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FABIO
The Construction of the Food and Agriculture Biomass Input–Output Model

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FABIO — The Construction of the Food and Agriculture Biomass Input–Output Model

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Abstract

Primary crops are linked to final consumption by networks of processes and actors that convert and distribute food and non-food goods. Achieving a sustainable metabolism of this bio-economy is an overarching challenge which manifests itself in a number of the UN Sustainable Development Goals. Modelling the physical dimensions of biomass conversion and distribution networks is essential to understanding the characteristics, drivers and dynamics of our societies' biomass metabolism. In this paper, we present the Food and Agriculture Biomass Input–Output model (FABIO), a set of multi-regional supply, use and input–output tables in physical units, that document the complex flows of agricultural and food products in the global economy. The model assembles FAOSTAT statistics reporting crop production, trade, and utilisation in physical units, supplemented by data on technical and metabolic conversion efficiencies, into a consistent, balanced, input–output framework. FABIO covers 191 countries and 130 agriculture, food and forestry products from 1986 to 2013. The physical supply-use tables offered by FABIO provide a comprehensive, transparent and flexible structure for organising data representing flows of materials within metabolic networks. They allow tracing biomass flows and embodied environmental pressures along global supply chains at an unprecedented level of product and country detail and can help to answer a range of questions regarding environment, agriculture, and trade.

1 Introduction

In the context of the Paris Agreement, the UN Sustainable Development Goals (SDGs) and related resource efficiency and circular economy agendas, the increasing displacement of

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*corresponding author: martin.bruckner@wu.ac.at environmental impacts from primary production through global trade has become a prominent issue in international policy debates (Kehoe et al., 2019). Traceability tools are needed to support both stakeholders and policy makers in monitoring and governing global trade-flows and their undesired impacts (Lambin et al., 2018).

Traceability tools must provide results which are trustworthy, comprehensive, and detailed enough to be able to guide policy response. We argue in this paper that current global supply chain databases, in the form of multi-region input–output (MRIO) models, are often inadequate a) to account for the specific environmental impacts associated to a large range of different agricultural products, and b) to capture the physical basis of the food system. Farming, grazing, and forestry activities are central in many sustainability challenges across health, water, energy, and biodiversity. Gaining an accurate picture of the physical metabolism of these goods through the global economy is arguably a prerequisite for addressing biomass goods in the context of sustainability goals.

Material flow analysis (MFA, Haberl et al., 2004) has developed into an important framework to study metabolic networks and support the governance of societal transitions. MFA aims at quantifying the biophysical dimension of socio-economic activities (Fischer-Kowalski et al., 2011) and identifying options to reduce their negative environmental impacts, such as global warming (Binder et al., 2013). The foundations of MFA reach back more than 40 years (Ayres and Kneese, 1969; Baccini and Brunner, 1991) and today, material flow accounts are core modules in the UN System of Environmental-Economic Accounts (SEEA, United Nations, 2012). Physical supply-use tables (PSUT) provide a comprehensive, transparent and flexible structure for organizing data on material flows within metabolic networks. The groundwork for PSUTs was laid by Kneese et al. (1970) and their application of the material balance approach to economic analysis. In the meantime, pilot PSUTs and physical input–output tables (PIOT) have been presented for a number of countries and regions, including the European Union, Austria, Germany, Finland, Italy, the Netherlands, Japan, and China (see, e.g., Bösch et al., 2015; Giljum and Hubacek, 2009; Hoekstra and van den Bergh, 2006; Liang et al., 2017). PSUTs are the basis for compiling PIOTs and provide a detailed description of the physical flows between the natural and the socio-economic system.

Bio-based inputs, such as crops and timber, are supplied by the natural environment and mostly introduced into the economic system by the agriculture and forestry sectors. Processing industries, such as livestock and food industries, use and transform these inputs of natural resources to generate products for intermediate or final consumption. Residuals are generated by both industries and households and are either treated further within the economy or released back to the environment.

The latest revision of the SEEA framework (United Nations, 2012) provides general methodological instructions for setting up environmental accounts in the format of supply and use accounts both in physical and monetary terms. The quantification of physical flows induced by trade and final demand reaches back as far as to the late 1960s (Ayres and Kneese, 1969). During the energy crises of the 1970s, a number of energy-related input–output models were developed to assess the impact of consumption on energy demand (for example, Bullard and Herendeen, 1975). In recent years, environmentally-extended multi-regional input–output (EE-MRIO) approaches have been widely used to study physical flows of materials induced by production and consumption activities in the global economy. Recent examples for such studies based on EE-MRIO analysis include applications of the MRIO databases Eora (Lenzen et al., 2012), GTAP (Bruckner et al., 2012), EXIOBASE (Giljum et al., 2016), and OECD ICIO (Giljum et al., 2019). Also the World Trade Model has been used to investigate global material flows (Duchin et al., 2015). Furthermore, the Trase.earth project (Godar et al., 2015) does not use an input–output or SEEA framework but instead is collecting detailed data on production and trade of critical commodities, such as soy and palm oil, pursuing a bottom-up approach to providing detail on key countries and commodities.

Despite the significant progress in recent years, the robustness of MRIO-based calculations of global physical biomass flows has been questioned. Three main problematic areas have been identified (for example, Bruckner et al., 2012; Koning et al., 2015; Majeau-Bettez et al., 2016; Schoer et al., 2012). First, the monetary structure of the economy does not always represent the quantities of physical product flows. Due to price variations of product flows between different customers, the assumption of proportionality between monetary and physical flows can lead to over- or underestimations of the allocation of impacts that should follow mass based allocation (Bruckner et al., 2015; Kastner et al., 2014b). Second, the limited detail of monetary input–output tables results in a grouping of products with differing environmental properties and use structures into homogeneous sectors (Koning et al., 2015). Third, there exist mismatches between agricultural and forestry statistics reported in physical units on the one hand, and macro-economic production statistics in monetary units on the other hand, for example due to different system boundaries (Schaffartzik et al., 2015).

In order to reduce uncertainties arising from the above mentioned limitations of input–output models, a number of studies have suggested moving from sector-level economic data towards a more detailed physical data basis. For example, Ewing et al. (2012) developed physical use accounts for agricultural products which model the first stage of agricultural supply chains in physical instead of monetary units and allocate crops to the first users reflecting detailed international trade and type of the first use provided by FAOSTAT. This approach was further developed by Weinzettel and Wood (2018) and applied to calculate footprints for biodiversity (Weinzettel et al., 2018), scarce water use (Weinzettel and Pfister, 2019), and net primary production (Weinzettel et al., 2019). A similar approach is applied by Croft et al. (2018), but going one step further for selected processed products such as vegetable oils. Liang et al. (2017) presented a 30-sector, mixed-unit PIOT for China to investigate material flows by aggregated product groups.

All these hybrid IO models rely on monetary IO data to track agricultural products from the first (or second) use stage to the final consumers. A growing number of researchers worldwide, however, argue that describing the structure of material conversion and distribution networks in physical terms, i.e., by means of detailed PSUTs, provides a beneficial basis for the analysis of material flows in metabolic networks (Heun et al., 2018; Kovanda, 2018). While Kastner et al. (2011) developed a trade accounting approach that tracks crops embodied in international trade purely based on physical data, they convert all products into primary crop equivalents. A system of physical supply-use or input–output tables instead transparently describes all intermediate uses and conversion processes, thereby retaining flow information at each step of the supply chain.

In this paper, we present the Food and Agriculture Biomass Input Output model (FABIO), a global set of trade-linked PSUTs and PIOTs capturing detailed supply chain information for 130 raw and processed agricultural and forestry products covering 191 countries from 1986 to 2013. By using agricultural statistics we obtain a significantly higher level of product and process detail compared to any available MRIO database and, moreover, cover supply chains in physical units, thereby alleviating the uncertainties introduced by the homogeneity, proportionality and consistency assumptions applied in IO analysis.

The model is built on top of the FAOSTAT databases, as well as data from UN Comtrade and BACI for commodity trade, IEA and EIA for information on biofuel, in addition to other sources. These are documented below in the Methods and Data section.

All data sets and R scripts are available to the research community under the GNU General Public License (GPL-v3) license via GitHub (`https://github.com/martinbruckner/fabio`) and the open science platform Zenodo (Bruckner, 2019), which is fully compliant with the FAIR guiding principles (Wilkinson et al., 2016) for the provision and management of open data in scientific research. We are convinced that openness, transparency and sharing contributes to the advancement of research and invite researchers to test and scrutinise our codes and results.

2 Overview of the FABIO model

Figure 1 illustrates the approach used to build FABIO. The procedure is described in detail in the following sections. First, we give a detailed overview of all data sources used to construct FABIO. In Section 3.2 we then describe how we deal with data gaps and inconsistencies. After that we elucidate how supply and use tables are built based on the available data. Finally, we show how national PSUTs are trade-linked and converted into a symmetric multi-regional PIOT.

2.1 Comparison with other MRIOs

The resulting FABIO database offers PSUTs and PIOTs with an unprecedented level of detail for agriculture and food products. In most standard IO tables, such as those provided by EUROSTAT, and also in the WIOD, ICIO, and Eora MRIO databases, these products are represented using 1-10 aggregate categories, while FABIO features 127 distinct products (Table 1). GTAP and EXIOBASE distinguish 21 and 27 agriculture and food products, respectively. We note that Eora offers more detail for some countries, the UK representing an extreme case with 80 agriculture and food products and 1022 products in total. Furthermore, FABIO provides more detail than most other MRIOs also regarding country detail and time coverage. Most importantly, it documents product flows in physical instead of monetary units, which is a unique feature of this MRIO database. However, other parts of the economy are not represented.

Table 1: Comparison of MRIO databases.

	GTAP	EXIOBASE	Eora	WIOD	ICIO	FABIO
Regions	140	49	190	43	69	192

Agriculture & food products	21	27	2-80	2	2	127
Forestry products	1	1	0-3	1	0	3
Other products & services	35	172	24-936	53	34	0
Years	2004, 2007, 2011	1995-2011	1990-2015	2000-2014	1995-2015	1986-2013
Units	USD	EUR	USD	USD	USD	tonnes, heads

3 Methods and data

In this section, we explain which data sources were used and how they were processed to build multi-regional PSUTs and PIOTs for agriculture, fish, forestry, and food products.

3.1 Data sources

Most of the data used for constructing the FABIO supply and use tables are provided by FAOSTAT, the Statistical Services of the Food and Agriculture Organisation of the United Nations (FAOSTAT, 2019). To build FABIO we used data from the following FAOSTAT domains:

- Production, Crops
- Production, Crops processed
- Production, Live animals
- Production, Livestock primary
- Production, Livestock processed
- Trade, Crops and livestock products
- Trade, Live animals
- Trade, Detailed trade matrix
- Commodity balances, Crops primary equivalent
- Commodity balances, Livestock and fish primary equivalent
- Forestry production and trade
- Forestry trade flows

Additionally, fodder crop production data (previously part of the aggregated item “Crops Primary (List)” in the *Production* domain) are required, but are no longer available from the FAOSTAT website. These data were often estimated, and as we understood FAO has become hesitant to publish such estimated data. However, we decided it was valid to continue using these estimates as (a) some estimate is better than estimating the amount of fodder crops at

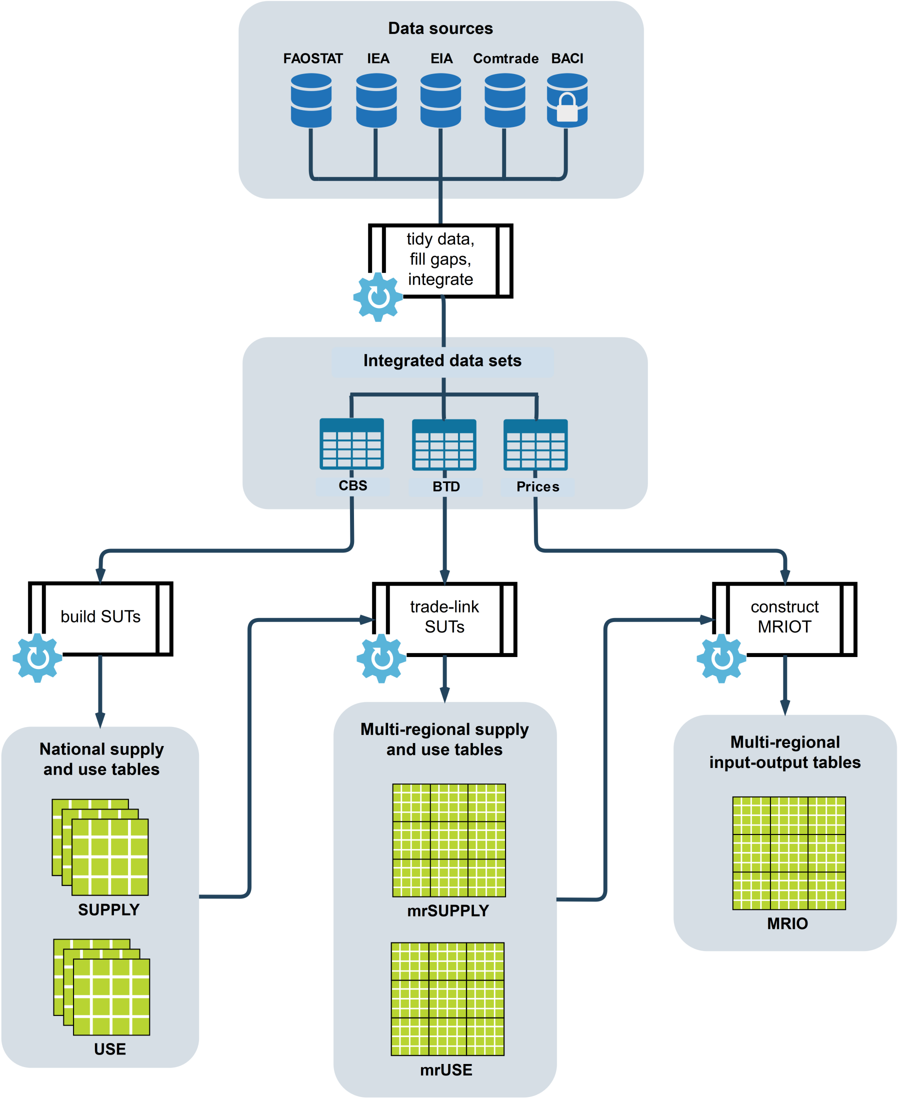

Figure 1: Flow chart illustrating the data sources and processing steps involved in building FABIO.

zero and (b) due to the way FABIO is constructed these estimates will be aligned and constrained with other datasets to inform the final FABIO model result. In order to replicate FABIO, it is necessary to request these data from FAOSTAT.

Global statistics on capture and aquaculture fish production were retrieved from FAO's fishery division (FAO, 2019). UN Comtrade, the international trade statistics database of the United Nations Statistics Division (2019), provides bilateral trade data, which are downloaded directly via an API. We use the Comtrade database for data on bilateral fish and ethanol trade from 1988 to 1994. Data for all other years are sourced from BACI, a reconciled and harmonised version of the UN Comtrade database, which is available for 1995 to 2017 (Gaulier and Zignago, 2010). The trade data are balanced as described below.

Production data for ethanol from agricultural sources are reported by FAOSTAT under the name *Alcohol, non-food*. However, large data gaps induced us to use production data on ethanol and biogasoline from both EIA (2019) and IEA (2019).

The data structures of all data sets were harmonized, particularly regarding their country and commodity classification. We defined 130 commodities, 121 processes and 191 countries to be covered in FABIO. The final classifications are given in the Appendix (see, Table 2, Table 3, and Table 4).

The Commodity Balance Sheets (CBS), available from FAOSTAT, are the core of the FABIO PSUTs. The CBS, also known as supply–utilization accounts, provide detailed and comprehensive supply and use data for primary and processed agricultural commodities in terms of physical quantities by matching supply (domestic production, imports, and stock removals) with utilization (food, feed, processing, seed, waste, other uses, and exports). Other uses "refer to quantities of commodities used for non-food purposes, e.g. oil for soap. [. . .] In addition, this variable covers pet food." (FAOSTAT, 2019) The CBS database structure is designed to cover each country's entire agricultural and food processing sector (FAO, 2001). About 200 different primary and processed crop and livestock commodities can be linked to form a consistent commodity tree structure using technical conversion factors (FAO, 2003).

While particularly the use accounts are an indispensable source of information for the development of PSUTs, an unavoidable limitation of these data is that for many cases crops and derived products are combined into a single CBS by converting products into primary equivalents. For example, the CBS for *wheat and products* comprises also trade and consumption of bread and pasta measured in wheat equivalents. Disaggregating primary from processed products, thus, represents an option for future refinements. However, we do not expect differentiating primary and processed products to have a significant influence on the results when using FABIO as a footprinting tool (compare Weinzettel and Wood, 2018), but it would be of relevance when linking FABIO to data from economic accounts.

As other domains of FAOSTAT (e.g. *Trade* and *Production*) give the actual weight of products, units had to be converted into primary equivalents where applicable. This was done using country specific technical conversion factors (TCF) for 66 products and global average TCF for 404 products, which for example give the kg of wheat required to produce an average kg of bread (FAO, 2003).

Trade data for crops and crop products, livestock and livestock products, timber, and fish are organized in different data domains of the FAO. We therefore harmonized their data structures and integrated them into one bilateral trade database (BTD). To reconcile discrepancies, i.e. the case that A's reported exports to B disagree with B's reported imports from A, only import data were used. We assumed that the importer will rather know the correct origin of a traded commodity, than the exporter the correct final destination. Moreover, import statistics use to be more complete as customs have comprehensible interest in thorough data collection for tax purposes. In the case of missing records for a country we obtained missing trade data from "mirror" statistics, i.e. trade partners' data.

3.2 Estimating missing values

Data gaps are a common problem in any heavily data-dependent research work. We used several approaches to estimate missing data.

3.2.1 Commodity balances

The CBS database does not cover some of the commodities included in the FABIO model, i.e. live animals, fodder crops (grasses, forages and silages), grazing (grasses and hay from grasslands), and timber. Therefore, commodity balances had to be built based on alternative sources. Production data for all missing commodities as well as trade data for live animals and timber are available from FAOSTAT. Fodder crops and grasses are assumed not to be traded internationally. Low prices and the consequent disproportionate transportation costs support this assumption. For simplicity, stock changes, seed use and waste were assumed to be zero. Domestic use of live animals is at large assigned to food processing (i.e. animal slaughtering), fodder crops and grazing to feed use, and timber to other uses.

The CBS and bilateral trade data for *Alcohol, non-food* were updated with production data from IEA and EIA (using the highest value respectively) and trade data from Comtrade/BACI.

For some countries, not included in the CBS domain (namely: Singapore, Qatar, Democratic Republic of the Congo, Bahrain, Syrian Arab Republic, Papua New Guinea, Burundi, Libya, Somalia, Eritrea, Timor-Leste, and Puerto Rico), all commodity balances were estimated based on available production, seed use[1] and trade data. Processing requirements, e.g. the rapeseed used for rapeseed oil production or the sugar cane used for sugar production, were estimated for each commodity based on production data for the derived products and the country specific TCF. If we then found data gaps for co-products, e.g. molasses from sugar production, we imputed these data using again the respective TCF.

In the CBS, a certain commodity might be reported for a country most of the time, but with a few years missing. While production and trade data are available from other data domains of FAOSTAT throughout the time series, the use structure of the commodities is only provided by the CBS. In there absence, we do linear inter- and extrapolation of the respective use structures. In total, for the case of the year 2013, 15,234 commodity balances were reported for the 191 countries included in FABIO, and 4271 were estimated (see Table 5 in the Appendix), representing less than 0.5 % of the covered global product supply.

3.2.2 Bilateral trade

The BTD was reconciled to receive a bilateral trade matrix b_c^{rs} in the format countries-by-countries ($r \times s$) for each commodity c and year as described in Section 3.1. The dataset, as provided by FAOSTAT, reveals significant gaps and discrepancies with the total import and export quantities reported in the CBS. We followed a multi-step approach to estimate a comprehensive set of bilateral trade data, which is in accordance with the CBS:

- We first derive a BTD estimate by spreading exports for each commodity over all countries worldwide according to their import shares. The elements of $B^{'}$ for a specific crop c and a country pair r, s are derived by $b_c^{'rs} = imp_c^r / imp_c \cdot exp_c^s$

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[1] FAO has stopped reporting the seed use in the production domain of FAOSTAT. Thus for future updates seed-production ratios reported in past years or for other countries will be taken. While production for seed is important, it is not especially large in physical terms. On average globally, 1.4% of crop production is used for seed in the following year, though this ranges between as much as 5.7% for pulses to 0.01% for vegetables.

- We repeat this procedure, but spreading imports for each commodity over all countries worldwide according to their export shares: $b''^{rs}_c = exp^s_c / exp_c \cdot imp^r_c$
- We derive the average of the two estimates $\bar{b}^{rs}_c$ and proceed.
- We calculate the difference between the total exports of crop c from country r documented in the BTD and those reported in the CBS dataset.
- We populate the gaps in $\mathbf{B}$, i.e. those fields that are N/A, with the corresponding values from $\bar{\mathbf{B}}$ up-/down-scaling them to meet the target export sum for each commodity and each exporting country as reported in the CBS.
- We balance the resulting trade matrices using the RAS technique.

The resulting bilateral trade matrix is fully consistent with the import and export totals given by the CBS per country and commodity.

3.3 Building the supply tables

Populating the supply table is straightforward, as production data is available from FAOSTAT and can be attributed to a specific process. First, we identify the processes, supplying more than one output, i.e. joint products or by-products. We find a reasonable list of multi-output processes such as the crushing of oilseeds, the production of sugar, alcoholic beverages, and livestock products (see Table 7). We insert the compiled production data for each process-item combination into a supply table. Ten livestock commodities are supplied by multiple processes. Production values of those have to be divided between the respective processes:

- Milk and butter from 5 different animal groups are aggregated into one CBS item. At the same time, FAOSTAT reports detailed production data for fresh milk by animal type (e.g. cattle, goats, camels). These are used to split the aggregates over the supplying animal sectors in FABIO.
- The same is true for meat, hides and skins, where the CBS provide less detail than the FAO's production statistics. We use the latter to allocate meat supply to the detailed slaughtering processes.
- Slaughtering by-products such as edible offals, animal fats, and meat meal are split among the animal categories according to their respective share in overall meat production.

We receive one supply table $\mathbf{S}$ with i commodities by p processes for each country and year.

3.4 Building the use tables

The Commodity Balance Sheets distinguish the following uses: exports, food, feed, processing, seed, waste, and other uses. Moreover, we invert the supply item *stock removals*, thereby converting it into the additional use item *stock additions*.

Waste can be treated in a physical accounting framework in different ways (Giljum and Hubacek, 2004). On-farm waste of biomass can be regarded as an output flow that would either be returned to the environment or serve as an input to other processes. Such an accounting perspective enables assessing the actual physical flows within metabolic networks (Nakamura et al., 2009). Alternatively, waste flows can be allocated to the process where the waste occurs, thus considering losses synonymous to an own use. As opposed to the tracking of actual physical flows in option one, the second option allows for the tracking of embodied flows, which is required for consumption-based (or footprint) accounting (compare Weinzettel, 2012). In this first version of FABIO, we decided to implement the latter option, but plan to release an alternate version with waste streams reported as out-flows as well.

Seed is considered an own use of the process which later harvests a crop. Exports, stock additions, food, and other uses are considered final demand categories. Exports will later be spread over the receiving countries, while food, stock additions and other uses together comprise the final demand categories of FABIO.

In the following, we describe the allocation of feed and processing use.

3.4.1 Allocation of processing use

Processing uses are allocated to the respective processes distinguishing between several cases.

Single-process commodities: Commodities that are only processed by one single process include oil crops (processed in the respective oil extraction processes), hops (used in beer production), seed cotton (separated into cotton lint and cotton seed in the cotton production process), and live animals (processed by the respective slaughtering sectors). Given processing quantities are directly allocated to the respective processes.

Multi-purpose crops: Crops that are used by several processes are allocated by estimating the input requirements to each process based on technical conversion factors giving the conversion efficiencies for food processing. The use of product i in process p is determined by $u_i^p = \sum_j (s_j^p \cdot \phi_{ij}^p)$, where s_j^p is the supply of product j by process p and ϕ_{ij}^p is the conversion efficiency from product i to product j in process p. For example, $\phi_{ij}^p = 0.5$ indicates, that process p converts each ton of product i into 0.5 tons of product j. This approach is used to estimate the use of sugar crops in sugar production, rice in ricebran oil extraction, maize in maize germ oil extraction, and grapes in wine production.

Ethanol feedstock: For Brazil and the US, responsible for over 85 % of the global ethanol production in 2014 (IEA, 2019), the feedstock composition is known. Brazil uses sugar cane, while the ethanol industry of the US is mainly based on maize, with less than 2 % coming from sorghum, barley, cheese whey, sugar cane, wheat, and food and wood wastes (RFA, 2010). For all other countries, i.e. less than 15 % of global ethanol production, feedstocks are estimated based on the availability of useful feedstock crops and their respective conversion rates.

Alcoholic beverages: Crops are allocated to the processes which supply alcoholic beverages by solving an optimization problem. We have given the national production of beer and other alcoholic beverages s_j, the total available feedstock supply u_i which was not allocated already to other processes, and the conversion efficiencies ϕ_{ij}, e.g., from barley to beer. With these inputs, we solve the following constrained least-squares optimization problem:

$$min \sum \left(\left(\frac{\mathbf{s} - \tilde{\mathbf{s}}}{\bar{\phi}} \right)^2 + (\mathbf{u} - \tilde{\mathbf{u}})^2 \right),$$

where

$$\tilde{s}_j = \sum_{i=1}^{n} \left(\tilde{u}_{ij} \cdot \phi_{ij} \right),$$

s.t.

$$\sum_{j=1}^{m} \tilde{u}_{ij} = u_i \pm 0.1,$$

and receive a table of crop use per alcoholic beverage and country, which we insert into the use table.

3.4.2 Allocation of feed use

The quantities of each crop used as animal feed are reported by FAOSTAT. This feed supply is allocated to the 14 animal husbandry sectors specified in FABIO (Appendix Table 3) according to their feed intake requirements. The procedure is explained in the following three steps:

- **Feed supply:** Retrieve detailed data on feed supply from FAO in fresh weight, and convert them into dry matter (DM).
- **Feed demand:** Calculate feed demand of 14 livestock groups in tons of DM.
  - **Cattle, buffaloes, pigs, poultry, sheep and goats:** Bouwman et al. (2011) published estimates on the feed demand in kg DM per kg product (e.g. milk, beef, fat) for 1970, 1995 and 2030, differentiating specific dietary requirements and feed composition (i.e. feed crops, grass, animal products, residues, and scavenging) for livestock in 17 world regions. We interpolate the given feed conversion rates to get year-specific values and multiply them with the reported production quantities of animal products to get the total feed requirements per product. For this step, it was important to consider trade with live animals in order to correctly assign feed demand to the country, where the animals were raised.
  - **Horses, asses, mules, camels, other camelids, rabbits and hares, other rodents, other live animals:** Krausmann et al. (2008) provide average feed demand coefficients for the above listed animal groups in kg DM per head, which are multiplied with the reported livestock numbers to calculate total feed requirements.
- **Match supply and demand:** We then balance the generated feed requirements per country to match the reported feed supply by proportional up- or downscaling. Finally, we convert the quantities into the fresh weight of every single feed crop.

3.5 Trade-linking

Once the supply and use tables for all countries are filled, they are linked into multi-regional supply and use tables. The multi-regional supply table $\mathbf{S}$ with the dimensions $\{r, i\} \times \{s, p\}$ contains zeros at the trade blocks (where $r \neq s$) and is filled with the domestic supply tables where $r = s$.

The national use tables are trade-linked by spreading the use of a product i in a process p in country s over the source countries r of that product: $u_{ip}^{rs} = u_{ip}^{s} \cdot h_i^{rs}$, where $h_i^{rs} = s_i^{rs}/s_i^s$ and s_i^{rs} is the total supply of product i in country s sourced from country r. Finally, we receive a matrix $\mathbf{U}$ with the dimensions $\{r, i\} \times \{s, p\}$.

3.6 Constructing symmetric IO table

The transformation from supply-use tables into symmetric input–output tables requires assumptions on how to deal with multiple-output processes, i.e. a process supplying more than one product such as, e.g., soybean crushing delivering soybean oil and cake. The issue of how to allocate process inputs to outputs is discussed both in the fields of input–output economics and life cycle analysis, with clear parallels in the allocation approaches (Majeau-Bettez et al., 2014; Suh et al., 2010). When applying the widely used industry technology assumption for the transformation of rectangular process-by-product SUTs into symmetric product-by-product IOTs, process inputs are allocated to its respective outputs according to the supply shares documented in the supply table. For example, in the case of soybean crushing, the input quantities of soybeans are allocated to the outputs of oil and cake. We do this by deriving the product mix matrix or transformation matrix $\mathbf{T} = \hat{\mathbf{g}}^{-1}\mathbf{S}$, where $\hat{\mathbf{g}}$ is a diagonalized vector with the row sums of $\mathbf{S}$, and multiplying the use and the transformation matrix $\mathbf{Z} = \mathbf{UT}$.

Assuming PSUTs in weight units, this allocates inputs according to the relative weight of the outputs. In order to facilitate analyses of the economic drivers of resource flows, we derive also a version generated that uses the relative economic value for the allocation. We therefore convert the supply tables into monetary values (based on price information from FAOSTAT and IEA) before deriving the transformation matrix as explained above. Thereby, we switch from mass to value allocation, i.e. allocating the inputs of each process to its outputs in relation to their value rather than their weight.

This allows us to test the effects that the different allocation decisions have on the resulting PIOTs. This is particularly relevant for products from processes that produce outputs with highly varying value-weight ratios. It should be noted that, in accordance with the requirements of a specific research question, allocation could be performed also according to supply shares in other units, for example based on the carbon, nitrogen, phosphorous or protein content.

3.6.1 Heatmaps PIOT

Figure 2 illustrates the trade structure of FABIO with the help of a heatmap. We aggregate the transaction matrix $\mathbf{Z}$ for the year 2013 into a matrix with country-by-country format and plot the logarithm of the contained values. This reveals some major exporters such as countries 7 (Argentina), 8 (Australia), 50 (France), 71 (India), 173 (Ukraine), and 174 (USA), as well as importers such as 31 (China, mainland). The largest flows are found within countries, i.e. on the main diagonal.

We now aggregate $\mathbf{Z}$ into a global transaction matrix with product-by-product format, illustrating the product inputs to the production of derived products for all countries worldwide Figure 3. This figure makes evident that FABIO's PIOTs are highly sparse matrices with flows

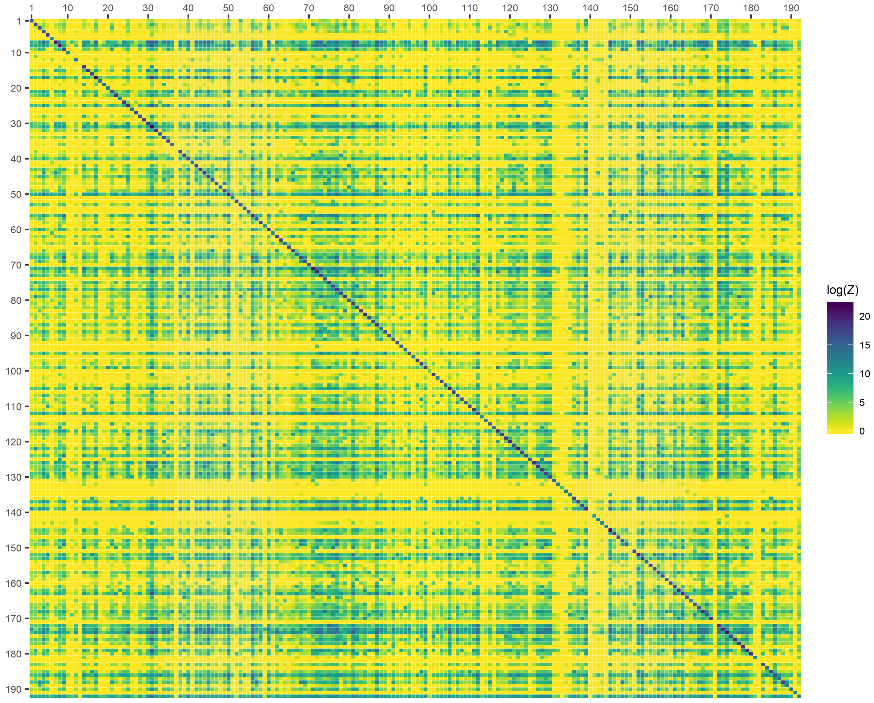

Figure 2: Heatmap of physical input–output table for 2013 in country-by-country format on a logarithmic scale.

mainly on the main diagonal, besides some important processing activities. These include the feed use in the livestock sector, feedstock input for the production of alcoholic beverages and ethanol, oil crops processed into oils and cakes, as well as live animals converted into animal products.

4 Results

We extend the FABIO model by cropland use data sourced from FAOSTAT (2019) and calculate exemplary land footprint results for China, the EU-28, and the US, distinguishing plant-based and livestock-based products for food and non-food uses from 1986 to 2013. We apply both versions of FABIO, i.e. using mass and value allocation. Figure 4 presents the results derived with the FABIO model based on mass allocation (in the upper part), the difference between mass and value allocation (in the middle part), and the share of imports in the overall footprint (in the lower part). The figure reveals characteristic patterns and distinct trends for these three major agricultural producer and consumer regions. While animal source foods take the highest but declining share in the EU and the US cropland footprint, their place is still only second after plant-based food in China, albeit showing a rapid increase throughout the time series. Other uses, i.e. mainly industrial non-food uses, are particularly increasing in China and the US. In the EU, we see a shift from animal-based to plant-based non-food products. The middle part of Figure 4 illustrates the impact of using mass or value allocation for by-products in the construction of FABIO on the cropland footprints. While the overall footprint only changes slightly, the composition changes significantly. In China and the EU, livestock products have a

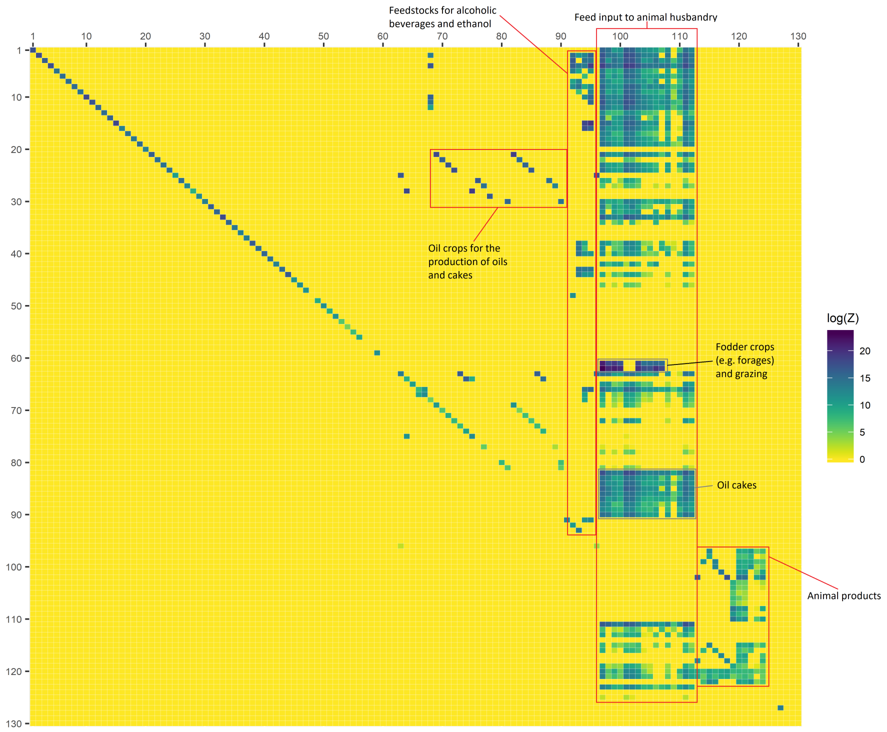

Figure 3: Heatmap of global input–output table for 2013 in product-by-product format on a logarithmic scale.

smaller footprint when using value allocation. This is mainly due to the lower price of soybean cake as compared to soybean oil. Accordingly, non-food uses of crop products such as soybean oil receive a higher share of the land inputs. In contrast, the products from the livestock sector used by non-food industries, for instance hides and skins, are usually cheaper than those intended for human consumption. China constitutes an exception, as prices of animal hides are driven by the high demand of industries and often exceed meat prices, thus shifting more of the inputs to hides when switching from mass to value allocation. The relative impact of allocation choice is significant, with a maximum of 59% of the total impact of the food-livestock product group, 63% of the other uses of livestock products, and 38% of the other uses of crops being affected by choice of allocation. The evolution of import shares, shown at the bottom of Figure 4, reveals an increasing reliance on imports for China's use of livestock products and crops for other uses. The EU, at the same time, reduced import dependence for most product groups, albeit starting from high levels. The US import share of crop products for other uses declined by roughly half, while increasing slightly for the other product groups.

For a first comparison of our results with other land footprint studies, we amend the comparison of net-trade flows of embodied land for China in 2004 presented in Hubacek and Feng (2016), including numbers from Qiang et al. (2013), Kastner et al. (2014b), Meyfroidt et al. (2010), Weinzettel et al. (2013) and Yu et al. (2013), with results generated with FABIO (see Figure 5).

FABIO is evidently very much in line with other physical accounting methods, although applying the IO method. We could determine net-imports of 21 Mha cropland, both with mass and value allocation. This, however, could change when further tracing the supply chains of

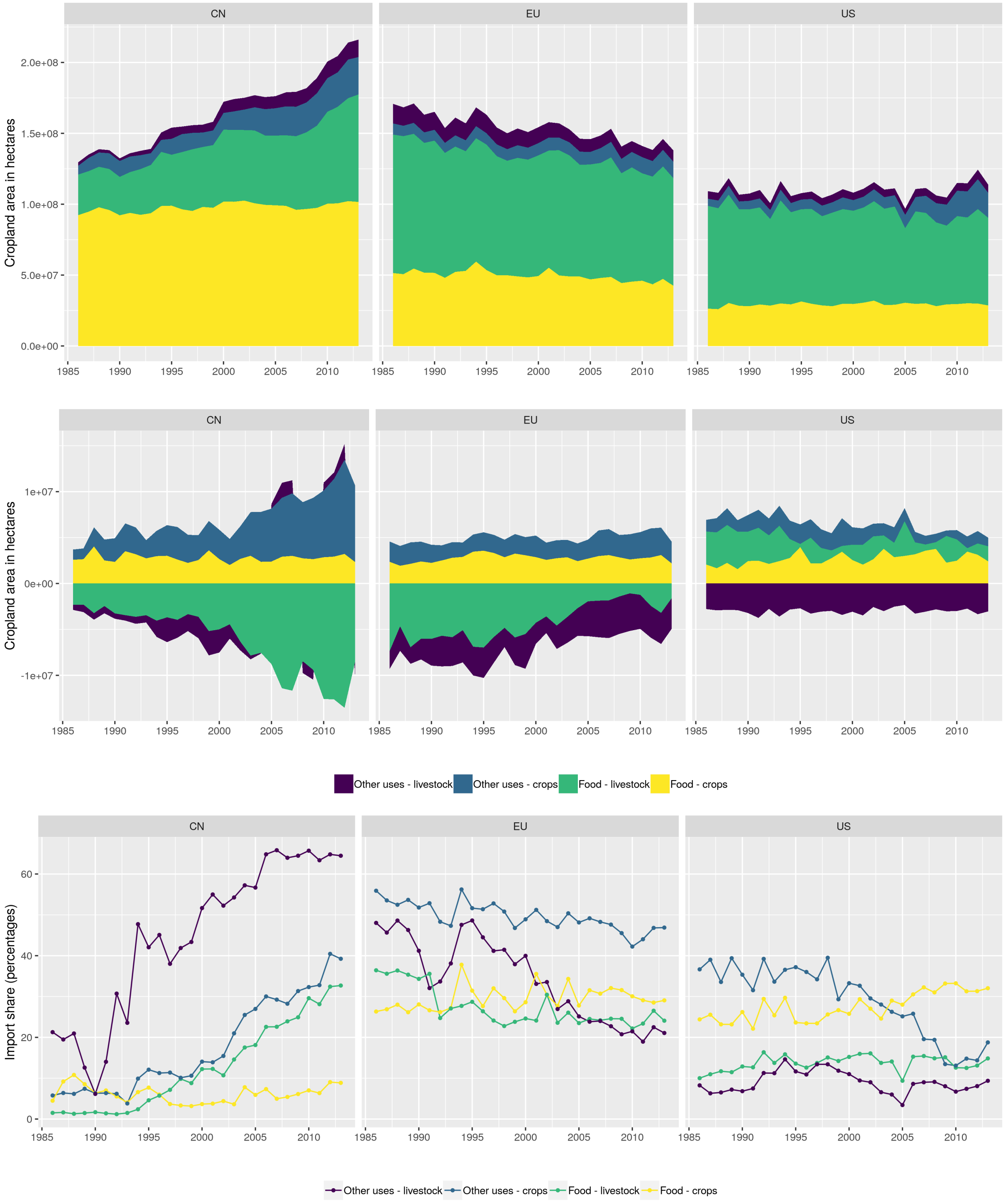

Figure 4: Plant and animal based food and non-food cropland footprint of China, the EU-28, and the USA, 1986-2013; Top: overall footprint; center: difference due to allocation method (with positive values meaning higher footprints based on value allocation); bottom: share of imports in the footprint

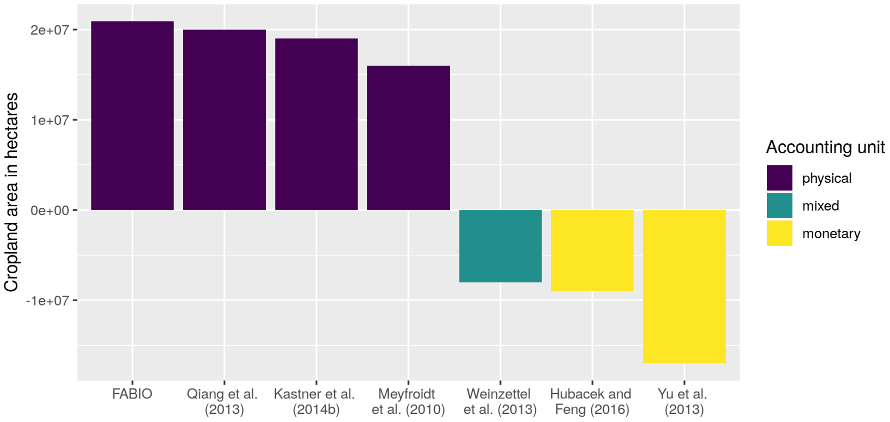

Figure 5: Comparison of China's net-trade with embodied cropland in 2004. Note: The results in Yu et al. (2013) are based on 2007 data, while all others are 2004 data.

non-food uses (e.g. the further export of derived cotton/leather products such as clothing and furniture). In total, 27 Mha of cropland were embodied in other uses of agricultural products in Chinese industries in 2004. Many of these might produce for export markets, thus reducing China's net-imports. Yet, net-exports of 17 Mha as shown by Yu et al. (2013) couldn't be reached, even if China exported all of its manufacturing products. A detailed model comparison is beyond the scope of this article and is being prepared separately.

5 Discussion

5.1 Limitations and next steps

5.1.1 Estimating feed production and demand

Achieving accurate estimates of feed production and demand is extremely challenging. On the production side, crops grown for feed are reported inconsistently, or not at all, to FAO. In some cases a crop is grown for feed and reported, in other cases a crop is used for both human consumption and animal feed (e.g. cereal grains are used for food and the straw used for feed), and in other cases crops may be grown for feed but not reported. On the consumption side, there are no international statistics on the total herd food consumption from grazing versus concentrate feed. Cattle and sheep can vary widely in their feed demands, in the extreme by perhaps up to an order of magnitude (compare a small undernourished street cow in urban India, foraging opportunistically with little provided feed, to a prizewinning Austrian dairy cow). FABIO attempts to use the best available data with global coverage (i.e., Bouwman et al., 2011; Krausmann et al., 2008) and reconcile feed production and feed demand estimates into a mass-balance consistent model, but nevertheless it must be kept in mind that estimates of feed demand remain a source of uncertainty in the results.

5.1.2 Model uncertainty

The global PSUT provided by FABIO is an underdetermined system, i.e. not all data elements in the result are explicitly informed by input data. As described above in the Methods, some elements are inferred by disaggregating or pro-rating more aggregate totals. Thus, every element of the global PSUT output is best understood not as a "true" value but rather as an estimate which is subject to some degree of uncertainty. Formalising or estimating this uncertainty remains an open task for future versions of the model. In the meantime, we suggest that values in FABIO be treated as mean expected values of a normal distribution with a standard deviation equal to 20% of the mean. This coefficient of variation can be used with Monte Carlo methods to estimate the variance of model results (Lenzen et al., 2010; Moran and Wood, 2014).

5.1.3 Linear dependency

The high similarity in the feed input composition among monogastric as well as among ruminant animals results in some degree of linear dependency between the columns of the input–output table $\mathbf{Z}$, thus impeding invertibility. The Leontief inverse therefore can be approximated using the power series expansion, i.e. $\mathbf{L} = \mathbf{I} + \mathbf{A} + \mathbf{A}^2 + \mathbf{A}^3 + ... + \mathbf{A}^\infty$, where $\mathbf{I}$ is the identity matrix and $\mathbf{A}$ is the technology matrix, which is generated by the equation $\mathbf{A} = \mathbf{Z}\hat{\mathbf{x}}^{-1}$, where $\hat{\mathbf{x}}$ is the diagonalized vector of total production output. Alternatively, the matrix becomes invertible by making an incremental change (e.g. $-1e-10$) to those values at the main diagonal of the Leontief matrix $\mathbf{I} - \mathbf{A}$ which are exactly equal to one.

5.1.4 Industrial uses

The final demand category *other uses* of FABIO comprises all industrial non-food uses. Further trade and final consumption of these products cannot be traced based on FAO data, therefore these supply chains are truncated at the place where a commodity enters a non-food industry. As shown by Bruckner et al. (2019), non-food products are responsible for about one quarter of the EU's cropland footprint, a share which was constantly rising over the past 20 years. This emphasises the relevance and importance of correctly accounting for trade and consumption of crop- and livestock-based non-food products such as biofuels, cosmetics, textiles and leather products. This could be avoided by integrating FABIO with a monetary MRIO into a hybrid IO system in order to track flows of non-food products along monetary supply chains (see, e.g., Weinzettel and Wood, 2018; Croft et al., 2018). Currently FABIO, as well as other biophysical accounting approaches (e.g. Kastner et al., 2014a), considers other uses a final consumption category. Yet, hybridization of FABIO is an obvious development option.

5.1.5 SEEA compatibility

In its current version, FABIO is not fully compliant with the SEEA guidelines for physical flow accounts for agriculture, forestry and fisheries (FAO, 2018). First, natural inputs (e.g. carbon dioxide, soil minerals, water), technical inputs (e.g. fertilizers, fuels, pesticides), and residuals (food waste, oxygen, water vapour, unused biomass, not incorporated technical inputs) are not fully captured by the PSUTs. Moreover, the commodity balances are reported in primary equivalents, aggregating agricultural and food products. Primary and secondary products can thus in many cases not be distinguished. This is a substantial limitation, as it means that FABIO's classification is not compatible with that of national accounts and it is therefore difficult to connect with economic modelling approaches using a standard industry classification such as ISIC or NACE. While production and trade data are available for agricultural and food products separately, use information is only obtainable in aggregate form. This could be overcome applying additional assumptions and some standard estimation procedures for input–output tables such as RAS or maximum entropy modelling (see Többen et al., 2018). For the first version of FABIO, we decided to stick as far as possible to the data as reported by FAOSTAT, thus not further splitting commodity balances into primary and secondary products.

5.2 Transparency and flexibility

PSUTs represent a highly transparent and flexible way of organizing physical flow data. SUTs were introduced into economic accounting in order to give a transparent framework for reporting economic transactions without the need for assumptions. They give an integrated framework for checking the consistency and completeness of data, and report transactions in natural units (products as inputs and outputs, industries as activities that transform products). From SUT data, a variety of assumptions can be made in order to utilise the data for various analytical purposes (Majeau-Bettez et al., 2014).

5.2.1 Allocation

The critical aspect here for environmental footprint or life-cycle type approaches is when co-production (joint products/by-products) occurs such that inputs into one activity are used to produce more than one output. Either disaggregation of co-production must occur, or some form of assumption (based on weight, value, the protein or energy content, etc.) must be applied to allocate the inputs into the co-production process to the respective product outputs (Weinzettel, 2012; Pelletier et al., 2015). This is the step that transforms a SUT to an IOT where inputs are uniquely represented in relation to the production and further use of products.The current version of the FABIO database comprises two sets of IO tables based on value and mass allocation. While value allocation, and the resultant footprints, pursue an economic logic, when assigning responsibility for inputs to the output product, mass allocation represents a biophysical logic, splitting inputs based on the physical outputs independent of their value for the economic system.

The choice of unit used in the allocation has a large effect on results. We compared both physical and economic allocation for transformation of PSUT to IOT, and found significant differences for livestock products and other uses of crops. These product groups are based on processes with highly differing prices of co-products. The choice of allocation procedure for these co-products can thus easily have a large impact on net-trade results. While we couldn't find significant differences in net-trade of China, calculations for Germany revealed a change in the sign. We found that Germany was a net-exporter of 0.42 Mha in the year 2013 when using mass allocation. This result, however, changed to net-imports of 0.31 Mha when applying value allocation.

It is important to note that the allocation procedure discussed here solely focuses on the allocation of inputs to co-produced products (the step to form an IOT). The further allocation according to subsequent usage of the product (performed during the Leontief inverse) fully follows a physical logic in our approach (i.e. the IOT is in physical terms). For example, the land use impacts of wheat production are allocated to the subsequent users of wheat based on the kg of wheat equivalents used, and not the dollar value of wheat equivalents used.

5.2.2 Drivers

Moreover, in contrast to other biophysical accounting approaches such as presented by Kastner et al. (2014a) and Tramberend et al. (2019), any data analysis methods applicable to matrix structures can be applied to FABIO. Structural decomposition analysis, for example, can be used to identify the drivers of changes in the global agriculture and land use system.

FABIO exposes the detailed composition and origin of renewable raw materials and related land embodied in a wide range of final products. Applying decomposition methods reveals the main driving factors, such as technology or feed mix, supply structure or affluence, responsible for changes in biomass consumption and related supply chains in different world regions over the past three decades. Such an assessment will deliver an important empirical basis for identifying potential future trade-offs arising from the increased competition for global biomass and for designing actions by business and policy makers to reduce competing demands.

5.2.3 Economic modelling

FABIO can be used as a stand-alone tool to perform scenario analyses in the tradition of IO analysis, addressing questions such as: What would be the impact on global land use if final consumption of a certain product would increase by $x\%$? However, these analyses assume that physical shares in production inputs are constant, e.g. that beef producers in one country use a fixed amount of soy cake from another country per ton of produced beef. Economic models, such as CGE and econometric models, can be combined with FABIO in order to introduce dynamic changes, such as altered bilateral trade shares based on relative price changes. At the same time, FABIO can strengthen existing economic simulation models by contributing additional product and country detail.

6 Conclusions

We developed a time series of physical biomass supply and use tables, as well as input–output tables based on international statistics reporting agricultural and forestry commodity production, trade, and use in physical units. The resulting publicly available FABIO tool traces the flows of 127 agriculture and food products across 192 countries over 27 years and thus comes at an unprecedented level of temporal and product granularity. Beyond standalone applications, it can be easily soft-coupled with existing global CGE models, such as GTAP, for agricultural sector specific scenario analyses. We expect FABIO to improve the ability of sustainability research and monitoring initiatives to produce more reliable estimates of the environmental footprints of global production and consumption patterns.

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8 Appendix

Table 2: List of commodities

Com.Code	FAO.Code	FAO.Name	Com.Group
c001	2805	Rice (Milled Equivalent)	Cereals
c002	2511	Wheat and products	Cereals
c003	2513	Barley and products	Cereals
c004	2514	Maize and products	Cereals
c005	2515	Rye and products	Cereals
c006	2516	Oats	Cereals
c007	2517	Millet and products	Cereals
c008	2518	Sorghum and products	Cereals
c009	2520	Cereals, Other	Cereals
c010	2531	Potatoes and products	Roots and tubers
c011	2532	Cassava and products	Roots and tubers
c012	2533	Sweet potatoes	Roots and tubers
c013	2534	Roots, Other	Roots and tubers
c014	2535	Yams	Roots and tubers
c015	2536	Sugar cane	Sugar crops
c016	2537	Sugar beet	Sugar crops
c017	2546	Beans	Vegetables, fruit, nuts, pulses, spices
c018	2547	Peas	Vegetables, fruit, nuts, pulses, spices
c019	2549	Pulses, Other and products	Vegetables, fruit, nuts, pulses, spices
c020	2551	Nuts and products	Vegetables, fruit, nuts, pulses, spices
c021	2555	Soyabeans	Oil crops
c022	2556	Groundnuts (Shelled Eq)	Oil crops
c023	2557	Sunflower seed	Oil crops
c024	2558	Rape and Mustardseed	Oil crops
c025	328	Seed cotton	Oil crops
c026	2560	Coconuts - Incl Copra	Oil crops
c027	2561	Sesame seed	Oil crops
c028	254	Oil, palm fruit	Oil crops
c029	2563	Olives (including preserved)	Oil crops
c030	2570	Oilcrops, Other	Oil crops
c031	2601	Tomatoes and products	Vegetables, fruit, nuts, pulses, spices
c032	2602	Onions	Vegetables, fruit, nuts, pulses, spices
c033	2605	Vegetables, Other	Vegetables, fruit, nuts, pulses, spices
c034	2611	Oranges, Mandarines	Vegetables, fruit, nuts, pulses, spices

Table 2: List of commodities *(continued)*

Com.Code	FAO.Code	FAO.Name	Com.Group
c035	2612	Lemons, Limes and products	Vegetables, fruit, nuts, pulses, spices
c036	2613	Grapefruit and products	Vegetables, fruit, nuts, pulses, spices
c037	2614	Citrus, Other	Vegetables, fruit, nuts, pulses, spices
c038	2615	Bananas	Vegetables, fruit, nuts, pulses, spices
c039	2616	Plantains	Vegetables, fruit, nuts, pulses, spices
c040	2617	Apples and products	Vegetables, fruit, nuts, pulses, spices
c041	2618	Pineapples and products	Vegetables, fruit, nuts, pulses, spices
c042	2619	Dates	Vegetables, fruit, nuts, pulses, spices
c043	2620	Grapes and products (excl wine)	Vegetables, fruit, nuts, pulses, spices
c044	2625	Fruits, Other	Vegetables, fruit, nuts, pulses, spices
c045	2630	Coffee and products	Coffee, tea, cocoa
c046	2633	Cocoa Beans and products	Coffee, tea, cocoa
c047	2635	Tea (including mate)	Coffee, tea, cocoa
c048	677	Hops	Vegetables, fruit, nuts, pulses, spices
c049	2640	Pepper	Vegetables, fruit, nuts, pulses, spices
c050	2641	Pimento	Vegetables, fruit, nuts, pulses, spices
c051	2642	Cloves	Vegetables, fruit, nuts, pulses, spices
c052	2645	Spices, Other	Vegetables, fruit, nuts, pulses, spices
c053	2662	Jute	Fibre crops
c054	2663	Jute-Like Fibres	Fibre crops
c055	2664	Soft-Fibres, Other	Fibre crops
c056	2665	Sisal	Fibre crops
c057	2666	Abaca	Fibre crops
c058	2667	Hard Fibres, Other	Fibre crops
c059	2671	Tobacco	Tobacco, rubber
c060	2672	Rubber	Tobacco, rubber
c061	2000	Fodder crops	Fodder crops, grazing
c062	2001	Grazing	Fodder crops, grazing
c063	2559	Cottonseed	Fibre crops
c064	2562	Palm kernels	Oil crops
c065	2541	Sugar non-centrifugal	Sugar, sweeteners
c066	2544	Molasses	Sugar, sweeteners
c067	2818	Sugar, Refined Equiv	Sugar, sweeteners
c068	2543	Sweeteners, Other	Sugar, sweeteners
c069	2571	Soyabean Oil	Vegetable oils
c070	2572	Groundnut Oil	Vegetable oils

Table 2: List of commodities *(continued)*

Com.Code	FAO.Code	FAO.Name	Com.Group
c071	2573	Sunflowerseed Oil	Vegetable oils
c072	2574	Rape and Mustard Oil	Vegetable oils
c073	2575	Cottonseed Oil	Vegetable oils
c074	2576	Palmkernel Oil	Vegetable oils
c075	2577	Palm Oil	Vegetable oils
c076	2578	Coconut Oil	Vegetable oils
c077	2579	Sesameseed Oil	Vegetable oils
c078	2580	Olive Oil	Vegetable oils
c079	2581	Ricebran Oil	Vegetable oils
c080	2582	Maize Germ Oil	Vegetable oils
c081	2586	Oilcrops Oil, Other	Vegetable oils
c082	2590	Soyabean Cake	Oil cakes
c083	2591	Groundnut Cake	Oil cakes
c084	2592	Sunflowerseed Cake	Oil cakes
c085	2593	Rape and Mustard Cake	Oil cakes
c086	2594	Cottonseed Cake	Oil cakes
c087	2595	Palmkernel Cake	Oil cakes
c088	2596	Copra Cake	Oil cakes
c089	2597	Sesameseed Cake	Oil cakes
c090	2598	Oilseed Cakes, Other	Oil cakes
c091	2655	Wine	Alcohol
c092	2656	Beer	Alcohol
c093	2657	Beverages, Fermented	Alcohol
c094	2658	Beverages, Alcoholic	Alcohol
c095	2659	Alcohol, Non-Food	Ethanol
c096	2661	Cotton lint	Fibre crops
c097	866	Cattle	Live animals
c098	946	Buffaloes	Live animals
c099	976	Sheep	Live animals
c100	1016	Goats	Live animals
c101	1034	Pigs	Live animals
c102	2029	Poultry Birds	Live animals
c103	1096	Horses	Live animals
c104	1107	Asses	Live animals
c105	1110	Mules	Live animals

Table 2: List of commodities *(continued)*

Com.Code	FAO.Code	FAO.Name	Com.Group
c106	1126	Camels	Live animals
c107	1157	Camelids, other	Live animals
c108	1140	Rabbits and hares	Live animals
c109	1150	Rodents, other	Live animals
c110	1171	Live animals, other	Live animals
c111	2848	Milk - Excluding Butter	Milk
c112	2740	Butter, Ghee	Milk
c113	2744	Eggs	Eggs
c114	2746	Wool (Clean Eq.)	Hides, skins, wool
c115	2731	Bovine Meat	Meat
c116	2732	Mutton & Goat Meat	Meat
c117	2733	Pigmeat	Meat
c118	2734	Poultry Meat	Meat
c119	2735	Meat, Other	Meat
c120	2736	Offals, Edible	Meat
c121	2737	Fats, Animals, Raw	Animal fats
c122	2748	Hides and skins	Hides, skins, wool
c123	2749	Meat Meal	Meat
c124	843	Pet food	Meat
c125	2745	Honey	Honey
c126	2747	Silk	Hides, skins, wool
c127	2960	Fish, Seafood	Fish
c128	1864	Wood fuel	Wood
c129	1866	Industrial roundwood, coniferous	Wood
c130	1867	Industrial roundwood, non-coniferous	Wood

Table 3: List of processes

Proc.Code	Process	Proc.Type
p001	Rice production	Primary production
p002	Wheat production	Primary production
p003	Barley production	Primary production
p004	Maize production	Primary production
p005	Rye production	Primary production
p006	Oat production	Primary production

Table 3: List of processes *(continued)*

Proc.Code	Process	Proc.Type
p007	Millet production	Primary production
p008	Sorghum production	Primary production
p009	Cereals production, Other	Primary production
p010	Potatoes production	Primary production
p011	Cassava production	Primary production
p012	Sweet potatoes production	Primary production
p013	Roots production, Other	Primary production
p014	Yams production	Primary production
p015	Suga cane production	Primary production
p016	Sugar beet production	Primary production
p017	Beans production	Primary production
p018	Peas production	Primary production
p019	Pulses production, Other	Primary production
p020	Nuts production	Primary production
p021	Soyabeans production	Primary production
p022	Groundnuts (Shelled Eq) production	Primary production
p023	Sunflower seed production	Primary production
p024	Rape and Mustardseed production	Primary production
p025	Seed cotton production	Primary production
p026	Coconuts production	Primary production
p027	Sesame seed production	Primary production
p028	Oil palm fruit production	Primary production
p029	Olives production	Primary production
p030	Oilcrops production, Other	Primary production
p031	Tomatoes production	Primary production
p032	Onions production	Primary production
p033	Vegetables production, Other	Primary production
p034	Oranges, Mandarines production	Primary production
p035	Lemons, Limes production	Primary production
p036	Grapefruit production	Primary production
p037	Citrus production, Other	Primary production
p038	Bananas production	Primary production
p039	Plantains production	Primary production
p040	Apples production	Primary production
p041	Pineapples production	Primary production
p042	Dates production	Primary production

Table 3: List of processes *(continued)*

Proc.Code	Process	Proc.Type
p043	Grapes production	Primary production
p044	Fruits production, Other	Primary production
p045	Coffee production	Primary production
p046	Cocoa Beans production	Primary production
p047	Tea production	Primary production
p048	Hops production	Primary production
p049	Pepper production	Primary production
p050	Pimento production	Primary production
p051	Cloves production	Primary production
p052	Spices production, Other	Primary production
p053	Jute production	Primary production
p054	Jute-Like Fibres production	Primary production
p055	Soft-Fibres production, Other	Primary production
p056	Sisal production	Primary production
p057	Abaca production	Primary production
p058	Hard Fibres production, Other	Primary production
p059	Tobacco production	Primary production
p060	Rubber production	Primary production
p061	Fodder crops production	Primary production
p062	Grazing production	Primary production
p063	Cotton production	Processing
p064	Sugar production, non-centrifugal	Processing
p065	Sugar production	Processing
p066	Sweeteners production, Other	Processing
p067	Soyabean Oil extraction	Processing
p068	Groundnut Oil extraction	Processing
p069	Sunflowerseed Oil extraction	Processing
p070	Rape and Mustard Oil extraction	Processing
p071	Cottonseed Oil extraction	Processing
p072	Palmkernel Oil extraction	Processing
p073	Palm Oil production	Processing
p074	Coconut Oil extraction	Processing
p075	Sesameseed Oil extraction	Processing
p076	Olive Oil extraction	Processing
p077	Ricebran Oil extraction	Processing
p078	Maize Germ Oil extraction	Processing

Table 3: List of processes *(continued)*

Proc.Code	Process	Proc.Type
p079	Oilcrops Oil extraction, Other	Processing
p080	Wine production	Processing
p081	Beer production	Processing
p082	Beverages production, Fermented	Processing
p083	Beverages production, Alcoholic	Processing
p084	Alcohol production, Non-Food	Processing
p085	Cattle husbandry	Primary production
p086	Buffaloes husbandry	Primary production
p087	Sheep husbandry	Primary production
p088	Goats husbandry	Primary production
p089	Pigs farming	Primary production
p090	Poultry Birds farming	Primary production
p091	Horses husbandry	Primary production
p092	Asses husbandry	Primary production
p093	Mules husbandry	Primary production
p094	Camels husbandry	Primary production
p095	Camelids husbandry, other	Primary production
p096	Rabbits husbandry	Primary production
p097	Rodents husbandry, other	Primary production
p098	Live animals husbandry, other	Primary production
p099	Dairy cattle husbandry	Primary production
p100	Dairy buffaloes husbandry	Primary production
p101	Dairy sheep husbandry	Primary production
p102	Dairy goats husbandry	Primary production
p103	Dairy camels husbandry	Primary production
p104	Cattle slaughtering	Processing
p105	Buffaloes slaughtering	Processing
p106	Sheep slaughtering	Processing
p107	Goat slaughtering	Processing
p108	Pigs slaughtering	Processing
p109	Poultry slaughtering	Processing
p110	Horses slaughtering	Processing
p111	Asses slaughtering	Processing
p112	Mules slaughtering	Processing
p113	Camels slaughtering	Processing
p114	Camelids slaughtering, other	Processing

Table 3: List of processes *(continued)*

Proc.Code	Process	Proc.Type
p115	Rabbits slaughtering	Processing
p116	Rodents slaughtering, other	Processing
p117	Live animals slaughtering, other	Processing
p118	Beekeeping	Processing
p119	Silkworm breeding	Processing
p120	Fishing	Primary production
p121	Forestry	Primary production

Table 4: List of countries

FAO.Code	Country	ISO	Continent
1	Armenia	ARM	ASI
2	Afghanistan	AFG	ASI
3	Albania	ALB	EUR
4	Algeria	DZA	AFR
7	Angola	AGO	AFR
8	Antigua and Barbuda	ATG	LAM
9	Argentina	ARG	LAM
10	Australia	AUS	OCE
11	Austria	AUT	EU
12	Bahamas	BHS	LAM
13	Bahrain	BHR	ASI
14	Barbados	BRB	LAM
15	Belgium-Luxembourg	BLX	EU
16	Bangladesh	BGD	ASI
19	Bolivia (Plurinational State of)	BOL	LAM
20	Botswana	BWA	AFR
21	Brazil	BRA	LAM
23	Belize	BLZ	LAM
25	Solomon Islands	SLB	OCE
26	Brunei Darussalam	BRN	ASI
27	Bulgaria	BGR	EU
28	Myanmar	MMR	ASI
29	Burundi	BDI	AFR
32	Cameroon	CMR	AFR
33	Canada	CAN	NAM

Table 4: List of countries *(continued)*

FAO.Code	Country	ISO	Continent
35	Cabo Verde	CPV	AFR
37	Central African Republic	CAF	AFR
38	Sri Lanka	LKA	ASI
39	Chad	TCD	AFR
40	Chile	CHL	LAM
41	China, mainland	CHN	ASI
44	Colombia	COL	LAM
46	Congo	COG	AFR
48	Costa Rica	CRI	LAM
49	Cuba	CUB	LAM
50	Cyprus	CYP	EU
51	Czechoslovakia	CSK	EU
52	Azerbaijan	AZE	ASI
53	Benin	BEN	AFR
54	Denmark	DNK	EU
55	Dominica	DMA	LAM
56	Dominican Republic	DOM	LAM
57	Belarus	BLR	EUR
58	Ecuador	ECU	LAM
59	Egypt	EGY	AFR
60	El Salvador	SLV	LAM
63	Estonia	EST	EU
66	Fiji	FJI	OCE
67	Finland	FIN	EU
68	France	FRA	EU
70	French Polynesia	PYF	OCE
72	Djibouti	DJI	AFR
73	Georgia	GEO	ASI
74	Gabon	GAB	AFR
75	Gambia	GMB	AFR
79	Germany	DEU	EU
80	Bosnia and Herzegovina	BIH	EUR
81	Ghana	GHA	AFR
83	Kiribati	KIR	OCE
84	Greece	GRC	EU

Table 4: List of countries *(continued)*

FAO.Code	Country	ISO	Continent
86	Grenada	GRD	LAM
89	Guatemala	GTM	LAM
90	Guinea	GIN	AFR
91	Guyana	GUY	LAM
93	Haiti	HTI	LAM
95	Honduras	HND	LAM
96	China, Hong Kong SAR	HKG	ASI
97	Hungary	HUN	EU
98	Croatia	HRV	EU
99	Iceland	ISL	EUR
100	India	IND	ASI
101	Indonesia	IDN	ASI
102	Iran (Islamic Republic of)	IRN	ASI
103	Iraq	IRQ	ASI
104	Ireland	IRL	EU
105	Israel	ISR	ASI
106	Italy	ITA	EU
107	Côte d'Ivoire	CIV	AFR
108	Kazakhstan	KAZ	ASI
109	Jamaica	JAM	LAM
110	Japan	JPN	ASI
112	Jordan	JOR	ASI
113	Kyrgyzstan	KGZ	ASI
114	Kenya	KEN	AFR
115	Cambodia	KHM	ASI
116	Democratic People's Republic of Korea	PRK	ASI
117	Republic of Korea	KOR	ASI
118	Kuwait	KWT	ASI
119	Latvia	LVA	EU
120	Lao People's Democratic Republic	LAO	ASI
121	Lebanon	LBN	ASI
122	Lesotho	LSO	AFR
123	Liberia	LBR	AFR
124	Libya	LBY	AFR
126	Lithuania	LTU	EU

Table 4: List of countries *(continued)*

FAO.Code	Country	ISO	Continent
128	China, Macao SAR	MAC	ASI
129	Madagascar	MDG	AFR
130	Malawi	MWI	AFR
131	Malaysia	MYS	ASI
132	Maldives	MDV	ASI
133	Mali	MLI	AFR
134	Malta	MLT	EU
136	Mauritania	MRT	AFR
137	Mauritius	MUS	AFR
138	Mexico	MEX	LAM
141	Mongolia	MNG	ASI
143	Morocco	MAR	AFR
144	Mozambique	MOZ	AFR
146	Republic of Moldova	MDA	EUR
147	Namibia	NAM	AFR
149	Nepal	NPL	ASI
150	Netherlands	NLD	EU
151	Netherlands Antilles	ANT	LAM
153	New Caledonia	NCL	OCE
154	The former Yugoslav Republic of Macedonia	MKD	EUR
155	Vanuatu	VUT	OCE
156	New Zealand	NZL	OCE
157	Nicaragua	NIC	LAM
158	Niger	NER	AFR
159	Nigeria	NGA	AFR
162	Norway	NOR	EUR
165	Pakistan	PAK	ASI
166	Panama	PAN	LAM
167	Czech Republic	CZE	EU
168	Papua New Guinea	PNG	OCE
169	Paraguay	PRY	LAM
170	Peru	PER	LAM
171	Philippines	PHL	ASI
173	Poland	POL	EU
174	Portugal	PRT	EU

Table 4: List of countries *(continued)*

FAO.Code	Country	ISO	Continent
175	Guinea-Bissau	GNB	AFR
176	Timor-Leste	TLS	ASI
177	Puerto Rico	PRI	LAM
178	Eritrea	ERI	AFR
179	Qatar	QAT	ASI
181	Zimbabwe	ZWE	AFR
183	Romania	ROU	EU
184	Rwanda	RWA	AFR
185	Russian Federation	RUS	ASI
186	Serbia and Montenegro	SCG	EUR
188	Saint Kitts and Nevis	KNA	LAM
189	Saint Lucia	LCA	LAM
191	Saint Vincent and the Grenadines	VCT	LAM
193	Sao Tome and Principe	STP	AFR
194	Saudi Arabia	SAU	ASI
195	Senegal	SEN	AFR
197	Sierra Leone	SLE	AFR
198	Slovenia	SVN	EU
199	Slovakia	SVK	EU
200	Singapore	SGP	ASI
201	Somalia	SOM	AFR
202	South Africa	ZAF	AFR
203	Spain	ESP	EU
207	Suriname	SUR	LAM
208	Tajikistan	TJK	ASI
209	Swaziland	SWZ	AFR
210	Sweden	SWE	EU
211	Switzerland	CHE	EUR
212	Syrian Arab Republic	SYR	ASI
213	Turkmenistan	TKM	ASI
214	China, Taiwan Province of	TWN	ASI
215	United Republic of Tanzania	TZA	AFR
216	Thailand	THA	ASI
217	Togo	TGO	AFR
220	Trinidad and Tobago	TTO	LAM

Table 4: List of countries *(continued)*

FAO.Code	Country	ISO	Continent
221	Oman	OMN	ASI
222	Tunisia	TUN	AFR
223	Turkey	TUR	EUR
225	United Arab Emirates	ARE	ASI
226	Uganda	UGA	AFR
228	USSR	SUN	ASI
229	United Kingdom	GBR	EU
230	Ukraine	UKR	EUR
231	United States of America	USA	NAM
233	Burkina Faso	BFA	AFR
234	Uruguay	URY	LAM
235	Uzbekistan	UZB	ASI
236	Venezuela (Bolivarian Republic of)	VEN	LAM
237	Viet Nam	VNM	ASI
238	Ethiopia	ETH	AFR
244	Samoa	WSM	OCE
248	Yugoslav SFR	YUG	EUR
249	Yemen	YEM	ASI
250	Democratic Republic of the Congo	COD	AFR
251	Zambia	ZMB	AFR
255	Belgium	BEL	EU
256	Luxembourg	LUX	EU
272	Serbia	SRB	EUR
273	Montenegro	MNE	EUR
276	Sudan	SDN	AFR
277	South Sudan	SSD	AFR
999	RoW	ROW	ROW

Table 5: Number of commodity balances reported and estimated for each country in 2013

Country	reported	estimated
Singapore	0	115
Qatar	0	112
Democratic Republic of the Congo	0	110

Table 5: Number of commodity balances reported and estimated for each country in 2013 *(continued)*

Country	reported	estimated
Bahrain	0	109
Syrian Arab Republic	0	103
Papua New Guinea	0	100
Burundi	0	94
Libya	0	91
Somalia	0	88
Eritrea	0	63
Lesotho	47	54
Democratic People's Republic of Korea	53	39
Turkmenistan	49	39
Lao People's Democratic Republic	65	37
Afghanistan	62	33
Viet Nam	83	31
Angola	81	31
Timor-Leste	47	31
South Sudan	0	29
Chad	63	28
Tajikistan	65	27
Sao Tome and Principe	62	27
Puerto Rico	0	27
Myanmar	88	25
United States of America	100	24
Kuwait	92	24
Mozambique	92	24
Liberia	67	24
Solomon Islands	63	23
China, mainland	104	22
Mexico	103	22
Thailand	103	22
Dominican Republic	87	22
Peru	98	21
Egypt	97	21
Iraq	86	21
Uzbekistan	78	21
Sierra Leone	74	21

Table 5: Number of commodity balances reported and estimated for each country in 2013 *(continued)*

Country	reported	estimated
Brazil	102	20
France	102	20
Canada	101	20
Germany	101	20
Netherlands	101	20
United Kingdom	101	20
Bulgaria	99	20
Spain	99	20
Colombia	98	20
Nepal	95	20
New Zealand	95	20
Côte d'Ivoire	94	20
Norway	94	20
Israel	91	20
Bolivia (Plurinational State of)	91	20
Bosnia and Herzegovina	89	20
Congo	85	20
Montenegro	78	20
South Africa	104	19
Philippines	103	19
Italy	102	19
Australia	101	19
Belgium	100	19
Czech Republic	100	19
Republic of Korea	100	19
Venezuela (Bolivarian Republic of)	100	19
Malaysia	99	19
China, Taiwan Province of	98	19
United Arab Emirates	98	19
Austria	98	19
Switzerland	97	19
Kenya	97	19
Ethiopia	95	19
Ecuador	95	19
Kazakhstan	95	19

Table 5: Number of commodity balances reported and estimated for each country in 2013 *(continued)*

Country	reported	estimated
Ghana	93	19
Ukraine	91	19
Serbia	89	19
Algeria	87	19
Brunei Darussalam	84	19
Cabo Verde	76	19
Mongolia	70	19
Samoa	64	19
Kiribati	53	19
Ireland	100	18
India	100	18
Indonesia	100	18
Poland	99	18
Greece	97	18
Guatemala	97	18
Romania	97	18
Russian Federation	96	18
Honduras	95	18
Nicaragua	95	18
Slovakia	95	18
Panama	93	18
Senegal	93	18
Uganda	92	18
Argentina	92	18
China, Hong Kong SAR	91	18
Iran (Islamic Republic of)	90	18
Albania	89	18
Burkina Faso	88	18
Rwanda	85	18
Niger	84	18
Bahamas	82	18
Gambia	80	18
Guinea-Bissau	65	18
Vanuatu	64	18
Japan	103	17

Table 5: Number of commodity balances reported and estimated for each country in 2013 *(continued)*

Country	reported	estimated
United Republic of Tanzania	103	17
Portugal	102	17
Pakistan	101	17
Nigeria	98	17
Hungary	97	17
Zambia	97	17
Madagascar	95	17
Morocco	95	17
Croatia	92	17
Uruguay	92	17
Botswana	92	17
Belarus	91	17
Swaziland	90	17
Jordan	90	17
Zimbabwe	90	17
Saudi Arabia	90	17
Tunisia	87	17
Guinea	86	17
Cuba	84	17
Kyrgyzstan	82	17
French Polynesia	79	17
Haiti	79	17
Denmark	98	16
Oman	98	16
Chile	97	16
Turkey	97	16
Costa Rica	96	16
Sweden	96	16
Mauritius	89	16
Malta	88	16
The former Yugoslav Republic of Macedonia	88	16
Trinidad and Tobago	87	16
New Caledonia	86	16
Azerbaijan	86	16
Malawi	86	16

Table 5: Number of commodity balances reported and estimated for each country in 2013 *(continued)*

Country	reported	estimated
Fiji	85	16
Republic of Moldova	84	16
Gabon	81	16
Antigua and Barbuda	80	16
Suriname	80	16
Maldives	78	16
Belize	75	16
Djibouti	67	16
Dominica	66	16
Saint Vincent and the Grenadines	66	16
Slovenia	96	15
Sri Lanka	96	15
Lebanon	95	15
Cameroon	93	15
Bangladesh	92	15
Namibia	92	15
Luxembourg	92	15
Finland	91	15
Latvia	91	15
Estonia	90	15
Jamaica	88	15
Cambodia	87	15
Benin	86	15
Georgia	86	15
Paraguay	86	15
Iceland	85	15
Mali	84	15
Barbados	81	15
Guyana	80	15
El Salvador	94	14
Lithuania	93	14
Cyprus	90	14
Togo	87	14
Central African Republic	66	14
Armenia	86	13

Table 5: Number of commodity balances reported and estimated for each country in 2013 *(continued)*

Country	reported	estimated
Mauritania	77	13
Saint Lucia	71	13
China, Macao SAR	68	13
Yemen	83	12
Saint Kitts and Nevis	69	12
Grenada	73	10
Netherlands Antilles	52	8
Sudan	92	4
Belgium-Luxembourg	0	0
Czechoslovakia	0	0
Serbia and Montenegro	0	0
USSR	0	0
Yugoslav SFR	0	0

Table 6: Detailed list of processes with multiple in- or outputs.

Process type	Process	Outputs	Inputs
Oilseed crushing	Soybean crushing	Soybean oil; Soybean cake Soybeans	
	Groundnut crushing	Groundnut oil; Groundnut cake	Groundnuts
	Sunflower seed crushing	Sunflower seed oil; Sunflower seed cake	Sunflower seed
	Rape and mustard seed crushing	Rape and mustard seed oil; Rape and mustard seed cake	Rape and mustard seed
	Cottonseed crushing	Cottonseed oil; Cottonseed cake	Cottonseed
	Coconut crushing	Coconut oil; Coconut cake	Coconuts

Table 6: Detailed list of processes with multiple in- or outputs. *(continued)*

Process type	Process	Outputs	Inputs
	Sesame seed crushing	Sesame seed oil; Sesame seed cake	Sesame seed
	Palm kernel crushing	Palm kernel oil; Palm kernel cake	Palm kernels
	Oilcrop crushing, other	Oilcrop oil, other; Oilcrop cake, other	Oilcrops, other
Sugar and sweetener production	Sugar production, non-centrifugal	Sugar, non-centrifugal; Molasses	Sugar cane
	Sugar production, refined	Sugar, refined; Molasses	Sugar beet; Sugar cane
	Sweetener production	Sweeteners, other	Barley; Cassava; Maize; Potatoes; Rice; Sweet potatoes; Wheat
Alcohol production	Alcohol production, non-food	Alcohol, non-food	Apples; Barley; Cassava; Cereals, other; Fruits, other; Grapes; Maize; Molasses; Potatoes; Rice; Rye; Sorghum; Sugar beet; Sugar cane; Wheat; Wine
	Beer production	Beer	Barley; Rice
	Beverages production, fermented	Beverages, fermented	Apples; Bananas; Barley; Cereals, other; Dates; Fruits, other; Grapes; Maize; Molasses; Oats; Plantains; Potatoes; Rice; Rye; Sorghum; Sugar beet; Sugar cane; Sugar, non-centrifugal; Sugar, refined; Sweet potatoes; Sweeteners, other; Wheat; Wine

Table 6: Detailed list of processes with multiple in- or outputs. *(continued)*

Process type	Process	Outputs	Inputs
	Beverages production, alcoholic	Beverages, alcoholic	Apples; Bananas; Fruits, other; Grapes; Maize; Millet; Plantains; Rice; Sorghum; Wheat
Livestock processing	Cattle processing	Bovine meat; Butter; Fats, animals, raw; Hides and skins; Meat meal; Milk; Offals, edible	Cattle
	Buffalo processing	Bovine meat; Butter; Fats, animals, raw; Hides and skins; Meat meal; Milk; Offals, edible	Buffaloes
	Sheep processing	Fats, animals, raw; Hides and skins; Meat meal; Milk; Mutton & goat meat; Offals, edible; Wool	Sheep
	Goat processing	Fats, animals, raw; Hides and skins; Meat meal; Milk; Mutton & goat meat; Offals, edible; Wool	Goats
	Horse processing	Bovine meat; Fats, animals, raw; Hides and skins; Meat meal; Offals, edible	Horses
	Ass processing	Bovine meat; Fats, animals, raw; Hides and skins; Meat meal; Offals, edible	Asses
	Mule processing	Bovine meat; Fats, animals, raw; Hides and skins; Meat meal; Offals, edible	Mules
	Camel processing	Bovine meat; Fats, animals, raw; Hides and skins; Meat meal; Offals, edible	Camels
	Camelid processing, other	Bovine meat; Fats, animals, raw; Hides and skins; Meat meal; Offals, edible	Camelids, other

Table 6: Detailed list of processes with multiple in- or outputs. *(continued)*

Process type	Process	Outputs	Inputs
	Pig processing	Fats, animals, raw; Hides and skins; Meat meal; Offals, edible; Pigmeat	Pigs
	Poultry processing	Eggs; Fats, animals, raw; Meat meal; Offals, edible; Poultry meat	Poultry birds
	Rabbit processing	Fats, animals, raw; Hides and skins; Meat meal; Meat, other; Offals, edible	Rabbits
	Rodent processing, other	Fats, animals, raw; Hides and skins; Meat meal; Meat, other; Offals, edible	Rodents, other
	Live animal processing, other	Fats, animals, raw; Hides and skins; Meat meal; Meat, other; Offals, edible	Live animals, other

Table 7: Processes with multiple in- or outputs.

Process	Outputs	Inputs
Oilseed crushing (represented by a single process for each input crop)	Oil and cake	Soybeans; Groundnuts; Sunflower seed; Rape and mustard seed; Cottonseed; Coconuts; Sesame seed; Palm kernels; Oilcrops, other
Sugar production (represented by a single process for refined and non-centrifugal sugar production)	Sugar, refined; Sugar, non-centrifugal; Molasses	Sugar beet; Sugar cane
Sweetener production	Sweeteners, other	Barley; Cassava; Maize; Potatoes; Rice; Sweet potatoes; Wheat

Table 7: Processes with multiple in- or outputs. *(continued)*

Process	Outputs	Inputs
Alcohol production (represented by a single process for each output product)	Alcohol, non-food; Beer; Beverages, fermented; Beverages, alcoholic; Wine	Apples; Bananas; Barley; Cassava; Cereals, other; Dates; Fruits, other; Grapes; Maize; Millet; Molasses; Oats; Peas; Plantains; Potatoes; Pulses, other; Rice; Rye; Sorghum; Sugar beet; Sugar cane; Sugar, non-centrifugal; Sugar, refined; Sweet potatoes; Sweeteners, other; Wheat; Wine
Livestock processing (a single process for each input product, i.e. animal category)	Bovine meat; Butter; Eggs; Fats, animals, raw; Hides and skins; Meat meal; Meat, other; Milk; Mutton & goat meat; Offals, edible; Pigmeat; Poultry meat; Wool	Cattle; Buffaloes; Sheep; Goats; Horses; Asses; Mules; Camels; Camelids, other; Pigs; Poultry birds; Rabbits; Rodents, other; Live animals, other

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