Global Shifts of Greenhouse Gas Emissions and Requirements for Water and Bio-Productive Land: The Case of Norway

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Introduction

The use of various "footprints" to quantify environmental pressures has gained increased attention among sustainability researchers in recent years. Inspired by the communicative success of the "Ecological Footprint" (EF) introduced by Rees (Rees and Wackernagel 1996; Rees 1992; Wackernagel and Rees 1996) around two decades ago, the term has been transferred to assessments of humanity's appropriation of freshwater resources, and more recently to anthropogenic greenhouse gas emissions[1], under the terms "Water Footprint" (WF) (Chapagain and Hoekstra 2004; Hoekstra and Hung 2002) and "Carbon Footprint" (CF) (Hertwich and Peters 2009), respectively.

All three footprints are important measures of sustainability. The EF measures appropriation of biologically productive land, while the WF measures consumption of freshwater – perhaps the two most fundamental resources available to us. The CF measures our need for another capacity of the earth, namely that of assimilating greenhouse gases in order to keep their atmospheric concentrations more or less stable, to prevent anthropogenic climate change.

Common to their methodologies is that they all aim to quantify the total environmental stress of their particular kind, including all indirect and upstream contributions, embodied in consumed products. However, in the case of EF and WF, the calculation of the indirect contributions has often been performed in an unsatisfactory manner. Increasingly complex processing networks means that environmental impacts are in a sense shifted increasingly further away from the consumer, thus obscuring impacts of consumption. Furthermore, given the dominant role of trade in the current global economy, one would expect a significant portion of the footprints of an average consumable to have occurred in another country than that of consumption.

For CF, national accounts have been produced for footprints on a consumption basis by Hertwich and Peters (2009) as well as by Davis and Caldeira (2010). In these studies, multi-regional input-output (MRIO) tables have been applied to properly and comprehensively account for complete supply-chain impacts. EF and WF embodied in trade have so far, to the authors' knowledge, only been estimated for selected products; only a few studies have applied input-output analysis (IOA) to account for EF (Hubacek and Giljum 2003; Lenzen and Murray 2001; Wiedmann et al. 2006) and WF (Lenzen and Foran 2001) of other traded products.

In the present study we unite the prevailing methodologies for CF, WF and EF in a single harmonized modeling framework, founded on a multi-regional input-output model of the global economy. Founding footprint analyses on an MRIO analytical framework allows for complete accounts of footprints embodied in consumption, tracking footprints incurred throughout the supply chain back to primary production. Another significant contribution referring to the field of quantitative

[1] Only the term is new, carbon footprints have in fact been calculated for a long time already, notably within the field of life cycle assessment where it is known as "global warming potential" (GWP).

sustainability assessments is the unification of three unique footprint indicators into a single modeling framework. This allows a more comprehensive assessment of the true environmental sustainability of e.g. alternative policy strategies or the total bill of consumption for a given region, by quantifying sustainability along three separate dimensions within the environmental sustainability sphere.

Methodology

An environmentally extended MRIO model was constructed based on the GTAP 7 database, which describes economic flows for the world disaggregated into 113 countries/regions of 57 economic sectors each recorded for the year 2004, as described by Hawkins et al. (submitted) and Weinzettel et al. (2011). The following few paragraphs outline the analytical foundation of the MRIO methodologies discussed here, based on the equations given by Peters and Solli (2010).

Generally, the input-output balance equation for a region *r* composed of *n* industries consists of an *n*-by-*n* interindustrial flow matrix Z^r, an element z_{ij} of which describes industry *j*'s total purchases from industry *i* over the period, a matrix y^r of total final demand by consumers in region *r*, and a matrix e^r showing total export demand on each of region *r*'s industries (one column for each importing region *s*). In addition, a vector m^r of total imports must be included if Z^r and y^r includes purchases of imported products by industries and final consumers. In that case the balance equation for region *r* is described by

$$x^r = \vec{Z}^r + \vec{y}^r + \vec{e}^r - m^r \tag{1}$$

where x^r is the vector of total industrial output in region *r*, and the arrow represents summation of a matrix across its columns. If imports are removed from Z^r and y^r, so that the rows represent flows of domestically produced goods only, we get

$$x^r = \vec{Z}^{rr} + \vec{y}^{rr} + \vec{e}^r \tag{2}$$

where Z^{rr} and y^{rr} denote industrial and final purchases of domestically produced goods.

From this, the domestic interindustrial requirements matrix A^{rr}, each element a_{ij} of which describes industry *j*'s requirements of domestic product *i* per unit of industry *j*'s output, is estimated by

$$A^{rr} = Z^{rr} \hat{x}^{r^{-1}} \tag{3}$$

where the circumflex ^ denote diagonalization of a vector.

For environmental analysis, a matrix F^r of direct environmental interventions incurred in each industry per unit produced can be derived from a matrix of total interventions in the same fashion:

$$F^r = \overline{F}^r \hat{x}^{r^{-1}} \tag{4}$$

In equation (4), the bar distinguishes the matrix of annual totals from the normalized intensity matrix.

Environmental impacts embodied in international trade can be calculated in different ways within the input-output framework.

Impacts embodied in bilateral trade (BLT) concerns the impacts occurring within a country during the production of goods that are exported rather than consumed domestically. It is evaluated "at the border", so that one may for instance calculate total impacts occurring in Norway, embodied in aluminium produced in Norway and exported to Sweden by observing the flow of Norwegian aluminium across the border, meaning that the subsequent faith of the aluminium is not considered. The aluminium could go to final consumers in Sweden directly, or (more likely) to further processing into new products that might also be exported, perhaps back to Norway for final use there. Using this method, the total impacts f^{rs} occurring in region r to produce goods that are exported to region s are calculated as (Peters and Solli 2010):

$$f_{BLT}^{rs} = F^{r}(I - A^{rr})^{-1} e^{rs} \tag{5}$$

where e^{rs} denote the appropriate column of e^{r}, representing total exports from region r to region s, and I is the n-by-n identity matrix.

Total impacts embodied in exports from region r is then

$$f_{BLT}^{r,\exp} = \sum_{s} f^{rs} , \tag{6}$$

and conversely, total impacts embodied in region r's imports are given by

$$f_{BLT}^{r,imp} = \sum_{s} f^{sr} . \tag{7}$$

For studies that are focused on creating a breakdown of the territorial impacts in a certain country, this might be a useful accounting method. However, since the impact calculation is based on A^{rr}, this also means that any impacts occurring outside of region r due to the production of the goods included in e^{rs} are excluded.

Full MRIO trade impact calculations allow tracking of complete impacts of consumed products. This consumption perspective is more relevant for sustainability sciences and for environmental policy discussions on an international level, because impacts can be allocated to final consumers across national borders. The full MRIO trade analysis is more computationally demanding than impacts embodied in bilateral trade, because it requires information on the destination of the exports included in e^{rs}, that is whether they go to final consumption or further processing in region s, and in the latter case, to which sectors the products go. In other words we need to separate e^{rs} into a flow matrix Z^{rs} giving purchases of industries in region s from industries in region r, and a matrix y^{rs} of purchases of region r's products by final consumers in region s, so that

$$e^{rs} = \vec{Z}^{rs} + \vec{y}^{rs} . \tag{8}$$

With the availability of the matrices Z^{rs}, we then calculate matrices A^{rs} of the import requirements of the industries in region s from the industries in region r per unit of output:

$$A^{rs} = Z^{rs} \hat{x}^{s^{-1}} \tag{9}$$

The complete MRIO balance equation for all *m* regions can now be described by:

$$\begin{bmatrix} x^1 \\ x^2 \\ \vdots \\ x^m \end{bmatrix} = \begin{bmatrix} A^{11} & A^{12} & \cdots & A^{1m} \\ A^{21} & A^{22} & & \\ \vdots & & \ddots & \\ A^{m1} & & & A^{mm} \end{bmatrix} \begin{bmatrix} x^1 \\ x^2 \\ \vdots \\ x^m \end{bmatrix} + \begin{bmatrix} \vec{y}^1 \\ \vec{y}^2 \\ \vdots \\ \vec{y}^m \end{bmatrix} \tag{10}$$

Here, the final term on the right-hand side is a column vector where the first element represents total final demand placed on industry 1 in region 1 by all (domestic as well as foreign) final consumers.

If we denote the global matrices in eq. (10) simply by *x*, *A*, and *y*, so that for the world as a whole,

$$x = Ax + \vec{y}\,, \tag{11}$$

and we similarly define a global impacts matrix *F*, then total global impacts *f* are given by

$$f = F\,(I - A)^{-1}\,\vec{y}\,. \tag{12}$$

Note that the matrix y has dimensions *mn*-by-*m*, i.e. it has one column for each consuming region[2]. By applying the vector $y = imp^r$, which includes only region *r*'s imports, we get the total impacts embodied in the imports of region *r* from all other regions:

$$f_{MRIO}^{r,imp} = F\,(I - A)^{-1}\,imp^r \tag{13}$$

By diagonalizing imp^r in equation (13), we get the impacts broken down on the regions from which the imports were made. This type of result is important if we want to say something about how dependent economy *r* is on resources from other regions. The disadvantage of this method is that the sum of footprints of imports for several regions does not have any practical meaning, since many environmental interventions are calculated multiple times.

Finally, it might be more interesting to researchers within the field of sustainable development to rather consider the imported footprints of consumption for a region *r*; in other words to answer the question: "*In which parts of the world do the various footprints of production to satisfy our domestic consumption occur?*" This result is achieved by a slight modification of equation (13): The complete vector of final demand for region *r* is applied (demand on domestic as well as imported goods), and the impacts intensities vector *F* is disaggregated into a matrix with one row for each environmental intervention occurring in each trading region distinguished.

Footprint indicator descriptions

[2] For clarity only one (total) category of final demand is considered for each region.

The CF was calculated based on the greenhouse gas emission inventories provided in the GTAP 7 database. This includes emissions of fossil CO_2 as well as the most important non-CO_2 greenhouse gases by all regions and sectors. CO_2 emissions for each region were scaled according to emission data reported by the Carbon Dioxide Information Analysis Center (CDIAC), corresponding to the procedure of Davis and Caldeira (2010). Carbon Footprint is measured in kilotons of CO_2-equivalents.

WF quantifies consumption of freshwater, measured in m^3. It is commonly reported in terms of three components: green, blue and grey water. Whereas green and blue water are components of the water used directly by industries or by plants during their growth, grey water is related to water pollution from production processes, by quantifying the water required to dilute pollutants to acceptable concentration levels. For the green and blue water, the WF for a crop is calculated as (Mekonnen and Hoekstra 2010):

$$WF = \frac{CWU}{Y} \tag{14}$$

where *CWU* is the crop water use in m^3 per hectare and *Y* is the crop yield in tons per hectare.

The EF measures human appropriation of biologically productive land measured in "global hectares" rather than actual land use. A global hectare (gha) is defined as the average hectare of all biologically productive land on the earth. Thus the actual area required to produce a certain crop is multiplied first by a *yield factor* to account for the existence of different types of productive land, and secondly by an *equivalence factor* to account for the fact that there can generally be large yield variations from one country to another.

The EF of a produced crop is generally calculated as (Ewing et al. 2010):

$$EF = \frac{P}{Y_N} \times YF \times EQF \tag{15}$$

where *P* is the produced amount in tons, Y_N is the specific national yield for that product, and *YF* and *EQF* are the conversion factors described above.

Footprints embodied in trade for Norway

Table 1 shows Carbon, Ecological and Blue Water footprints associated with Norwegian imports, from three different perspectives. The 112 exporting regions in GTAP are aggregated to five continents. The first column shows footprints embodied in imports from the bilateral trade perspective. Referring to equation (5), an element k in this column shows footprints occurring within region *k* due to production of goods that are exported from region *k* to Norway. The second column shows footprints embodied in imports from the MRIO perspective, see equation (13). Finally, the k^{th} element in the third column shows the total footprints occurring in region *k* because of the total Norwegian final consumption (excluding exports). Hence in the second column it is not distinguished where in the world the footprints occur, while in the first column it is instead not distinguished where the final demand is placed.

	Footprints embodied in Norwegian imports, BLT perspective	Footprints embodied in Norwegian imports, MRIO perspective	Norway's imported footprints of consumption
Carbon Footprint			
Europe	2,7E+04	3,4E+04	2,2E+04
America	8,4E+03	9,4E+03	7,6E+03
Asia	1,2E+04	1,4E+04	1,4E+04
Africa	2,0E+03	2,2E+03	2,3E+03
Oceania	2,9E+02	3,4E+02	4,6E+02
Sum	**4,9E+04**	**5,9E+04**	**4,6E+04**
Ecological Footprint			
Europe	1,5E+07	1,8E+07	1,3E+07
America	3,5E+06	3,8E+06	3,1E+06
Asia	3,8E+06	4,2E+06	4,2E+06
Africa	6,9E+05	7,5E+05	7,9E+05
Oceania	9,4E+04	1,1E+05	1,8E+05
Sum	**2,3E+07**	**2,7E+07**	**2,1E+07**
Blue Water Footprint			
Europe	1,6E+08	2,4E+08	1,4E+08
America	6,7E+07	7,5E+07	6,9E+07
Asia	2,0E+08	2,2E+08	2,3E+08
Africa	3,1E+07	3,4E+07	3,4E+07
Oceania	3,9E+06	4,4E+06	6,2E+06
Sum	**4,7E+08**	**5,8E+08**	**4,8E+08**

Table 1. Footprints associated with Norwegian imports from five aggregated regions of the world, analyzed from three different perspectives. Units are kt CO2-equivalents for CF, gha for EF, and m^3 for WF.

Not surprisingly, Table 1 shows that for CF and EF, Europe is generally the most important trading region for Norway no matter which perspective is taken. For WF, the pattern is a bit different, with Asia playing an equally important role as Europe. Comparing across columns, trends are generally the same for the various perspectives across all footprint types. A notable exception occurs for Oceania, which is a relatively bigger contributor in terms of imported footprints of Norwegian consumption. This suggests that even though the amount of goods exported from Oceania to Norway might be relatively insignificant, the footprints actually occurring in Oceania due to final consumption in Norway are less so. Another notable feature of Table 1 is the higher relevance of Europe in terms of footprints embodied in imports from the MRIO perspective compared to the two other perspectives. This reflects the fact that most of Norway's imports indeed come from other European countries, but at the same time it indicates that the actual footprints are to a high degree incurred outside of Europe.

Comparing the imported footprints associated with Norwegian consumption in the third column of Table 1 to the total footprints of consumption for Norway (see Table 3), we see that 61% of CF, 46%

of EF and 70% of blue WF associated with Norwegian consumption occur outside of Norway, which are all significant numbers.

Table 2 shows corresponding results as Table 1, this time around considering exports from Norway instead. Hence, the first column now shows impacts occurring in Norway due to production of goods that are ultimately exported to each of the five regions, the second column shows total footprints occurring in the whole world due to final demand of Norwegian products by each other region, and the third column shows all footprints occurring in Norway due to each region's total consumptions. Again, it is evident that Europe is by far the most important region across all perspectives, however in this case the same pattern is true also for blue WF. The magnitudes of the values for Europe relative to the sum across all regions are also remarkably similar across all three footprint types and all three analysis perspectives, ranging from 70% to 81%. In other words around three fourths of Norway's exported footprints can be attributed to exports to, as well as final consumption in, other European countries. Furthermore, Table 2 suggests that in terms of footprints associated with exports from Norway, the relative importance of Africa and Oceania is very small, in the order of 1% of the world total.

	Footprints embodied in Norwegian exports, BLT perspective	Footprints embodied in Norwegian exports, MRIO perspective	Norway's exported footprints of consumption
Carbon Footprint			
Europe	2,4E+04	3,4E+04	2,2E+04
America	4,3E+03	5,9E+03	5,6E+03
Asia	2,3E+03	4,2E+03	3,3E+03
Africa	1,2E+02	2,6E+02	4,0E+02
Oceania	5,5E+01	1,3E+02	1,8E+02
Sum	**3,1E+04**	**4,5E+04**	**3,1E+04**
Ecological Footprint			
Europe	2,4E+07	2,8E+07	2,2E+07
America	2,0E+06	2,7E+06	2,7E+06
Asia	3,4E+06	4,2E+06	4,1E+06
Africa	1,7E+05	2,3E+05	3,0E+05
Oceania	5,8E+04	8,8E+04	1,3E+05
Sum	**2,9E+07**	**3,5E+07**	**2,9E+07**
Blue Water Footprint			
Europe	8,2E+07	1,5E+08	7,5E+07
America	1,0E+07	2,1E+07	1,3E+07
Asia	1,1E+07	2,3E+07	1,4E+07
Africa	7,0E+05	1,7E+06	1,3E+06
Oceania	3,8E+05	8,5E+05	6,7E+05
Sum	**1,0E+08**	**2,0E+08**	**1,0E+08**

Table 2. Footprints associated with Norwegian exports to five aggregated regions of the world, analyzed from three different perspectives. Units are kt CO2-equivalents for CF, gha for EF, and m^3 for WF.

When looking at footprints associated with exports, it makes sense to compare the third column of Table 2 with Norway's total territorial footprints in Table 3. The comparison shows that 51% of CF, 54% of EF, and 33% of blue WF occurring within Norway's border is due to final consumption taking place in other countries.

	Carbon Footprint	Ecological Footprint	Blue Water Footprint
Total territorial footprints	6,1E+04	5,4E+07	3,1E+08
Total footprints of consumption	7,6E+04	4,6E+07	6,9E+08

Table 3. Norway's total footprints for the year 2004.

Discussion and conclusion

A couple of comments on the comparability of the three footprints analyzed here are in order. First, since this study concerns virtual flows of environmental impacts between regions of the world associated with trade, it is important to note that ultimate environmental impacts associated with EF and WF are local, whereas the same is not true for CF. In other words the Indians will directly feel the shortage of land and water due to production of the cotton that goes into a shirt purchased in Norway, whereas the potential effects of global warming due to greenhouse gas emissions in the process are spread globally[3]. Nevertheless, the CF is still of interest in this context in relation to climate negotiations; the Kyoto protocol considers territorial emissions regardless of where the final consumption takes place. Secondly, the reader should be aware that the WF is purely a descriptive quantification of the freshwater directly and indirectly consumed in production processes, it does not incorporate any scarcity measure and is as such not in fact an environmental impact measure. Obviously, the environmental consequences of extraction of the same amount of water are different in rainy Norway compared to in arid regions like the Middle East.

The analysis showed three different ways to analyze environmental impacts related to international trade, taking the example of Norway. Since the methods all measure different things, each method also gives a different amount of environmental impacts associated to each of Norway's trading partners. This might lead to one partner looking significantly "worse" compared to the others from one perspective, while it might look relatively better from another; this is why it is so important for analysts to specifically state what question is sought answered and exactly what is measured by the chosen method, because results may ultimately be used in international environmental negotiations.

The results for Norway suggested that for the CF and WF, roughly half of the total footprints of production and consumption for Norway are involved in Norway's exports and imports respectively, whereas for WF, more than two thirds of Norway's WF of consumption were imported while only a third of the WF of production in Norway were exported. Furthermore, Europe is generally quite clearly the most important region in terms of traded footprints. Other than Europe, Asia and America are both relatively important as could be expected.

[3] However, not evenly so

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