use types and land use intensities (a) and in different regions (b).

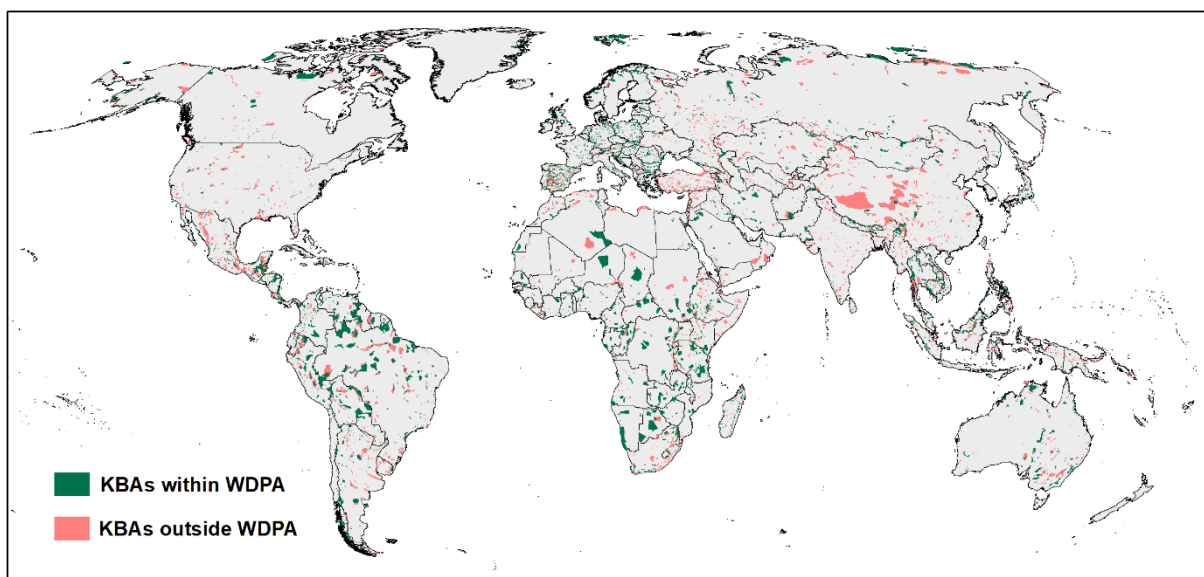


**Figure S 8.16.** Intersections between KBAs and the World Database on Protected Areas (WDPA).

## 8.4 Supporting information to chapter 5

### 8.4.1 Supplementary Methods

#### **Biomass carbon and soil organic carbon in current vegetation**

The calculation of aboveground biomass carbon (AGBC) and belowground biomass carbon (BGBC) is based on the latest harmonized carbon density map in the year 2010 developed by Spawn et al.<sup>358</sup>. For herbaceous crops, Spawn et al. employed gridded crop maps from EarthStat<sup>35</sup>, and we used the latest crop maps from Spatial Production Allocation Model (SPAM)<sup>390</sup> in 2010 and method from Spawn et al.<sup>358</sup> to get the latest AGBC and BGBC maps of herbaceous crops. For woody crops and pasture, we extract AGBC and BGBC from the latest harmonized carbon density maps directly.

#### ***Primary crops and fodder:***

The production and harvested area of 163 types of primary crops and 16 types of fodder crops in 2010 come from FAOSTAT<sup>357</sup>. The fodder crops are not available in FAOSTAT now, and are provided by one of developers of The Food and Agriculture Biomass Input-Output model (FABIO)<sup>36</sup>. We then use the SPAM<sup>390</sup> to build a spatially-explicit picture of crop production. SPAM employs a cross-entropy approach to make estimates of 42 crop maps in 2010 at 5 arc min resolution. Since “Pearl Millet” and “Small Millet” are not split in FAOSTAT, we aggregate them into millet; similarly “Arabica Coffee” and “Robusta Coffee” are not split and we aggregate them into “Coffee”. These 40 crops are aggregated from an average of 163 types of primary crops contained in the FAOSTAT database between 2009 and 2011. Therefore, we used national data from FAOSTAT in 2010 to calibrate the SPAM for each country. However, since SPAM does not include fodder crop maps, we use EarthStat fodder maps<sup>35</sup> at 5 arc min resolution in 2000. We aggregate the 16 fodder maps into one fodder map for ease of analysis.

#### ***Pasture***

There are many ways to estimate pasture for grazing. Ramankutty et al. created a map in which they estimate the percentage of pasture per grid cell at 5 min resolution<sup>35</sup> in 2000. Sloat et al., updated this map to the year 2010 at 500 meters resolution<sup>393</sup>. They considered a grid cell to be pasture if it fell into a livestock category on the global livestock production systems (GLPS) map and also contained at least 30% pasture by area<sup>393</sup>. Marques et al.,<sup>12</sup> used pasture map from Ramankutty et al.,<sup>35</sup> as permanent pasture, and excluded non-productive area (below NPP over  $20 \text{ g C m}^{-2} \text{ yr}^{-1}$ ) is used to feed livestock in the year 2000. In the end, we employed the pasture map developed by Sloat et al.<sup>393</sup> because their dataset is the latest and the time is in line with our research. We assume pasture layer was capped if all land-use types (cropland, infrastructure, and forest) fill 100% of the grid cell. For forest, we employed fractional tree cover from MODIS in 2010<sup>426</sup>. We linearly stretched values such that 80% was treated as complete tree cover (100%), since MODIS tree cover estimates saturate at around 80%, following Spawn et al.<sup>358</sup>. For infrastructure, we used ESA CCI Land cover Maps at 300 meters resolution in 2010<sup>427</sup>.

#### **GHG emissions**

For animal-specific sectors, this includes: “Enteric Fermentation”, “Manure Management”, “Manure applied to Soils”, and “Manure left on Pasture”. For crop-specific sectors, this includes: “Rice Cultivation”, “Crop Residues”, and “Burning - Crop Residues”. There are two outstanding, high-emission sectors: “Synthetic Fertilizers”, and “Energy Use” which are not allocated to specific agricultural sectors. In FAOSTAT, GHG emission of “Synthetic Fertilizers” is only derived from nitrogen fertilizers, so we first classify their GHG emissions into 28 countries/regions, and 13 crop groups based on the amount of nitrogen fertilizer use

from the International Fertilizer Association (IFA) in 2010 <sup>428</sup>. Mapping relationship of countries and crops between FABIO and IFA see Tables S5 and S6. We then allocate GHG emission of “Synthetic Fertilizers” of 28 countries/regions, and 13 crop groups into separated countries and agricultural sectors in FABIO based on the monetary value of crops in each group from FAOSTAT <sup>357</sup>. Similarly, we allocate CO<sub>2</sub>, CH<sub>4</sub>, and N<sub>2</sub>O from the “Energy Use” sector into 49 countries/regions and 14 agricultural sectors based on the combustion emissions of CO<sub>2</sub>, CH<sub>4</sub>, N<sub>2</sub>O in EXIOBASE v3.6. Mapping relationship of countries and sectors between FABIO and EXIOBASE see Supplementary Tables S7 and S8. We then allocate these cases from “Energy Use” into agricultural sectors and countries using FABIO and based on the monetary value of crops from FAOSTAT in every group.

#### 8.4.2 Supplementary Discussion

##### **Potential opportunities for carbon sequestration.**

Climate-smart agriculture may provide another opportunity to increase carbon benefits <sup>429</sup>. For example, novel plants like intermediate wheatgrass (*Thinopyrum intermedium* (Host) Barkworth & D.R.Dewey) is an emerging cool-season perennial grain (the name for commercialized grain is “Kernza”) and forage dual-use grass, and its extensive root system can improve belowground carbon fixing and reduce soil erosion <sup>430</sup>. Intermediate wheatgrass is becoming commercially available to farmers for some areas in the US <sup>431</sup>. A further opportunity is biochar. While carbon stocks will saturate when the land restores to mature and stable vegetation, biochar can break the biophysical limits of carbon sequestration <sup>379</sup>. Feedstocks for biochar come from residues of forest/crop/pasture, animal manure, and food waste <sup>379</sup>. Removing forest residue can reduce risks of wildfire, but may disturb habitats of some fungi and wildlife, along with other ecosystem services <sup>379</sup>. This represents a tradeoff among carbon sequestration and other ecosystem services <sup>379</sup>. New technologies in agricultural production can also help to mitigate climate change. For example, 3-nitrooxypropanol (3NOP), a methane inhibitor, can persistently decrease enteric methane emissions by 30% under industry-relevant conditions without affecting animal productivity negatively <sup>432</sup>, and has been approved as a feed additive in the European Union <sup>433</sup>.

##### **Potential carbon offset.**

Here, we focus on dietary change in high-income countries where most food supply is higher than the recommendation in the EAT diet, and the dietary change could increase carbon sequestration and reduce CO<sub>2</sub> emission. However, the carbon benefit may be offset by population growth and malnutrition in some low- and middle-income countries in the long term <sup>327</sup>. For example, most low- and middle-income countries face a severe double burden of malnutrition which means simultaneous manifestation of both undernutrition and overweight and obesity <sup>434</sup>. The obesity in low- and middle-income countries is due to overconsumption of cheap ultra-processed food and beverages which is an unhealthy diet <sup>434</sup>. The EAT diet is not suitable in low-income countries because they cannot afford it, and it estimated at least 1.58 billion people are not able to pay for the cost of the EAT diet in the world <sup>397</sup>. People will consume more food with income growth, especially animal products in low- and middle-income countries <sup>45</sup>. In addition population growth low- and middle-income countries will increase food needs further. For example, population is projected to increase by 199% (1026·04 million in 2017 to 3071·21 million in 2100) in Sub-Saharan Africa <sup>420</sup>. The increasing food demand in low- and middle-income countries will offset carbon benefit from dietary change in high-income countries.

Another carbon offset is food waste in high-income countries. EAT diet recommends per-capita food intake instead of food purchase. Pre-capita food waste is positively related to per-capita

income, and most food waste occurs in consumption stage in high-income countries because of overstocking, and too much cooking or serving <sup>435</sup>. In addition, healthier diets would cause more food waste because healthier diets need more consumption of perishable produce such as fruit and vegetables, which has substantial hidden costs from food waste <sup>436</sup>. Therefore, it is very necessary to halt food waste and loss. It is estimated about one third of global food is lost or wasted <sup>222</sup>. If reducing 50% of global food waste and loss, another 0.9 Pg CO<sub>2</sub>e yr<sup>-1</sup> would be mitigated <sup>437</sup>.

Recently, organic food consumption and organic agriculture production are surging in high-income countries because they are more environmentally friendly (e.g. less fertilizer or pesticide input, and fewer biodiversity losses) also higher price compared to conventional farming <sup>438,439</sup>. However, organic production has lower yield which means it needs more land use to satisfy the same food demand <sup>438,439</sup>. The high quality and environmentally friendly food consumption is at the expense of carbon benefit.

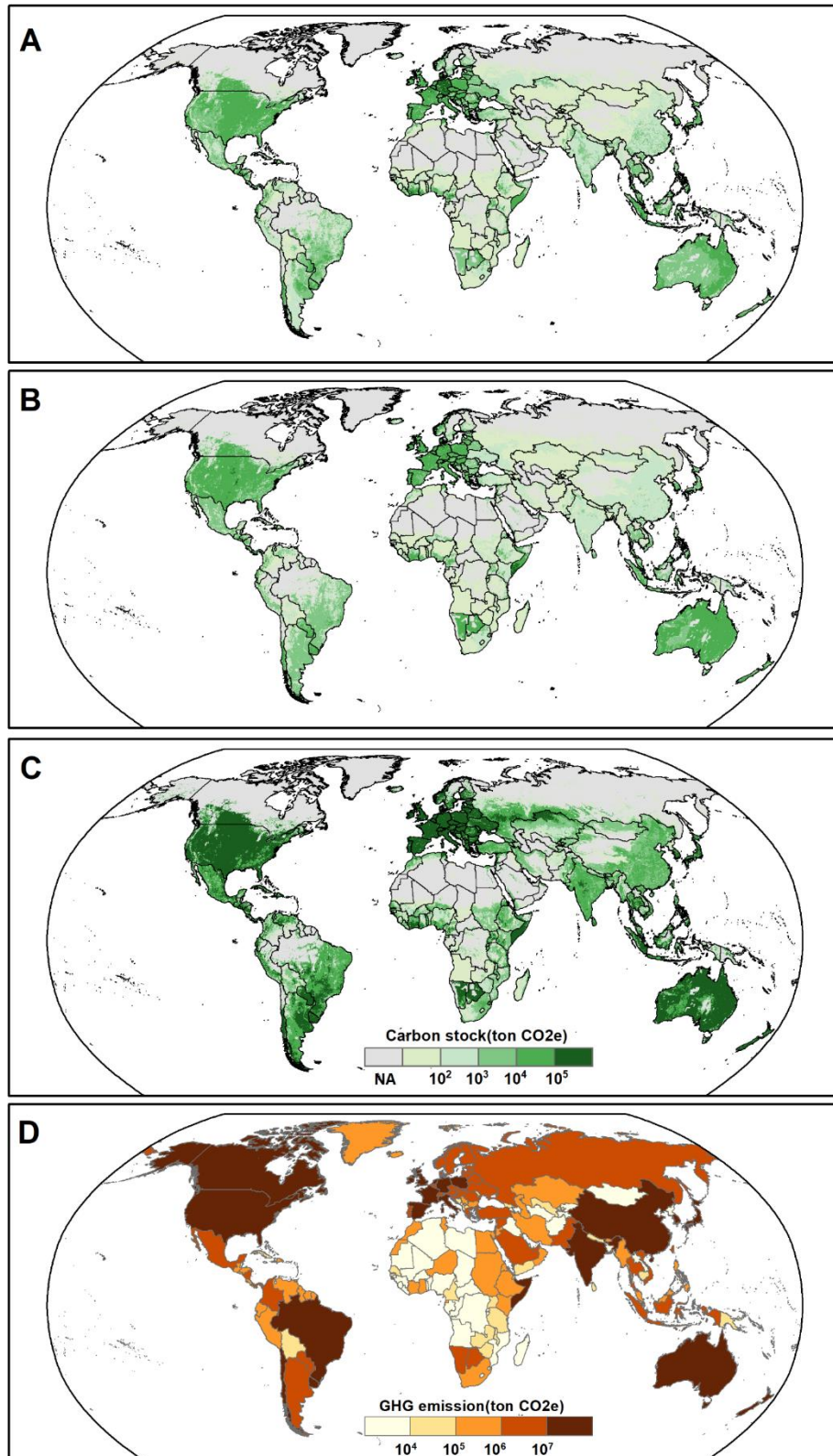


**Figure S 8.17.** Aboveground biomass carbon (AGBC, A), belowground biomass carbon (BGBC, B), soil organic carbon (SOC, C) and GHG emission (D) embodied in current national average diets of high-income countries.

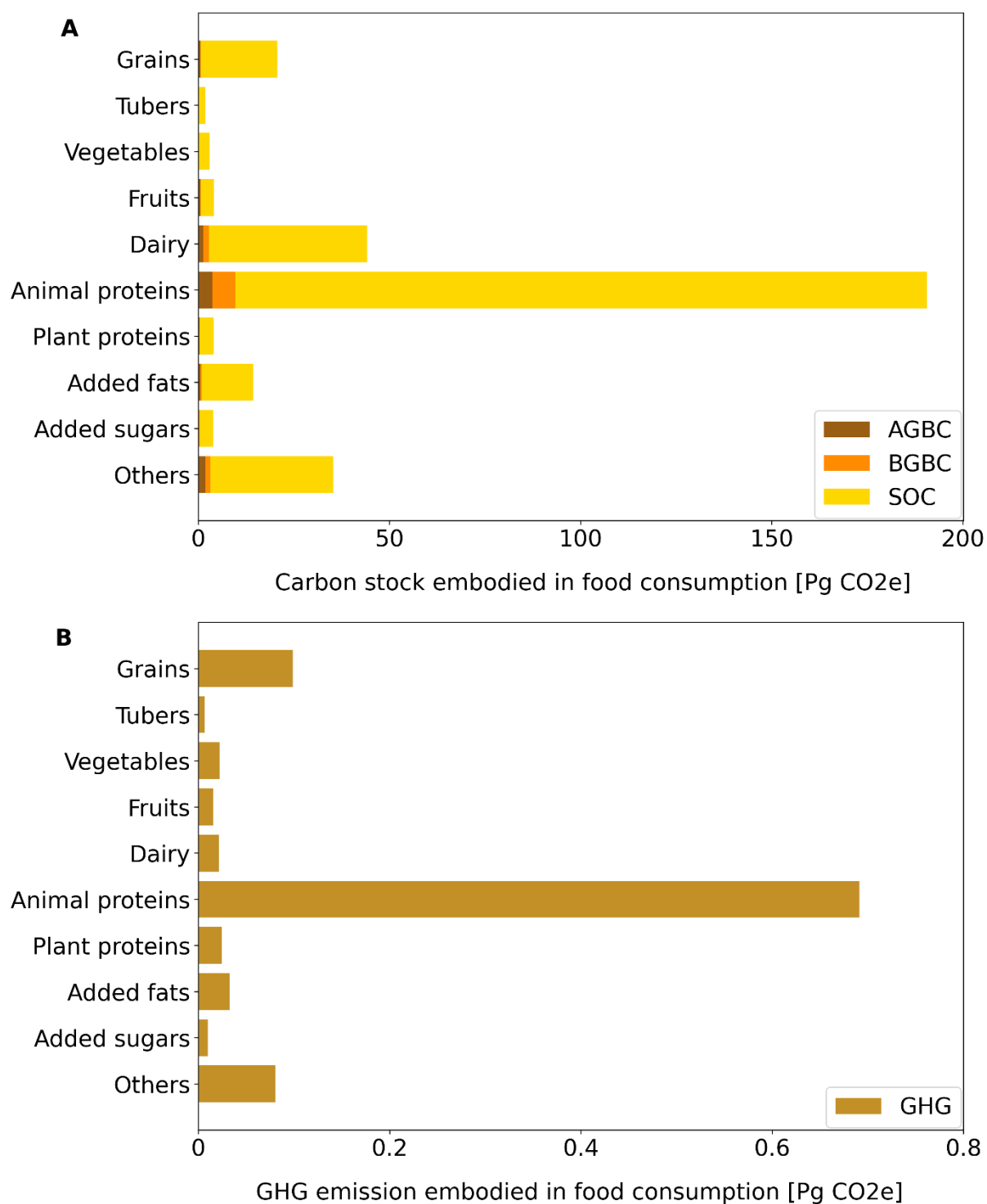


**Figure S 8.18.** Embodied carbon stocks (A) and GHG emission flows (B) in national average diets for high-income countries by food category. Carbon stock means aboveground biomass carbon (AGBC), belowground biomass carbon (BGBC), and soil organic carbon (SOC) in present agricultural production related vegetation (primary crops, fodder, and pasture) used for human food consumption.

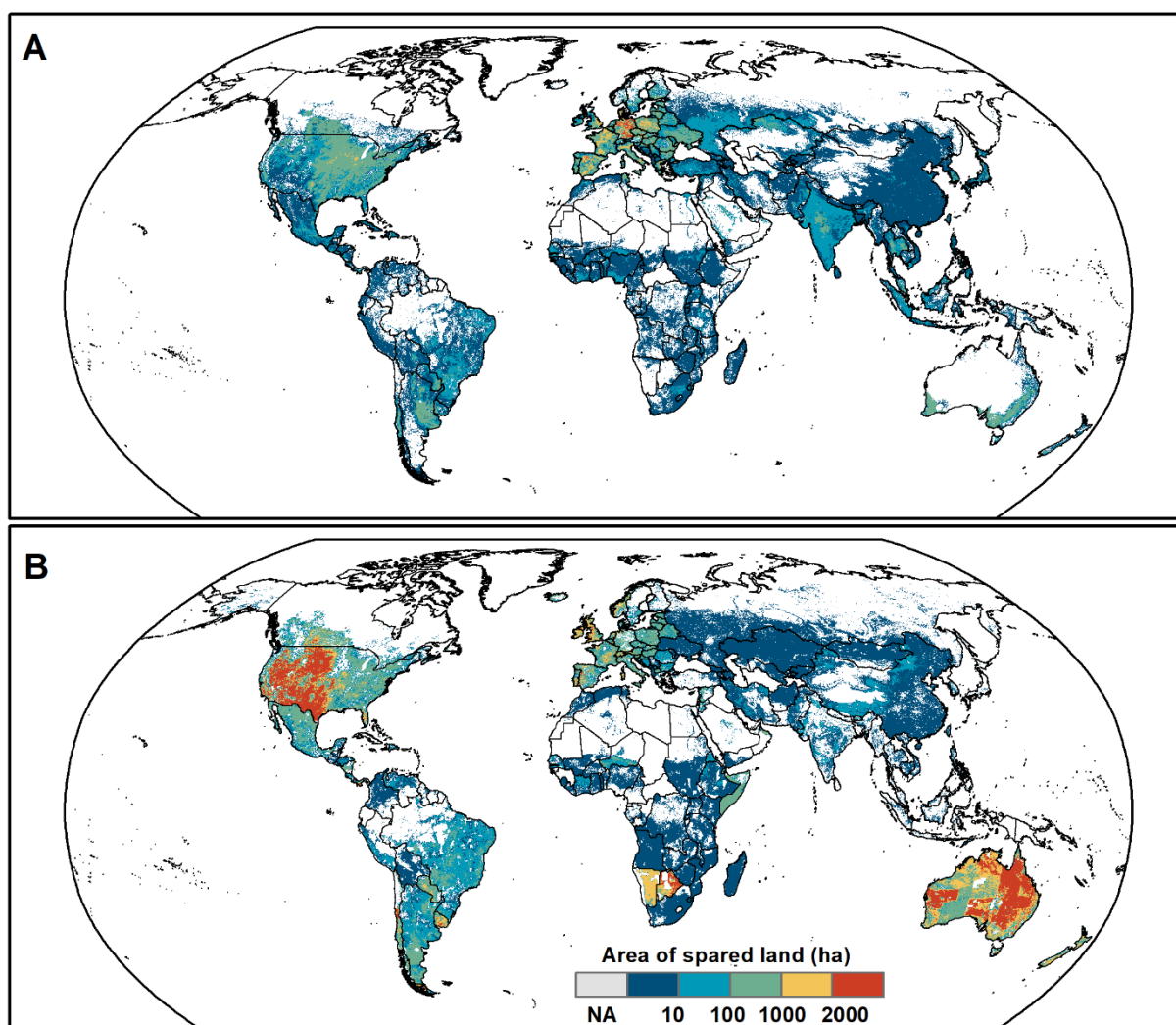


**Figure S 8.19.** Area of spared land due to dietary shift from national average diets to EAT diet in high-income countries for cropland (A) and pastureland (B).

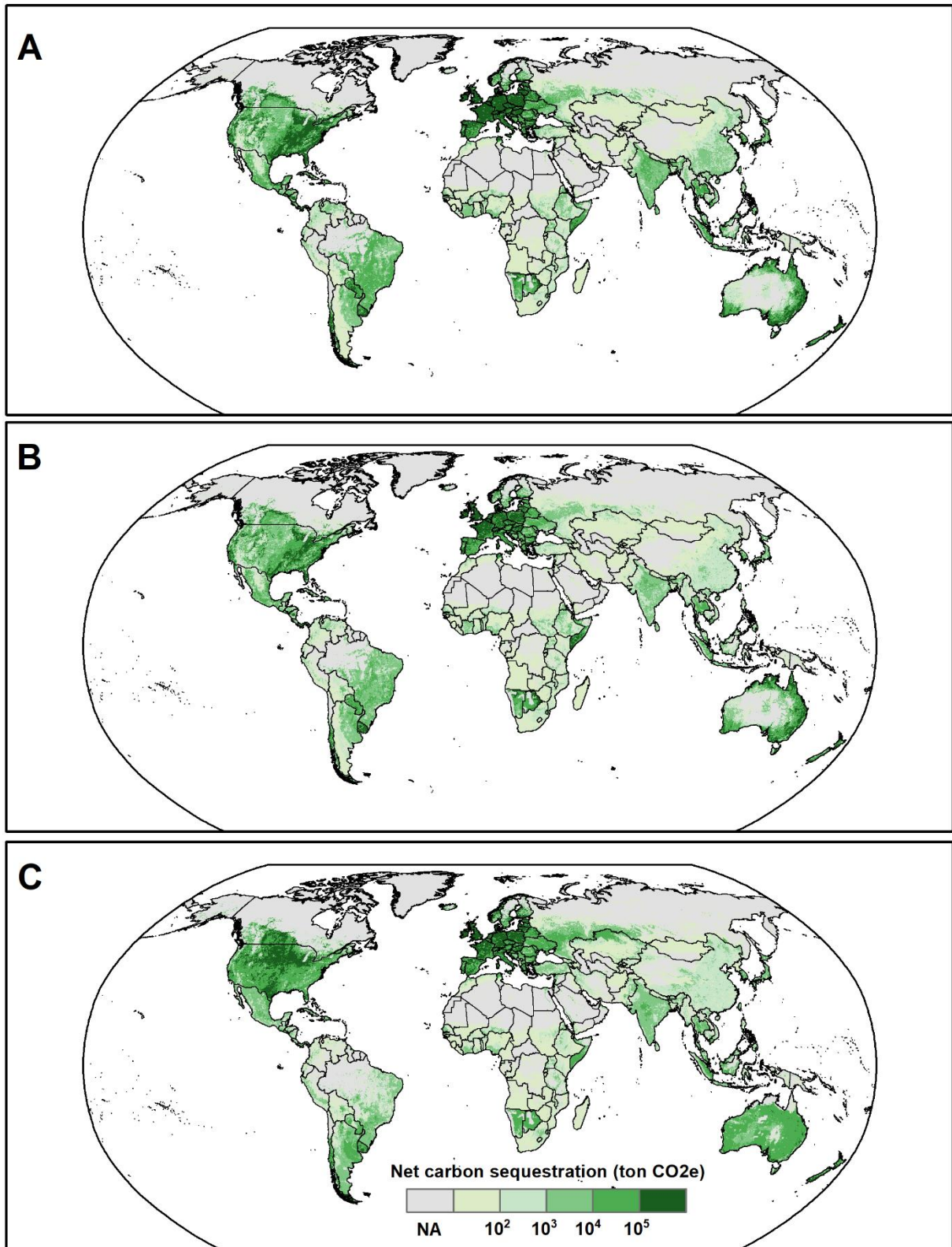


**Figure S 8.20.** Net carbon sequestration due to dietary shift from national average diets to EAT diet in high-income countries. Increasing amount of carbon sequestration in spared land due to dietary change for AGBC (A), BGBC (B), SOC (C).

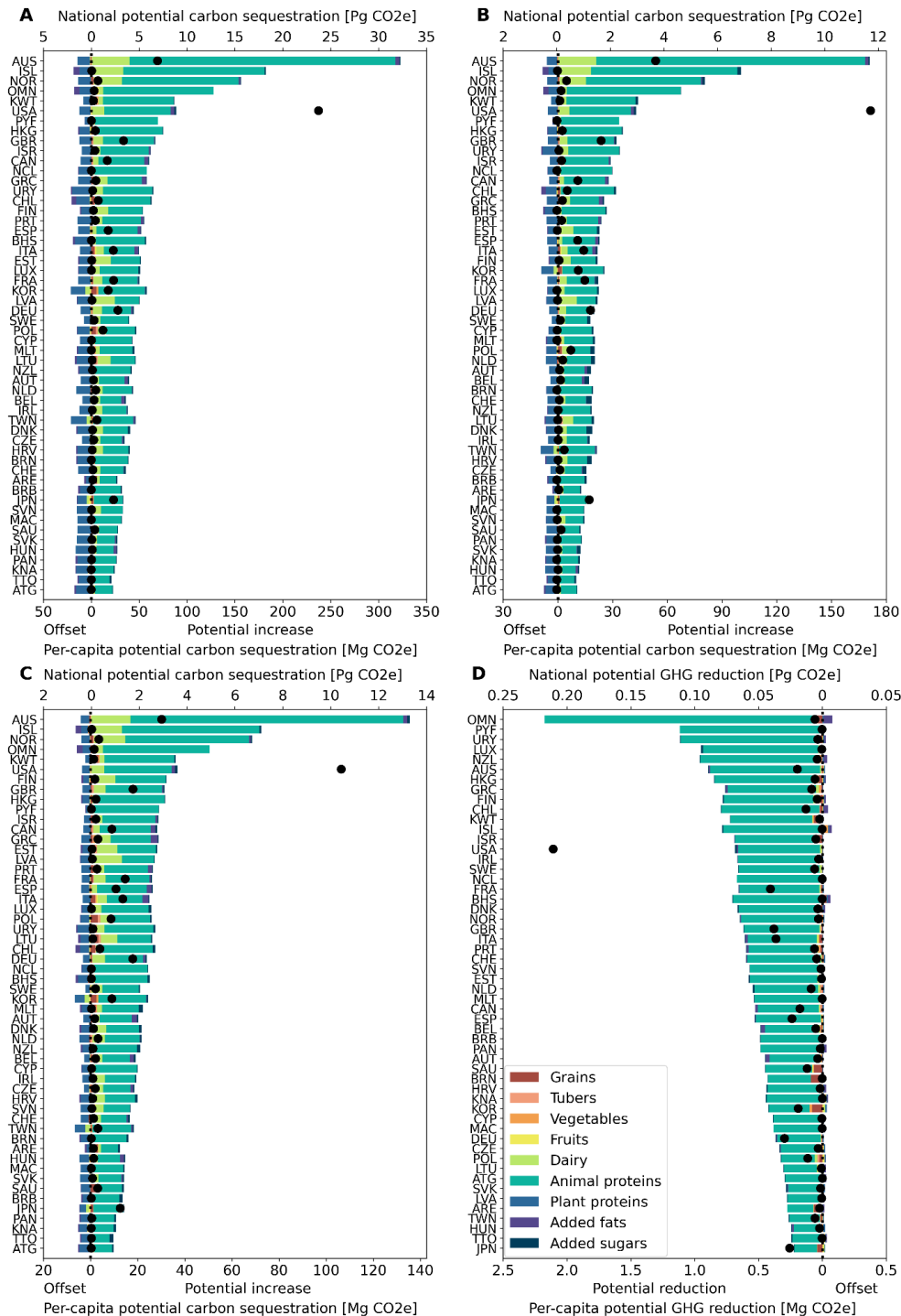


**Figure S 8.21.** National and Per-capita net carbon benefit due to dietary shift from national average diets to EAT diet in individual high-income country by food category. Increasing amount of carbon sequestration due to dietary change for AGBC (A), BGBC (B), SOC (C), and reducing amount of GHG emission (D) by food category. The bar means per-capita carbon sequestration and GHG emission change by food categories, and the dot means national net carbon sequestration and GHG emission change. The potential increase of carbon sequestration means carbon sequestration in potential natural vegetation minus that of current agricultural vegetation. The offset of carbon sequestration means carbon sequestration in potential natural vegetation minus that of increased agricultural vegetation. The carbon reduction of GHG emission means the GHG reduction due to reduction of food categories, and the offset means the GHG increase due to increase of food categories.