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

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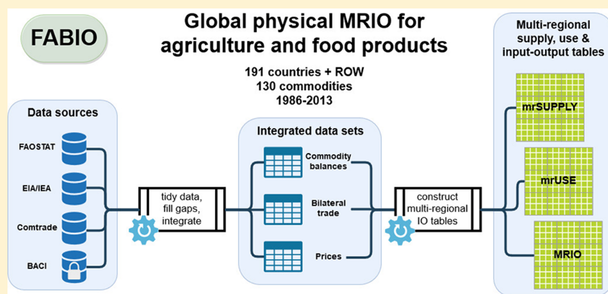
Supporting Information

ABSTRACT: Harvested biomass is linked to final consumption by networks of processes and actors that convert and distribute food and nonfood goods. Achieving a sustainable resource metabolism of the economy is an overarching challenge which manifests itself in a number of the UN Sustainable Development Goals. Modeling the physical dimensions of biomass conversion and distribution networks is essential to understanding the characteristics, drivers, and dynamics of the socio-economic biomass metabolism. In this paper, we present the Food and Agriculture Biomass Input−Output model (FABIO), a set of multiregional 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 utilization 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 organizing data representing flows of materials within metabolic networks. They allow tracing of 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. Here we apply FABIO to the case of cropland footprints and show the evolution of consumption-based cropland demand in China, the E.U., and the U.S.A. for plant-based and livestock-based food and nonfood products.



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 environmental impacts from primary production through global trade has become a prominent issue in international policy debates.[1] Traceability tools are needed to support both stakeholders and policy makers in monitoring and governing global trade-flows and their undesired impacts.[2]

Traceability tools should provide results, which are trustworthy, comprehensive, and detailed enough to be able to guide policy response. We argue in this work that current global supply chain databases, in the form of multiregion input−output (MRIO) models, are often inadequate (a) to account for the specific environmental impacts associated with 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, i.e., the networks of processes and actors that convert and distribute food and nonfood goods (metabolic networks), is arguably a prerequisite for addressing biomass goods in the context of sustainability goals.

Material flow analysis (MFA)[3] 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[4] and identifying options to reduce their negative environmental impacts, such as global warming.[5] 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.[6]

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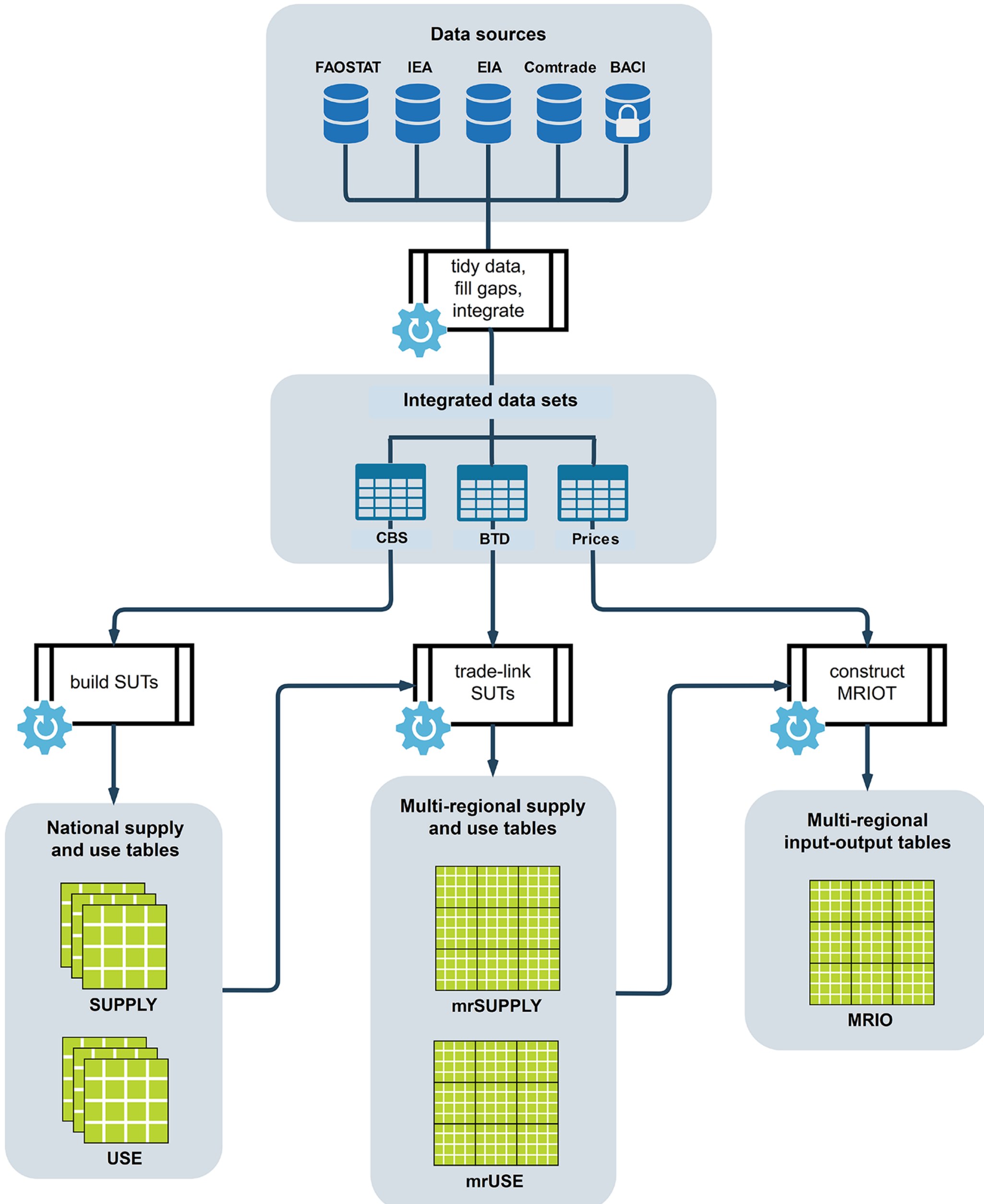

Figure 1. Flowchart illustrating the data sources and processing steps involved in building FABIO. (CBS = commodity balance sheets, BTD = bilateral trade data, SUT = supply use table, MRIOT = multiregional input−output table).

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.[7−10] PSUTs are the basis for compiling PIOTs and provide a detailed description of the physical flows between the natural and the socio-economic system.

Biobased 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 paper and food industries, use and transform these inputs of natural resources to generate products for intermediate or final consumption. Residuals are generated by both industry and households, and are either treated further within the economy or released back to the environment.

In recent years, environmentally extended multiregional 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. Despite the significant progress,[11] the robustness of MRIO-based calculations of global physical biomass flows has been questioned. Three main problematic areas have been identified.[12−15] First, the monetary structure of the economy does not always represent the quantities of physical product flows correctly. 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.[16,17] Second, the limited detail of monetary input−output tables results in a grouping of products with differing material and environmental properties and use structures into homogeneous sectors.[13] Third, there exist mismatches between agricultural

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and forestry statistics reported in physical units on the one hand, and macro-economic production statistics in monetary units however, for example due to different system boundaries.[18]

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 toward a more detailed physical data basis. For example, Ewing et al.[19] 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[20] and applied to calculate footprints for biodiversity,[21] scarce water use,[22] and net primary production.[23] A similar approach is applied by Croft et al.,[24] but going one step further for selected processed products such as vegetable oils. Liang et al.[10] 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 biomass 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.[25,26] While Kastner et al.[27] 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. The same is the case for the Trase.earth project,[28] which does not use an input−output 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 details on key countries and commodities. 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 work, 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 and one rest of world region from 1986 to 2013. By using agricultural statistics from FAOSTAT, we obtain a considerably 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.

We demonstrate this physical MRIO model applying it to the case of the cropland footprint of China, the E.U.-28, and the U.S.A. We reveal differences in trends and composition of cropland footprints and import shares over a period of nearly three decades, and highlight the role of allocation when tracing physical flows along processing steps.

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 the Estimating Missing Values section, 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 multiregional PIOT.

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 (see Supporting Information, SI, Table S.1). GTAP and EXIOBASE distinguish 21 and 27 agriculture and food products, respectively. We note that Eora offers more detail for some countries, the U.K. 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. However, other parts of the economy are not represented, which implies limitations for the tracking of nonfood commodities such as biofuels, wood, and fibers. These caveats are further elaborated in the Discussion Section.

Open Science. All data sets and R scripts are available to the research community under the GNU General Public License (GPL-v3) via GitHub (https://github.com/martinbruckner/fabio) and the open science platform Zenodo,[29] which is fully compliant with the FAIR guiding principles[30] for the provision and management of open data in scientific research. We hope that openness, transparency, and sharing of code contributes to further advancements and invite researchers to test and scrutinize our codes and results.

METHODS AND DATA

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

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 Organization of the United Nations.[31] 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 Web site. 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 zero and (b) due to the way FABIO is

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constructed these estimates will be aligned and constrained with other data sets 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.[32] UN Comtrade, the international trade statistics database of the United Nations Statistics Division,[33] provides bilateral trade data. 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 harmonized version of the UN Comtrade database, which is available for 1995 to 2017.[34] The trade data are balanced as described below.

Production data for ethanol from agricultural sources are reported by FAOSTAT under the name *Alcohol, nonfood*. However, large data gaps induced us to use production data on ethanol and biogasoline from both EIA[35] and IEA.[36]

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 plus one rest of world region to be covered in FABIO. The final classifications are given in the SI (see Tables S.2, S.3, and S.4).

The Commodity Balance Sheets (CBS), available from FAOSTAT, are the core of the FABIO PSUTs. The CBS 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."[31] Changes in moisture content, which may occur for many products between extraction and use, are neglected. The CBS database structure is designed to cover each country's entire agricultural and food processing sector.[37] About 200 different primary and processed crop and livestock commodities can be linked to form a consistent commodity tree structure using technical conversion factors.[38]

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,[20] 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.[38]

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.

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

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 silage from cropland), grazing (grasses and hay from grasslands), and timber. Therefore, commodity balances had to be built based on alternative sources. We estimated grazing production based on ref 39. Production data for all other 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, nonfood* 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, and trade data. 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. 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 coproducts, 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 their absence, we performed 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 Tables S.5 and S.6), representing less than 0.5% of the covered global product supply.

Bilateral Trade. The BTD was reconciled to receive a bilateral trade matrix b_c^{rs} in the format countries-by-countries (r

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$\times$ s) for each commodity c and year as described in the section Data Sources. The data set, as provided by FAOSTAT, reveals significant gaps and discrepancies with the total import and export quantities reported in the CBS. We followed a multistep 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 $b_c'^{rs} = \text{imp}_c^r / \text{imp}_c \times \text{exp}_c^s$
- We repeat this procedure, but spreading imports for each commodity over all countries worldwide according to their export shares: $b_c''^{rs} = \text{exp}_c^s / \text{exp}_c \times \text{imp}_c^r$
- We derive the average of the two estimates $\overline{b}_c^{rs}$ 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 data set.
- We populate the gaps in $\mathbf{B}$, i.e., those fields that are N/A, with the corresponding values from $\overline{\mathbf{B}}$ 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 bilateral trade matrices one product at a time using the RAS biproportional balancing technique[40] to ensure the original total imports and total exports are matched.

The resulting bilateral trade matrix is fully consistent with the import and export totals given by the CBS per country and commodity. In order to give an idea of the potential uncertainties, we show the discrepancies between the different FAO data sets, which are overcome with the help of the RAS method, in Table S.7 in the SI.

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 byproducts. We find a reasonable list of multioutput processes such as the crushing of oilseeds, the production of sugar, alcoholic beverages, and livestock products (see Table S.9). 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, and 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 byproducts such as edible offal, animal fats, and meat meal are split among the animal categories according to their respective share in overall meat production.

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

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.[41] 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 assessment of the actual physical flows within metabolic networks.[42] 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.[43] 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.

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.

Multipurpose 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 $u_i^p = \sum_j (s_j^p \times \phi_{ij}^p)$, 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 U.S.A., responsible for over 85% of the global ethanol production in 2014,[36] the feedstock composition is known. Brazil uses sugar cane, while the ethanol industry of the U.S.A. is mainly based on maize, with less than 2% coming from sorghum, barley, cheese whey, sugar cane, wheat, and food and wood wastes.[44] 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

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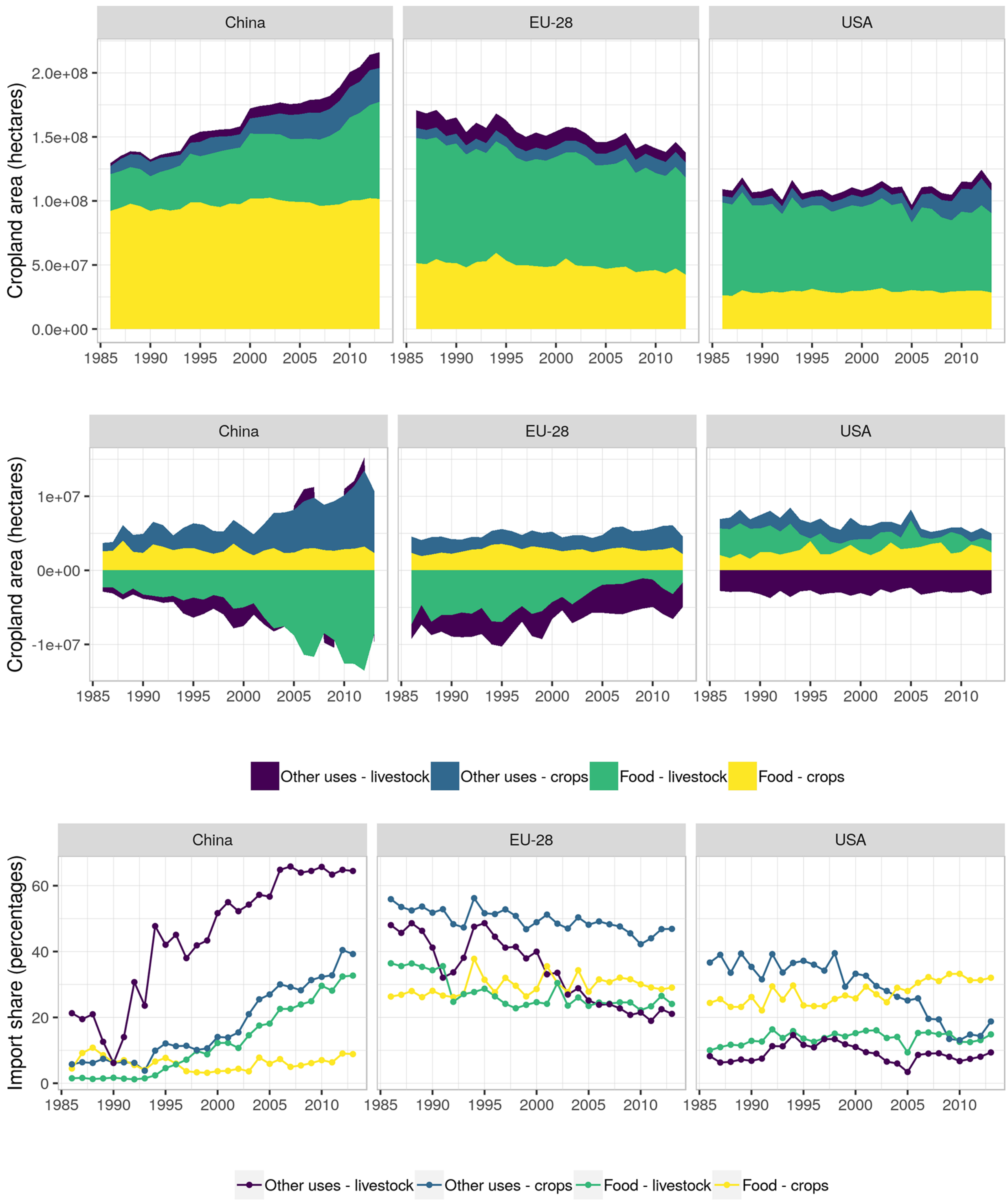

Figure 2. Plant and animal-based food and nonfood cropland footprint of China, the EU-28, and the U.S.A., 1986–2013; Top: overall footprint; center: difference due to allocation method (with positive values meaning higher footprints based on value allocation); bottom: share of imports in the footprint

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,

$$\tilde{s}_j = \sum_{i=1}^{n} (\tilde{u}_{ij} \times \phi_{ij})$$

s.t.

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

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

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 (Table S.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.
  (1) **Cattle, buffaloes, pigs, poultry, sheep, and goats:** Bouwman et al.[39] 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.
  (2) **Horses, asses, mules, camels, other camelids, rabbits and hares, other rodents, and other live animals:** Krausmann et al.[45] 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.

Trade-Linking. Once the supply and use tables for all countries are filled, they are linked into multiregional supply and use tables. The multiregional supply table **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 **U** with the dimensions $\{r, i\} \times \{s, p\}$.

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.[46,47] When applying the widely used industry technology assumption for the transformation of rectangular process-byproduct SUTs into symmetric product-byproduct 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 **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 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, phosphorus, or protein content.

■ RESULTS

Heatmaps of the resulting physical MRIO table for 2013 can be found in the SI. We extend the FABIO model by cropland use data sourced from FAOSTAT[31] and calculate exemplary cropland footprint results for China, the EU-28, and the U.S.A., distinguishing plant-based and livestock-based products for food and nonfood uses from 1986 to 2013. We apply both versions of FABIO, i.e., using mass and value allocation. Figure 2 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) based on mass allocation. 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 E.U. and the U.S.A. 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 nonfood uses, are particularly increasing in China and the U.S.A. In the E.U., we see a shift from animal-based to plant-based nonfood products. The middle part of Figure 2 illustrates the impact of using mass or value allocation for byproducts in the construction of FABIO on the cropland footprints. While the overall footprint only changes slightly, the composition changes significantly. In China and the E.U., livestock products have a smaller footprint when using value allocation. This is mainly due to the lower price of soybean cake (used as animal feed) as compared to soybean oil. Accordingly, nonfood 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 nonfood 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

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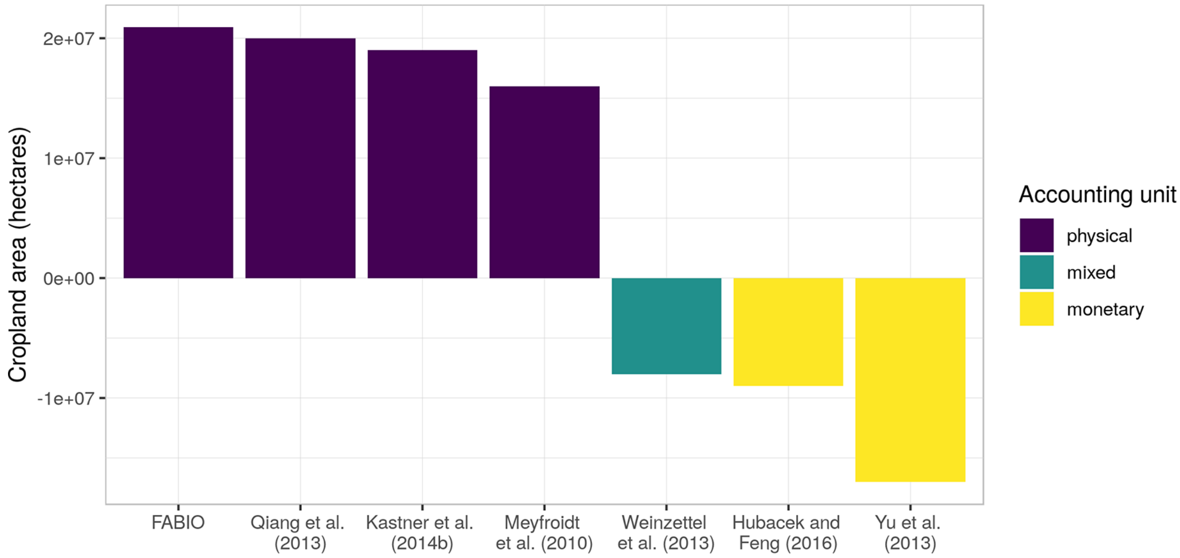

Figure 3. Comparison of China's net-trade with embodied cropland in 2004. Note: The results in Yu et al.[52] are based on 2007 data, while all others are 2004 data.

38% of the other uses of crops being affected by choice of allocation. The evolution of import shares, shown at the bottom of Figure 2, reveals an increasing reliance on imports for China's use of livestock products and crops for other uses. The E.U., at the same time, reduced import dependence for most product groups, albeit starting from high levels. The U.S.A. 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 cropland for China in 2004 presented in Hubacek and Feng,[48] including numbers from Qiang et al.,[49] Kastner et al.,[17] Meyfroidt et al.,[50] Weinzettel et al.,[51] and Yu et al.,[52] with results generated with FABIO (see Figure 3).

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 nonfood uses (e.g., the further export of derived cotton/leather products such as clothing and furniture). Currently, FABIO does not cover nonfood manufacturing industries (see Discussion section). 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.[52] could not be reached, even if China exported all of its manufacturing products. A detailed model comparison is beyond the scope of this work and is being prepared separately.

■ DISCUSSION

Limitations and Next Steps. *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 feed consumption from roughage (incl. grazed biomass) 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[39,45] 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.

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. We expect lower uncertainty for crops and derived products such as vegetable oils, as for these parts of FABIO we could draw on extensive FAOSTAT data with only minor needs for estimates or assumptions. The uncertainty for animal feed, particularly grasses, is presumably higher, as this module of FABIO is widely based on incomplete data, hence requiring comprehensive estimation algorithms. The number of commodity balances reported and estimated for each country and for each commodity for 2013 are given in Tables S.5 and S.6 in the SI. Formalizing or estimating this uncertainty remains an open task for future versions of the model. For example, standard deviation can be used with Monte Carlo methods to estimate the variance of model results.[53,54]

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., $\mathbf{L} = \mathbf{I} + \mathbf{A} + \mathbf{A}^2 + \mathbf{A}^3 + \ldots + \mathbf{A}^\infty$, 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,

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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. For the results presented here, we used the latter approach.

Industrial Uses. The final demand category *other uses* of FABIO comprises all industrial nonfood 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 nonfood industry. As shown by Bruckner et al.,[55] nonfood products are responsible for about one-quarter of the EU's cropland footprint, a share which was constantly rising over the past 20 years. These trends are confirmed by the results shown in this article for China, the E.U., and the U.S.A. (see Figure 2). We find that crop-based nonfood products are the only product category consistently showing increases throughout the three regions. This emphasizes the relevance and importance of correctly accounting for trade and consumption of nonfood products such as biofuels, cosmetics, textiles, and leather products. The truncation of nonfood supply chains could be avoided by integrating FABIO with a monetary MRIO into a hybrid IO system to track flows of nonfood products along monetary supply chains.[20,24] Currently FABIO, as well as other biophysical accounting approaches,[56] considers other uses a final consumption category. Yet, hybridization of FABIO is an obvious development option.

SEEA Compatibility. In its current version, FABIO is not fully compliant with the SEEA guidelines for physical flow accounts for agriculture, forestry, and fisheries.[57] First, natural inputs (e.g., carbon dioxide, soil minerals, water), technical inputs (e.g., fertilizers, fuels, pesticides), and residuals (food waste, oxygen, water vapor, 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 modeling 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 modeling.[58] 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.

Transparency and Flexibility. PSUTs represent a highly transparent and flexible way of organizing physical flow data strictly following a mass balancing principle. SUTs were introduced into economic accounting 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 utilize the data for various analytical purposes.[46]

Allocation. The critical aspect here for environmental footprint or life-cycle type approaches is when coproduction (joint products/byproducts) occurs such that inputs into one activity are used to produce more than one output. Either disaggregation of coproduction 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 coproduction process to the respective product outputs.[43,59] 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 the 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 coproducts. The choice of allocation procedure for these coproducts can thus easily have a large impact on net-trade results. While we found only minor differences in net-trade for China, the U.S.A., and the E.U. as a whole (see Figure 2), calculations for Germany revealed even a change in the direction of net-trade flows. 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 coproduced 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 used, and not its dollar value. In contrast, monetary IOTs would allocate wheat to users according to the users' payments, irrespective of actual physical flows.

Drivers. Moreover, in contrast to other biophysical accounting approaches such as presented by Kastner et al.[56] and Tramberend et al.,[60] 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.

Economic Modeling. FABIO can be used as a stand-alone tool to perform footprint and scenario analyses in the tradition of Leontief-style IO analysis. 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

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models, such as CGE and econometric models, can be combined with FABIO 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.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.est.9b03554.

A. Heatmaps of the physical input−output table for 2013; B. Tabular comparison of available MRIO databases with FABIO; and C. Auxiliary tables containing information on classifications, data gaps and discrepancies (PDF)

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