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Footprint Family Technical Report: Integration into MRIO model

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Technical Document

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Contents

Executive Summary

A footprint family was defined as a set of consumption based indicators to account for environmental burdens imposed by human society on the environment (Galli et al. 2011), allocating environmental impacts occurring in the production chain to the final use of the products.

National and international trade is increasingly separating consumers and producers, making it difficult to track environmental burdens related to consumption. Therefore, environmentally extended multiregional input-output (MRIO) analysis emerged and is now considered a well-suited tool to deal with indefinite loops of national and international trade (Hertwich and Peters 2010).

The main task of this part of the OPEN:EU project was to create the environmental extensions resulting in a full environmentally extended MRIO model based on the GTAP 7 database, which comprises the entire global economy in 2004, and distinguishes 57 sectors in 113 regions. The environmental extension enables the accounting of Ecological, Carbon and Water footprints. The challenge of this task is to keep the required level of detail for footprint calculations, particularly for Ecological and Water Footprints, since the product and sector resolution of MRIO models is considered as the main limitation of their use for this purpose.

The following report is intended for all researchers and academics as well as others interested in the potentials, limitations and theoretical background of environmentally extended MRIO analysis focusing on Carbon, Ecological and Water Footprints. It should also serve as a basis for the EUREAPA tool, which is built on the described model.

This report contains a detailed description of the integration of the footprint family into an environmentally extended multiregional input-output framework. After a brief introduction of the basics and applications of environmentally extended MRIO models, three different approaches are described for Ecological and Water Footprint integration. The approach of allocating primary products to their users in MRIO model was chosen for implementation within this project and an environmental extension was created based on the documented data sources.

This approach allows us to keep detailed information on international trade of primary crop and forestry products, which is available in international statistics and utilized in Ecological Footprint national accounts as well. Furthermore, specific information on the use of primary crop and forestry products by some MRIO sectors can be utilized, if such information is available. This is currently the case for primary crops used as seed and feed.

The report continues with a description of the use of the model and discusses its limitations, which are mainly the general limitations of input-output analysis.

In the following work, the model will be supplemented by advanced analysis routines such as contributional and structural path analysis. After its testing and verification it will be incorporated into the EURAPA web application.

1. Introduction

A footprint family was defined by Galli et al. (2011) in the technical document for work package 8 of this project. The aim of this set of footprint indicators is to account for environmental pressures induced by consumption in the whole production chains of the consumed products. The consumption perspective is important because it reflects the life-cycle impacts of the alternatives in question. Life-cycle impacts are relevant for decisions ranging from individual purchasing decisions through regional planning to technology adoption. On the national level, footprint indicators are important to reflect the increasing role of the international trade and the current trend in shifting industries into lower developed regions because of cheaper labor.

A multiregional input-output approach which was introduced by Hertwich and Peters (2010) in the technical document for work package 1 of this project is described as a proper tool to account for footprint type indicators, since it allows tracking infinite production chains with country specific data on the production technologies.

Since the footprint family should be used as one set of indicators, it is important to unify the concepts of the individual footprint indicators. The Carbon Footprint has already been implemented in an MRIO framework and the advantages of this concept were discussed elsewhere (Hertwich and Peters 2009b; Davis and Caldeira 2010). Therefore, it is reasonable to integrate all the footprints of the footprint family into a common multiregional input-output framework.

The biggest disadvantage of the MRIO framework is its sector aggregation. Especially Water and Ecological Footprint accounts are based on more detailed data for specific agricultural processes than what is available in the MRIO dataset. The aim of this technical document is to describe how the footprints were integrated into one consistent framework utilizing as much as possible detail from current national footprint accounts.

First, a background on environmentally extended MRIO is given, followed by a summary of the data necessary for footprint integration. Then, all the datasets and their integration into the MRIO framework are described in detail. Finally, the resulting MRIO model with integrated footprints is described.

2. Environmentally extended MRIO for Ecological, Water and Carbon Footprints

2.1. Background on EE-MRIO

The beginnings of input-output analysis (IOA) date back to early attempts to discern the laws governing production, consumption, and the distribution of wealth throughout an economy (Kurz and Salvadori 2000). The framework for modern IOA was developed by Leontief in order to aid in economic planning during and following the Second World War (Kohli 2001; Leontief 1951). He applied this framework to analyze the cost of air pollution abatement (Leontief 1970) during the period the U.S. Clean Air Act (42 USC 7401 1970) was adopted. Soon after, during the energy shortage of the 1970s, IO techniques were applied to connect energy use to consumption (Bullard and Herendeen 1975; Bullard et al. 1978; Casler and Wilbur 1984; Herendeen 1978b; Herendeen 1978a; Hannon et al. 1978). In more recent years models have been developed for calculating environmental impacts along the supply chains of products throughout a national economy (Lave et al. 1995; Hendrickson et al. 1998; Hendrickson et al. 2006; Suh 2003) and the impacts associated with internationally traded products (Wyckoff and Roop 1994; Kondo et al. 1996; Kondo and Moriguchi 1998; Peters et al. 2004; Peters and Hertwich 2006a; Peters and Hertwich 2006b; Weber and Matthews 2007; Weber and Matthews 2008).

Input-output models are made up of matrices describing transactions between actors within an economy. Rows represent product groups while columns represent the industry, government, or household sectors which consume them. Transactions are generally accounted for in monetary values however some IO tables based on mass or energy transactions have been constructed. Many national statistical agencies produce IO tables based on monetary transactions for their countries (USBEA 2008; Statistik Austria ; Statistics Denmark 2003; Statistics Canada 2008; Eurostat 2008; Australian Bureau of Statistics 2008).

Symmetric IO tables can be constructed in two forms: product by product or sector by sector. Product by product IO tables contain monetary transactions between different product groups, while sector by sector IO tables contain monetary transaction among economic sectors. These two types of IO tables are different because some economic sectors produce products different from their characteristic products (by-products).

In order to accurately represent trade flows and the economic structure involved in the production of imported products an IO model combining national-level IO tables through the use of international trade data is required. Such an international MRIO table depicts interdependencies between domestic and foreign sectors with different production technology, resource use and pollution intensities and is seen as a methodological sound approach for the enumeration of environmental impacts from consumption (Wiedmann et al. 2009). Environmentally extended MRIO models are able to assign impacts along the track of international supply chains across several trading partners[1].

[1] See Lenzen et al. (2004) and Munksgaard et al. (2009) for a distinction between uni- and multi-directional trade analysis.

The GTAP database (Burniaux and Truong 2008; GTAP 2007) is currently the most suitable dataset available for a construction of an MRIO model, since it is the only dataset which includes consistent bilateral trade data. GTAP is based on datasets provided by a worldwide network of national dataset providers as well as the UN Commodities Trade Database (UN Statistics 2008) The GRAM MRIO (Giljum et al. 2008) model has been developed based on the harmonized set of IO tables developed by the OECD (Yamano and Ahmad 2006). The EXIOPOL model is a new MRIO based on the Eurostat supply and use tables (Eurostat 2008) and national datasets provided by national statistical institutes for non-European countries (Tukker et al. 2008; Hawkins et al. 2008) developed for the analysis of the international environmental impacts of European policy. A general review of MRIO models used for consumption-based emission and resource accounting is presented in (Wiedmann et al. 2007) and (Wiedmann 2009a).

The IO method has several characteristics which make it particularly well suited for simplified environmental analysis of complex systems. First, IO datasets are freely available from most national statistical offices. This is in contrast with more detailed process-based life cycle inventory data which are costly or time consuming to collect and often unavailable due to proprietary concerns. Once the EEIO model is constructed, it can be quickly applied to analyze the complete supply chain of any final demand (Wiedmann et al. 2006). Second, IO tables cover the entire economy, ensuring a complete allocation of all environmental pressures caused by economic activities (and tracked by the model) to consumption activities.

Input-output analysis has been successfully applied to both Ecological and Water Footprint analyses in numerous studies[2]. It seems logical and consequent to utilize multi-region input-output modeling for Carbon, Ecological and Water Footprint estimates of nations and international trade. Consumption-based MRIO accounting in the form of national Carbon Footprint analysis have already informed discussions in global climate policy about allocation of responsibility (see e.g. (Peters 2008; Peters and Hertwich 2008b, 2008a; Hertwich and Peters 2009b; Zhou and Kojima 2009)).

Footprint indicators take a consumption perspective, meaning that all environmental impacts of any production activity are allocated to final consumers, no matter how far away these impacts might occur and through how many intermediate stages the production and distribution process may proceed. The allocation of indirect impacts is crucial, as we do not just consume food, fuels and materials directly, but also indirectly through the use of manufactured goods and services. An integration of MRIO modeling and footprint accounting is well placed to achieve this goal and provides the following additional advantages:

- Country-specific production factors with full international trade linkage improve the accuracy and comprehensiveness of estimates of footprints embodied in trade (Wiedmann 2009b);
- An MRIO framework is consistent with existing UN Accounting Standards (United Nations 2003), thus helping to develop and streamline footprint accounting standards further;

[2] Key references are (Bicknell et al. 1998); (Lenzen and Murray 2001); (McDonald and Patterson 2004); (Wiedmann et al. 2006); (RPA 2007); (Begum et al. 2009); (Wood and Garnett 2009) for the Ecological Footprint as well as (Lenzen and Foran 2001); (Velázquez 2006); (Guan and Hubacek 2007); (Hubacek et al. 2009); (Zhao et al. 2009) for the Water Footprint.

- Structural Path Analysis (SPA) allows for the investigation of specific international supply chains and is ideally suited to extract and prioritize hot spots of environmental impacts, and to link production with consumption elsewhere (Peters and Hertwich 2006b; Wood and Lenzen 2009);
- Comprehensive economic-environmental input-output model systems are well suited to perform scenario simulations of the environmental and socio-economic effects of implementing environmental policy measures;
- MRIO is also the only practically conceivable method for the comprehensive assessment of activities of multi-national corporations, since these essentially represent a production network spanning multiple sectors in multiple countries.

The IO method also has several drawbacks. The most important drawback of IO models in general is sectoral aggregation, which is of special importance in the case of Ecological and Water Footprints since they are largely determined by the consumption of agricultural products upstream in various production chains. The coarse grouping of products and industries introduces the potential for misrepresentation of an individual product or industry within the broader group (Lenzen 2001; Lenzen and Wachsmann 2004). Such coarse grouping can be the result of including a too wide range of product types, of not distinguishing distinct production processes, or of not adequately distinguishing geographic regions (Williams et al. 2009). A second drawback relevant to the calculation of footprints is the vintage of the IO datasets. For calculation of environmental metrics it is desirable to use very recent data and to update results frequently based on new data. Detailed IO data are generally at least 3 (Eurostat 2009) to 5 (BEA 2008) years old when published. A third commonly cited limitation is the use of monetary data as a proxy for physical flows (Lenzen and Murray 2001; Weisz and Duchin 2006). On the other hand, a monetary allocation approach is also used in the Ecological Footprint methodology and it was also recommended in life cycle assessment by several authors, since "economic relationships reflect the socio-economic demands" (Azapagic and Clift 1999), page 106. In general the economic allocation is better than the physical one, as otherwise waste or low-value byproducts would be allocated a lot of environmental impacts under physical allocation principles. However, in situations where the use of physical flows can overcome the disadvantages resulting from product and sector aggregation, e.g. aggregation of production, transmission and distribution of electricity, a different allocation may be smart. Representing flows in monetary units introduces uncertainties associated with variability in prices over time, between transactions, and between different physical products.

2.2. Environmentally extended input-output analysis – a general concept

An environmentally extended economic input-output (IO) model constitutes a complete inventory of all economic transactions and selected environmental interventions of individual sectors within a specified region during a period of time, most commonly for a country on an annual basis. An environmentally extended IO model is made up of four matrices: the intermediate transactions matrix (Z), the final demand matrix (Y), the value added matrix (W), and the environmental extensions matrix (F_r). Under symmetric input output tables, an economy is modeled as made up from n industries or product groups (depending on the type of the input output table, product by product versus industry by industry), d categories of final consumers, w types of factor inputs, and f types of environmental interventions. Z (n-by-n) is a square matrix where rows represent sales from each of the n industries (products) included in the system, while columns represent each industry's purchases (product's inputs), so that an element z_{ij} gives industry j's total purchases from industry i (and analogously for products within the product by product input-output table). Each column of Y (n-by-d) contains the purchases made by a specific group of final consumers, such as households and government, from each industry (by each product). Y also contains columns for tracking changes in stocks, changes in inventories, capital investments, and exports. Using MRIO instead of a single region IO table does not change anything of the general concept of IOA, with the exception of international trade. Therefore, exports are not part of final demand in MRIO model, but are allocated to the users in other regions, i.e. they are included in Z. Only when exports are used for final consumption in the receiving economy, they are part of the final demand. Entries in Y describe purchases by consumers which do not produce output which re-enters the economy. The rows of W represent labor payments, taxes, subsidies, and operating surplus and the columns represent industries or product groups. For environmental analysis, the W matrix is rarely used. The F_r matrix represents environmental interventions of each economic sector. It has one row for each included kind of intervention, such as CO_2 emissions, energy use and so on, and one column for each industry, such that its columns correspond to the columns of Z. Using these matrices a model can be constructed which allows the calculation of the total economic transactions and environmental interventions occurring along all supply chains associated with the production of a basket of products and services. The following equations are described as for sector by sector IO tables, but apply also for product by product IO tables with corresponding meaning of column and row representation.

The total output (x) from all the industries in the economy over the defined time period can be calculated using Z and y, a column vector of total final demand, equal to the row sum of Y:

(1) $$x = Zi + y$$

where i is a column vector of ones (for the summation of rows across columns of the matrix). Next we define a direct requirements matrix (A):

(2) $$A = Z\hat{x}^{-1}$$

Each element (a_{ij}) of A represents the purchases of product/service (i) required by industry/service sector (j) to produce one unit of its output. Substituting into the previous eq. (1) we obtain the following:

(3) $$x = Ax + y$$

Solving for x yields

(4) $$x^* = (I - A)^{-1} y^*$$

where I is the identity matrix. Note that this equation holds not only for the original x and y but through the Leontief inverse ($L = (I - A)^{-1}$) the total supply chain output (x^*) associated with an arbitrary demand vector (y^*) can be calculated.

A unit environmental extension matrix (F) can be defined as an environmental extension matrix (F_r) per unit of output of each sector:

(5) $$F = F_r \hat{x}^{-1}$$

The F matrix can be used to calculate total environmental interventions associated with an arbitrary final demand of products (y*):

(6) $$E^* = F(I - A)^{-1} y^*$$

Where E* is a vector of total environmental interventions resulting from the whole production phase of the arbitrary product vector y*.

2.3. Environmental extension for footprints

The footprints can be incorporated into an MRIO model through the environmental extension matrix. The methodology for GHG emissions, built up land use, water use, etc. is well established within the IO framework. Therefore, in this section we focus only on Water and Ecological Footprints related to primary crop and forestry products. Primary crop and forestry products refer to non-processed products which are directly harvested. Their direct Ecological and Water Footprints refer to water and land use needed for their growth excluding any up-stream requirements and other environmental interventions. The description of the complete footprints is provided at the end of this section.

Both Water and Ecological Footprints are based on production and consumption of primary crops at a much more detailed level than what is available in the MRIO models. Therefore, the environmental extension matrix should be based on these primary products distinguishing their country of origin with the same level of detail as it is used for standard footprint accounting and which is different from the MRIO system. Therefore we distinguish two systems: the monetary (MRIO) system and the physical (footprint – environmental extension) system. These systems differ regarding detail in primary crop and forestry products classification and country aggregation. The monetary system follows MRIO classification, while the physical system follows the classification required for footprint calculations, in this particular case the FAOSTAT classification system.

There are a few possibilities for how the primary products can be integrated into the F matrix depending on the data availability. In the next sections of this report we present three such possibilities for integration of footprints into an MRIO focusing especially on maintaining the level of detail used in national footprint accounts. The aim is to achieve consistency with standard footprint methodologies under which the footprints are calculated based on detailed data on production of many specific products with the distinction of many regions. The number of products and countries used in Ecological and Water Footprint accounts is generally higher than the detail available in MRIOs. The disaggregation of MRIO is not considered a feasible option for increasing the detail in footprint calculation using MRIO due to extensive data requirements.

When the primary products are included in the environmental extension matrix, they can be converted into footprints using specific conversion factors from the individual footprint methodologies.

2.3.1. APPROACH 1 – ALLOCATION OF PRIMARY PRODUCTS TO PRODUCING SECTORS

The most simplified approach for integrating footprints into an environmental extension matrix is to allocate the footprints of primary products to their producing sectors. The footprints of individual sectors are calculated from primary products produced by individual sectors in a specific country (larger level of detail on producing country can be maintained than what is available in the MRIO model). The footprints (E) of products on the final demand can be calculated by:

(7) $$E = F(I - A)^{-1} y$$

It is possible to increase the level of detail on the final demand side (without any influence on the intermediate transactions) using specific direct footprint data (i.e. direct land and water use) for primary products included in final demand and using the following equation for the calculation of up-stream footprints E_{IND} for all products:

(8) $$E_{IND} = F(I - A)^{-1} Ay$$

The total footprints are the sum of the direct footprints of primary products (calculated directly using specific data from footprint accounts) and the up-stream footprints E_{IND}. The up-stream footprints of primary products are usually neglected in footprint accounts.

The additional multiplication of final demand by matrix A is necessary to avoid double counting of direct footprints of sectors producing primary products. This multiplication translates final demand into purchases of the producing sector, therefore, the direct footprint of the producing sector is left out from this calculation.

This option is preferable in case that no other data on trade of primary products between regions and sectors is available, because it is the simplest method to implement.

2.3.2. APPROACH 2 – ALLOCATION OF PRIMARY PRODUCTS TO THEIR USERS (CONSUMING SECTORS AND FD)

Another option is to utilize additional data on trade of individual primary products available from other statistics and to allocate primary products to their users. This is not equivalent to a disaggregation of the MRIO model, since all the primary products are assumed to be produced by their corresponding (more aggregated) MRIO sectors.

The information about the origin and type of primary product has to be kept in order to calculate the footprints in a proper manner. Two types of information regarding the use of specific primary products by MRIO sectors and regions can be available. The first one comprises international trade of primary products; the second comprises direct use of some primary products by some MRIO sectors, for example for feed and seed, see Figure 1 for better understanding. It is usually not possible to distinguish the country of origin for each particular primary product which is consumed by a specific sector within the consuming country, but the overall composition of supplying countries for each primary product is well distinguished. Since detailed information on the use of all primary products by all individual sectors of the MRIO model is generally not available, the allocation of the rest of primary products to individual sectors within MRIO regions can be done using the appropriate monetary flows within the MRIO model (the monetary flow of the respective product group of the respective region). This is generally done by the Leontief inverse in the previous approach as well, but using the same patterns for all products of one product group. The advantage of this approach is the distinction of the consuming region for individual primary products and utilizing specific data on the use of some primary products such as feed and seed by MRIO sectors. For example, if more primary products are aggregated in one MRIO product group and only one primary product is traded internationally, this detail will be kept by this approach. The distinction in the use of the rest of primary products within the same MRIO product group for intermediate consumption and final demand will not be addressed since its distribution within the same region is based on the monetary flows only.

When the footprints are implemented this way into the F matrix, it is necessary to account separately for direct footprints (E_{DIR}) of primary products included in the final demand (y) and all indirect footprints (E_{IND}) of all products included in the final demand (y) using the following equations[3]:

(9) $$E_{DIR} = F_{DIR} y$$

(10) $$E_{IND} = F(I - A)^{-1} y$$

Where F_{DIR} is a matrix for converting primary products in final demand into their direct footprints. F_{DIR} therefore includes the conversion factors which are used in standard footprint methodologies for converting primary products into footprints. For definition of primary products and footprint methodologies see section 4 of this report. Note that in this case the equation for indirect footprints does not include multiplication of final demand by the A matrix, because the direct footprints are calculated from primary products excluded from the environmental extension (environmental extension is created from the use of primary products, therefore it does not include the use by final demand, which is in contrast to previous approach, where the primary products are allocated to producing sectors, i.e. the products on final demand are included in the environmental extension matrix).

Also this approach can utilize more detailed information about footprints of specific primary products in the final demand. When total footprints of a specific primary product from a specific country should be calculated, the specific information can be used for its direct footprint. Note that this calculation is based on information about physical quantities, while the final demand for a monetary input-output model has to be expressed in monetary units. Therefore, it is necessary to know the prices for these primary products in their specific regions. (In fact the prices have to be known also in the previous approach of footprint integration into an MRIO, when this approach is used.)

The prices can be estimated from different statistical sources and have to be adjusted in the sense that the total final demand of primary products in physical units multiplied with a set of prices is equal to the total final demand in monetary units of the respective product category and region in the MRIO model. This can be achieved by scaling each set of prices for the primary products of the same MRIO product group in a specific region by a scalar factor.

[3] A similar approach is applied in the carbon footprint calculation, where the direct GHG emissions from the use of fossil fuels delivered to final demand are calculated as E_{DIR} and the upstream emissions are calculated as E_{IND}.

2.3.3. APPROACH 3 – UTILIZING SPECIFIC INFORMATION FOR SELECTED SECONDARY PRODUCTS

Water and Ecological Footprint accounts include more detailed information for some secondary products[4]. It is again possible to utilize this more detail data in combination with detailed trade statistics on these secondary products. This approach is the most advanced and also complicated from the methodological point of view, since it is necessary to avoid double counting by additional adjustments. These adjustments are based on a set of assumption which have to be fulfilled: (1) corresponding MRIO product group is completely covered by the secondary products, i.e. the MRIO product group does not include any other products than the secondary products for which more detailed data is available, (2) the more detailed data on footprints of the secondary products cover only the direct consumption of primary products and do not go up-stream in the supply chain.

When these two assumptions are fulfilled it is possible to build upon the previous approach and integrate the secondary products into the F matrix allocating them to their user. In addition to that, the inputs which are used for calculation of footprints of the secondary products have to be subtracted from the use of sectors producing these secondary products. For example, feed used in livestock production is set to zero for the livestock producing sector, when the direct coefficients which are applied for calculation of footprints of the livestock products include this feed. The secondary products are allocated to their user.

The equations for footprint calculation are the same as in the previous approach. It is further possible to distinguish also secondary products on the final demand, which can be useful for scenarios related to food consumption.

2.3.4. SUMMARY OF IMPLEMENTATION OF PRIMARY PRODUCTS INTO ENVIRONMENTAL EXTENSION MATRIX

We have decided to implement the second approach as it most efficiently leads to the desired goal. By choosing this approach, the resulting F matrix would become too large, since the number of primary products is 179, the number of regions which is necessary to distinguish for footprint calculation is 238, and the number of MRIO sectors is 6441. The resulting environmental extension matrix would be of (179 * 238) = 42 602 rows (in order to distinguish all primary products in all producing countries) and 6441 columns (MRIO sectors), which requires too much RAM to be processed on conventional PCs of 2010 with 8 GB RAM. Therefore we created a “physical use matrix” for each of the 238 regions, giving the total use of all primary products produced within this country by each of the 6441 GTAP sectors and 452 GTAP final demand categories.

[4] Secondary products in the terminology of ecological and Water Footprints refer to products derived from primary products by one step of processing or the use of primary products, e.g. livestock products, which use primary products as feed. This meaning of this term is used in the whole section regardless its meaning within an IO framework.

Furthermore, due to calculation aspects (mainly computational time), we converted the physical use matrices into footprints, aggregated the 238 countries into 113 GTAP regions and created one matrix (Fr) of (113 x number of footprints) rows and 6441 columns. It is possible to distinguish the region where the footprints occur (on a level of 113 GTAP regions), but it is not possible to distinguish which primary product is responsible for the footprint. This reduction in detail is acceptable and the reduction in the size of the Fr matrix is sufficient.

The Carbon Footprint is not discussed in such detail as the Ecological and Water Footprints, since the methodology of its implementation into an MRIO model was already developed and has been previously used and discussed by others (Hertwich and Peters 2009a; Davis and Caldeira 2010).

For an overall description of the implementation method for footprints see Figure 1. Converting the use primary crop, forestry and fish products into their direct footprints significantly reduces computation times without influencing the accuracy of the footprints.

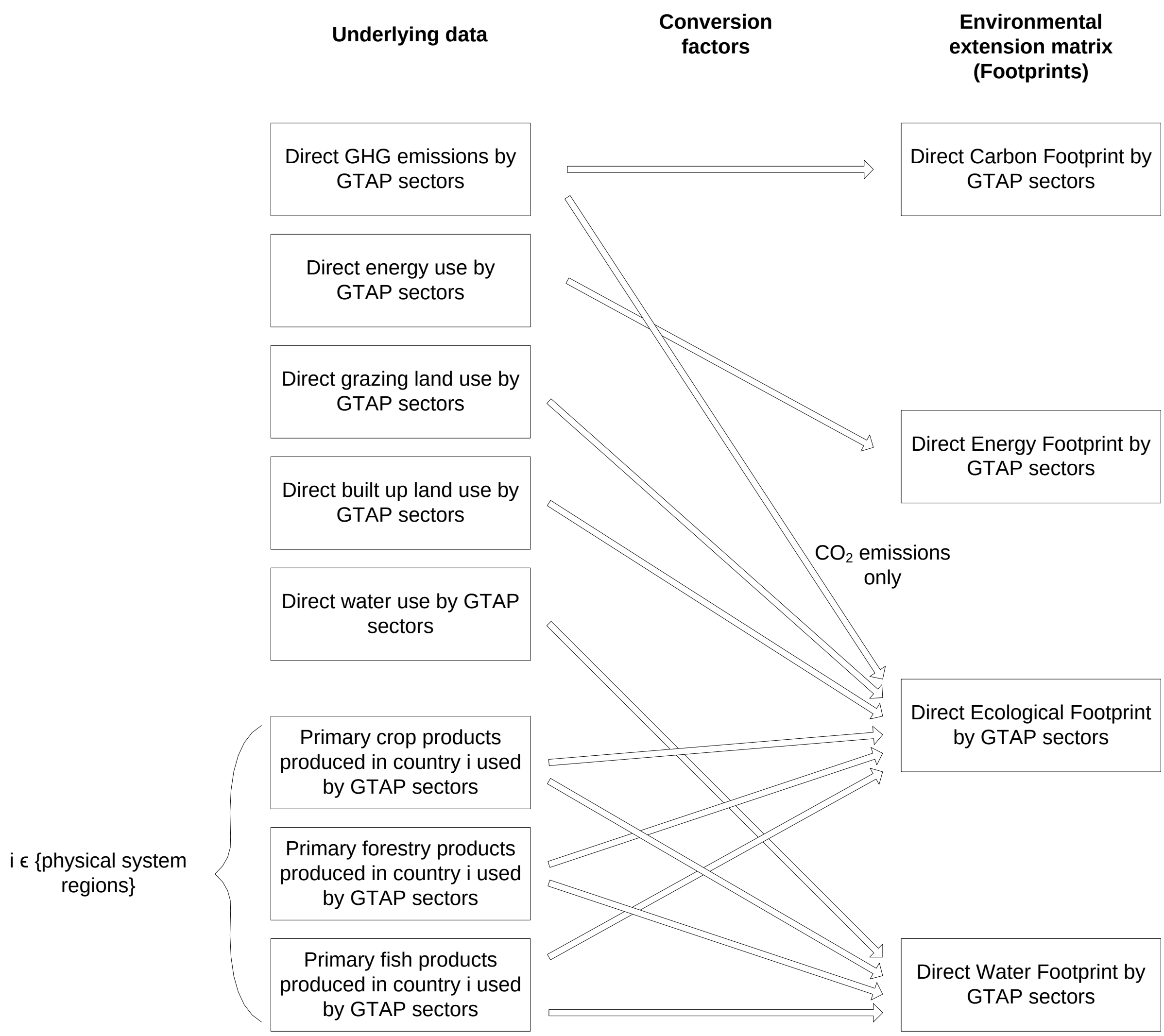

Figure 1: Description of environmental extension (physical system) for footprint calculation (Note that each rectangle represents a matrix which columns are MRIO (GTAP) sectors and rows are elements of the physical system, on the left, and direct footprints on the right).

3. Data requirements for the integration of footprints into MRIO according to the implemented approach

The data for Ecological and Water Footprints are overlapping since both concepts are partly based on the production and consumption of primary products.

It is necessary to have the following datasets:

Ecological Footprint

- Production of primary products by 238 countries and their consumption by GTAP sectors and final demand categories
- Built up area in 238 countries allocated to GTAP users (as explained below)
- Grazed grass consumption by GTAP sectors (no grazed grass is assumed to be consumed by final demand)
- CO_2 emissions by GTAP sectors and final demand categories
- Equivalence factors, i.e. coefficients needed to convert average hectares of specific land types into global hectares – gha)
    - Country specific yields and yield factors for primary crops
    - World average yields for other primary products
    - Coefficients to convert world average hectares of specific land types into global hectares
    - Carbon uptake by oceans
    - Carbon yield for forests

Water Footprint

- Production of primary products by 238 countries and their consumption by GTAP sectors and final demand categories
- Country specific coefficients for conversion of primary products into green, blue and grey Water Footprints
- Direct green, blue and grey water use by individual GTAP users

Carbon Footprint

- All GHG emissions by GTAP sectors and final demand categories

In the next section all the data incorporated into the MRIO model are described in detail.

4. Data integration into MRIO

4.1. Ecological Footprint

4.1.1 OVERVIEW AND GENERAL CALCULATION PROCESS

The Ecological Footprint (Wackernagel et al., 1999a,b; 2002) is a resource and emissions accounting tool measuring both direct and indirect human demand for the planet's regenerative capacity (biocapacity) expressed in units of hectares with global average productive capacity (called *global hectares*). Six main types of demand for bioproductivity are considered, each providing different ecosystem services: 1) cropland for the provision of plant-based food and fibre products; 2) grazing land and cropland for the provision of animal-based food and other animal products; 3) fishing grounds (both marine and inland) for the provision of fish-based food products; 4) forest areas for the provision of timber and other forest products; 5) carbon uptake land for the absorption of anthropogenic carbon dioxide emissions; and 6) built-up area, representing productivity lost due to the occupation of physical space for shelter and other infrastructure. A detailed description of the calculation procedure for each land type can be found in (Kitzes et al. 2009; Ewing et al. 2010; Galli et al. 2011); however a general description can be provided to explain the overall calculation method.

Many basic ecosystem services and ecological resources are provided by surfaces that are limited by physical and planetary constraints. The Ecological Footprint measures these resources and services, and tracks the bioproductive areas required to provide them. Each individual flow can be translated into the correspondent appropriation of bioproductive land area through a multiple-step process, described in the equation below:

(11) $$EF = \frac{P}{Y_N} \times YF \times EQF$$

where P is the amount of a product harvested or CO_2 emitted, Y_N is the national average yield for the product P (or its carbon uptake capacity in cases where P is carbon dioxide), and YF and EQF are the yield and equivalence factors, respectively, for the land use type in question. Yield factors serve the purpose of scaling national to global productivity within a given land use type, while equivalence factors are used to weight the different land use types based on their relative world average bioproductivity (Monfreda et al. 2004; Galli et al. 2007).

As reported by Ewing et al. (2010), for any given land use type L producing only one product, a country's yield factor YF_L, is given by

(12) $$YF_L = \frac{Y_N}{Y_W}$$

where Y_N is the national average yield for the product P (or its absorption/removal rate when P is carbon dioxide) and Y_W is the world average yield for the same product.

Since YF_L is defined as national divided by world yield, the national-average yields cancel out and the basic Ecological Footprint formula reported in (11) can thus be simplified to

(13) $$EF = \frac{P}{Y_W} \times EQF$$

Equation (13) reflects the actual implementation of Ecological Footprint calculations in Global Footprint Network's National Footprint Accounts.

This simplification is mathematically correct only for land types producing one single product (e.g., wood from forest land or grass from pasture land). This is the case for all land types considered in the Ecological Footprint methodology except for cropland. Croplands produce more than one primary product and equation (14) below thus best represents croplands' yield factor calculation.

(14) $$YF_L = \frac{\sum_{i \in U} A_{W,i}}{\sum_{i \in U} A_{N,i}}$$

where U is the set of all usable primary products that cropland yields and $A_{W,i}$ and $A_{N,i}$ are the areas necessary to furnish that country's annually available amount of product i at world and national yields, respectively. These areas are calculated as

(15) $$\mathrm{A}_{\mathrm{N,i}} = \frac{\mathrm{P_i}}{\mathrm{Y_N}} \quad \text{and} \quad \mathrm{A}_{\mathrm{W,i}} = \frac{\mathrm{P_i}}{\mathrm{Y_W}}$$

where P_i is the total national annual growth of product i and Y_N and Y_W are national and world yields, respectively. Thus $A_{N,i}$ is always the area that produces i within a given country, while $A_{W,i}$ gives the equivalent area of world-average land yielding i.

For the cropland footprint calculation, equation (11) should therefore be used rather than the simplified equation (13). However, in order to ensure consistency with Global Footprint Network's National Footprint Accounts, both equations were implemented into MRIO model. Equation (13) is used to check the results against GFN national accounts.

4.1.2. PRIMARY AND DERIVED PRODUCT ALLOCATION

The Ecological Footprint is tallied at the point of primary harvest or waste uptake and as such equation (13) refers to primary products or wastes only. However, tracking the Ecological Footprint embodied in derived products is essential to calculate the footprint of product end uses. To this end, primary and derived products are related by product specific extraction rates. The extraction rate for a derived product, $EXTR_D$, is used to calculate its effective yield as follows:

(16) $$Y_D = Y_P \times EXTR_D$$

where Y_P and Y_D are the yield for the primary product and the effective yield for the derived product, respectively.

Usually, $EXTR_D$ is simply the mass ratio of derived product to primary required input. This ratio is known as the technical conversion factor (FAO 2000a) for the derived product (TCF_D). There are few cases where multiple derived products are created simultaneously from the same primary product and thus the footprint of the primary product should be shared between the simultaneously derived goods to avoid double counting (e.g., soybean oil and soybean cake are both extracted concurrently from the same unit of soybean). The extraction rate for a derived product D is given by

(17) $$EXTR_D = \frac{TCF_D}{FAF_D}$$

where FAF_D is the footprint allocation factor. This allocates the footprint of a primary product between simultaneously derived products according to the TCF-weighted prices. The prices of derived products represent their relative contributions to the incentive for the harvest of the primary product (Kitzes et al. 2009). The equation for the footprint allocation factor of a derived product is:

(18) $$FAF_D = \frac{TCF_D V_D}{\sum TCF_i V_i}$$

where V_i is the market price of each simultaneously derived product. For a production chain with only one derived product, then, FAF_D is 1 and the extraction rate equals the technical conversion factor.

4.1.3. TOTAL ECOLOGICAL FOOTPRINT

By adding up the Ecological Footprint of all products consumed and the CO_2 emissions released by the residents of a nation due to their consumption activities, the final consumption Ecological Footprint of that nation is obtained as reported in the National Footprint Accounts. Consumption Ecological Footprint (EF_C) is calculated by adding to the final footprint value the footprint embedded in locally produced products (EF_P) and in the imported products (EF_I) and subtracting the footprint of exported products (EF_E), as in the equation below:

(19) $$EF_C = EF_P + EF_I - EF_E$$

4.1.4. SOURCE DATA

National Ecological Footprint values are updated and published on an annual basis by Global Footprint Network under the National Footprint Accounts (NFA) programme. More than 200 countries for the period 1961-2007 are currently tracked and approximately 50 million data points are used. Data are based on international datasets published by the United Nations Food and Agriculture Organization (FAOSTAT), United Nations Commodity Trade Statistics Database (UN COMTRADE), International Energy Agency (IEA) and Global Agro-Ecological Zones 2000 (FAO 2000b).

Prior to the calculation of each new edition of the NFA, initial raw data (used to calculate national Ecological Footprint values) are drawn from the above mentioned international statistical databases (see also table below for further details) and stored in an internal database maintained by Global Footprint Network. In calculating each country’s Ecological Footprint, this database is queried for the appropriate country and year values - via custom built data managing software - and the resulting information are organized in approximately 80 interconnected worksheets in a Microsoft Excel workbook; this NFA Excel workbook is subsequently populated for that specific country. Results for each country and each year are then stored back into the internal database and are available for distributions to users upon request.

All starting data used for the National Footprint Accounts calculation can be independently accessed by users, though a subscription might be required. There is no public access to the Global Footprint Network's internally maintained database while National Footprint Accounts Licenses and the most recent National Footprint Accounts calculation files are available for both commercial use and non-commercial review under license[5].

The EE-MRIO model described in this report calculates EF_P values as described above and then derives the Ecological Footprint embedded in imported and exported products (EF_I and EF_E) through the MRIO model. As such, only the raw data and factors used in the calculation of the Ecological Footprint of local productions are described in this section. Please note that the MRIO model described in this report builds on the production data used in the 2010 Edition of the National Footprint Accounts (GFN 2010).

Production statistics for agricultural primary and derived products and live animals as well as forestry and fisheries primary and derived products are obtained from the FAO ProdSTAT, FAO ForesSTAT and FAO FishSTAT Statisical Database, respectively. In the National Footprint Accounts 2010 Edition (GFN 2010), there are production data for 164 crop products, 15 live animals, 33 forest products and 1439 fish products expressed in tonnes produced or harvested per year. Production data are presented in the FAO commodity classifications and HS+ commodity classifications where possible. HS+ is an extended version of HS 2002 created by FAO to provide increased resolution and harmonize the FAO and HS commodity classifications.

It should be noted that under the classical Ecological Footprint methodology, the footprint embedded in the production of animals and livestock products is represented by the amount of regenerative capacity embedded in the various types of feeds and seeds used to feed the animals. The calculation starts with the number of livestock in a country and their feed requirements[6]. These feed requirements are filled through market feed (crops grown specifically to be fed to animals), residues (crop scraps that can be fed to livestock but not to humans), and cropped grasses (grasses that are grown on cropland and cut specifically to be fed to livestock). Once the feed demand satisfied by the above sources has been accounted for, the remaining amount of feed required is assumed to be provided by grazing land (Kitzes et al. 2009).

Yields are based on regeneration rates for all land use types except cropland, whose yields are calculated for each crop using the ratio of crops produced and harvest area. Grazing land yields are the average above-ground net primary production for grassland. Forest yields are calculated using net annual increment of biomass[7]. Fishing grounds yields are calculated for each species as the product of the inverse primary production rate and available primary productivity. The yield for carbon uptake land is calculated

[5] Full information about Ecological Footprint values licensing can be found at http://www.footprintnetwork.org/en/index.php/GFN/page/licenses1/.
[6] Feed requirement values are drawn from Haberl et al., 2007
[7] Net Annual Increment values are calculated as the gross annual increment less that of the natural losses to the growing stock due to natural mortality, disease, etc.

using a weighted-average for the above-ground net biomass growth in natural forest (IPCC 2006) and area (UNECE and FAO 2000) by ecological zone (Kitzes et al. 2009).

Equivalence factors are calculated using the suitability index from the Global Agro-Ecological Zones model (FAO 2000b) along with land cover data from CORINE Land Cover (CLC 1990, 2000, 2006), FAO ResourceSTAT (FAOSTAT), Global Land Cover (GLC 2000), SAGE (Univesity of Wisconsin 1992), and the GAEZ model itself.

The table below details the fundamental sources for data and yields' calculation and details a brief outline of how these are manipulated to give useful and usable data within the National Footprint Accounts.

Label	Dataset	Source	Description	Actual completeness and coverage	Action to achieve required dataset
EF.1	Production of primary agricultural products	FAO ProdSTAT section of the FAOSTAT web-site: http://faostat.fao.org/site/567/default.aspx#ancor	Data on physical quantities (tonnes) of primary products produced in each of the considered countries.	Data are available for almost 229 countries for the period 1961-2009 covering 164 primary crop products. Data coverage and reliability changes depending on the reporting countries.	None
EF.2	Import and Export of primary agricultural products	FAO TradeSTAT section of the FAOSTAT web-site: http://faostat.fao.org/site/535/default.aspx#ancor Detail trade data obtained from Faostat on special request.	Data on physical quantities (tonnes) of products imported and exported by each of the considered countries.	Data are available for almost 229 countries for the period 1961-2008 covering approximately 570 agricultural and livestock products. Data coverage and reliability changes depending on the reporting countries.	None
EF.3	Consumption of seeds	Data on crops used as seeds is calculated by Global Footprint Network based on data from the FAO ProdSTAT section of the FAOSTAT web-site: http://faostat.fao.org/site/567/default.aspx#ancor	Data on physical quantities (tonnes) of seed	Data are available for almost 229 countries for the period 1961-2009. Data coverage and reliability changes depending on the reporting countries.	No adjustments needed.
EF.4	Crop consumption by livestock	This dataset is calculated by GFN by the % feed-mix of crops using market feed supply mapping obtained by GFN; feed demand calculated from the feed efficiency (kg dry matter head^{-1} day^{-1}) (Haberl et al, 2007) and feed intake (tonnes dry matter year^{-1} and finally the total stock of livestock. Based upon the following datasets: - FAO Production for Livestock primary http://faostat.fao.org/site/569/default.aspx	Data on crop-based feed for livestock (tonnes of dry matter per year), split into different crop categories.	Data available for 17 livestock groups and 15 crop categories	None

		- (Haberl et al. 2007)			
EF.5	Production, import and export of primary forestry products	FAO ForeSTAT section of the FAOSTAT website: http://faostat.fao.org/site/630/default.aspx	Data on physical quantities (tonnes and m^3) of products (timber and wood fuel[8]) produced, imported and exported in each country.	Data available for 33 forest products for almost 130 countries over the period 1961-2007. Data coverage and reliability changes depending on the reporting country.	None
EF.6	Production of primary fishery products	FAO FishSTAT section of the FAOSTAT website: http://www.fao.org/fishery/statistics/en	Data on physical quantities (tonnes) of marine and inland fish species landed.	Data are available for 234 countries and territories for the period 1950-2009. Data coverage and reliability changes depending on the reporting countries. 1439 fish products	None
EF.7	Carbon dioxide emissions by sector	Data available directly in the GTAP database (see section on Carbon Footprint for more details)[9].	Data on total amounts of CO_2 emitted by each sector of a country's economy	All sectors	None
EF.8	Built-up/ infrastructure areas	A combination of data sources is used, in the following order of preference: 1. CORINE Land Cover. Data can be accessed at: http://terrestrial.eionet.europa.eu/CLC2000/ 2. FAO ResourceSTAT section of the FAOSTAT web-site. Data can be accessed here: http://faostat.fao.org/site/348/default.aspx 3. Global Agro-Ecological Zones (GAEZ) Model. Data can be accessed at: http://www.fao.org/ag/agl/agll/gaez/index.htm 4. Global Land Cover (GLC) 2000. Data can be accessed at http://www-tem.jrc.it/glc2000/ 5. Global Land Use Database from the Center for Sustainability and the Global Environment (SAGE) at	Built-up areas by infrustructure type and country. Except for data drawn from CORINE, all other data sources only provide total area values.	CORINE Land Cover - available only for Europe, year 1990, 2000, and 2006. FAOSTAT - all countries, all years GAEZ - all countries, year 2000 only GLC - all countries, year 2000 only SAGE - all countries, year 1992 only	Data for missing years are approximated using country-specific population and land area data from FAO and interpolated linearly

[8] In GFN national accounts "wood fuel" is signed as a derived product, but it is treated in the same manner as the primary products in the footprint calculation. Therefore, it is covered under primary products in the MRIO model.
[9] This is in contrast to GFN national account, which uses data on CO_2 emissions provided by International Energy Agency (http://www.iea.org/stats/index.asp).

		University of Wisconsin. Data can be accessed here: http://www.sage.wisc.edu:16080/iamdata/			
EF.9	Cropland yields	Data drawn directly from FAO ProdSTAT section of FAOSTAT web-site: http://faostat.fao.org/site/567/default.aspx#ancor	World average yield for 164 primary crop products	Data is available for the period 1961-2009.	None
EF.10	National yield factors for cropland	Calculated by Global Footprint Network based on cropland yields and Country specific un-harvested percentages.	Country specific yield factors for cropland	All countries	None
EF.11	Grazing land yields	Chad Monfreda (personal communication). 2008. SAGE, University of Wisconsin, Madison.	World average yield for grass production. It represents the average above-ground edible net primary production for grassland available for consumption by ruminants.	A single world average yield for grass production is available.	None
EF.12	Fish yields	Calculated by Global Footprint Network based on several data including: • Sustainable catch value (Gulland 1971) • Trophic levels of fish species (Froese and Pauly 2008) Data can be accessed here: http://www.fishbase.org • Data on discard factors, efficiency transfer, and carbon content of fish per tonne wet weight (Pauly and Christensen 1995).	World-average yields for fish species. They are based on the annual marine primary production equivalent.	Yields calculated for 1439 fish species for the 1961-2007 period.	An estimate of global total sustainable catch is converted to primary production equivalent, and this is divided by global total continental shelf areas to obtain an estimate of available primary production (see (Kitzes et al. 2009; Ewing et al. 2010) for an in-depth description).
EF.13	Forest yields	World average forest yield calculated by Global Footprint Network based on national Net Annual Increment (NAI) of biomass. NAI data is drawn from two sources: Temperate and Boreal Forest Resource Assessment – TBFRA (UNECE and FAO 2000). Data can be accessed here: http://www.unece.org/trade/timber/fra/welcome.htm Global Fiber Supply Model – GFSM (FAO 1998). Data can be accessed here:	World average forest yield. It is based on the forests' Net Annual Increment of biomass. NAI is defined as the average annual volume over a given reference period of gross increment less that of neutral losses on all trees to a minimum diameter of 0 cm (d.b.h.).	TBFRA – data available for 55 countries. GFSM – data available for 67 countries.	Word-average forest yield value is calculated as weighted average of national values. Minor estimates are required for missing countries as reported by Ewing et al. (2010)

		http://www.fao.org/docrep/006/x0105e/x0105e00.htm			
EF.14	Carbon Uptake land yield	Calculated by Global Footprint Network based on data on terrestrial carbon sequestration (IPCC 2006) and the ocean sequestration percentage (IPCC 2001). Further details can be found in (Kitzes et al. 2009), page 69.	World average carbon uptake capacity. Though different ecosystems have the capacity to sequester CO_2, carbon uptake land is currently assumed to be forest land only by the Ecological Footprint methodology.	A single world-average value is available.	Calculated as the weighted-average sequestration potential of world forests (IPCC 2006) by ecological zones, adjusted for the fraction of emissions sequestered by oceans.
EF.15	Equivalence Factors (EQF)	Calculated by Global Footprint Network based on data on land cover and agricultural suitability. Data on agricultural suitability is obtained from Global Agro-Ecological Zones (GAEZ). FAO and International Institute for Applied Systems Analysis 2000. http://www.fao.org/ag/agl/agll/gaez/index.htm. Land cover data are drawn from the ResourceSTAT section of the FAOSTAT website. Data can be accessed here: http://faostat.fao.org/site/377/default.aspx#ancor	EQF for crop, grazing, forest and marine land. Based upon the suitability of land as measured by the Global Agro-Ecological Zones model (FAO 2000b).	Equivalence factors are available for each land type tracked by the Ecological Footprint methodology, for the period 1961-2007.	GAEZ evaluates the biophysical limitations and potential for crop production using global terrain, soil and climate data. The results from GAEZ are utilized along with land cover data for crops, pasture and forest areas.

4.1.5. DATA INTEGRATION

Production of primary agricultural products (PP) (dataset EF.1) is used to calculate domestic consumption of domestically produced PP by subtracting the exported PP (dataset EF.2). The consumption of imported PP is given by imports derived from detail trade data including information about the country of origin. A part of the produced PP is first allocated to sectors according to data on seed (dataset EF.3) and feed (dataset EF.4) consumption. The use of the remaining PP by other MRIO users is estimated using the sales structure of the corresponding MRIO sector in the GTAP database.

Production and trade data of primary forestry and fuel wood products (dataset EF.5) are used in a similar way as PP, but there is no information on any specific use of these products by MRIO users. Therefore, only the trade data is utilized for distribution across countries. The allocation to MRIO users is only based on monetary flows of the respective products.

Production of primary fishery products (dataset EF.6) is allocated to consuming MRIO sectors according to the sales structure of the fisheries sectors in GTAP. No external data on trade or specific consumption was utilized for the fish products.

Carbon dioxide emissions data (dataset EF.7) is directly available in the GTAP database.

Built-up land[10] (dataset EF.8) is allocated to MRIO sectors and households based on several assumptions[11]: (1) *Continuous urban fabric* is split between households (50 %) and services (50 %). The allocation within service sectors is based on total output of these sectors. (2) *Discontinuous urban fabric* is allocated to households. (3) *Industrial or commercial units* built-up land is allocated to MRIO sectors excluding mining, transport and service sectors. (4) *Road and rail networks and associated land* is allocated to the 'Transport nec' sector. (5) *Port areas* built-up land is allocated to the 'Water transport' sector. (6) *Airports* built-up land is allocated to the 'Air transport' sector. (7*) Mineral extraction sites* land is allocated to mining sectors. (8) 50 % of *dump sites* land is allocated to households, the rest is allocated to all sectors. (9) *Construction sites* land is allocated to the 'Construction' sector. (10) *Green urban areas* land is allocated to households. (11) *Sport and leisure facilities* built-up land is allocated to recreational and other services sector.

Cropland yields (dataset EF.9) and equivalence factors (dataset EF.15) are used for construction of conversion factors of PP into footprints. Similarly, national yield factors (dataset EF. 10), grazing land yields (dataset EF.11), fish yields (dataset EF.12), forest yields (dataset EF.13) and carbon uptake land yield (dataset EF.14) are used for construction of conversion factors into footprints for built-up land, grazing land, marine land, forest land, and carbon uptake land, respectively.

[10] Note that built-up land has a very minor role for the total footprints. It contributes less than 5 % to total EF. Therefore, the allocation to MRIO sectors and households is a rough estimate.
[11] When the land is allocated to more sectors, it is always based on total output of these sectors.

4.2. Water Footprint

4.2.1. WATER FOOTPRINT OF PRIMARY CROPS

Water Footprint estimations (green, blue and grey) of primary crops are taken from the study by (Mekonnen and Hoekstra 2010). The green, blue and grey Water Footprints of primary crops are estimated in a spatially-explicit way. Calculations are done by taking a high-resolution approach, estimating the Water Footprint of the crops at a 5 by 5 arc minute grid.

The green and blue Water Footprint of a crop (WFcrop, m3/ton) is calculated as the green or blue component in crop water use (CWUi, m3/ha) divided by the crop yield (Y, ton/ha) where i indicates the component of Water Footprint, green and blue.

(20) $$WF_{proc,i} = \frac{CWU_i}{Y}$$

The green and blue components of crop water use (CWU, m3/ha) are calculated by accumulation of daily evapotranspiration (ET, mm/day) over the complete growing period:

(21) $$CWU_i = 10 \times \sum_{d=1}^{\mathrm{lgp}} ET_{i,d}$$

Where ETi,d represents evapotranspiration by type, i, either green or blue and by day, d. The factor 10 is used to convert mm into m3/ha. The summation is done over the period from the day of planting, d=1, for the entire length of growing period (lgp) until harvest.

The grey Water Footprint of a primary crop (WFcrop,grey, m3/ton) is calculated as the chemical application rate per hectare (AR, kg/ha) times the leaching rate (α) divided by the maximum acceptable minus the natural concentration for the pollutant considered (cmax – cnat, kg/m3) and the crop yield (Y, ton/ha).

(22) $$WF_{proc,grey} = \frac{(\alpha \times AR)/(c_{\max} - c_{nat})}{Y}$$

Grey water footprints are measured based on the (human-induced) loads that enter into freshwater bodies, not on the basis of the loads that can finally be measured in the river or groundwater flow at some downstream point. Since water quality evolves over time and in the course of the water flow as a result of natural processes, the load of a certain chemical at a downstream point can be distinctly different from the sum of the loads that once entered the stream (upstream). The choice to measure the grey water footprint at the point where pollutants enter the ground- or surface water system has the advantage that it is relatively simple – because one does not need to model the processes that change water quality along the river – and safe – because water quality may improve along the flow of a river by decay processes, but it is unclear why one should take improved water quality downstream as an indicator instead of measuring the immediate impact of a load at the point where it enters the system. While the grey water footprint indicator thus does not account for natural processes that may improve water quality along the water flow, it does also not account for processes that consider the combined effect of pollutants, which may sometimes be greater than what one may expect on the basis of the concentrations of chemicals when considered separately. In the end, the grey water footprint strongly depends on ambient water quality standards (maximum acceptable concentrations), which is reasonable given the fact that such standards are set based on the best available knowledge about the possible harmful effects of chemicals including their possible interaction with other chemicals."

The following section describes the data used for the calculation of Water Footprint of primary crops.

4.2.2 CROP WATER USE

In the model developed by Mekonen and Hoekstra (2010), a grid-based dynamic water balance model is used to calculate crop water use over time, with a time step of one day. The model takes into account the daily soil water balance and climatic conditions for each grid cell.

Monthly long-term average reference evapotranspiration data at 10 by 10 arc minute resolution were obtained from FAO (2008b). The 10 by 10 arc minute data were converted to 5 by 5 arc minute resolution by assigning the 10 by 10 minute data to each of the four 5 by 5 minute grid cells. Monthly values for precipitation, number of wet days and minimum and maximum temperature for the period 1996-2002 with a spatial resolution of 30 by 30 arc minute were obtained from CRU-TS-2.1 (Mitchell and Jones 2005). The 30 by 30 arc minute data were assigned to each of the thirty-six 5 by 5 arc minute grid cells contained in the 30 by 30 arc minute grid cell. Daily precipitation values were generated from the monthly average values using the CRU-dGen daily weather generator model (Schuol and Abbaspour 2007). Crop growing areas on a 5 by 5 arc minute grid cell resolution were obtained from Monfreda et al. (2008). For countries missing grid data in Monfreda et al. (2008), the MICRA2000 grid database as described in (Portmann et al. 2010) was used to fill the gap. The harvested crop areas as available in grid format were aggregated to a national level and scaled to fit national average crop harvest areas for the period 1996-2005 obtained from FAO (2008b).

Grid data on the irrigated fraction of harvested crop areas for 24 major crops were obtained from the MICRA2000 database (Portmann et al. 2010). For the other 102 crops considered, the data for 'other perennial' and 'other annual crops' as in the MICRA2000 database, depending on whether the crop is categorised under 'perennial' or 'annual' crops is used. Crop coefficients (Kc's) for crops were obtained from (Chapagain and Hoekstra 2004). Crop planting dates and lengths of cropping seasons were obtained from (Sacks et al. 2010; FAO 2008a; Portmann et al. 2010; USDA 1994). For some crops, values from Chapagain and Hoekstra (2004) were used. Grid-based data on total available water capacity of the soil (TAWC) at a 5 by 5 arc minute resolution were taken from ISRIC-WISE (Batjes 2006). An average value of TAWC of the five soil layers was used in the model.

4.2.3. CHEMICAL APPLICATION RATE AND LEACHING RATE

Country-specific nitrogen fertilizer application rates by crop have been estimated based on Heffer (2009), FAO (2006, 2009) and IFA (2009). Since grid-based fertilizer application rates are not available, it is assumed that crops receive the same amount of nitrogen fertilizer per hectare in all grid cells in a country.

4.2.4. WATER FOOTPRINT OF OTHER SECTORS

The Water Footprint of industrial products and industrial sectors can be calculated in a similar way as described for agricultural products. However, there are a high number of industrial products and production categories and statistics related to production for each sector and related water consumption data is difficult to find. In addition industrial products show a relatively high heterogeneity and different production methods for the same kind of product. Thus, a simplified approach is used for the estimation of the green, blue and grey Water Footprint of industrial sectors.

The blue Water Footprint of each industrial sector i (WFi , m3/year) is estimated as:

(23) $$WF_{blue,i} = WW_i \times CF_i$$

Here WWi is the industrial water withdrawal (m3/yr) for the industrial sector i in a country, while CFi is consumption coefficient for the each industrial sector.

The grey component of the Water Footprint for each industrial sector is estimated as:

(24) $$WF_{grey,i} = WW_i \times (1 - CF_i) \times DF_i$$

Where WWi is the industrial water withdrawal (m3/yr) for the industrial sector i in a country.

Blue Water Footprint of industry sector is estimated based on statistical data on water withdrawal from national statistical offices, Eurostat database (Eurostat 2010), Aquastat database (FAOSTAT 2010). Australian industrial water withdrawal values for the year 2000 are taken from Australian Bureau of Statistics, Water Accounts 2000-2001 (ABS 2004). Estimated use of water for industrial sectors for USA is taken from U.S. Geological Survey Circular 1268 (USA 2004). Data for Canadian water use is obtained from Statistics Canada (StatCan, 2005). For European Union member countries, candidate countries, EFTA and Balkan countries, industrial water data is obtain from Eurostat statistical database for the year 2000 (Eurostat 2010). Industrial water use data are taken from Aquastat database (FAOSTAT 2010).

Blue Water Footprint for each industry sectors is estimated by multiplying water withdrawal with consumption coefficients. Consumption coefficients for each industrial sector are estimated based on the studies of Shiklomanov (2000) and Vassalo and Doll (2005).

Label	Type of data required	Availability (yes/no) and completeness	Data source	Time	Sector disaggregation	Regional completeness	Actions to achieve required dataset	Implications of actions and unavailable data
WF.a	Blue Water Footprint of primary crops	Yes, complete	(Mekonnen and Hoekstra 2010)	Average of 1996-2005	146 primary crops (FAO codes)	209 countries	as described in the text	
WF.b	Green Water Footprint of primary crops	Yes, complete	(Mekonnen and Hoekstra 2010)	Average of 1996-2005	146 primary crops (FAO codes)	209 countries	as described in the text	
WF.c	Grey Water Footprint of primary crops	Yes, complete	(Mekonnen and Hoekstra 2010)	Average of 1996-2005	146 primary crops (FAO codes)	209 countries	as described in the text	
WF.d	Water Footprint of forestry	Yes, only partly available	(van Oel et al. 2009)	Average of 1996-2005	Total Water Footprint of forestry by biomass	23 major wood producing countries	none	
WF.e	Direct Water Footprint of other sectors	Yes, partly available	National Water Statistics, Eurostat (2010), FAOSTAT (2010)	2004 for most of the countries, closest year is taken where no data is available for 2004	Except for the data from national statistical offices (USA, Australia, and Canada) and Eurostat, only one aggregated value is available	Complete dataset except: Taiwan, Hong Kong, Luxembourg, Croatia,	none	Only one single aggregated value for most of the countries. The disaggregated data per country is not available. Further improvement can be done working country by country.

4.2.5. DATA INTEGRATION

Characterization matrices were created from the Water Footprint intensities (datasets WF.a, WF.b and WF.c) to convert primary crops produced in individual countries into their Water Footprints. World average Water Footprint intensities were used for the countries were no specific data was available. The primary crops consumed by individual GTAP sector were translated into Water Footprints using the characterization matrices.

Direct Water Footprints of other sectors (dataset WF.e) were disaggregated into GTAP sectors according to the total turnover of the sectors, resulting in equal direct Water Footprint intensities per monetary output. World average values were used for countries with no data available.

Since the Water Footprint intensities are not available for specific wood and forestry products, the total Water Footprint of forestry sectors (dataset WF.d) were allocated to forestry sectors in individual countries. World average Water Footprint intensities of monetary output of forestry sectors were used for the countries were no data was available. The Water Footprint of primary forestry and wood products comprises only the green Water Footprint (no irrigation is assumed).

4.3. Carbon Footprint

4.3.1 DEFINITION AND DATA REQUIREMENTS

The concept of Carbon Footprint is described in detail by (Galli et al. 2011) in an OPEN:EU technical document for work package 8. The Carbon Footprint comprises all anthropogenic greenhouse gases (GHG) which are directly or indirectly released during an activity or use of a product and accumulated over the life stages of a product or a set of products. The Carbon Footprint of a nation refers to Carbon Footprint of all products consumed by the nation.

An MRIO framework was applied by (Hertwich and Peters 2009a) to calculate the Carbon Footprint of nations, and by (Davis and Caldeira 2010) to account for CO_2 emissions embodied in international trade. Expressing Carbon Footprint of nations using MRIO framework requires the following datasets:

- Direct GHG emissions released by individual economic sectors in all countries
- GHG emissions released in the use phase of products purchased by households and government (final demand)

GHG emissions should include all emissions which are considered to contribute to anthropogenic climate change (except for water vapors (steam)). The following GHGs are included in the Kyoto protocol (UN 1998) and therefore should be included in the Carbon Footprint: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulphur hexafluoride (SF_6). Emissions of these GHGs are converted into a common unit using widely accepted coefficients (usually into kg of CO_2-equivalents (CO_2-eq.) using coefficients provided by IPCC for global warming potential over a 100 year perspective – commonly referred to as GWP100).

All anthropogenic sources of GHG emissions should be considered, e.g. direct emissions from fossil fuel combustion processes, process CO_2 emission not related to combustion, GHG emissions related to land use change and GHG emissions related to livestock[12]. These emissions have to be allocated to the economic sectors which are responsible for them. GHG emissions related to combustion of fossil fuels and process non-fossil fuels emissions are allocated to sectors which emit them. GHG emissions from livestock are usually allocated to agriculture (livestock production).

A different situation may occur when there is no connection between the driving sector and the sector which runs the activity leading to the emissions, e.g. the forestry sector changes the land cover and provides the land for agriculture. The forestry sector is a supplier of the land but there are usually no monetary flows, since the forestry sector has revenues from the wood it extracts. This case requires special attention to the fact that the forestry sector is not the driver for the land use change but rather a provider of the land use change. In this particular case, monetary flows within the MRIO model do not serve for re-allocation of emissions from land use change from forestry sector to agriculture sector. Therefore, emissions from land use change have to be properly allocated to the driving sector (agriculture in the previous example). For the future, we need a better understanding of what drives deforestation and land use changes in important regions in the world.

All life cycle stages of products should be included in the Carbon Footprint. All production phases are included due to the use of an MRIO model. A core part of any input-output model is the "Leontief inverse" matrix, which accounts for all processes connected through monetary transactions. The use phase is accounted for using a separate matrix converting final demand into the resulting emissions. The end-of-life treatment is not accounted for single products and has to be considered separately by additional demand of decommissioning and waste treatment activities. In the calculation of national footprints the end-of-life stage is included, since it is part of the economy and waste treatment is purchased either by final consumers or by other economic sectors.

In this analysis CO_2 emissions from biomass are considered climate neutral and therefore they are not included in the Carbon Footprint. This assumption is currently under revision in the scientific community and in future it will most likely be adjusted in order to reflect the contributions of biogenic CO_2 to climate change.

4.3.2 DATA AVAILABILITY

The GTAP database includes CO_2 emissions from fossil fuel combustion and non-CO_2 GHG emissions, both disaggregated by GTAP sectors and regions; see Table A 1and Table A 2 for the list of GTAP sectors and regions. CO_2 emissions are further disaggregated according to fossil fuels. This is used for estimating CO_2 emissions from products purchased for final consumption, and it allows for the disaggregation of the Carbon Footprint according to contributing fossil fuels, which is expected to be useful for scenario modeling.

The CO_2 emissions available in the GTAP database do not correspond to other data sources on CO_2 emissions and do not include CO_2 emissions from several sources, such

[12] Note that these are ideal data requirements and not all of it is available; see next section on the data actually included in the model.

as cement production and bunker fuels. Therefore we utilized data provided by Carbon Dioxide Information Analysis Center (CDIAC) to adjust total national CO_2 emissions from fossil fuels as proposed by Davis and Caldeira (2010). Furthermore, we included non energy CO_2 emissions from cement production and gas flaring.

The non-CO_2 emissions available in GTAP database cover emissions of gases listed in Table 1. These emissions are disaggregated according to drivers such as energy use, land use, fertilizer, and capital. This disaggregation of non-CO_2 GHG is not expected to be used in the MRIO model and therefore the emissions are aggregated over the drivers. The units used within the model are kt of CO_2-eq calculated using GWP100 characterization factors.

Table 1: Non-CO2 greenhouse gases included in the database and their 100-year global warming potential (GWP100), (IPCC 1996; Rose and Lee 2008).

Gas	**GWP**
Carbon dioxide (CO_2)	1
Methane (CH_4)	21
Nitrous oxide (N_2O)	310
HFC-23	11 700
HFC-32	650
HFC-125	2 800
HFC-134a	1 300
HFC-143a	3 800
HFC-152a	140
HFC-227ea	2 900
HFC-236ea	2 900
HFC-236fa	6 300
HFC-4310mee	1 300
CF_4	6 500
C_2F_6	9 200
C_4F_{10}	7 000
C_6F_{16}	7 400
SF_6	23 900

The data included in the GTAP database is documented within the GTAP documentation (Rose and Lee 2008; Lee 2008).

Non-fossil CO_2 emissions are not available in the GTAP database.

4.3.3. MISSING DATA AND ITS CONSEQUENCES

The CO_2 emissions related to “bunker fuels” and land use and land use change and forestry (LULUCF) are missing in this analysis. The overall error introduced by the lack of this data is estimated to be less than 20 % of the total GHG emissions (Solomon et al. 2007; Bernstein et al. 2007). If better GHG or just CO_2 emissions data become available in future, it is possible to adjust the MRIO model accordingly. The actual accuracy of the

EE-MRIO model is discussed in the final report for work package 3 of the OPEN:EU project.

5. Model specifications, description and use

5.1. Model overview

The general concept of the environmentally extended MRIO model (EE-MRIOM) which has been created as a basis for the EUREAPA tool is explained in previous sections of this report. This part of the report is focused on the summary of the main characteristics of this model and the description of its use.

The EE-MRIOM is based on the GTAP 7 data base and therefore adopts the main characteristics of this data base, which are listed in Table 2.

Table 2: GTAP 7 and EE-MRIOM main characteristics.

Monetary system		**Physical system**	
Base year	2004	Base year	2004
Units	Million USD (year 2004)	Units	Metric tonnes, m^3, number
Number of regions	113	Number of countries	238
Number of sectors (products)	57	Number of primary crop products	159
		Number of primary forestry products	15
		Number of primary fish products	1702

The detailed lists of regions and sectors (products) are presented in Table A 1, Table A 2, Table A 3 and Table A **2**4in the appendix of this report.

An environmental extension (EE) matrix was created in addition to the MRIO model according to the method described in a previous section of this report. The environmental extension matrix (F) consists of Carbon Footprint (CF), Energy Footprint (NF), Ecological Footprint (EF), and Water Footprint (WF). The detailed list of elements in the environmental extension matrix is presented in

Table **3**.

Table 3: List of impact categories in the environmental extension matrix.

Row	Impact category	Unit in F matrix (current version)
1	**CF total**	kt CO_2-eq. / million USD
2	CF CO_2 non fossil (not included)	kt CO_2-eq. / million USD
3	CF N_2O	kt CO_2-eq. / million USD
4	CF CH_4	kt CO_2-eq. / million USD
5	CF Fgas	kt CO_2-eq. / million USD
6	CF coal combustion	kt CO_2-eq. / million USD
7	CF oil combustion	kt CO_2-eq. / million USD
8	CF gas combustion	kt CO_2-eq. / million USD
9	CF petroleum products combustion	kt CO_2-eq. / million USD
10	CF electricity use (generally equals to zero)	kt CO_2-eq. / million USD
11	CF manufactured gas combustion	kt CO_2-eq. / million USD
12	**NF total (of primary fossil energy)**	Mt of oil eq. / million USD
13	NF coal	Mt of oil eq. / million USD
14	NF oil	Mt of oil eq. / million USD
15	NF gas	Mt of oil eq. / million USD
16	NF petroleum products	Mt of oil eq. / million USD
17	NF electricity	Mt of oil eq. / million USD
18	NF manufactured gas	Mt of oil eq. / million USD
19	**EF total**	gha / million USD
20	EF crop land	gha / million USD
21	EF grazing land	gha / million USD
22	EF forest	gha / million USD
23	EF marine	gha / million USD
24	EF carbon	gha / million USD
25	EF built-up	gha / million USD
26	**WF total**	m^3 / million USD
27	WF green	m^3 / million USD
28	WF blue	m^3 / million USD
29	WF grey	m^3 / million USD
30	EF carbon coal	gha / million USD
31	EF carbon oil	gha / million USD
32	EF carbon gas	gha / million USD
33	EF carbon petroleum products	gha / million USD
34	EF carbon electricity	gha / million USD
35	EF carbon manufactured gas	gha / million USD
36	EF crop land country GFN simplified method	gha / million USD

Carbon Footprint of CO_2 emissions released from non-combustible processes is not included in the current version of the model, but the EE is prepared to cover it. The EE was extended beyond the scope of the EUREAPA tool through the Energy Footprint. The CO_2 part of Carbon Footprint and the carbon uptake part of the Ecological Footprint are presented disaggregated according to the use of energy carriers (mainly fossil fuels). These two details are included in order to enable modeling of the scenarios of the transition from fossil fuels towards biofuels. The list of energy carriers is presented in Table 4.

Table 4 Energy products provided by GTAP.

1	Coal
2	Oil
3	Gas
4	Petroleum products
5	Electricity
6	Manufactured gas

5.2. Capabilities (functions) of the model

The model was constructed to be capable of calculating the desired footprints of products specified in monetary units. Products are either the 57 GTAP product groups or the primary products directly. The footprints of individual products depend on the origin of products. Regarding final demand expressed in monetary units, 113 GTAP regions are distinguished, and regarding footprints of primary products, 238 UN countries of origin are distinguished. It was also desirable to enable specification of the final demand directly on the producing country, which enables arbitrary shifts in production site independently of the current trade patterns regarding the products on the final demand. Furthermore, the option of specifying the final demand on the physical and monetary systems at the same time was enabled. All in all, then, there are six different ways of defining the final demand (physical, monetary and mixed unit for both producing and consuming region). Therefore, it is possible to utilize the level of detail in footprints of primary products.

It was also considered that the region where the footprints occur might be of interest; hence the F matrix was created in two forms: (a) aggregated form for fast calculation not distinguishing country of origin of the footprint (denoted as matrix F, of 36 rows and 6441 columns) and (b) in a disaggregated version according to GTAP regions of the occurrence of the footprint (denoted as Flarge, which has 4 068 = 36 (number of impact categories) * 113 (GTAP regions) rows and 6 441 = 57 (GTAP sectors) * 113 (GTAP regions) columns.

Therefore, it is possible to distinguish exactly where in the world the footprints of consumption occur, thus enabling an analysis of the footprints embodied in trade in order to serve the final demand.

5.3. Components of the EE-MRIOM

The model consists of three main parts:

- Transformation of final demand
- Calculation of direct footprints

- Calculation of indirect footprints

In the first part (transformation of final demand) the input final demand is transformed into the shape required for the calculation of direct and indirect footprints. This process includes: calculation of primary products included in the final demand distinguishing country of origin of the primary product; transformation of the final demand from consumption perspective into output of individual GTAP regions and sectors. The resulting dimensions of the final demand are 6 441 = 113 (GTAP regions) * 57 (GTAP sectors) rows and 113 (GTAP regions) columns. The dimensions of primary products included in the final demand are 42 602= 179 (primary products) * 238 (UN countries) rows and 113 (GTAP regions) columns. The calculation of Ecological Footprint related to direct consumption of fish species is much more complicated due to number of fish species. Therefore, a matrix was created which translates monetary final demand directly to marine Ecological Footprint.

In the second step the direct footprints (matrix E_{DIR}) are calculated using the F_{hh} matrix and a set of coefficients (C matrix) for conversion of primary products into footprints:

$E_{DIR} = F_{hh} * y_m + C * y_p + F_{hhbuiltup}$

Where y_m and y_p are final demand in monetary and physical units respectively and $F_{hhbuiltup}$ is the direct land use by households, which is not allocated to consumption of any product. Matrix F_{hh} is described in detail in previous section of this report. It consists of direct footprints resulting from the use of products on the final demand, expressed per unit of final demand of the respective products group.

The third part of the model consists of the calculation of indirect footprints (E_{IND}) using EE and the Leontief inverse matrix:

$E_{IND} = F \, . \, (I - A)^{-1} . \, y_m$

Note that all products in the final demand are included in the monetary final demand y_m.

5.4. Use of the model

The whole model is written in a Matlab environment using Matlab scripts and pre-calculated data files. Since Matlab is not considered suitable for input of the analyzed data and to present the results, Excel files are used as data interface for the model, i.e. the input data are read from Excel files and the results are saved into another Excel file. Two Matlab scripts were created to run the model. First, a general script "analysis.m" was written to analyze user defined final demands. Second, a custom script "national_footprints.m" was written to deal specifically with the calculation of national footprints. Both scripts call other scripts and functions which they share together. To be able to run the scripts, it is important that all files are stored in the correct folder structure.

The main difference in these scripts is that while national_footprints.m reads the final demand from the GTAP database, analysis.m reads user specified final demand. Furthermore, the advanced analysis routines implemented by NTNU are implemented only in analysis.m. The detailed description of the advanced analysis routines is provided within the technical report for work package 3 of this project.

The model will be used to pre-calculate results for the EUREAPA web application.

5.5. Limitations and recommendations

The general limitations of this model reflect the limitations of all input-output analyses, such as aggregation of the producing companies into economic sectors and specific products into product groups. Therefore, the average technology of the respective country is applied on the whole sector and product group.

Another main limitation of this model is its focus on flows. This model is based on flows within one year. Therefore it can only be used to calculate flows induced by consumption of products with an approximate timeframe of one year. This means that the creation of the capital which is needed for production is not considered. In any scenario, this model will only show the flows under certain conditions which are assumed, e.g. if the infrastructure is created, how the flows would look, but it will not cover the creation of the infrastructure. The limited result provided by this model is still valuable, since it can provide information whether it makes sense to create the infrastructure or how much of certain infrastructure should be created.

Another issue is the interpretation of the results. There is one issue in particular related to the EF and CF. Since EF also covers carbon emissions it hardly changes at all when analyzing a transition from fossil fuels to bio-fuels, while CF is considerable reduced. Therefore, when these indicators are presented together, it appears that switching from fossil fuels to biomass is an improvement, since one indicator is not changed and the other is improved. Such an interpretation is logical, but misleading, since the decrease in carbon emissions is accounted twice, once as a reduction of CF, but also as a reduction of carbon uptake part of the EF, which would otherwise increase significantly. Therefore, the EF is almost not affected, because of its broader scope. In this case the EF tells directly that there is a shift from one type of environmental burden towards the other. Therefore, the conclusions derived from the development of these indicators should be rather based on careful assessment of individual indicators and not from their overall performance.

This model is focused on the situation in one particular year (2004). The use of this model for estimating flows in different years requires some assumptions regarding the trade patterns and production technology. The possibility to create yearly specific models for wider time span is limited by the availability of data for multiregional input-output analysis.

6. Discussion and Outlook

Due to the increasingly important role of international trade, environmentally extended MRIO models are appropriate for calculation of national Ecological, Carbon and Water Footprints. The challenge is to keep the required level of detail in the underlying data for Ecological and Water Footprints while integrating the footprints into the environmental extension of the MRIO model. Three different approaches based on footprints of primary crops are discussed in this report. The chosen one which was implemented within work package 2 of this project is based on the allocation of primary products to the users – the MRIO sectors and final demand categories.

This approach enables the keeping of detailed information on international trade of primary crops which is available in international statistics and utilized in Ecological Footprint national accounts as well. Furthermore, specific information on the use of primary products by some MRIO users can be utilized, if such information is available. This is currently the case for primary crops used as seed and feed.

The environmentally extended MRIO model was constructed based on the data for the year 2004, based on the GTAP database, which includes 57 sectors in 113 regions and covers the entire global economy. The environmental extension for Ecological, Carbon and Water Footprints is based on consumption of primary products, direct GHG emissions and water and land use.

The uncertainty of the underlying data is unknown. Data in international statistics are sometimes conflicting and do not match. Therefore additional adjustments had to be done, sacrificing some specific data spots. This is the case mainly for information on the use of primary crops as feed. The overall national footprints should correspond to national accounts based on different methodologies at least from the territorial perspective (footprint of production). In the next work package (WP3) the environmentally extended MRIO model will be tested and validated.

In work package 4 the model will be used to pre-calculate results for the EUREAPA web application and in work package 5 it will be used for scenario analysis. The limitations of input-output analysis stem from the fact that an input-output model is a snap shot of an economy over one year. Input-output models are not intended for predictions, but for understanding the current or the modeled situation. The relations within the economy, such as production functions, have fixed parameters unless being changed exogenously, e.g. while modeling scenarios. The other parameters of the MRIO model do not respond to this change. Therefore, the modeling of a given scenario is based on the exogenous change of certain variables, while all other parameters which are not changed exogenously, are assumed to remain constant. Static, demand-pull input-output models do not have endogenous mechanisms for shifting inputs required to produce an output as a result of, e.g., changing prices. Such shifts are less important on a very product-specific level, but more important for economies on the aggregate. This type of modeling is helpful to understand the role of individual parameters of the model, but it cannot serve for predicting future developments.

Another important limitation of this environmentally extended MRIO model is the exogenous treatment of capital. Investments are treated as a final consumption, and depreciation of capital is treated as a part of value added. The resulting implication is that this model cannot provide impacts due to investments which are necessary to get into the state described by scenarios, but it assumes that these investments have occurred in the past. Some analyses have included approximations for replacing the capital required to produce a given output using capital formation in different sectors and depreciation to estimate the input requirements to hold each sector's capital stock at a steady state (Lenzen and Treloar 2004; Peters and Hertwich 2006a). It is still valuable to analyze the system under the modeled scenarios since it is important to see whether the investment can make any change, and how the contributions of different changes interact.

7. Appendix

Table A 1: Table A1 MRIO sectors (products) (https://www.gtap.agecon.purdue.edu/databases/v7/v7_sectors.asp).

1	'Paddy rice'
2	'Wheat'
3	'Cereal grains nec'
4	'Vegetables, fruit, nuts'
5	'Oil seeds'
6	'Sugar cane, sugar beet'
7	'Plant-based fibers'
8	'Crops nec'
9	'Bovine cattle, sheep and goats, horses'
10	'Animal products nec'
11	'Raw milk'
12	'Wool, silk-worm cocoons'
13	'Forestry'
14	'Fishing'
15	'Coal'
16	'Oil'
17	'Gas'
18	'Minerals nec'
19	'Bovine meat products'
20	'Meat products nec'
21	'Vegetable oils and fats'
22	'Dairy products'
23	'Processed rice'
24	'Sugar'
25	'Food products nec'
26	'Beverages and tobacco products'
27	'Textiles'
28	'Wearing apparel'
29	'Leather products'
30	'Wood products'
31	'Paper products, publishing'
32	'Petroleum, coal products'
33	'Chemical, rubber, plastic products'
34	'Mineral products nec'
35	'Ferrous metals'
36	'Metals nec'
37	'Metal products'

38	'Motor vehicles and parts'
39	'Transport equipment nec'
40	'Electronic equipment'
41	'Machinery and equipment nec'
42	'Manufactures nec'
43	'Electricity'
44	'Gas manufacture, distribution'
45	'Water'
46	'Construction'
47	'Trade'
48	'Transport nec'
49	'Water transport'
50	'Air transport'
51	'Communication'
52	'Financial services nec'
53	'Insurance'
54	'Business services nec'
55	'Recreational and other services'
56	'Public Administration, Defense, Education, Health'
57	'Dwellings'

Table A 2: MRIO (GTAP) regions (https://www.gtap.agecon.purdue.edu/databases/regions.asp?Version=7.211).

1	Australia
2	New Zealand
3	Rest of Oceania
4	China
5	Hong Kong
6	Japan
7	Korea
8	Taiwan
9	Rest of East Asia
10	Cambodia
11	Indonesia
12	Lao People's Democratic Republic
13	Myanmar
14	Malaysia
15	Philippines
16	Singapore
17	Thailand
18	Vietnam

19	Rest of Southeast Asia
20	Bangladesh
21	India
22	Pakistan
23	Sri Lanka
24	Rest of South Asia
25	Canada
26	United States of America
27	Mexico
28	Rest of North America
29	Argentina
30	Bolivia
31	Brazil
32	Chile
33	Colombia
34	Ecuador
35	Paraguay
36	Peru
37	Uruguay
38	Venezuela
39	Rest of South America
40	Costa Rica
41	Guatemala
42	Nicaragua
43	Panama
44	Rest of Central America
45	Caribbean
46	Austria
47	Belgium
48	Cyprus
49	Czech Republic
50	Denmark
51	Estonia
52	Finland
53	France
54	Germany
55	Greece
56	Hungary
57	Ireland
58	Italy
59	Latvia
60	Lithuania

61	Luxembourg
62	Malta
63	Netherlands
64	Poland
65	Portugal
66	Slovakia
67	Slovenia
68	Spain
69	Sweden
70	United Kingdom
71	Switzerland
72	Norway
73	Rest of EFTA
74	Albania
75	Bulgaria
76	Belarus
77	Croatia
78	Romania
79	Russian Federation
80	Ukraine
81	Rest of Eastern Europe
82	Rest of Europe
83	Kazakhstan
84	Kyrgyzstan
85	Rest of Former Soviet Union
86	Armenia
87	Azerbaijan
88	Georgia
89	Iran, Islamic Republic of
90	Turkey
91	Rest of Western Asia
92	Egypt
93	Morocco
94	Tunisia
95	Rest of North Africa
96	Nigeria
97	Senegal
98	Rest of Western Africa
99	Rest of Central Africa
100	Rest of South Central Africa
101	Ethiopia
102	Madagascar

103	Malawi
104	Mauritius
105	Mozambique
106	Tanzania
107	Uganda
108	Zambia
109	Zimbabwe
110	Rest of Eastern Africa
111	Botswana
112	South Africa
113	Rest of South African Customs Union

Table A 3: Physical system regions.

Code	Name	GTAP
2	'Afghanistan'	XSA
3	'Albania'	ALB
4	'Algeria'	XNF
5	'American Samoa'	XOC
6	'Andorra'	XER
7	'Angola'	XAC
258	'Anguilla'	XCB
8	'Antigua and Barbuda'	XCB
9	'Argentina'	ARG
1	'Armenia'	ARM
22	'Aruba'	XCB
10	'Australia'	AUS
11	'Austria'	AUT
52	'Azerbaijan'	AZE
12	'Bahamas'	XCB
13	'Bahrain'	XWS
16	'Bangladesh'	BGD
14	'Barbados'	XCB
57	'Belarus'	BLR
255	'Belgium'	BEL
23	'Belize'	XCA
53	'Benin'	XWF
17	'Bermuda'	XNA

18	'Bhutan'	XSA
19	'Bolivia'	BOL
80	'Bosnia and Herzegovina'	XER
20	'Botswana'	BWA
21	'Brazil'	BRA
24	'British Indian Ocean Territory'	GBR
239	'British Virgin Islands'	XCB
26	'Brunei Darussalam'	XSE
27	'Bulgaria'	BGR
233	'Burkina Faso'	XWF
29	'Burundi'	XEC
115	'Cambodia'	KHM
32	'Cameroon'	XCF
33	'Canada'	CAN
35	'Cape Verde'	XWF
36	'Cayman Islands'	XCB
37	'Central African Republic'	XCF
39	'Chad'	XCF
259	'Channel Islands'	XER
40	'Chile'	CHL
351	'China'	CHN
42	'Christmas Island'	AUS
43	'Cocos (Keeling) Islands'	AUS
44	'Colombia'	COL
45	'Comoros'	XEC
46	'Congo'	XCF
47	'Cook Islands'	XOC
48	'Costa Rica'	CRI
107	'Côte d''Ivoire'	XWF
98	'Croatia'	HRV
49	'Cuba'	XCB
50	'Cyprus'	CYP
167	'Czech Republic'	CZE
116	'Democratic People''s Republic of Korea'	CZE
250	'Democratic Republic of the Congo'	CZE
54	'Denmark'	DNK

72	'Djibouti'	XEC
55	'Dominica'	XCB
56	'Dominican Republic'	XCB
58	'Ecuador'	ECU
59	'Egypt'	EGY
60	'El Salvador'	XCA
61	'Equatorial Guinea'	XCF
178	'Eritrea'	XEC
63	'Estonia'	EST
238	'Ethiopia'	ETH
62	'Ethiopia PDR'	ETH
65	'Falkland Islands (Malvinas)'	XSM
64	'Faroe Islands'	XER
66	'Fiji'	XOC
67	'Finland'	FIN
68	'France'	FRA
69	'French Guiana'	XSM
70	'French Polynesia'	XOC
74	'Gabon'	XCF
75	'Gambia'	XWF
73	'Georgia'	GEO
79	'Germany'	DEU
81	'Ghana'	XWF
82	'Gibraltar'	XER
84	'Greece'	GRC
85	'Greenland'	XNA
86	'Grenada'	XCB
87	'Guadeloupe'	XCB
88	'Guam'	XOC
89	'Guatemala'	GTM
90	'Guinea'	XWF
175	'Guinea-Bissau'	XWF
91	'Guyana'	XSM
93	'Haiti'	XCB
94	'Holy See'	XER
95	'Honduras'	HKG

96	China, Hong Kong SAR'	CHN
97	'Hungary'	HUN
99	'Iceland'	XEF
100	'India'	IND
101	'Indonesia'	IDN
102	'Iran, Islamic Republic of'	IRN
103	'Iraq'	XWS
104	'Ireland'	IRL
264	'Isle of Man'	GBR
105	'Israel'	XWS
106	'Italy'	ITA
109	'Jamaica'	XCB
110	'Japan'	JPN
112	'Jordan'	XWS
108	'Kazakhstan'	KAZ
114	'Kenya'	XEC
83	'Kiribati'	XOC
118	'Kuwait'	XWS
113	'Kyrgyzstan'	KGZ
120	'Lao People''s Democratic Republic'	LAO
119	'Latvia'	LVA
121	'Lebanon'	XWS
122	'Lesotho'	XSC
123	'Liberia'	XWF
124	'Libyan Arab Jamahiriya'	XNF
125	'Liechtenstein'	XEF
126	'Lithuania'	XEA
256	'Luxembourg'	XEA
129	'Madagascar'	MDG
130	'Malawi'	MWI
131	'Malaysia'	MYS
132	'Maldives'	XSA
133	'Mali'	XWF
134	'Malta'	MLT
127	'Marshall Islands'	XOC
135	'Martinique'	XCB

136	'Mauritania'	XWF
137	'Mauritius'	MUS
270	'Mayotte'	XEC
138	'Mexico'	MEX
145	'Micronesia, Federated States of'	XOC
140	'Monaco'	XER
141	'Mongolia'	XEA
273	'Montenegro'	XER
142	'Montserrat'	XCB
143	'Morocco'	MAR
144	'Mozambique'	MOZ
28	'Myanmar'	MMR
147	'Namibia'	XSC
148	'Nauru'	XOC
149	'Nepal'	XSA
150	'Netherlands'	NLD
151	'Netherlands Antilles'	XCB
153	'New Caledonia'	XOC
156	'New Zealand'	NZL
157	'Nicaragua'	NIC
158	'Niger'	XWF
159	'Nigeria'	NGA
160	'Niue'	XOC
161	'Norfolk Island'	XOC
163	'Northern Mariana Islands'	XOC
162	'Norway'	NOR
299	'Occupied Palestinian Territory'	XWS
221	'Oman'	XWS
164	'Pacific Islands Trust Tr'	USA
165	'Pakistan'	PAK
180	'Palau'	XOC
166	'Panama'	PAN
168	'Papua New Guinea'	XOC
169	'Paraguay'	PRY
170	'Peru'	PER
171	'Philippines'	PHL

172	'Pitcairn'	GBR
173	'Poland'	POL
174	'Portugal'	PRT
177	'Puerto Rico'	XCB
179	'Qatar'	XWS
117	'Republic of Korea'	XWS
146	'Republic of Moldova'	XWS
182	'Réunion'	XEC
183	'Romania'	ROU
185	'Russian Federation'	RUS
184	'Rwanda'	XEC
187	'Saint Helena'	XWF
188	'Saint Kitts and Nevis'	XCB
189	'Saint Lucia'	XCB
190	'Saint Pierre and Miquelon'	XNA
191	'Saint Vincent and the Grenadines'	XCB
244	'Samoa'	XOC
192	'San Marino'	XER
193	'Sao Tome and Principe'	XCF
194	'Saudi Arabia'	XWS
195	'Senegal'	SEN
272	'Serbia'	XER
186	'Serbia and Montenegro'	XER
196	'Seychelles'	XEC
197	'Sierra Leone'	XWF
200	'Singapore'	SGP
199	'Slovakia'	SVK
198	'Slovenia'	SVN
25	'Solomon Islands'	XOC
201	'Somalia'	XEC
202	'South Africa'	ZAF
203	'Spain'	ESP
38	'Sri Lanka'	LKA
206	'Sudan'	XEC
207	'Suriname'	XSM
209	'Swaziland'	XSC

210	'Sweden'	SWE
211	'Switzerland'	TWN
212	'Syrian Arab Republic'	TWN
214	China, Taiwan province of'	CHN
208	'Tajikistan'	XSU
216	'Thailand'	THA
154	'The former Yugoslav Republic of Macedonia'	THA
176	'Timor-Leste'	XSE
217	'Togo'	XWF
218	'Tokelau'	XOC
219	'Tonga'	XOC
220	'Trinidad and Tobago'	XCB
222	'Tunisia'	TUN
223	'Turkey'	TUR
213	'Turkmenistan'	XSU
224	'Turks and Caicos Islands'	XCB
227	'Tuvalu'	XOC
226	'Uganda'	UGA
230	'Ukraine'	UKR
225	'United Arab Emirates'	XWS
229	'United Kingdom of Great Britain and Northern Ireland'	GBR
215	'United Republic of Tanzania'	GBR
231	'United States of America'	USA
240	'United States Virgin Islands'	USA
234	'Uruguay'	URY
235	'Uzbekistan'	XSU
155	'Vanuatu'	XOC
236	'Venezuela (Bolivarian Republic of)'	XOC
237	'Viet Nam'	VNM
242	'Wake Island'	USA
243	'Wallis and Futuna Islands'	XOC
205	'Western Sahara'	XNF
249	'Yemen'	XWS
251	'Zambia'	ZMB
181	'Zimbabwe'	ZWE

Table A 4: Physical system primary products.

Code	Name
15	'Wheat'
27	'Rice, paddy'
44	'Barley'
56	'Maize'
68	'Popcorn'
71	'Rye'
75	'Oats'
79	'Millet'
83	'Sorghum'
89	'Buckwheat'
92	'Quinoa'
94	'Fonio'
97	'Triticale'
101	'Canary seed'
103	'Mixed grain'
108	'Cereals, nes'
116	'Potatoes'
122	'Sweet potatoes'
125	'Cassava'
135	'Yautia (cocoyam)'
136	'Taro (cocoyam)'
137	'Yams'
149	'Roots and Tubers, nes'
156	'Sugar cane'
157	'Sugar beet'
161	'Sugar crops, nes'
176	'Beans, dry'
181	'Broad beans, horse beans, dry'
187	'Peas, dry'
191	'Chick peas'
195	'Cow peas, dry'
197	'Pigeon peas'
201	'Lentils'
203	'Bambara beans'
205	'Vetches'

210	'Lupins'
211	'Pulses, nes'
216	'Brazil nuts, with shell'
217	'Cashew nuts, with shell'
220	'Chestnuts'
221	'Almonds, with shell'
222	'Walnuts, with shell'
223	'Pistachios'
224	'Kolanuts'
225	'Hazelnuts, with shell'
226	'Arecanuts'
234	'Nuts, nes'
236	'Soybeans'
242	'Groundnuts, with shell'
249	'Coconuts'
254	'Oil palm fruit'
260	'Olives'
263	'Karite Nuts (Sheanuts)'
265	'Castor oil seed'
267	'Sunflower seed'
270	'Rapeseed'
275	'Tung Nuts'
280	'Safflower seed'
289	'Sesame seed'
292	'Mustard seed'
296	'Poppy seed'
299	'Melonseed'
311	'Kapokseed in Shell'
328	'Seed cotton'
333	'Linseed'
336	'Hempseed'
339	'Oilseeds, Nes'
358	'Cabbages and other brassicas'
366	'Artichokes'
367	'Asparagus'
372	'Lettuce and chicory'
373	'Spinach'
388	'Tomatoes'

393	'Cauliflowers and broccoli'
394	'Pumpkins, squash and gourds'
397	'Cucumbers and gherkins'
399	'Eggplants (aubergines)'
401	'Chillies and peppers, green'
402	'Onions (inc. shallots), green'
403	'Onions, dry'
406	'Garlic'
414	'Beans, green'
417	'Peas, green'
420	'Leguminous vegetables, nes'
423	'String beans'
426	'Carrots and turnips'
430	'Okra'
446	'Maize, green'
449	'Mushrooms and truffles'
459	'Chicory roots'
461	'Carobs'
463	'Vegetables fresh nes'
486	'Bananas'
489	'Plantains'
490	'Oranges'
495	'Tangerines, mandarins, clem.'
497	'Lemons and limes'
507	'Grapefruit (inc. pomelos)'
512	'Citrus fruit, nes'
515	'Apples'
521	'Pears'
523	'Quinces'
526	'Apricots'
530	'Sour cherries'
531	'Cherries'
534	'Peaches and nectarines'
536	'Plums and sloes'
541	'Stone fruit, nes'
544	'Strawberries'
547	'Raspberries'
549	'Gooseberries'

550	'Currants'
552	'Blueberries'
554	'Cranberries'
558	'Berries Nes'
560	'Grapes'
567	'Watermelons'
568	'Other melons (inc.cantaloupes)'
569	'Figs'
571	'Mangoes, mangosteens, guavas'
572	'Avocados'
574	'Pineapples'
577	'Dates'
587	'Persimmons'
591	'Cashewapple'
592	'Kiwi fruit'
600	'Papayas'
603	'Fruit, tropical fresh nes'
619	'Fruit Fresh Nes'
656	'Coffee, green'
661	'Cocoa beans'
667	'Tea'
671	'Maté'
677	'Hops'
687	'Pepper (Piper spp.)'
689	'Chillies and peppers, dry'
692	'Vanilla'
693	'Cinnamon (canella)'
698	'Cloves'
702	'Nutmeg, mace and cardamoms'
711	'Anise, badian, fennel, corian.'
720	'Ginger'
723	'Spices, nes'
748	'Peppermint'
754	'Pyrethrum,Dried'
773	'Flax fibre and tow'
777	'Hemp Tow Waste'
778	'Kapok Fibre'
780	'Jute'

782	'Other Bastfibres'
788	'Ramie'
789	'Sisal'
800	'Agave Fibres Nes'
809	'Manila Fibre (Abaca)'
813	'Coir'
821	'Fibre Crops Nes'
826	'Tobacco, unmanufactured'
836	'Natural rubber'
839	'Gums Natural'
636	'Maize for forage and silage'
637	'Sorghum for forage and silage'
638	'Rye grass for forage and silage'
639	'Grasses Nes for forage;Sil'
640	'Clover for forage and silage'
641	'Alfalfa for forage and silage'
1601	'Sawlogs+Veneer Logs (C)'
1602	'Pulpwood,Round&Split(C)'
1603	'Pulpwood,Round&Split(NC)'
1604	'Sawlogs+Veneer Logs (NC)'
1614	'Pulpwood,Round&Split Trd'
1623	'Other Indust Roundwd(C)'
1625	'Other Indust Roundwd Trd'
1626	'Other Indust Roundwd(NC)'
1627	'Wood Fuel(C)'
1628	'Wood Fuel(NC)'
1629	'Wood Fuel Trd'
1651	'Ind Rwd Wir (C)'
1657	'Ind Rwd Wir (NC) Tropica'
1670	'Ind Rwd Wir (NC) Other'

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