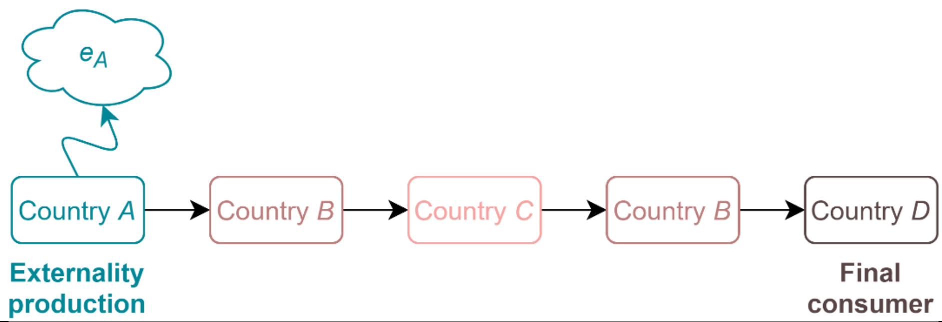
Supplementary Material

Supplementary data

		Location of Final demand		
		Germany	EU	Non-EU
Location of CO_2 emissions	Germany	273	104	171
	EU	74	31	51
	Non-EU	255	111	188

Table S.1 – Throughflow matrix of the CO_2 emissions associated with the German economy (Mt of CO_2). *The throughflow matrix captures the upstream CO_2 emissions caused by the supply chains involving the German economy. Rows correspond to countries where emissions physically occur, columns correspond to the countries where the associated supply chains terminate. For instance, 51 Mt of CO_2 are caused in EU Member States to supply the final demand in non-EU countries through the German economy. The data correspond to those shows in fig. 3.*

Supplementary figure



Country	A	B	C	D
PBA	e_A	0	0	0
CBA	0	0	0	e_A
TBA	e_A	e_A	e_A	e_A
BBA	$(e_A)^*$	$2e_A$	e_A	$(e_A)^*$
TiVA	e_A	$e_A + e_A^+$	e_A	e_A

Figure S.1 - Allocation of an externality along an illustrative supply chain within different accounting frameworks. *The table presents to which countries an externality is allocated to each of the countries involved in the supply chain represented above. This supply chain is causing an externality in country A, goes through countries B and C before traversing country B again. Finally, the supply chain reaches its' final user in country D. The Production Based Accounting (PBA) and Consumption Based Accounting (CBA) frameworks allocate the externality to the country directly causing them (A) and to the country where the final product is consumed (D), respectively. Both frameworks omit the involvement of countries B and C. The Throughflow Based Accounting (TBA) acknowledges the contribution of all countries equally, identifying the externality as* exported *for country A,* traversing *for countries B and C and* imported *for country D. The Betwenness Based Accounting (BBA) and Trade in Value Added (TiVA) frameworks also identify the contribution of intermediates (B and C) but count the contribution of country B's exports twice. Note that in the original definition of the BBA, the contribution of the producing and the consuming sectors are not included (Liang et al., 2016). Tokito et al. (2022) have proposed an alternative formulation of the BBA that accounts for these contributions. This alternative definition of the BBA entails the externality noted with an asterisk (*). The TiVA framework explicitly allows the isolation of the double counted component (Koopman et al., 2010, 2014), noted with a cross in the table (+).*

Demonstrations and additional information

In what follows, we propose a formulation of the throughflow as a spatially explicit matrix and the decomposition of *local externalities* into two elements. We further provide the demonstration of the TBA decomposition and we detail the relation between the TBA and the decomposition proposed by

Hanaka et al. (2022). Finally, we expose the method used to map CO_2 emission data with the MRIO table. We ask the reader to refer to the main text for the notations.

Spatially explicit TBA matrix

The throughflow is introduced as a scalar quantity in equation (13). Using the elements of the TBA decomposition (equations (14-17)), the throughflow can also be expressed as a spatially explicit matrix $\mathbf{TBA}^c$, of dimensions $N \times N$. Element tba_{rs}^c of this matrix captures the volume of externalities caused in country r to supply the final users in country s through country c. Such element is generally defined as:

$$tba_{rs}^c = [\mathbf{q}^r \mathbf{L} \mathbf{Y}^s - (1 - \delta_{rc}) \mathbf{q}^r \bar{\mathbf{L}}^c \mathbf{Y}^s (1 - \delta_{cs})] \mathbf{e}, \tag{S.1}$$

where δ_{ij} denotes the Kronecker symbol, which equals 1 if and only if i and j are equal and 0 otherwise.

It is easy to show that the sum of the elements of such spatially explicit formulation of the throughflow equals the scalar throughflow. First, the sum of the elements of the $\mathbf{TBA}^c$ matrix is:

$$\sum_r \sum_s tba_{rs}^c = \left[\left(\sum_r \mathbf{q}^r \right) \mathbf{L} \left(\sum_s \mathbf{Y}^s \right) - \left(\sum_r (1 - \delta_{rc}) \mathbf{q}^r \right) \bar{\mathbf{L}}^c \left(\sum_s \mathbf{Y}^s (1 - \delta_{cs}) \right) \right] \mathbf{e}. \tag{S.2}$$

Then, using the properties of the Kronecker delta and equations (2), (3), (11) and (12), we have:

$$\sum_r \sum_s tba_{rs}^c = (\mathbf{q} \mathbf{L} \mathbf{Y} - \bar{\mathbf{q}}^c \bar{\mathbf{L}}^c \bar{\mathbf{Y}}^c) \mathbf{e} = \mathrm{tba}^{\mathrm{c}}. \tag{S.3}$$

Finally, such spatially explicit throughflow matrix intuitively displays the elements of the TBA decomposition. Using the properties of the Kronecker delta, it is trivial that, for any country r and s other than c:

$$\begin{cases} tba_{cc}^c = \mathbf{q}^c \mathbf{L} \mathbf{Y}^c \mathbf{e} = loc^c; \\ tba_{rc}^c = \mathbf{q}^r \mathbf{L} \mathbf{Y}^c \mathbf{e} = imp_r^c; \\ tba_{cs}^c = \mathbf{q}^c \mathbf{L} \mathbf{Y}^s \mathbf{e} = exp_s^c; \\ tba_{rs}^c = \mathbf{q}^r (\mathbf{L} - \bar{\mathbf{L}}^c) \mathbf{Y}^s \mathbf{e} = tra_{rs}^c. \end{cases} \tag{S.4}$$

Therefore, the c-th row of the TBA matrix shows the decomposition of the externalities caused in country c (PBA approach) and the c-th column of the TBA matrix contains the externalities caused by the final demand in country c (CBA approach). All externalities outside of the c-th row and column are *traversing* externalities.

Sub decomposition of the local supply chains

Local externalities are captured by equation (14). These can be further decomposed in *purely local externalities* ($ploc^c$) and *re-imported externalities* (rei^c). For that purpose, we introduce the matrix of input coefficients within country c, $\mathbf{A}^{\mathbf{c}}$, being the block matrix associated with country c in $\mathbf{A}$ (i.e. the $(c-1)n$-th to cn-th rows and columns of $\mathbf{A}$). Element $a_{ir \to js}^c$ is defined as:

$$\mathbf{A}^c = (a_{ir \to js}^c) = \begin{cases} a_{ir \to js} \; if \; r = c \; and \; s = c \\ 0 \; otherwise \end{cases}. \tag{S.5}$$

From the matrix of input coefficients within country c, we build the Leontief inverse restricted to country c, $\mathbf{L}^c$ as:

$$\mathbf{L}^c = (\mathbf{I} - \mathbf{A}^c)^{-1}. \tag{S.6}$$

Element $l_{ic \to jc}^{c}$ captures how much inputs from sector i in country c are needed to produce one unit of output j in country c. Using these notations, we define *purely local externalities* ($ploc^c$) as the externalities caused in country c for supplying final users in country c along supply chains staying within country c:

$$ploc^c = \mathbf{q}^c \mathbf{L}^c \mathbf{Y}^c \mathbf{e}. \tag{S.7}$$

Conversely, *re-imported externalities* (rei^c) are caused in country c for the production of commodities finally used in country c but whose associated supply chain traverse other countries:

$$rei^c = \mathbf{q}^c (\mathbf{L} - \mathbf{L}^c) \mathbf{Y}^c \mathbf{e}. \tag{S.8}$$

The externalities captured as *re-imported* are similar to the ones captured as *purely local*, except that they are caused by supply chains involving other countries. From the perspective of the rest of the world, such externalities are *traversing externalities*. It is trivial that the sum of *re-imported* and *purely local externalities* corresponds to the *local externalities* introduced in equation (14).

Demonstration of the TBA decomposition

In order to demonstrate the equivalence between equation (13) and (18), we decompose equation (13) using the notations introduced in equations (11) and (12):

$$tba^c = [(\mathbf{q}^c + \overline{\mathbf{q}}^c)\mathbf{L}(\mathbf{Y}^c + \overline{\mathbf{Y}}^c) - \overline{\mathbf{q}}^c \overline{\mathbf{L}}^c \overline{\mathbf{Y}}^c]\mathbf{e}, \tag{S.9}$$

From equation (S.9), we decompose the throughflow into four elements:

$$tba^c = \mathbf{q}^c \mathbf{L} \mathbf{Y}^c \mathbf{e} + \overline{\mathbf{q}}^c \mathbf{L} \mathbf{Y}^c \mathbf{e} + \mathbf{q}^c \mathbf{L} \overline{\mathbf{Y}}^c \mathbf{e} + \overline{\mathbf{q}}^c (\mathbf{L} - \overline{\mathbf{L}}^c) \overline{\mathbf{Y}}^c \mathbf{e}. \tag{S.10}$$

The first term of equation (S.10) corresponds directly to equation (14):

$$\mathbf{q}^c \mathbf{L} \mathbf{Y}^c \mathbf{e} = loc^c. \tag{S.11}$$

Applying equation (12) to the second term yields:

$$\overline{\mathbf{q}}^c \mathbf{L} \mathbf{Y}^c \mathbf{e} = \sum_{r \neq c} \mathbf{q}^r \mathbf{L} \mathbf{Y}^c \, \mathbf{e}. \tag{S.12}$$

And by comparing with equation (15):

$$\overline{\mathbf{q}}^c \mathbf{L} \mathbf{Y}^c \mathbf{e} = \sum_{r \neq c} imp_r^c = |\mathbf{imp}^c|. \tag{S.13}$$

Likewise, in the third term of equation (S.10), introducing equation (11) gives:

$$\mathbf{q}^c \mathbf{L} \overline{\mathbf{Y}}^c \mathbf{e} = \sum_{s \neq c} \mathbf{q}^c \mathbf{L} \mathbf{Y}^s \mathbf{e}, \tag{S.14}$$

that is, in relation to equation (16):

$$\mathbf{q}^c \mathbf{L} \overline{\mathbf{Y}}^c \mathbf{e} = \sum_{s \neq c} exp_s^c = |\mathbf{exp}^c|. \tag{S.15}$$

Finally, using equations (11) and (12) the fourth and latter term of equation (S.10) becomes:

$$\overline{\mathbf{q}}^c (\mathbf{L} - \overline{\mathbf{L}}^c) \overline{\mathbf{Y}}^c \mathbf{e} = \sum_{r \neq c} \sum_{s \neq c} \mathbf{q}^s (\mathbf{L} - \overline{\mathbf{L}}^c) \mathbf{Y}^s \, \mathbf{e}. \tag{S.16}$$

Comparing to equation (17), this corresponds to:

$$\bar{\mathbf{q}}^c(\mathbf{L}-\bar{\mathbf{L}}^c)\bar{\mathbf{Y}}^c\mathbf{e} = \sum_{r\neq c}\sum_{\neq c} tra_{rs}^c = |\mathbf{TRA}^c|. \tag{S.17}$$

The TBA decomposition of equation (18) directly follows from the reintroduction of equations (S.11), (S.13), (S.15) and (S.17) into equation (S.10).

Comparison of the TBA with previous decomposition of the HEM

The TBA is the decomposition of the throughflow, which is itself the result of the Hypothetical Extraction Method applied to externality accounting. Hanaka et al. (2022) have proposed a comparable decomposition of the HEM into seven types of supply chains. This decomposition is different to ours in two aspects. First, the decomposition introduced here is defined at the country scale, while the decomposition of Hanaka et al. (2022) is applied at the sector scale. Second, Hanaka et al. (2022) differentiates between the trade of intermediate products and the trade of final products. Using the notations of Hanaka et al., our definition of *local externalities* coincides with their component (7), *importing externalities* gather components (2) and (5), *exported externalities* corresponds to the aggregation of elements (1) and (4) and *traversing externalities* are equivalent to component (3).

Besides this decomposition into seven terms, Hanaka et al. (2022) also define Production-, Betweenness- and Consumption-oriented emission's accounts. Each of these *emission types* is formed by the weighted sum of four of the seven terms of their initial decomposition. Given that these weights alter the elements of the initial decomposition, these *emission types* are not directly comparable to our definitions, nor to the canonical PBA, BBA or CBA frameworks.

Mapping of the CO_2 emissions in EORA

We apply a tailored procedure to assign emissions data from the PRIMAP datasets (J. Gütschow et al., 2020, 2021) to the economic sectors in the EORA 26 trade network dataset (Lenzen et al., 2012, 2013), referred to as Multi-Scale Mapping (MSM) method from now on. CO_2 emissions are reported in the PRIMAP databases using the 2006 hierarchical categorisation defined by the International Panel on Climate Change (IPCC) for the UNFCCC (Eggleston et al., 2006). IPCC emission categories form a nested list of emission categories, referred hereafter as an *emission tree*. We use a mapping table to associate IPCC emission categories to EORA sectors (Table S.2). As many aggregated IPCC emission categories relate to more than one economic sector, the construction of the mapping table requires to unfold the emission tree until a subcategory can be associated unambiguously with a single economic sector (referred to as *end-category)*.

The PRIMAP-hist database reports aggregated emission categories for all IPCC countries (J. Gütschow et al., 2021) and PRIMAP-crf reports more detailed categories but only for Annex I countries of the UNFCCC (J. Gütschow et al., 2020). The MSM method exploits a two-step procedure to reconstruct an emission tree for each of the 182 countries included in both the PRIMAP-hist and EORA databases. End-categories' emissions are finally associated to economic sectors from EORA (fig. S.2) using the mapping table (table S.2). In the first step of the procedure, data from the PRIMAP-crf database are extrapolated to every country of the world using economic data from EORA 26 (fig. S.3). In the second step, estimated emission data are reconciled with the aggregated information contained in PRIMAP-hist (fig. S.4).

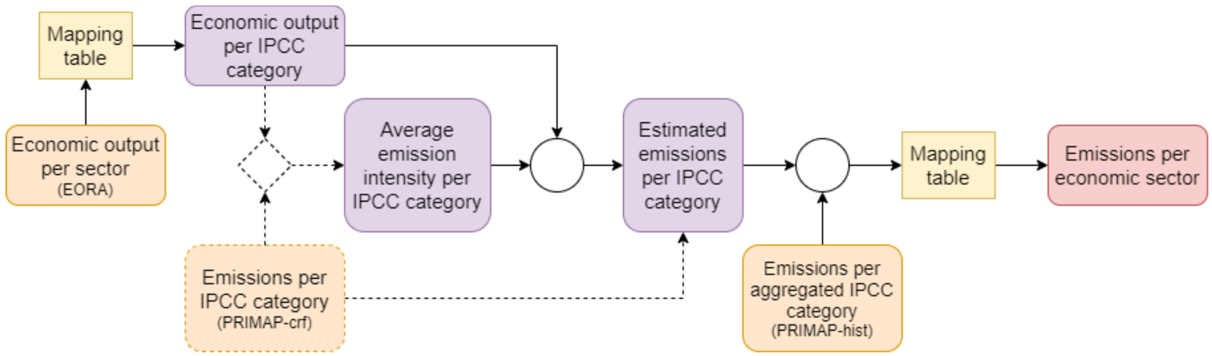


Figure S.2 - Overview of the MSM method that maps CO2 emissions to MRIO data. *First, the PRIMAP-crf emission database (J. Gütschow et al., 2020) is combined with sectoral economic output from EORA (Lenzen et al., 2012, 2013) to produce an initial estimation of emissions per IPCC category for each country. Second, these estimated emission data are reconciled with the aggregated information from the PRIMAP-hist database (J. Gütschow et al., 2021). Orange boxes represent inputs of the MSM method, the red box represents the output of the MSM method. Yellow boxes correspond to the table mapping EORA economic sectors to IPCC emission categories. Purple boxes represent intermediate data. Solid lines represent operations applied to all countries of the dataset. Dotted lines are only applied to countries covered in the PRIMAP-crf database (Annex I countries of the UNFCCC). Blank circles correspond to the two main steps of the algorithm. The dashed diamond corresponds to the initial estimation of the average emission intensities.*

In the first step, average emission intensities are derived from PRIMAP-crf and EORA data for all *end-categories*. We note k the end-category from the IPCC emission tree and i the associated sector in the EORA database. For example, IPCC category 1A2A reports emissions associated with Fuel Combustion for Energy Production in the Iron and Steel Industry. This emission category is mapped with activities of the *Manufacturing of Metal Products* in the EORA 26 database. The world average emission intensity for end-category k, e_k^*, is defined as the volume of non-null emissions reported by countries c covered in PRIMAP crf for this category e_k^c, divided by the economic output of the associated national sectors x_{ic}, as reported in the MRIOT:

$$e_k^* = \frac{\sum_{c, e_k^c \neq 0} e_k^c}{\sum_{c, e_c^k \neq 0} x_{ic}}. \qquad (S.18)$$

In our example, the PRIMAP-crf database contains data for the CO_2 emissions of category 1A2A for 38 countries, amounting to a total of 347 Mt of CO_2 in 2015. This figure corresponds to the numerator of equation (S.18). Reciprocally, the gross economic output of the *Metal products* industry in these 38 countries is valued in total to 3,34 trillion US$ in 2015. Using the emission volume as the numerator and the economic output as the denominator, we estimate the average emission intensity of Fuel Combustion for Energy Production in the Iron and Steel Industry to 103g of CO_2 emitted per current US$ of Metal Products.

Then, an estimated emission tree is created for every country covered in the EORA MRIOT (fig. S.3). The emission tree is first filled with data reported in PRIMAP-crf. Such values are labelled as *sourced*. In countries for which no emissions are reported in PRIMAP-crf, a volume of emissions $\overline{e_k^c}$ is estimated for country c using the average emission coefficient and the economic output of the corresponding sector x_{ic}:

$$\overline{e_k^c} = e^c * x_{ic}. \qquad (S.19)$$

Such value is labelled as *estimated*. For instance, PRIMAP-crf does not include information on Chinese emissions. In absence of such *sourced* data, we assume provisionally that the Chinese *Metal products* industry has an emission intensity equal to the world average. The *Manufacturing of metal products* sector in China had an output value of 3,47 trillion US$ in 2015 The world average emission intensity of Fuel Combustion for Energy Production in the Iron and Steel Industry is 103g of CO_2/US$ according to equation (S.18). Following equation (S.19), Chinese emissions for category 1A2A are initially estimated to 229 $MtCO_2$ in 2015.

PRIMAP-crf also include information on aggregated categories. Aggregated categories are filled consecutively by "climbing" the emission tree, that is, starting from the most detailed category to the volume of national emissions (fig S.3). As for end-categories, categories for which emission values are reported into the PRIMAP-crf database are directly entered into the emission tree and labelled as *sourced*. Aggregated categories not covered in PRIMAP-crf are estimated from the sub-categories previously informed and labelled as *estimated*. For countries not reported in the PRIMAP-crf database, the emission tree built here is entirely estimated from national production data and from world average emission intensities.

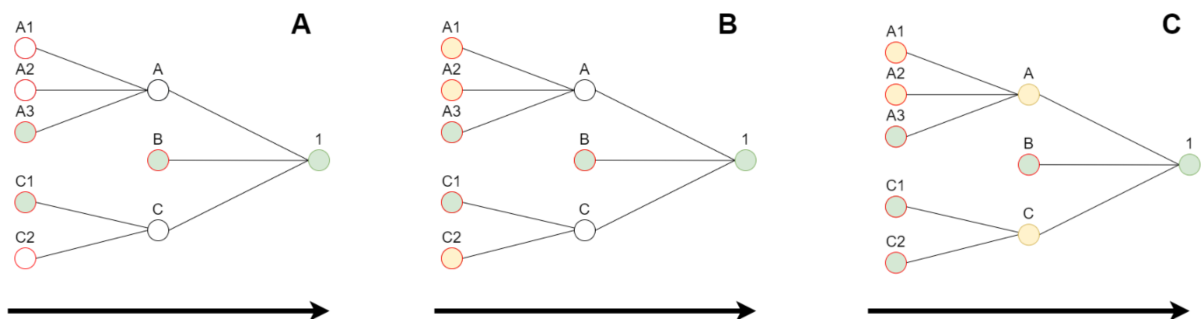


Figure S.3 – Description of the bottom-up aggregation process for the emission tree of a country. *This procedure is applied to build an estimated emission tree using economic output from EORA, average emission intensity coefficients for each end-category and emission data from the PRIMAP-crf database. Panel A represents the emission tree of a country. Dots represent IPCC emission categories. The categories on the left-end of each branch correspond to* end-categories*, i.e. are associated with EORA economic sectors (red circles, A1-3, B, C1-2). Green dots correspond to categories available for this country in the PRIMAP-crf database. Blank dots are categories not covered for such country in PRIMAP-crf. In panel B,* end-categories *not covered in PRIMAP-crf are estimated using the average intensity coefficients of the corresponding category and the national economic output of the associated economic sector (A1, A2, C2, in yellow). In Panel C, emissions of subcategories are summed up to estimate the values of aggregated categories not reported in PRIMAP-crf (A, C, in yellow).*

In the second step of the MSM method, estimated emission data are reconciled with the aggregated information contained in the PRIMAP-hist database. First, emission categories known from PRIMAP-hist are inserted into the national emission trees, replacing the data estimated or retrieved from PRIMAP-crf. Second, the emission tree of each country is browsed down to reconcile aggregated emission values with more detailed emission categories (fig. S.4). When aggregated emission volumes differ from the sum of the corresponding subcategories, *estimated* subcategories are scaled proportionally to meet the volume of emissions reported in the parent node. If such rescaling is not possible by rescaling *estimated* nodes, *sourced* nodes are also adjusted.

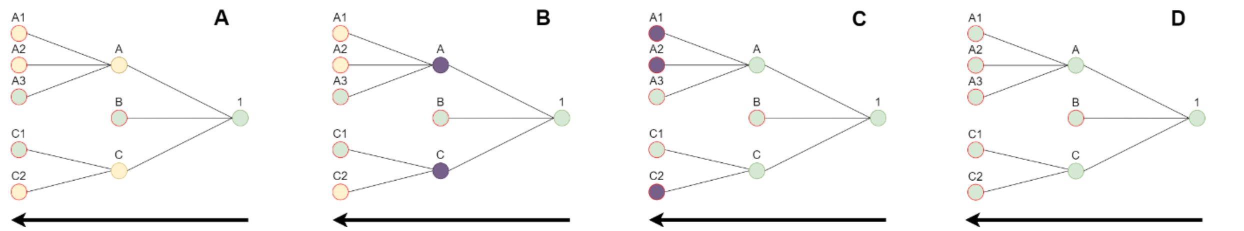


Figure S.4 – Description of the top-down adjustment process for the emission tree of a country. *This procedure is applied to reconcile an estimated emission tree (see fig. S.3) with all data available, either from PRIMAP-crf or from PRIMAP-hist. Panel A represents the estimated emission tree of a country (see fig. S.3.C). The top-down balancing procedure is applied from the most aggregated node of the tree (node 1), down to end-categories (A1-3, B, C1-2). Panel B represents the first operation of the process. Nodes A and C (in purple) are proportionally adjusted so that the sum of nodes A, B and C corresponds to value of node 1. Node B is left unadjusted, because it was directly extracted from the PRIMAP-crf database (see fig. S.3.A). In panel C, the same procedure is applied at a lower level of the tree: nodes A1 and A2, and C2 are adjusted with regard to nodes A and C, respectively. Note that if nodes of a level cannot be adjusted consistently with the nodes of the upper level (i.e. if the total of* sourced *nodes is already exceeding the parent node),* estimated *nodes are set to 0 and* sourced *nodes are adjusted consistently with the parent node. The outcome of this procedure is shown in Panel D, where all nodes of the emission tree have been adjusted consistently with the most aggregated nodes.*

For countries not covered in the PRIMAP-crf database, the estimated emission tree resulting from the first step of the MSM method assumed that their production technologies were identical to the world average. This assumption is relaxed during the second step of the algorithm when detailed emission categories are reconciled with aggregated values. For instance, the initial estimate of Chinese emissions for fuel combustion in Iron and Steel production is increased by 78% after introducing aggregated data from PRIMAP-hist.

Economic sectors can cause emissions through different processes, hence be mapped to different IPCC categories. For example, the *Metal Products* industry from EORA cause emissions due to fuel combustion for Iron and Steel (1A2A) and non-Ferrous Metals (1A2B) production, but also from direct reactions such as Iron smelting (2C). Hence, we simply sum all these contributions to obtain the total direct emissions related to the *Metal Products* sector. Reciprocally, an IPCC emission category may be associated with more than one economic sector. In that case, the economic output of all the corresponding sector is aggregated to compute the emissions intensity and the estimated emission volumes. Estimated emissions from this category are then allocated to all the associated sectors proportionally to their respective economic output.

Code	IPCC Emission Category	Eora Sector
0	**Total emissions**	
1	*Energy*	
1A	Fuel Combustion Activities (Sectoral Approach)	
1A1	Energy Industries	
1A1A	Main Activity Electricity and Heat Production	Electricity, Gas and Water
1A1B	Petroleum Refining	Petroleum, Chemical and Non-Metallic Mineral Products
1A1C	Manufacture of Solid Fuels and Other Energy Industries	Petroleum, Chemical and Non-Metallic Mineral Products
1A2	Manufacturing Industries and Construction	
1A2A	Iron and Steel	Metal Products
1A2B	Non-Ferrous Metals	Metal Products
1A2C	Chemicals	Petroleum, Chemical and Non-Metallic Mineral Products
1A2D	Pulp, Paper and Print	Wood and Paper
1A2E	Food Processing, Beverages and Tobacco	Food & Beverages
1A2F	Non-Metallic Minerals	Petroleum, Chemical and Non-Metallic Mineral Products
1A2G	Transport Equipment	Transport Equipment
1A2H	Machinery	Electrical and Machinery
1A2I	Mining and Quarrying	Mining and Quarrying
1A2J	Wood and Wood Products	Wood and Paper
1A2K	Construction	Construction
1A2L	Textile and Leather	Textiles and Wearing Apparel
1A2M	Other	
1A3	Transport	
1A3A	Civil Aviation	Transport
1A3B	Road Transportation	
1A3B1	Cars	Final Demand
1A3B2	Light-Duty Trucks	Transport

IPCC Emission Category						Eora Sector
1	1A	1A3	1A3B	1A3B3	Heavy-Duty Trucks and Buses	Transport
				1A3B4	Motorcycles	Final Demand
			1A3C		Railways	Transport
			1A3D		Water-borne Navigation	Transport
			1A3E		Other Transportation	Transport
		1A4			Other Sectors (Fuel Combustion)	
			1A4A		Commercial/Institutional	Final Demand
			1A4B		Residential	Final Demand
			1A4C		Agriculture/Forestry/Fishing/Fish Farms	
				1A4C1	Stationary	Agriculture
				1A4C2	Off-road vehicles and other machinery	Agriculture
				1A4C3	Fishing	Fishing
		1A5			Non-Specified	Final Demand
	1B				Fugitive Emissions from Fuels	Mining and Quarrying
		1B1			Solid Fuels	Mining and Quarrying
		1B2			Oil and Natural Gas	Mining and Quarrying
		1B2A			Oil	
			1B2A1		Venting	Mining and Quarrying
			1B2A2		Flaring	Mining and Quarrying
			1B2A3		All other	
				1B2A31	Exploration	Mining and Quarrying
				1B2A32	Production and Upgrading	Mining and Quarrying
				1B2A33	Transport	Transport
				1B2A34	Refinig	Petroleum, Chemical and Non-Metallic Mineral Products
				1B2A35	Distribution of Oil Products	Petroleum, Chemical and Non-Metallic Mineral Products
				1B2A36	Other	Mining and Quarrying
		1B2B			Natural Gas	
			1B2B1		Venting	Mining and Quarrying

IPCC Emission Category		Eora Equivalent
4	Waste	Recycling
5	Other	
M0EL	Total CO2 equivalent emissions, without land use, land-use change and forestry, table10s1/s2/s6	
MAG	Total Agriculture, CRF table 3	Agriculture

Table S.2 – Mapping between the UNFCCC emission categories and the EORA production sectors. *The columns on the left indicate the emission categories as defined by the IPCC (Eggleston et al., 2006) and the associated category codes. The column on the right shows the EORA production sector to which emissions have been allocated. Columns in grey indicate aggregated categories or categories which have not been classified. Indentations for the IPCC emission categories represent the hierarchy between emission categories, i.e. the structure of the emission tree (see fig. S2-3).*

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