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Sector aggregation bias in Environmentally Extended Input Output modelling of raw material flows in Finland.

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ABSTRACT
This paper presents the impact of sector aggregation bias in Environmentally Extended Input Output (EEIO) models, focusing on raw material flows. Finnish industries are aggregated in different ways and causes of bias are studied. The results show that industries with high raw material use deserve special attention in EEIO models. For Finland, particularly problematic is the aggregation of biomass extractive sectors, since the relative importance of forestry causes noticeable deviations. Sources and strategies to prevent errors, are described separately for biomass and mineral raw materials. A brief comparison between raw material flows and greenhouse gas emissions is also made. It is shown that aggregation of extractive sectors biases more in material flows analyses. This issue might be of significance in the near future, owing to the foreseeable changes in the European Union accounting framework.

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1. Introduction

On the path towards sustainability, a deeper understanding of the relationship between the economy and the environment is required. To this end, special attention has been paid to two questions: firstly, what are the biophysical flows that fuel the economy and, secondly, how consumers drive environmental deterioration. In respect to the former, the framework of Material Flow Accounting or Economy-wide Material Flow Analysis (Ew-MFA) helps clarifying the biophysical roots of economic prosperity, by measuring the exchanges between the economy and the environment in mass units. Concerning the role of consumers, ‘footprint’ type analyses explore the attribution of environmental pressures to final use categories. In both spheres of research, Environmentally Extended Input Output (EEIO) models have gained growing attention, since their outcomes enable us to trace environmental loads along the supply chain. EEIO models are derived from economic input output (IO) models. Original economic IO models were introduced to depict product flows within the economy using a broad categorization in sectors or industries (Leontief, 1936). This implies unavoidable simplification and aggregation of information, such as averaging data of several firms with different production formulas. As a consequence, significant deviations in results might appear determined by how industries or products are grouped in the model, what is known in the literature as sector aggregation bias. In EEIO, the economic IO framework is broadened to study relevant environmental burden flows, albeit categorization necessity and risks of errors remain. Moreover, heterogeneity of firm-nature interfaces within an industry add an extra level of complexity when studying sector aggregation bias in EEIO (Zhou et al., 2013). Aggregation bias in EEIO has been explored previously, although studies focused mostly on GHG emissions. Nevertheless, there is evidence that aggregation impacts differently depending upon the environmental dimension under consideration (Bouwmeester and Oosterhaven, 2013). The
main purpose of this article is to contribute to the discussion of aggregation bias in the use of EEIO models within the framework of Ew-MFA, by also studying end users as driving forces of material extraction. The focus is on raw material (RM) flows and for reasons of comparison, on greenhouse gas (GHG) emissions using data from Finland. To this end, we use the ENVIMAT\textsubscript{2010} model, which has been designed to study environmental pressure of the Finnish economy. We aggregate ENVIMAT\textsubscript{2010} classification scheme in different manners and report deviations in outcomes.

2. Ew-MFA, attribution of materials to final demand and EEIO models

Ew-MFA measures the flow of materials through the economy on the basis of mass conservation. Since the publication of pioneer studies, such as Ayres, Kneese, & D’Arge (1970), Ew-MFA has matured to an established method (Fischer-Kowalski et al., 2011). Ew-MFA is a useful tool to measure progress toward sustainability, since the overall turnover of material exchange is a generic environmental pressure indicator (Bringezu et al., 2003). For reasons of data availability, the most popular Ew-MFA indicators among statistics agencies are Domestic Material Consumption (DMC) and Direct Material Input (DMI) (Kovanda and Weinzel, 2013). DMI quantifies all materials entering the economy that is, Domestic Extraction (DE) plus the mass of imports (or ‘direct imports’ in Ew-MFA’s terminology), and DMC measures total material used for domestic production and consumption. In other words, DMC equals DMI minus mass of exports (i.e. ‘direct exports’). However, it has been acknowledged that DMC and DMI do not successfully track biophysical flows associated with foreign trade, since products crossing borders are considered at different stages of processing, whereas domestic products are only accounted in raw material terms. This differentiated treatment of products might cause that
some environmental burden shifting is not successfully captured, when a
given country imports high material-intensive products. To overcome this
situation, the use of more consistent Raw Material Equivalents (RME) of
trade products was proposed, where RM requirement for imports and
exports is also measured (EUROSTAT, 2001). By doing so, it is possible to
estimate the Raw Material Consumption (RMC) and the Raw Material Input
(RMI) of the economy, in which products are accounted in terms of RM
requirements. For estimating RME, upstream RM employed in the
manufacturing of traded products need to be calculated. This is called ‘used
indirect flows’ in the Ew-MFA’s nomenclature, or RM ‘embodied’, using
the terminology of footprint analyses. There are three methodological
approaches to this end: EEIO models, coefficients based on process analysis
or a combination of both; each hold advantages and drawbacks (see
Hischnitz-Gabers et al., 2014). In this article, only methods using EEIO
models are further addressed.

EEIO models allow material extraction to be reattributed to final
user’s consumption, and it is this property that makes them useful for RME
estimation. Simplest EEIO models consider IO data and RM use by
industries for a single country. Under these circumstances, RM embodied in
final consumption can be affected by which assumption is followed to
compile imports: whether imported and domestic intermediates are
accounted together or not (Su and Ang, 2013). If no extra information is
included, RME estimates presume that the technology used to produce
imports is the same as that of the receiver nation, called ‘domestic
technology assumption’. This approach is followed by Muñoz et al. (2009),
although noticeable errors have been reported under such assumption in
Koskela et al. (2011). One way to deal with this simplification is to use
world coverage IO models. In this regard, two general methods can be
distinguished (Peters, 2008): Single country IO tables could be further
linked with bilateral trade data to relocate environmental loads of imports;
or the world economy can be considered a whole IO entity by itself, which is called Multi Regional Input Output (MRIO) model. Both methods differ in how environmental burdens of imports for intermediate consumption are allocated, making MRIO models more suitable to pinpoint environmental burdens along the global production chain (Peters, 2008; Su and Ang, 2011) and therefore, theoretically more consistent with the RME concept. MRIO models applied following Ew-MFA’s principles can be found in Tukker et al. (2014) and Wiedmann et al. (2013). Another feasible option is combining EEIO models with Life Cycle Assessment (LCA) (Kovanda, Weinzettel, & Hák, 2010; Schaffartzik, Eisenmenger, Krausmann, & Weisz, 2014; Schoer, Weinzettel, Kovanda, Giegrich, & Lauwigi, 2012; Seppälä et al., 2011).

LCA is a ‘bottom-up’ approach that pays attention to the exchanges between natural and social spheres that occur during all the stages of the product life cycle. Thus, it is possible to carry out LCA of imports and link the information with EEIO models. This method is called Hybrid LCA or Input Output LCA (IO-LCA). IO-LCA can also be employed in order to avoid truncation errors when performing an LCA that is, by where the system’s boundaries are set (Lenzen, 2000). In a sense, this might be seen as the corresponding methodological shortcoming of sector aggregation bias when coming down from macro to micro levels (Majeau-Bett ez et al., 2011). Both IO-LCA and MRIO approaches in RME estimation have advantages and drawbacks, and their merits are under much discussion (Eisenmenger et al., 2013; Schoer et al., 2013).

EEIO models can be also utilized for studying the role of consumers as drivers of material extraction, similarly to what is done in footprint type analyses. At this point, some clarification of the terminology is needed. Footprint analyses can be carried out applying different techniques, usually LCA, EEIO (single country or MRIO) or combinations of both (European Comission et al., 2014). Thus, dissimilar approaches may be labelled by the same name. However, the opposite is also true, for example RMC and
material footprint can be assumed to be equivalent concepts (Wiedmann et al., 2013). In the following, footprint analyses will mean those grounded totally or partially in EEIO.

In Ew-MFA studies, individual attention to the role of consumers as drivers of material extraction seldom occurs, something that has been identified as a task ahead (see Fischer-Kowalski et al., 2011). In general, this is not the case in footprint analyses, in which more detailed attention is paid to different final use categories and groups of industries or products. Moreover, distortions at industry level can offer valuable information to understand aggregation bias (Steen-Olsen et al., 2014), more precisely variations in the ‘multipliers’ (RM or GHG emissions embedded per unit of final product). For these reasons, industry level is the finest resolution considered in this paper. Additionally, given their policy importance, two more coarse levels of analyses are assessed: final use categories and Ew-MFA indicators.

### 3. Sector Aggregation Bias in Environmentally Extended Input Output models

In EEIO modelling, the goal is often to re-attribute environmental loads along the production chain. However, sector aggregation can compromise outcomes i.e., loads could be wrongly allocated. For example, in Finland, biomass products (from agriculture, fishing and forestry) have dissimilar RM requirements and uses in the economy. Agricultural products have usually lower RM requirement than forestry products, that is, per unit of output agriculture extracts less biomass from nature than forestry. Therefore, if they are combined to a generic ‘biomass extractive sector’ and, accordingly, an average RM requirement is selected for modelling, RM requirement of agricultural products (e.g. of food industry) would be overestimated, whereas the opposite would happen for forestry products (e.g. of paper industry). These deviations might eventually be transferred to
different end users (e.g. food for households vs. paper products for exports),
which would cause distortions in macro indicators. This issue is particularly
relevant when such indicators are used in discussing mitigation
responsibilities (Lenzen et al., 2004).

To further explain aggregation bias, some notation is required: lower
case denotes vector, always in column form, whereas capital letter denotes
matrix. Additionally, superscripts $^{-1}$ and $'$; and accent $\hat{\text{\textsuperscript{}}}$, denote non-singular
matrix inversion, matrix transpose and diagonal matrix, respectively. The
general expression of the IO model is,

$$g = (I - A)^{-1}f$$

(1)

where $g$ is total output, $f$ is total final uses, $A$ is the technical coefficients
matrix and $(I - A)^{-1}$ is the Leontief Inverse. The latter is a key feature
because it represents the indirect and direct requirements of input per unit of
output (for further details see Miller & Blair 2009).

Commonly, IO models are used to get an approximation about how
much change in total output $g$ is induced by variations in final demand.
From a practitioner’s perspective, aggregation bias occurs when different
resolution or combination of sectors in IO models give dissimilar total
output $g$ per economic sector. When sectors with different technology (or
matrix $A$) are collapsed together, the outcome might be different than if such
aggregation would not have taken place. Aggregation bias has been
extensively studied in the literature targeting a consistent or ‘perfect’
dimensions for IO models (Kymn and Norsworthy, 1976).

In EEIO, the general IO scheme needs to be ‘extended’ to allocate
environmental loads to each industry. These environmental loads might be
considered as necessary inputs for production processes, such as RM
extracted or water consumption; or as inevitable outputs, such as emissions
or solid waste. More precisely, the ‘intensity’ vector of environmental load
$e'$, which describes for each industry environmental loads per output unit is
added, as shown in equation 2. Furthermore, considering that $f = Fi$, where
i is a vector of ones, the total final uses vector can be substituted by the final uses matrix \( F \):

\[
I = e'(I - A)^{-1}F
\]  \hspace{1cm} (2)

With equation 2, it is possible to estimate total indirect and direct environmental loads for each final use category, denoted by \( I \).

Studies focusing on aggregation bias in EEIO are more recent. The question is, how to prevent sector aggregation bias in the estimation of total indirect and direct environmental loads \( I \). Earlier studies have described sector aggregation bias in EEIO, although primarily focused on CO\(_2\) or GHG emissions and only recently on other environmental loads. Wyckoff & Roop (1994) performed a sensitivity analysis for aggregation bias by comparing their benchmark 33-sector model with a 6-sector model, which caused an around 30% underestimation of GHG emissions embodied in imports for the countries under study. Lenzen et al. (2004) analyzed changes in CO\(_2\) multipliers and carbon trade between Denmark, key trade partners and the rest of the world, using three MRIO models of different complexity. For studying aggregation bias, original tables, which distinguish between 39 and 133 sectors, were collapsed to 10 industries. They showed how aggregation to sector ‘electricity, gas and water’ causes a CO\(_2\) trade deficit for Denmark ten times higher in the aggregate version. Su, Huang, Ang, & Zhou (2010) pioneered the systematic study of this issue and laid the foundations for a formal approach. Furthermore, they studied the effects of sector aggregation on CO\(_2\) emissions embodied in China’s and Singapore’s exports and concluded that the optimal aggregation level is around 40 sectors. Marin, Mazzanti, & Montini (2012) carried out a similar exercise, comparing different aggregation schemes using data for Spain and Italy for several air pollutants. They reported significant biases in results, in ways specific for each country. According to them, particularities of the economic structure of countries must also be taken into account when designing aggregation level. Lenzen (2011) concluded that, in case of divergence in
resolution between IO tables and environmental data, disaggregation of IO
data rather than aggregation to the closest common level is preferable,
because of sector aggregation bias. Bouwmeester & Oosterhaven, (2013)
explored sector aggregation errors using a MRIO model, arising from
estimating CO\textsubscript{2} emissions and embodied water use, and found that
consequences for the latter are much larger than for the former. In addition,
they also revealed noticeable differences across countries. Zhou et al. (2013)
aggregated randomly a MRIO model for 10 selected Asian-Pacific 76-
sectors economies, extended for carbon footprint analysis. Outcomes
showed that even though on average aggregation has a moderate effect,
grouping certain sectors can entail noticeable errors. Accordingly, they
claimed that aggregation bias is rather a problem of which sectors are
collapsed (e.g. ‘iron and steel’ or ‘chemical fertilizers and pesticides’ for
China), than strictly speaking of number of sectors. Furthermore, they stated
that grouping in general affects more aggregated industries than
unaggregated, although there are cases in which unaggregated sectors can be
seriously influenced as well (e.g. ‘milled grain and flour’ in Indonesia).
Steen-Olsen et al. (2014) analyzed how sensitive CO\textsubscript{2} multipliers are to
sector aggregation using four MRIO databases. They developed a common
classification comprising 41 regions and 17 sectors and aggregated the
databases to that level. Overall, significant errors were reported, more
intense when higher is the disaggregation of original data. In addition, some
examples about how bias is passed on the production chain are offered. For
example, similarly to ‘milled grain and flour’ in Indonesia in Steen-Olsen et
al. (2014), remarkable deviations appear in the ‘construction sector’, not
aggregated in their experiment. Cement, a CO\textsubscript{2} intensive input whose effect
is distorted when is grouped with less polluting products, is pointed out to
be the reason.

Work on understanding the uncertainly in material footprint
calculation with MRIO and the resolution in MRIO on material footprint is
in early stages, with a notable recent contribution by de Koening et al. (2015). They compared the EXIOBASE MRIO model most disaggregated version, 200 products by 163 industries, to an aggregated version of 60 by 60, for different raw materials categories and GHG emissions. They report that product and spatial aggregation has a larger effect on material footprints than for carbon footprint. Moreover, at product level, deviations might be of 100% or more, which could limit usefulness of IO in Ew-MFA studies.

Another inherent grouping error to IO is spatial or regional aggregation. In this case, deviations might arise due to dissimilar technologies within a large region such as China (Su and Ang, 2014, 2010), or between countries in worldwide input output models (Andrew et al., 2009; Bouwmeester and Oosterhaven, 2013; de Koning et al., 2015).

Although spatial and sector aggregation biases are related errors and can be the cause of the other (e.g. when linking data from different countries, modelers are forced to collapse industries), spatial aggregation is not discussed further in this paper.

4. The ENVIMAT\textsubscript{2010} model

The ENVIMAT\textsubscript{2010} model presents a structure of detailed EEIO combined with biophysical information from LCA Inventories and other sources. ENVIMAT\textsubscript{2010} shows environmental and economic information of 230 product groups and 147 national industries for year 2010, based on the highest disaggregated public Supply and Use Tables (SUT) (Koskela, Mattila, Antikainen, & Mäenpää, 2013; Mattila, Koskela, Seppälä, & Mäenpää, 2013; Seppälä et al., 2011; Tuusjärvi et al., 2014). It updates the previous version of the model ENVIMAT\textsubscript{2008}, which had an even higher resolution, but confidentiality restrictions have become stricter recently. The environmental extension is represented by satellite accounts of waste emissions, material flows and energy transformation. Finally, to avoid the problems derived from the use of the domestic technology assumption for
goods, a hybrid approach mostly based on the Ecoinvent Database is adopted for the moment (Koskela et al., 2011). On the contrary, for services the domestic technology assumption is followed.

The ENVIMAT$_{2010}$ industry classification is based on the Statistical classification of economic activities in the European Community (NACE) revision (Rev.) 2; while products classification relies on the European Classification of Products by Activity (CPA) version 2008. However, in order to avoid sector aggregation bias, some products and industries have been disaggregated using unpublished data or additional sources. Hereafter, digits correspond to international standard classifications CPA and NACE and the following lower case to the ENVIMAT$_{2010}$ own classification system (full classification in Supporting Information (SI)). Thus, lower case always indicates a product or industry classification, which has been designed to satisfy both confidentiality restrictions and modelling purposes. NACE Rev. 2 and CPA are derived classifications of the International Standard Industrial Classification of all Economic Activities of the United Nations (ISIC) Rev. 4 and Central Product Classification of the United Nations (CPC) Rev. 2, respectively. Therefore, the results presented in this paper are applicable also outside the European Union (EU).

Table 1 illustrates how aggregation bias is prevented in ENVIMAT$_{2010}$. Forestry activities are quite important for the Finnish economy in terms of output but, at the same time, are crucial drivers in material mobilization. A review of the dissimilarity of products and activities within the category informs about possible deviations due to aggregation bias. For example, within ‘021 Silviculture and other forestry activities’, disparate products in material terms are included such as ‘02101a Forest nursery services’ and ‘02103b Pulp wood’. The former, planting new trees to maintain the forestry sector, does not imply any substantial material extraction, whereas the latter is a primary input for the paper industry, which is the main driver in biomass removal in Finland. Aggregation would,
therefore, materialize forest nursery services causing distortions in results. Accordingly, to avoid biased allocation of RM, in the ENVIMAT2010, fine resolution for key forestry products has been adopted. Similar procedures are followed for divisions ‘01 Crop and animal production, hunting and related service activities’; ‘08 Other mining and quarrying’; and ‘35 Electricity, gas, steam and air conditioning supply’.

Table 1.

5. Description of the study

5.1. Aggregation schemes

To study sector aggregation bias in EEIO models, six different aggregation levels have been defined. Firstly, the benchmark scheme closest to a hypothetical reality is called the ‘ENVIMAT Reference Level’, which includes 147 industries and 230 products. The second level is the ‘ENVIMAT 147 by 147 industries’, in which reference products are aggregated to reference industry level. This procedure allows analyzing loss of information when allocation of environmental loads of first usage of goods is not carried out on a product level.

Further, two different aggregation schemes are set at 64-level, in order to study possible consequences of recent changes in EU accounting legislation. The new European System of National and Regional Accounts (ESA 2010), defined in the Annex B of the Council Regulation (EU) No 549/2013 of the European Parliament and of the Council of 21 May 2013, replaces ESA 1995 that has regulated the EU accounting framework until now. This regulation brings in two important changes: Firstly, it advocates the use of NACE Rev. 2 by EU members’ statistics offices, which incorporates noticeable novelties in comparison to the predecessor NACE Rev. 1.1. For instance, economic sectors in NACE Rev. 2 have been reorganized into 88 divisions, while in NACE rev.1.1 only 62 were recognized. Moreover, the aggregation system for the transmission of SUT has changed substantially. In ESA 1995, SUT were required on 60 by 60-
basis, which might be used from single country EEIO to more sophisticated MRIO models, such as the EORA model (see Lenzen, Moran, Kanemoto, & Geschke, 2013). Similarly, in ESA 2010, SUT are requested with dimension 64 by 64. However, what is important for EEIO modeling, and especially for Ew-MFA studies, is that mining sectors are aggregated in ESA 1995 and 2010 in diametrically opposed manners. In ESA 1995, five mining sectors are considered: extraction of coal, lignite and peat; crude petroleum and natural gas; uranium and thorium ores; metal ores; and other mining and quarrying. In contrast, in ESA 2010, the equivalent divisions are now required to be aggregated into a broad ‘Mining and quarrying’ category. While this choice might be sensible in terms of employment or value added, it might jeopardize their utility when studying material flows with EEIO models. Paradoxically, it might contradict official EU recommendations, where the study of material flows using EEIO is explicitly encouraged (e.g. European Environment Agency, 2013). In order to explore what would happen if ESA 2010’s 88 divisions were rearranged keeping the extractive sectors separate, an aggregation level inspired by ESA 1995 has been defined, called ‘Old 64 by 64 industries’ (O-64). The O-64 is based on NACE Rev. 2 and distinguishes 64 sectors, but its defining characteristic is that it implies more mining and quarrying industries and less services. It could be considered a NACE Rev. 2 version of the aggregated scheme utilized in de Koning et al. (2015). In a complementary manner, the other 64 scheme, named ‘New 64 by 64 industries’ (N-64), is based on ESA 2010, in which all the mining sectors are aggregated.

Two more classifications have been added in order to analyze the sector aggregation effects more thoroughly. An aggregation scheme around 40 industries has been set for two reasons: On one hand, on that level sector aggregation deviations for GHG embodied in exports seems to decrease considerably (Su et al., 2010). On the other hand, the MRIO model WIOD (World Input-Output Database) (Timmer, 2012; Timmer et al., 2015),
frequently used in environmental assessments, presents a 35 industries resolution. One hurdle to cross was that WIOD relies on NACE Rev. 1.1, while ENVIMAT uses Rev. 2. Trying to convert ENVIMAT to Rev. 1.1 and then aggregate similar to WIOD would be futile, due to the large differences between the two systems. Therefore, it was decided to design a NACE Rev. 2 scheme inspired by the WIOD classification, which was denominated ‘WIOD 37 by 37 industries’ (W-37). The most interesting features of W-37 are that all biomass extractive sectors are now aggregated together. Finally, the results are presented at 25 industries level as well. This scheme, called ‘Presentation Level 25 by 25’ (P-25), is based on the EORA MRIO model (Lenzen et al., 2013), as this level is used in some cases.

5.2. The framework

The study consists of two complementary tasks for all aggregation schemes, the parallel estimations of RM and GHG emissions for each final use category distinguishing between domestic and imported products. Consequently, the technical coefficients matrix $A$ and total final demand $F$ are split into domestic and imported components, respectively, $A_d$ and $A_m$; and $F_d$ and $F_m$ (henceforth, the subscripts $d$ and $m$ designate products’ origin).

To explain how the ENVIMAT Reference Level (E-RL) is built, the starting points are the SUT. SUT can be transformed to IO tables by using assumptions or additional data. There are four methods to transform SUT to IO tables, each with drawbacks and advantages (EUROSTAT, 2008). In environmental analyses, the choice is dependent mainly upon the goals as well as the kind of data available (Rueda-Cantuche, 2013). In this respect, in the ENVIMAT model, the so-called ‘fixed product sales structure assumption’ is followed. Deviations due to the method chosen are out of the scope of this paper, however, we support the conclusions drawn in Marin et
al. (2012), according to which little differences between the procedures are detected.

To describe the input requirements of products per unit of industry output, the use coefficient matrices for domestic products \( Z_d \) and imports \( Z_m \) can be expressed using equations \( Z_d = U_d \hat{g}^{-1} \) and \( Z_m = U_m \hat{g}^{-1} \), where \( \hat{g} \) denotes total industry output, \( m \) total imports, \( U_d \) the domestic use matrix and \( U_m \) the use matrix of imports. Similarly, the market shares matrix \( D \) which depicts contribution of each industry to products’ output, can be achieved through \( D = S'\hat{q}_d^{-1} \), where \( S \) is the supply matrix and \( q_d \) is total domestic products output. Accordingly, \( A_d \) and \( F_n \) can be obtained using \( A_d = DZ_d \) and \( F_n = DY_d \), where \( Y_d \) is the final use matrix for domestic products. For imports, the picture is more complex, because the limitation, instead of using the Finnish \( D \), it is assumed that foreign industries produce only one product type. In practice, it means that we define an aggregation matrix industry by product \( N \), whose elements are 1 or 0 appropriate placed, in such a manner that \( A_m \) and \( F_m \) can be estimated using \( A_m = NU_m \hat{g}^{-1} \) and \( F_m = NY_m \), where \( Y_m \) is the final use matrix for imports.

In terms of environmental extension, in ENVI MAT environmental information comes from fragmentary sources, therefore, at times it is preferable to build the intensity vector on a product basis and others on industry basis. For this reason, RM intensities are compiled on a product basis, whereas GHG are reported by the Finnish Environment Institute on an industry basis. For domestic products, RM direct coefficients \( p \) are calculated based on multiple national statistics (details in SI). In contrast, for imports a hybrid LCA perspective is adopted; that is to say, coefficients for imports also include environmental loads embodied in products. In order to highlight this method difference, hereafter imports are marked with the Greek alphabet. Thus, \( \beta \) expresses indirect and direct loads...
per euro of product imported. The intensity vector can refer to all RM flows or to some of them (e.g. minerals). Finally, the expression used to estimate RM in E-RL is presented in equation 3, in which the environmental loads are allocated to first users of products on a product basis.

\[ l = (p'Z_d + \delta'Z_m)(I - A_d)^{-1}F_d + p'Y_d + \delta'Y_m \]  

(3)

In order to study loads according to product origin, the latter equation can be split as shown in equation 4 and 5,

\[ l_d = (p'Z_d)(I - A_d)^{-1}F_d + p'Y_d \]  

(4)

\[ l_m = (\delta'Z_m)(I - A_d)^{-1}F_d + \delta'Y_m \]  

(5)

where \( l_d \) and \( l_m \) denote loads for domestic products and imports respectively. Because of different procedures utilized for their estimation, whenever possible, we present separate results for both. In this way, we can also analyze the effects of sector aggregation bias when using hybrid approaches. In contrast to RM, GHG emissions’ allocation to first users is only possible for imported products, since domestic emissions are provided on an industry basis. Hence, E-RL for RM and GHG are different, the latter being closer to ‘ENVIMAT 147 by 147 industries’ (E-147) aggregation scheme.

To transform our E-RL to industry basis E-147, the intensities and final demands need to be converted using equations \( e' = p'\tilde{q}_dN'\tilde{g}^{-1} \) and \( \alpha' = \delta'\tilde{m}N'\tilde{g}^{-1} \). In addition, SUT are aggregated, and their components denoted with a dot superscript. The following are considered: the supply matrix \( \tilde{S} = NS \); the use matrix of domestic products \( \tilde{U}_d = NU_d \); the use matrix of imports \( \tilde{U}_m = NU_m \); the final use matrix of domestic products \( \tilde{Y}_d = NY_d \), the final use matrix of imports \( \tilde{Y}_m = NY_m \); and, lastly, the total supply of products per industry \( \tilde{q}_d = Nq_d \). At this stage, total output per industry \( g \) in E-RL and E-147 is the same. Based on this, the use coefficient matrices can be defined as \( \tilde{Z}_d = U_d\tilde{g}^{-1} \) and \( \tilde{Z}_m = U_m\tilde{g}^{-1} \) and the market
shares matrix as $\hat{D} = \hat{S}' \hat{q}_d^{-1}$ for the E-147 level. In the same way than for E-RL, it is possible to carry out $\hat{A}_d = \hat{D} \hat{Z}_d$ and $\hat{F}_d = \hat{D} \hat{Y}_d$; as well as $\hat{A}_m = \hat{N} \hat{Z}_m$ and $\hat{F}_m = \hat{N} \hat{Y}_m$. Equation 6 summarizes how the environmental loads per final use are estimated at the E-147 level\(^1\).

$$l = (e' + \alpha' A_m) (I - A_d)^{-1} \hat{F}_d + \alpha' \hat{F}_m$$  \hspace{1cm} (6)

For the following aggregate schemes, the procedure is analogous for all. For the sake of simplicity, components of O-64, N-64, W-37 and P-25 are distinguished with an asterisk superscript.

To further aggregate the model, firstly, appropriate aggregation matrices $M$ are designed. Further, the necessary aggregate components are calculated as follows: $U'_d = MNU_d M'$; $U'_m = MNU_m M'$ and $S' = MNSM'$; $Y'_d = MNY_d$; $Y'_m = MNY_m$; $g' = Mg$ and $q_d' = MNq_d$.

Lastly, for environmental intensities it is possible to carry out $e'' = e' \hat{g} M \hat{g}^{-1}$ and $\alpha'' = \alpha' \hat{g} M \hat{g}^{-1}$. The expression used to study loads induced by final users at more aggregated schemes is summarized in equation 7.

$$l' = (e'' + \alpha'' A_m') (I - A_d')^{-1} \hat{F}_d' + \alpha'' \hat{F}_m'$$  \hspace{1cm} (7)

Finally, sector aggregation bias $\tau$ can be defined as the difference in total environmental loads for each final use category, between a given aggregated scheme the reference level, as seen in equation 8. For deviations between E-RL and E-147, $l'$ is substituted with $\hat{l}$.

$$\tau = l' - \hat{l}$$  \hspace{1cm} (8)

Overall, biases can come from two sources: aggregation of IO data and aggregation of environmental information in the intensity vector. In the former case, more dissimilarity between the inputs’ structure of each collapsed industry tend to cause higher biases. In the latter, aggregation of industries that hold dissimilar relationship with the environment can have an

\(^1\) There is no point to keep now on separate products' first users, since considering the power series expansion:

$$l_d = e' \hat{F}_d + e' \hat{F}_d \hat{A}_d + e' \hat{F}_d \hat{A}_d^2 + ... = e' (I - \hat{A}_d)^{-1} \hat{F}_d$$
analogous effect (Lenzen, 2011; Su et al., 2010), which is expected to be more pronounced for those environmental loads, such as raw material extraction, that are spread out unevenly among economic sectors (de Koning et al., 2015). To study this issue, environmental loads are estimated, combining aggregated environmental extensions with disaggregated SUT data, and the effects of aggregated Leontief inverses are combined with reference intensities. For environmental loads, $\bar{e}'' = e''D'MN$; and $\bar{a}'' = a''MN$; can be applied, which represents aggregated intensities rearranged on reference products classification level. Thus, environmental burdens to final uses $\bar{I}''$ can be reattributed as shown in equation 9, in which the reference SUT skeleton is kept unaltered.

$$\bar{I}'' = (\bar{e}''Z_d + \bar{a}''Z_m)(1 - A_d)^{-1}F_d + \bar{e}''Y_d + \bar{a}''Y_m \quad (9)$$

The inverse exercise is also conducted for studying effects of aggregation of industries with different inputs $\bar{I}'$. In this case, the weighting matrix $G = \tilde{g}M\tilde{g}^{-1}$ is used as shown in equation 10 (more details in SI).

$$\bar{I}' = (p'Z_dG + \delta Z_mG)(1 - A'_d)^{-1}F'_d + p'Y_d + \delta Y_m \quad (10)$$

6. Results and discussion

6.1. Comparing RM flows and GHG emissions

Figure 1 compares RM and GHG emissions embodied in final use bundles. At this level of analysis, aggregation causes more distortion in RM than in GHG estimates, in line with outcomes of de Koning et al. (2015). Grouping tends to overestimate RM requirements of private consumption at cost of investments for domestic products, and exports for imported products.
In Figure 2, sector aggregation bias is presented in percentage\(^2\) of the difference between E-RL and each scheme using a heat-map, so the higher the deviation for a given category, the deeper red the corresponding cell is. The bias can be an overestimation or an underestimation which is described by positive and negative values, respectively.

Figure 2.

Looking at these figures, some key messages emerge. Firstly, aggregation bias increases when moving from the reference level to more aggregated schemes, although in different ways and to a different extent, depending on the indicator. Additionally, in more aggregated schemes W-37 and P-25, there are similar deviations despite the significant decrease in the number of sectors. This backs the idea that sector aggregation bias depends on which sectors are aggregated, rather than purely on the number of economic branches, as pointed out in Zhou et al. (2013). Overall, there are no large differences between E-RL and E-147, since the deviations in all cases are below 5%. Therefore, E-147 is a suitable approach when more disaggregated information is not available.

Moreover, the O-64 scheme shows a superior performance in comparison to N-64 when studying RM, whereas these differences are not apparent in GHG emissions. This supports the notion that the new EU accounting framework can be detrimental for EEIO studies focusing on RM.

Figure 3 informs about the source of bias, for schemes O-64, N-64 and W-64 using equation 9 and 10 for RM.

Figure 3.

It is observed that the critical issue is the simplification of material intensities, since averaging them in the semi-aggregated scheme \(I'\) of N-64 and W-37, causes similar errors than in fully aggregated ones. On the other hand, in O-64 dissimilar inputs structure, assessed using semi-aggregated

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\(^2\) Aggregation bias in percentage \(\tau\) (%) is obtained from \(t \cdot I^{-1}\), multiply by 100.
scheme $I^*$, is relatively more important. To shed some light on this issue, a more careful study per RM type is presented in the next section.

Results for GHG are expected, and commented only briefly. In Finland, the main sectors releasing GHG are energy supply (38%), transportation (16%), agriculture (10%) and manufacturing (24%). In E-RL and E-147, energy supply encompass four sectors (electricity, gas, district heating and industrial steam), whereas it is represented by one sector in schemes O-64, N-64, W-37 and P-25. Grouping these four sectors is the main reason for differences observed between E-147 and forward. Notably, domestic consumption tends to be underestimated, when GHG emissions of district heating, one of the most polluting sectors essential due to cold weather are allocated to different users than households. At W-37 and P-25 major relative deviations seen for domestic products are mostly due to aggregation of agriculture and forestry products. Accordingly, GHG emissions from growing crops and farming are passed on forestry, which holds high uses in investments. For imports, aggregation of chemical products with less GHG intensive pharmaceutical ones explains the deviation observed for public consumption. Overall, outcomes for GHG emissions are consistent with the literature (see results for Finland of Bouwmeester and Oosterhaven (2013)). However, finer comparisons are cumbersome because of varying aggregation schemes utilized among studies.

### 6.2. Raw Material Flows in detail

For a more detailed analysis, it is appropriate to distinguish between two broad groups of materials: biomass and minerals, since aggregation bias can affect distinctively according to such division. Figure 4 describes aggregation bias in absolute values (million tonnes, Mt) per final use category and type of RM.

**Figure 4.**
It is observed that grouping can bias even in contrary directions dependent on RM, as seen for investments and exports. The comprehensive nature of Ew-MFA seems to be the root of these divergences as well as its sensitivity to sector aggregation bias when relying on EEIO.

In the following, industries are referred to in two ways: when more precise classification is required, the ENVIMAT/NACE-CPA classification name is given in quotation marks. Alternatively, common synonyms without quoting marks are often used. Further information about the statements outlined below can be found in the SI.

6.2.1. Biomass Flows

There are three key sectors typically responsible for providing biomass to the economy: agriculture, forestry and fishing. Given its relevance, modifications of original ENVIMAT’s forestry classification cause major deviations in biomass flows.

When aggregating from E-RL to E-147, only small deviations appear at final users’ level. In absolute terms, the most remarkable deviations affect domestic products and take place in investments and exports, as seen in Figure 4. In particular, in E-147 biomass embodied in investments is overestimated by 4.9 Mt, whereas exports are underestimated by 5.4 Mt. The main reason is that in E-RL an averaging material intensity for the group ‘021 Silviculture and other forestry activities’ of 14.9 kg/euro is assumed for all products within the category, as Table 1 indicates. This causes for example, that uses in E-147 of ‘02101a Forest nursery services’ are attributed a mass of almost 3.5 Mt. An overestimation in one final use category implies a parallel underestimation in another bundle. In this case, the export-oriented sector ‘171 Manufacture of pulp, paper and paperboard’ is the source of such biomass. The explanation is that reference material
intensity of paper industry’s main input ‘02103b Pulp wood’, is markedly reduced (see Table 1).

In O-64 and N-64, deviations for biomass remain low, although errors in investments and exports are exacerbated, mainly because all forestry activities are aggregated to division level ‘02 Forestry and logging’. The aggregation of these groups, whose material intensities are very low or null, causes an overall reduction of material intensity of other forestry products to 8.3 kg/euro (Table 1). At these levels, overestimations for domestic products in investments are accentuated by 3.6 Mt due to high uses of ‘025 Net growth of forests’, which is assumed immaterial in more disaggregated schemes. As expected, the underestimation mentioned before for the exporting paper industry is at these levels even larger. Finally, aggregation to division ‘01 Crop and animal production, hunting and related services’ also produces an overestimation of biomass embodied in crop products and an underestimation of animal products. Nevertheless, for Finland this deviation is of relatively little importance and is mostly offset within the private consumption bundle.

At levels W-37 and P-25, the aggregation of divisions 01 to 03 into a broad ‘Agriculture, forestry and fishing’ causes significant deviations for Finland. The reason is that aggregation of all biomass extractive sectors increases material intensity for agricultural and fishing products at the expense of forestry products, the biomass intensity of which falls to 4.7 kg/euro. As a consequence, a significant overestimation takes place in private consumption, since households are the major consumers of agricultural and fishing products. In addition, when calculating the biomass embodied in final products via Leontief inverse, this overestimation is also transferred to the food industry, a principal client of the agricultural sector (as it was foreseen in the example of section 3). Table 2 shows changes in domestic biomass multipliers\(^3\) of food products in comparison to those of

\(^3\) In this section the term ‘multiplier’ refers to indirect loads that is, upstream flow of RM.
wood and paper products. Overall, these variations cause that around 5 Mt
are reallocated to private consumption in W-37 and P-25. As well, it can be
recognized that another important compensating decrease happens in ‘682
Renting and operating of own or leased real estate’, which despite being a
service with a low multiplier, has one of the largest shares of domestic final
demand (see $F_5$ in Table 2).

Table 2.

The underestimation is explained by inputs coming from the energy
supply sector. In Finland, ‘02103d Forest chips’ is an important fuel in
electricity generation, district heating and industrial steam. Further,
considering they are produced mainly from the residues of logging
activities, their price is quite low and their intensity high (Table 1).
Underestimation begins at 64 industries level, but it is accentuated at W-37
and P-25, because the forest chips’ material intensity is considerably
reduced (to 4.7 kg/euro). Accordingly, biomass requirements of renting real
estate activities together with private consumption, drop when re-attribution
of loads is carried out. In addition, aggregation to a heterogeneous biomass
extractive sector causes that at these levels, previous deviations in
investments are alleviated (see Figure 4). Lastly, it is worth noting that
similar deviations arise for imported products as well, since Finland imports
considerable amounts of pulp wood along with crop products, especially
fruits.

6.2.2. Mineral Flows

Within this category, three broad groups are studied: fossil fuels,
metals and non-metallic minerals. They are studied together because all are
very sensitive to aggregation of mining sectors; taking into account that they
hold different material intensities and are intended for a variety of purposes.
Non-metallic minerals are primarily domestic, whereas in metals and fossil
fuels imports predominate. The main fossil fuels used to power the Finnish
economy, crude oil, natural gas and coal are all extracted abroad. However, domestic extracted fuel peat plays a notable role as well. For metal ores, the most important product in terms of mass is iron ore, which was also imported in its entirety in 2010. Although the most remarkable deviations for these flows are caused at N-64 level and forward, there are other relevant outcomes to be mentioned.

In E-147, the most important complementary deviations appear in investments and exports for domestic products. Specifically, 3.3 Mt of minerals are transferred from investments to exports, as shown in Figure 4. Construction activities require a significant amount of ‘08121a Gravel, sand and crushed stone’ for making concrete and similar products, which holds a high material intensity (166.5 kg/euro). Nevertheless, at E-147 level, this allocation is done through a broader ‘08b Quarrying of gravel, sand and clay’, the material intensity of which results from averaging goods and services within the category, as indicated in Table 3. This allows biased allocation of material to some exporting industries, main users of the category’s services.

Table 3.

Regarding the O-64 level, noticeable deviations for domestic products take place in investments, exports, and public consumption (see Figure 4); mostly as a result of aggregating ‘08a Mining and quarrying of other minerals’ and ‘08b Quarrying of gravel, sand and clay’. It can be deduced from Table 3 that mineral requirements of users of gravel, sand and crushed stone are at this level even more underestimated, since the product group’s material intensity drops substantially by averaging. Next, this error is passed on along the production chain and as a result, multipliers of ‘41 Construction of buildings’ and ‘42 Civil engineering’ decrease, as shown in Table 4. This explains as well the fall observed in investments in Figure 1 and 4, since buildings are accounted as such ($F_1$ in Table 4). In a similar manner, Table 4 also reveals that lower multipliers in civil engineering and
road and railway maintenance cause a significant distortion, which explains the color intensity observed in government consumption in Figure 2 (deviation of -29.9% from reference level). The other side of the coin is that mineral embodied in exports of some manufacturing increases, notably in the basic chemical industry, the iron industry and the paper industry (see Table 4). The problems described above illustrate why in the ENVIMAT\textsubscript{2010}’s classification system a distinction within other mining and quarrying is considered.

Table 4.

In N-64, W-37 and P-25, all mining sectors (divisions 05-09) are aggregated together into one heterogeneous ‘Mining and quarrying’ category. Table 5 complements Table 3, showing consequences in mining intensities of further aggregation. The effect is that it raises the intensity of those less material intensive mining industries (peat, non-ferrous metals and services) and vice versa. For domestic products, the most noticeable consequences are that construction activities are more underestimated, which exacerbates the decline in RM attributable to investments mentioned previously (observe fall of multipliers for N-64 and W-37 in Table 4). In parallel, RM embodied in exports of metal industries increases, although in a different manner than between N-64 and the two more aggregated schemes. In N-64, mineral requirements are mostly re-allocated to exports of ‘241 Manufacture of basic iron and steel and of ferro-alloys’. In contrast, in W-27 and P-25, due to coarse manufacturing classification, the overestimation is also spread out within ‘25 Manufacture of fabricated metal products, except machinery and equipment’. As a result equal multipliers are obtained (1.86 kg/euro in Table 4).

Table 5.

Moreover, at N-64 and forward bias is especially problematic for imports. In Table 6, aggregated values for minerals embodied per euro of product imported, obtained following a LCA approach, are presented. A
product-industry table as presented for domestic products is not disclosed due to imports data protection issues. Table 6 suggests that grouping causes a rearrangement of material embodied, from metal minerals to fossil fuels. Furthermore, bias is passed on via Leontief inverse causing a reduction of RM embodied in exports of ‘244 Manufacture of basic precious and other non-ferrous metals’, as seen in multipliers in Table 7. Interestingly, bias helps to decrease the multiplier of the basic iron and steel industry to reach almost reference levels. Underestimation in metals is mainly counterweighted by increases in RM allocated in exports of ‘192 Manufacture of refined petroleum products’ (see Table 7). Thus, these two changes are mostly mutually cancelled at final use level. However, because households use a significant amount of petroleum refining products, some metal mineral requirements end up in private consumption.

Table 6.

Finally, inputs of the electricity supply industries (hard coal, natural gas and fuel peat) are also overestimated. Deviations in electricity supply are in turn transmitted to other final use categories, mostly via ‘682 Renting and operating of own or leased real estate’ in private consumption; and public administration, education and human health activities in public consumption (see multipliers and final uses in Table 7).

Table 7.

6.3. Deviations in Ew-MFA’s indicators

Regarding Ew-MFA indicators, Figure 5 shows changes in RMC and RME of exports according to RM type. As expected for an open economy with important manufacturing and extractive sectors, high differences between RME and direct exports appear. Considering the particularities of the Finnish economy, it is not surprising that aggregation bias affects relatively more to RME of biomass flows. For RMC, aggregation bias begins being relevant at W-37 and P-25, causing the variance between RMC and DMC to disappear along with gains of using RME of trade products.
Figure 6 shows changes in RMC and RME of exports, according to product origin. For domestic products, deviations are offset between biomass and minerals flows and as a result, RMC and RME of exports fluctuate slightly. For instance, for W-37, there is an underestimation of Finland’s RMC of domestic products of about 11 Mt. This is because around 21 Mt of mineral flows are underestimated, partially counteracted by 10 Mt biomass overestimation. For imports, the picture is significantly different since, in this case, both flows influence in the same way and RME of exports are remarkably underestimated. Considering the same example again, in W-37 the RMC of imports increased up to 22 Mt, 18 coming from mineral flows and almost 4 from biomass flows. However, because deviations happen in opposite directions for domestic products and imports, overall RMC and RME of exports are not much affected, sharing around 50% each of total RM in all schemes.

Conclusions

In this paper, EEIO’s sector aggregation bias has been studied focusing on raw material (RM) flows using Finland’s data. The results demonstrate that grouping extractive sectors creates significant errors when studying RM, whilst the bias is less significant for GHG emissions. Similar results have been reported by de Koning et al. (2015), which indicated that both reduced material and spatial resolution have a larger effect on material than carbon footprint. Therefore, recent changes in the EU accounting framework —towards aggregation of all mining activities together— would be heading in the wrong direction and will likely be fueling errors in studies based on these data. Similar patterns were observed for domestic products and imports, even when the model’s input data were estimated in a different manner.
Comparing sources of bias, it was shown that what grouping pattern is followed in the RM intensity vector is crucial. Hence, careful attention should be paid to its design when using EEIO models in Ew-MFA. For Finland, particularly problematic is the aggregation of forestry activities with other biomass extractive sectors. This could cause problems in input output models, in which such distinction is not considered. In general, similar errors must be expected in economies with high extractive profiles (e.g. oil exporting countries) coarse categorized in EEIO models. To overcome this situation, examples about how aggregation bias is prevented in the ENVIMAT\textsubscript{2010} model were offered. As a rule of thumb, materials which hold clear distinctive uses and intensities must be considered separately (e.g. sand and gravel from metal minerals).

The bias originates from the aggregation of forestry, agriculture and fishing, and from the aggregation of mining sectors. Also de Koning et al. (2015) found that, worldwide, aggregation bias is highest for agricultural products, and mining and quarrying products. Further, it was found that errors are passed along the whole supply chain via Leontief inverse, affecting estimation on RM embodied in final products. However, consequences of the bias depend upon the level of analysis. At industry level, bias causes important deviations in RM estimates, especially in construction and manufacturing sectors (e.g. food, paper, iron and chemical industries) but also in services with high final demand (e.g. real estate activities, public services). Thus, cross-checking results with bottom-up approaches, such as LCA, is advisable at this level. In contrast, at the macro spheres, deviations are often offset and consequently, not appreciated. Nonetheless, errors can also result in imprecise attribution of environmental loads to final use categories (e.g. biomass of forest products from exports to households), an important issue when discussing mitigation responsibilities or resource management strategies. Lastly, MFA macro indicators (RMC, RMI) are a step further in broadness and, accordingly, less affected by
grouping errors. Only in more aggregated schemes grouping shows
noticeable effects for Finland.

More research will be needed to help EEIO modelers in designing
adequate IO classification schemes. To this effect, studying aggregation bias
in EEIO focusing on other environmental dimensions should be performed.

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### Table 1. Supply, Domestic Extraction and biomass intensity of forestry and logging products for Finland in year 2010

<table>
<thead>
<tr>
<th>Code</th>
<th>Product</th>
<th>Domestic Supply (Million euros)</th>
<th>DE (Million kg)</th>
<th>Biomass intensity (kg/euro)</th>
</tr>
</thead>
<tbody>
<tr>
<td>02101a</td>
<td>Forest nursery services</td>
<td>415</td>
<td>0</td>
<td>0.0</td>
</tr>
<tr>
<td>02103a</td>
<td>Logs</td>
<td>1,014</td>
<td>10,881</td>
<td>10.7</td>
</tr>
<tr>
<td>02103b</td>
<td>Pulp wood</td>
<td>410</td>
<td>15,029</td>
<td>36.6</td>
</tr>
<tr>
<td>02103c</td>
<td>Fuel wood</td>
<td>200</td>
<td>2,905</td>
<td>14.5</td>
</tr>
<tr>
<td>02103d</td>
<td>Forest chips</td>
<td>120</td>
<td>3,498</td>
<td>29.2</td>
</tr>
<tr>
<td>02103e</td>
<td>Other wood in the rough</td>
<td>0</td>
<td>0</td>
<td>0.0</td>
</tr>
<tr>
<td>02103f</td>
<td>Other products incidental to forestry and logging</td>
<td>8</td>
<td>0</td>
<td>0.0</td>
</tr>
<tr>
<td>021</td>
<td>Silviculture and other forestry activities</td>
<td>2,166</td>
<td>32,312</td>
<td>14.9</td>
</tr>
<tr>
<td>022</td>
<td>Logging</td>
<td>903</td>
<td>0</td>
<td>0.0</td>
</tr>
<tr>
<td>023</td>
<td>Gathering of wild growing non-wood products</td>
<td>80</td>
<td>33</td>
<td>0.0</td>
</tr>
<tr>
<td>024</td>
<td>Support services to forestry</td>
<td>404</td>
<td>1,139</td>
<td>0.4</td>
</tr>
<tr>
<td>025</td>
<td>Net growth of forests</td>
<td>460</td>
<td>0</td>
<td>2.8</td>
</tr>
<tr>
<td>02</td>
<td>Forestry and logging</td>
<td>4,013</td>
<td>33,485</td>
<td>8.3</td>
</tr>
</tbody>
</table>

**Code** = product code used in the model. Digits corresponds to CPA version 2008/NACE Rev.2 and the following lower case to the ENVIMAT 2010 own classification system. **DE** = Domestic Extraction.

### Table 2. Multipliers of biomass for food products, forestry products and real estate activities (kg/euro) for Finland in year 2010

<table>
<thead>
<tr>
<th>Code</th>
<th>Sector</th>
<th>E-RL</th>
<th>E-147</th>
<th>O-64</th>
<th>W-37</th>
<th>F_d</th>
<th>F_d</th>
<th>F_d</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>p Z_{A,L}</td>
<td>e A_{L}</td>
<td>e A_{L}</td>
<td>e A_{L}</td>
<td>P _d</td>
<td>P _d</td>
<td>P _d</td>
</tr>
<tr>
<td>101</td>
<td>Processing and preserving of meat and production of meat products</td>
<td>0.66</td>
<td>0.72</td>
<td>0.57</td>
<td>1.38</td>
<td>990</td>
<td>8</td>
<td>194</td>
</tr>
<tr>
<td>105</td>
<td>Manufacture of dairy products</td>
<td>0.90</td>
<td>0.97</td>
<td>0.57</td>
<td>1.38</td>
<td>1,086</td>
<td>-2</td>
<td>494</td>
</tr>
<tr>
<td>107</td>
<td>Manufacture of bakery and farinaceous products</td>
<td>0.15</td>
<td>0.13</td>
<td>0.57</td>
<td>1.38</td>
<td>525</td>
<td>1</td>
<td>100</td>
</tr>
<tr>
<td>108</td>
<td>Manufacture of other food products</td>
<td>0.54</td>
<td>0.27</td>
<td>0.57</td>
<td>1.38</td>
<td>659</td>
<td>7</td>
<td>267</td>
</tr>
<tr>
<td>11-12</td>
<td>Manufacture of beverages, Manufacture of tobacco products</td>
<td>0.25</td>
<td>0.20</td>
<td>0.57</td>
<td>1.38</td>
<td>670</td>
<td>0</td>
<td>203</td>
</tr>
<tr>
<td>161</td>
<td>Sawmilling and planing of wood</td>
<td>3.33</td>
<td>4.71</td>
<td>2.84</td>
<td>1.65</td>
<td>10</td>
<td>3</td>
<td>1184</td>
</tr>
<tr>
<td>162</td>
<td>Manufacture of products of wood, cork, straw and plaiting materials</td>
<td>1.06</td>
<td>1.48</td>
<td>2.84</td>
<td>1.65</td>
<td>10</td>
<td>18</td>
<td>868</td>
</tr>
<tr>
<td>171</td>
<td>Manufacture of pulp, paper and paperboard</td>
<td>1.70</td>
<td>0.91</td>
<td>0.78</td>
<td>0.42</td>
<td>45</td>
<td>72</td>
<td>8455</td>
</tr>
<tr>
<td>172</td>
<td>Manufacture of articles of paper and paperboard</td>
<td>0.53</td>
<td>0.30</td>
<td>0.78</td>
<td>0.42</td>
<td>117</td>
<td>2</td>
<td>286</td>
</tr>
<tr>
<td>682</td>
<td>Renting and operating of own or leased real estate</td>
<td>0.20</td>
<td>0.19</td>
<td>0.13</td>
<td>0.08</td>
<td>23,910</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

**Code** = sector code used in the model. Digits corresponds to NACE Rev.2 and the following lower case to the ENVIMAT 2010 own classification system. **F_d** denotes final consumption expenditure of domestic products (Households + Government), **F_d** exports of domestic products, **L** the Leontief Inverse \( L = (I - A_{L})^{-1} \) and **M€** indicates million euros.

### Table 3. Supply, Domestic Extraction and material intensity of construction minerals for Finland in year 2010

<table>
<thead>
<tr>
<th>Code</th>
<th>Product</th>
<th>Domestic Supply (Million euros)</th>
<th>DE (Million kg)</th>
<th>Material intensity (kg/euro)</th>
</tr>
</thead>
<tbody>
<tr>
<td>08111</td>
<td>Ornamental or building stone</td>
<td>35</td>
<td>611</td>
<td>17.5</td>
</tr>
<tr>
<td>08112</td>
<td>Limestone and gypsum</td>
<td>78</td>
<td>3,970</td>
<td>51.1</td>
</tr>
<tr>
<td>089a</td>
<td>Other mining and quarrying products n.e.c.</td>
<td>260</td>
<td>11,401</td>
<td>43.9</td>
</tr>
<tr>
<td>08a</td>
<td>Mining and quarrying of other minerals</td>
<td>373</td>
<td>15,982</td>
<td>42.9</td>
</tr>
<tr>
<td>0810</td>
<td>Quarrying, sorting, grinding etc. Services of gravel or sand (^{1})</td>
<td>157</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>08121a</td>
<td>Gravel and sand, crushed stone</td>
<td>383</td>
<td>63,818</td>
<td>166.5</td>
</tr>
<tr>
<td>08122</td>
<td>Clays and kaolin</td>
<td>8</td>
<td>20</td>
<td>2.7</td>
</tr>
<tr>
<td>08b</td>
<td>Quarrying of gravel, sand and clay</td>
<td>548</td>
<td>63,838</td>
<td>116.6</td>
</tr>
<tr>
<td>08</td>
<td>Other mining and quarrying</td>
<td>920</td>
<td>79,820</td>
<td>86.8</td>
</tr>
</tbody>
</table>

**Code** = product code used in the model. Digits corresponds to CPA version 2008/NACE Rev.2 and the following lower case to the ENVIMAT 2010 own classification system. \(^{1}\) Classification considered in Statistics Finland. **DE** = Domestic Extraction.
Table 4. Mineral multipliers of construction and selected manufacturing and services (kg/euro) for Finland in year 2010

<table>
<thead>
<tr>
<th>Code</th>
<th>Sector</th>
<th>E-147</th>
<th>O-64</th>
<th>N-64</th>
<th>W-37</th>
<th>F_d</th>
<th>F_e</th>
<th>F_d²</th>
<th>F_e²</th>
</tr>
</thead>
<tbody>
<tr>
<td>171</td>
<td>Manufacture of pulp, paper and paperboard</td>
<td>0.54</td>
<td>0.53</td>
<td>0.77</td>
<td>0.72</td>
<td>0.66</td>
<td>44</td>
<td>72</td>
<td>8,455</td>
</tr>
<tr>
<td>201a</td>
<td>Manufacture of basic chemicals, plastics and synthetic rubber in primary forms</td>
<td>0.89</td>
<td>0.85</td>
<td>2.70</td>
<td>2.09</td>
<td>2.17</td>
<td>54</td>
<td>-62</td>
<td>2,655</td>
</tr>
<tr>
<td>241</td>
<td>Manufacture of basic iron and steel and of ferro-alloys</td>
<td>0.73</td>
<td>0.72</td>
<td>1.84</td>
<td>2.78</td>
<td>1.86</td>
<td>22</td>
<td>156</td>
<td>3,380</td>
</tr>
<tr>
<td>244</td>
<td>Manufacture of basic precious and other non-ferrous metals</td>
<td>3.26</td>
<td>3.45</td>
<td>1.84</td>
<td>2.78</td>
<td>1.86</td>
<td>3</td>
<td>65</td>
<td>2,615</td>
</tr>
<tr>
<td>251</td>
<td>Manufacture of structural metal products</td>
<td>0.30</td>
<td>0.30</td>
<td>0.37</td>
<td>0.48</td>
<td>1.86</td>
<td>18</td>
<td>1</td>
<td>347</td>
</tr>
<tr>
<td>256</td>
<td>Treatment and coating of metals; machining</td>
<td>0.29</td>
<td>0.28</td>
<td>0.37</td>
<td>0.48</td>
<td>1.86</td>
<td>8</td>
<td>75</td>
<td>664</td>
</tr>
<tr>
<td>41</td>
<td>Construction of buildings</td>
<td>2.22</td>
<td>2.03</td>
<td>1.67</td>
<td>1.24</td>
<td>1.30</td>
<td>0</td>
<td>18,633</td>
<td>3</td>
</tr>
<tr>
<td>42</td>
<td>Civil engineering</td>
<td>4.97</td>
<td>4.57</td>
<td>1.67</td>
<td>1.24</td>
<td>1.30</td>
<td>437</td>
<td>3,087</td>
<td>13</td>
</tr>
<tr>
<td>845</td>
<td>Road maintenance</td>
<td>2.03</td>
<td>1.90</td>
<td>0.16</td>
<td>0.17</td>
<td>0.17</td>
<td>451</td>
<td>0</td>
<td>4</td>
</tr>
<tr>
<td>846</td>
<td>Railway maintenance</td>
<td>0.85</td>
<td>0.80</td>
<td>0.16</td>
<td>0.17</td>
<td>0.17</td>
<td>1718</td>
<td>0</td>
<td>4</td>
</tr>
</tbody>
</table>

Code = sector code used in the model. Digits corresponds to NACE Rev. 2 and the following lower case to the ENVIMAT own classification system.

Table 6. Minerals embodied in imports α obtained using LCA

<table>
<thead>
<tr>
<th>Code</th>
<th>Sector</th>
<th>E-147</th>
<th>O-64</th>
<th>N-64</th>
<th>Intermediate Imports (Million euros)</th>
</tr>
</thead>
<tbody>
<tr>
<td>05a</td>
<td>Extraction of fossil fuels</td>
<td>4.1</td>
<td>4.1</td>
<td>9.1</td>
<td>5,975</td>
</tr>
<tr>
<td>07</td>
<td>Mining of metal ores</td>
<td>24.4</td>
<td>24.4</td>
<td>9.1</td>
<td>1,706</td>
</tr>
<tr>
<td>08a</td>
<td>Mining and quarrying of other minerals</td>
<td>48.3</td>
<td>38.8</td>
<td>9.1</td>
<td>73</td>
</tr>
<tr>
<td>08b</td>
<td>Quarrying of gravel, sand and clay</td>
<td>34.0</td>
<td>38.8</td>
<td>9.1</td>
<td>143</td>
</tr>
<tr>
<td>099</td>
<td>Support activities for other mining and quarrying</td>
<td>1.9</td>
<td>1.9</td>
<td>9.1</td>
<td>3</td>
</tr>
</tbody>
</table>

Code = product code used in the model. Digits corresponds to CPA version 2008/NACE Rev.2 and the following lower case to the ENVIMAT own classification system. α obtained following the domestic technology assumption.
<table>
<thead>
<tr>
<th></th>
<th>RM Domestic products</th>
<th></th>
<th>RM Imports</th>
<th></th>
<th>Total RM</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.1 -2.8 8.1 33.7 37.6</td>
<td>-1.6 5.1 22.6 31.1 35.4</td>
<td>-1.0 2.2 17.2 32.0 36.2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Priv.Cons</td>
<td>3.8 -29.9 -25.6 -14.7 -16.8</td>
<td>1.4 9.9 21.6 55.3 51.5</td>
<td>2.7 -11.5 -3.8 17.6 14.8</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pub.Cons</td>
<td>2.6 -11.8 -26.4 -30.0 -30.0</td>
<td>4.6 4.5 4.1 11.2 11.4</td>
<td>3.1 -7.4 -18.1 -18.9 -18.8</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Investments</td>
<td>-3.0 16.4 24.7 16.3 15.0</td>
<td>-0.3 -3.4 -10.6 -17.4 -18.8</td>
<td>-1.3 3.6 1.8 -5.6 -6.9</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Exports</td>
<td>E-147 O-64 N-64 W-37 P-25</td>
<td>E-147 O-64 N-64 W-37 P-25</td>
<td>E-147 O-64 N-64 W-37 P-25</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>GHG Domestic products</td>
<td>GHG Imports</td>
<td>Total GHG</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>---------------</td>
<td>-----------------------</td>
<td>-------------</td>
<td>-----------</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>E−147</td>
<td>0.0</td>
<td>0.4</td>
<td>−0.8</td>
<td>0.1</td>
<td>−1.5</td>
<td>0.4</td>
</tr>
<tr>
<td>O−64</td>
<td>−0.9</td>
<td>−3.8</td>
<td>0.9</td>
<td>1.3</td>
<td>0.5</td>
<td>−2.1</td>
</tr>
<tr>
<td>N−64</td>
<td>−0.8</td>
<td>−3.7</td>
<td>0.3</td>
<td>1.3</td>
<td>−2.5</td>
<td>−2.5</td>
</tr>
<tr>
<td>W−37</td>
<td>−2.6</td>
<td>−1.4</td>
<td>26.3</td>
<td>−2.5</td>
<td>−6.9</td>
<td>−4.6</td>
</tr>
<tr>
<td>P−25</td>
<td>−1.6</td>
<td>−0.9</td>
<td>28.1</td>
<td>−3.8</td>
<td>−8.7</td>
<td></td>
</tr>
</tbody>
</table>

The table shows the values for GHG Domestic products, GHG Imports, and Total GHG, with columns representing different regions or categories (Priv.Cons, Pub.Cons, Investments, Exports) and rows representing different GHG categories (E−147, O−64, N−64, W−37, P−25). The values are color-coded with a legend indicating the percentage change (%).
Direct Material Consumption (DMC)

<table>
<thead>
<tr>
<th>E−RL</th>
<th>E−147</th>
<th>O−64</th>
<th>N−64</th>
<th>W−37</th>
<th>P−25</th>
</tr>
</thead>
<tbody>
<tr>
<td>152.8</td>
<td>149.5</td>
<td>136.8</td>
<td>140.2</td>
<td>149.7</td>
<td>152</td>
</tr>
</tbody>
</table>

Raw Material Consumption (RMC) (Mt)

- **Biomass**
  - E−RL: 25.6
  - E−147: 31.4
  - O−64: 34.7
  - N−64: 34.7
  - W−37: 39.7
  - P−25: 39.9

- **Minerals**
Direct exports 41 Mt
Figure

Click here to download Figure: Figures_High Resolution_bw.pdf
<table>
<thead>
<tr>
<th>Term</th>
<th>RM Domestic products</th>
<th>RM Imports</th>
<th>Total RM</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>E−147 O−64 N−64 W−37 P−25</td>
<td>E−147 O−64 N−64 W−37 P−25</td>
<td>E−147 O−64 N−64 W−37 P−25</td>
</tr>
<tr>
<td>Priv.Cons</td>
<td>0.1 −2.8 8.1 33.7 37.6</td>
<td>−1.6 5.1 22.6 31.1 35.4</td>
<td>−1.0 2.2 17.2 32.0 36.2</td>
</tr>
<tr>
<td>Pub.Cons</td>
<td>3.8 −29.9 −25.6 −14.7 −16.8</td>
<td>1.4 9.9 21.6 55.3 51.5</td>
<td>2.7 −11.5 −3.8 17.6 14.8</td>
</tr>
<tr>
<td>Investments</td>
<td>2.6 −11.8 −26.4 −30.0 −30.0</td>
<td>4.6 4.5 4.1 11.2 11.4</td>
<td>3.1 −7.4 −18.1 −18.9 −18.8</td>
</tr>
<tr>
<td>Exports</td>
<td>−3.0 16.4 24.7 16.3 15.0</td>
<td>−0.3 −3.4 −10.6 −17.4 −18.8</td>
<td>−1.3 3.6 1.8 −5.6 −6.9</td>
</tr>
</tbody>
</table>

$\tau(\%)$
<table>
<thead>
<tr>
<th></th>
<th>GHG Domestic products</th>
<th>GHG Imports</th>
<th>Total GHG</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>E-147</td>
<td>O-64</td>
<td>N-64</td>
</tr>
<tr>
<td>Private Cons</td>
<td>0.0</td>
<td>-0.9</td>
<td>-0.8</td>
</tr>
<tr>
<td>Public Cons</td>
<td>0.4</td>
<td>-3.8</td>
<td>-3.7</td>
</tr>
<tr>
<td>Investments</td>
<td>-0.8</td>
<td>0.9</td>
<td>0.3</td>
</tr>
<tr>
<td>Exports</td>
<td>0.1</td>
<td>1.3</td>
<td>1.3</td>
</tr>
</tbody>
</table>

|                | G−147                  | O−64        | N−64      | W−37      | P−25      |
|                | -3.2                   | 2.2         | 1.0       | 2.3       | 4.5       |
| Public Cons    | 0.4                   | 0.2         | -0.7     | 31.0      | 29.1      |
| Exports        | 1.6                   | -2.0        | -0.8     | -6.9      | -8.7      |

|                | G−147                  | O−64        | N−64      | W−37      | P−25      |
|                | -1.5                   | 0.5         | 0.1       | -0.4      | 1.2       |
| Exports        | 0.4                   | -2.1        | -2.5     | 11.9      | 11.4      |

The color bar represents the percentage change in GHG emissions. The increasing shades of gray indicate a decrease in GHG emissions, while the decreasing shades indicate an increase.
Direct Material Consumption (DMC)

187.8 Mt

Raw Material Consumption (RMC) (Mt)

- E-RL: 152.8 Mt
- E-147: 149.5 Mt
- O-64: 136.8 Mt
- N-64: 140.2 Mt
- W-37: 149.7 Mt
- P-25: 152 Mt

- Biomass
- Minerals

E-RL:
- Biomass: 25.6 Mt
- Minerals: 127.2 Mt

E-147:
- Biomass: 31.4 Mt
- Minerals: 118.1 Mt

O-64:
- Biomass: 34.7 Mt
- Minerals: 102.1 Mt

N-64:
- Biomass: 34.7 Mt
- Minerals: 105.5 Mt

W-37:
- Biomass: 39.7 Mt
- Minerals: 109.9 Mt

P-25:
- Biomass: 39.9 Mt
- Minerals: 112.1 Mt
Direct exports 41 Mt

Raw Material Equivalents (RME) of Exports (Mt)

<table>
<thead>
<tr>
<th></th>
<th>Biomass</th>
<th>Minerals</th>
</tr>
</thead>
<tbody>
<tr>
<td>E-RL</td>
<td>35.2</td>
<td></td>
</tr>
<tr>
<td>E-147</td>
<td>29.4</td>
<td></td>
</tr>
<tr>
<td>O-64</td>
<td>26.1</td>
<td></td>
</tr>
<tr>
<td>N-64</td>
<td>26.1</td>
<td></td>
</tr>
<tr>
<td>W-37</td>
<td>21.1</td>
<td></td>
</tr>
<tr>
<td>P-25</td>
<td>20.9</td>
<td></td>
</tr>
</tbody>
</table>

- E-RL
- E-147
- O-64
- N-64
- W-37
- P-25
Figure 1. RM requirements and GHG emissions embodied per final use category

Figure 2. Sector aggregation bias in percentage $\tau(\%)$

Figure titles
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Figure 3. Total aggregation bias per source of error (schemes O-64, N-64 and W-37)

Figure 4. Total aggregation bias per type of raw material (values appear when bias is over 1.5 Mt)
Figure 5. RMC and RME of exports per type of raw material

Figure 6. RMC and RME of exports according to origin of products (y-axis represents % of Raw Material Input)
Supplementary Material
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