Author: Sun, Z.
Title: Going global to local: achieving agri-food sustainability from a spatially explicit input-output analysis perspective
Issue Date: 2021-06-01

6.

Chapter 6.
General discussion

6 General Discussion

Modern food systems have created large-scale environmental pressures yet do not result in food security for all. Due to the significant spatial heterogeneity of food production pressures, and complex supply chains, the assessment of such problems in the global agri-food system cannot be sufficiently addressed by classical GMRIO analyses. Such approaches are capable of analyzing how (in this case: food) consumption drives via international supply chains the pressures of production, but only as an average of a production sector in a country. Since food production and the related pressures depend highly on the location where this production takes place, this thesis has experimented with an alternative approach: Spatially explicit multi-regional input-output analysis (SMRIO). As indicated in the introduction, in principle SMRIO could make three elements of a traditional GMRIO matrix spatially explicit, i.e. pressures of production, expenditures related to consumption, and the intermediate inputs and outputs of production. Given the already high complexity of building traditional GMRIO databases, this thesis mainly focused on the first element by linking GMRIO databases like EXIOBASE, and the very detailed FABIO database covering agri-food products, with spatially explicit agricultural production maps. Using SMRIO, this thesis aims to answer the following overarching research question, next to drawing methodological conclusions on further improvement of the SMRIO method:

How can spatially explicit multi-regional input-output approaches be used to evaluate sustainability in the global agri-food system?

This chapter first reviews the progress made towards the specific research questions proposed in Chapter 1 and then answers the overall research question (section 6.1). It then discusses the experiences with the SMRIO method, and the prospects for developing improvements of SMRIO databases in relation to limitations experienced in the research for this thesis (section 6.2). Finally, the chapter discusses the policy implications for agri-food sustainability derived by this SMRIO perspective (section 6.3).

6.1 Answers to the research questions

Question 1: What is the current status of spatially explicit input-output analysis? (Chapter 2)

Environmentally Extended Input-Output (EEIO) analysis has been widely applied to many different environmental issues. However, EEIO analyses have been historically based on country-level analysis and hides spatial information of these impacts at a finer scale. Spatially explicit input-output analysis may offer improved visibility of heterogeneous environmental impacts along the supply chain. Chapter 2 reviewed studies of spatially explicit input-output analysis and summarized current developments. Spatially explicit input-output analyses can reveal finer spatial information of environmental impacts depending on which part of the table is disaggregated: spatially explicit environmental extensions (category 1), spatially explicit final demand (category 2), or a spatially explicit transaction matrix (category 3). Although a spatially explicit transaction matrix, as described by category 3, is ideal, it is extremely challenging and potentially intractable until a significant increase in production, transportation and consumption data becomes available. Category 2 aims to provide a better insight into consumption impacts of different consumers in the same country – for example between high-income and low-income consumers and mainly relies on regional statistics (e.g. household or enterprise surveys). With the development of high-resolution environmental impact maps, Category 1 has already seen wide use and is likely to become more popular in the future but could benefit from improved approaches for allocating production for domestic consumption and production for export.

Question 2: What are the local production hotspots of crops and livestock driven by global consumption and how does this impact food security through trade?

International trade plays a crucial role in global food security, with localizing primary crops and livestock. Chapter 2 shows that primary crop and livestock footprints were highly unequal among countries. Footprints for high-income countries are distributed over larger areas when compared to lower-income countries, since high-income countries have more trade links. Compared with primary crops, livestock consumption is mainly sourced from domestic production instead of import. In addition, consumption of primary crops and livestock in almost all high-income countries was beyond the tentative target for a safe operating space for humanity in terms of agricultural resource use. This is because high-income nations consume large amounts of animal products. Excessive consumption in high-income nations may threaten local food security in regions where they consumed.

The work also presented a different method for allocation of local and international consumption. In contrast to previous studies that assumed proportionality between production volumes and locations, this study used data from the Global Roads Inventory Project (GRIP) to allocate the spatial distribution of primary crops and livestock between domestic consumption and exports. This assumes exports of primary crops and livestock occur in locations with good transportation conditions. The study compared the results for Brazil for a previous national analysis using subnational trade data and it showed agreement, however a statistical comparison was not made due to data limitations. As a first attempt at such an approach for improving this allocation it shows promise.

Question 3: How does land use driven by final consumption affect global biodiversity within key biodiversity areas?

As an urgent, global, complex issue, biodiversity represents a critical common action problem. Key Biodiversity Areas (KBAs) are critical regions in efforts to preserve global biodiversity. However, KBAs are yet to be broadly protected by national and international treaties and as such can still be under pressure from human activities. The issue is addressed as the second application of SMRIO (Chapter 4).

The study found that land use significantly and disproportionately impacts global biodiversity within key biodiversity areas. In fact, land use within KBAs caused 16% of global plant loss and 12% of global vertebrate loss, with only 7% of total land use. This land use driven loss is especially high in tropical regions. The land use is mostly driven by consumption of animal products and housing, accounting for ~51% and 8% of species lost respectively. On its own, the consumption of bovine meat contributed to around 40% of biodiversity loss within KBAs. The type of land use also impacts biodiversity, for example, pastureland with light use contributed to around half of all species loss within KBAs. Finally, since 25%-33% of land use within KBAs is driven by international trade, it is clear that biodiversity protection needs international cooperation between producers and consumers.

Question 4: What are the global interactions between carbon emissions and carbon sequestration driven by diets and diet changes in high-income nations?

Current food system emissions may already preclude the limiting of climate change to 1.5 or even 2 °C[42]. Dietary shifts in high-income nations may help mitigate climate change by both reducing greenhouse gas (GHG) emissions from direct agricultural production and via an indirect increase in carbon sequestration if spared land is restored to its potential natural vegetation. As such, dietary change offers an opportunity for a double carbon dividend from both (1) reduced direct agricultural production emissions and (2) carbon sequestration via the land sparing whereby agricultural lands can revert to other uses. Therefore, the third application based on SMRIO is used to measure this double carbon benefit from dietary change (Chapter 5). This study found that dietary changes in high-income nations could reduce the global carbon emission of 0.61 Pg CO_2e yr^{-1} from direct agricultural production. The dietary change could also result in an increased carbon sequestration potential of 115.57 Pg CO_2e over the long term (~2.3 years of global CO_2e yr^{-1} emissions in 2010). Carbon sequestration would predominately locate in large countries with large amounts of agricultural production, especially feed crops and pasture. Often overlooked food and beverage items outside the EAT-Lancet diet could offer further potential carbon benefits but may prove difficult to harness since they include alcohol and other stimulants (a maximum increase of 27.78 Pg CO_2e sequestration and reduction of 0.08 Pg CO_2e yr^{-1} GHG emission).

In addressing these research questions this thesis shows several answers to the overall research question "*How can spatially explicit multi-regional input-output approaches be used to evaluate sustainability in the global agri-food system?*".

The thesis answered this question by providing a literature review of previous approaches and three new analyses based on a critical global issue. The review showed that SMRIO can help assess sustainability in many ways unique to this model. It was shown across all chapters that monetary-physical hybrid GMRIO datasets, when combined with spatial analyses can provide significant insights into the global food system. For instance, the spatial distribution of primary crops and livestock driven by global consumption showed the improvement potential to ensure global food security; and the comparison of per-capita primary crop and livestock footprints with a tentative target suggested a dietary change direction for each nation (Chapter 3). As a major driver of biodiversity loss and climate change, this framework was used to assess biodiversity loss driven by land use within Key Biodiversity Areas (Chapter 4) and the possibility of carbon sequestration via dietary change (Chapter 5). The results connected global food consumption to spatially explicit hotspots driven by local agricultural production.

In summary, the SMRIO approach can fully utilize spatial information and trace spatial differences along the global supply chain. With the approach, it is possible to identify actual locations where environmental pressures are predominantly driven by specific consumers. In addition, the consumption of different products caused the diverse spatial distribution of environmental pressures. The highly sectorial monetary-physical hybrid GMRIO datasets means environmental pressures can be explored on a product-resolution basis. The identified regions and specific drivers could suggest targeted implications to achieve agri-food sustainability by connecting producers, consumers, and governments along the global supply chain. While this thesis describes findings that have potentially international importance to other scientists, policy makers, and the public, there are many ways these assessments can be improved and avenues for future research.

6.2 Limitations and future research – ways forward for SMRIO

Chapter 2 provided an overview of what data would ideally be available to perform a comprehensive spatially explicit input-output analysis:

- Spatially explicit insight in production locations and the environmental pressures they cause.
- Spatially explicit insight in patterns of final demand.
- Spatially explicit insight in transaction matrices that describe value chain linkages between production and consumption activities at any spatial unit.

These three points describe options for spatializing the matrices (i.e. environmental extensions, final demand, and transaction matrix in Figure 1.1) involved in environmentally extended multi-regional input-output tables. The first point has been widely applied, given the availability of spatial datasets of extended environmental accounts. Linkage of such spatially explicit data sets on environmental pressures to GMRIO is a relatively recent phenomenon, though. Three case studies in this thesis all followed this concept for linking the spatial datasets of agri-food systems with GMRIO tables. Below I discuss the limitation of this approach and future avenues for research. I discuss the development of natural science datasets which may provide more opportunities to improve environmental pressure maps for SMRIO analysis in section 6.2.1. Locating specific consumption locations is more challenging than specific production locations given the complexity of human consumption behaviors. A blueprint or standard for geocoding consumption information for specific products in the GMRIO table is still missing and I discuss this further in section 6.2.2. The ideal situation of a full SMRIO analysis related to the third point above is intractable in the short term, given limitations in data collection, data quality, and computing power. However, proxies may be able to to help provide insights in the short term, and these are discussed in section 6.2.3.

6.2.1 **Improving environmental pressure maps for SMRIO**

This thesis relied heavily on global land use datasets, especially crop-specific maps. For example, the crop maps used in Chapter 3 to Chapter 5 were from the Spatial Production Allocation Model (SPAM), recognized as the best crop-specific maps available and widely used in research [353,377,399,400]. Most crop maps generally use a cross-entropy approach to downscale statistical data at different administrative levels depending on data availability. This cross-entropy approach optimizes the crop distribution considering related information, such as land cover and crop suitability. However, the method is still a top-down allocation approach, which may not reflect the actual crop distribution at the level of the grid cell.

Some studies have employed a remote sensing approach to illustrate the spatial distribution of some specific crops in particular regions, such as maize, wheat, soybean, barley, potato, rice, sugarcane, and cotton in the US, Zambia, India, China, Germany [313,401–404]. However, it is challenging to incorporate these case studies into a harmonized global crop atlas because these studies have different accuracies, use different interpretations of remote sensing data, and have different temporal ranges [405]: Further, definitions of cropland are sometimes inconsistent due to different application purposes and classification methods (and differs from statistical surveys), since it is difficult to identify cropland in a highly fragmented landscape with mixed cropland and other land cover types. Furthermore, satellite sensors struggle to characterize the human activities within cropland, for example, abandoned cropland from official statistics can still be detected as cropland by satellite sensors [405]. Some studies have used approaches based on machine learning to create a harmonized global picture for crops (e.g. oil palm) using remote sensing data[406]. However, these studies generally focus on one crop only and a globally harmonized crop-specific atlas will need a lot of resources and attention from the research community.

A further issue is that spatial information from satellites can only map natural impacts and not human activities. Therefore, improving the quality and attribution of natural science data to economic activities or commodities is as important as increasing spatial resolution of natural science data to better link with the economic model being used (i.e. an MRIO) [2]. A 10 km by 10 km grid cell (resolution of SPAM) may contain several types of crops and a number of associated environmental stressors (e.g. water use, GHG emissions) or impacts (e.g. biodiversity loss). Some recent projects have combined natural science datasets from satellite and *in situ* sites to estimate local production and associated impacts using artificial intelligence and machine learning [2]. If more natural stressors or impacts can be linked to GMRIO tables, an assessment with SMRIO could evaluate multiple indicators at once, which would provide a more comprehensive view of sustainable development.

6.2.2 **Locating consumption of specific products for SMRIO**

Chapter 2 argued that consumption-based environmental footprints were generally performed at the local authority level. Although a very high-resolution carbon footprint was shown, the spatial information was derived from the global gridded population dataset (at a 250-m resolution) and purchasing power datasets (the world is divided into 20,159 regions) rather than high-resolution maps of final consumption for specific products. [107]. With the development of the Internet of Things (IoT), increasing amounts of customer transaction data are digitally recorded. An increasing coverage and availability of transaction data may provide an opportunity to locate the final consumption of specific products. However, it is very challenging to harmonize these datasets since they are recorded by different suppliers and each dataset implies commercial interests.

Some geocoded consumption datasets, such as takeaway orders from an online food delivery platform in China [407,408], transactions from bank card records for point-of-sales terminals in Spain [409] and China [410], express delivery in China [411], building stocks in the US [412], and electricity consumption from supplying companies in Switzerland [413], have been applied in estimating environmental pressures. However, these datasets are samples of consumption (i.e. they do not fully cover the consumption of specific products) within a nation and do not link with GMRIO tables. In addition, there are concerns over data privacy given the high level of granularity of such data. Ideally, samples should be anonymized and data collection/application should follow international standards such as those suggested by the American Association for Public Opinion Research.

6.2.3 **Improving the accuracy of the transaction matrix within GMRIO tables**

In the available monetary GMRIO tables, economic sectors and regions are highly aggregated, especially for agricultural products. Monetary-physical hybrid MRIO frameworks are able to extend the number of product categories by connecting detailed agricultural products (e.g. in physical units in FABIO) and larger economic sectors (e.g. in monetary units in EXIOBASE). As such, the framework can trace the downstream impacts associated with agricultural production along the supply chain. However, there is no feedback from non-agricultural products to agricultural commodities within this framework. That is, this framework is unable to connect non-agricultural products and agricultural commodities (e.g. the processing or transportation of products). In addition, the number of regions in FABIO (192 countries/regions) differs from that in EXIOBASE (49 countries and nations), so the integrated framework cannot fully reveal the spatial heterogeneity across all countries. However, there are efforts to produce a version of EXIOBASE with all countries disaggregated[414].

Although adding finer spatial units and more sectors in GMRIO tables can improve SMRIO analysis, it is challenging to develop a GMRIO covering all economic sectors for all individual nations. Lenzen et al.(2017) designed a GMRIO lab, which can compile a GMRIO with any combination of regions and economic sectors according to need of users or policy makers [415]. However, the lab still needs more data sources and related technical support to achieve its ultimate goal.

In general, SMRIO studies link spatially explicit datasets with GMRIO tables and ignore the subnational trade or spatial differences in input and output transactions of the same sector within a nation. That is, the input and output coefficients are the same for each sector, regardless of location (i.e. local production is allocated to domestic consumption and export proportionally). This proportional allocation approach will create uncertainties, especially for large countries (e.g. the US, China, Brazil, Australia, and India). A robust approach for increasing spatial resolution would be to embed sub-national MRIO datasets within GMRIO datasets. For instance, Yang et al. (2020) linked China's high-resolution carbon emission maps with an integrated province-level Chinese MRIO embedded in GMRIO tables (Eora) using a proportional allocation assumption as described above[22]. However, China's material footprints derived using a proportional allocation show deviations from actual customs statistics [416]. As such, the proportional allocation approach may be an issue for other environmental pressures also. With the wider availability of national MRIO tables (e.g. the US, Japan, China, and Indonesia) and subnational trade data (e.g. the US, Brazil, Canada, Germany, Spain, and Japan) [417], linking national MRIO and subnational trade data with GMRIO can contribute to the further development of the SMRIO approach.

However, national MRIO tables or subnational trade are not available for each country. Therefore, finding a proxy is another way to allocate local production for SMRIO analysis. Chapter 3 used road density (Global Roads Inventory Project, GRIP) as a proxy to distinguish production for domestic consumption or export. However, other biophysical variables (e.g. slope and precipitation) and socio-economic variables (e.g. GDP and population density) have been found to influence local production [23]. In addition, in the absence of actual data such as local surveys the approach is not validated globally. To avoid introducing uncertainties that could be propagated through the model, Chapter 4 and Chapter 5 reverted to the proportional allocation approach.

Some recent work may help further address this proportionality issue. For production output, Malek et al. (2020) employed a cascade of related biophysical variables and socio-economic variables to create a probability map that describes the likelihood that a grid cell links with the market [23]. The allocation approach could be calibrated by trade data at the highest spatial detail available [417].

6.3 Policy implications

Locating environmental pressure hotspots driven by the demand of consumers at a high spatial resolution can help to connect local producers, consumers, environmentalists, and government to better target sustainable development[33,361]. While conventional MRIO analysis can provide policy information at a national level for social and environmental footprints, it cannot pinpoint hotspots in a spatially explicit way. The results of this thesis may help uncover the opportunities available to actors in product supply networks to address their corresponding responsibility in reducing these impacts. In terms of upstream impacts, spatially explicit hotspot maps can guide local producers to reduce social and environmental impacts. From a downstream perspective, the results can suggest options for sustainable consumption.

In practice this means actors along supply chains as identified by SMRIO could share technology and optimize financial investment to maximize global biodiversity conservation and climate mitigation [418]. Given the fact that the current net direction of traded goods moves from low- to high-income nations while high-income nations often have the technological and financial resources available to mitigate impacts, there is a large opportunity for international cooperation. The basis of this cooperation can be related to the spatial distribution of local pressures driven by the final consumption of specific nations. For example, the identified spatially explicit hotspots of primary crops and livestock could guide governments, retailers or final consumers in importing countries to support investments in pressure-reducing mitigation measures in regions which produce the food they consume, for example in improving agricultural productivity (e.g. closing yield gap) (Chapter 3). The consumption-based species loss of Western Europe and North America is mainly embodied in the imported products from tropical KBAs in Latin America, Africa, and Asia (Chapter 4). However, these tropical regions are facing rapid population growth, serious hunger and undernutrition issues, and show a rapid economic development largely relying on agriculture [419,420]. Therefore, future cropland expansion is more likely to occur in these regions to meet increasing demand for agricultural products on the one hand and expansion of economic activity on the other hand. To avoid further biodiversity loss in these biodiverse regions, Western Europe and North America could help their providers develop sustainable intensification of agricultural production. Some initiatives have highlighted an interest in international cooperation to address impacts and aid global sustainable development. For example, the Amsterdam Declarations (https://ad-partnership.org/) aims to eliminate deforestation associated with agricultural production. Similarly, The New York Declaration on Forests (https://forestdeclaration.org/) aims to halt global deforestation and restore forests. However, policies related to reducing consumption-based environmental impacts still see limited deployment. For example, less than 1% of EU's deforestation policy options address imported deforestation [421]. In addition, the implementation of policy interventions needs international cooperation across national borders. For example, the fact that biodiversity rich land areas cross socio-political boundaries could lead to a fragmentation of land use on the one hand and fragmented policy response on the other hand, and therefore drive biodiversity loss [422].

Implementing such improvement options should take the implications into account that may arise from changing production systems via policy and consumption changes in high-income nations. For examples, this thesis shows a need for addressing animal product consumption across nations as the largest driver of biodiversity loss and increasing carbon sequestration. The estimated spatial distribution of carbon benefits due to diet change led to the suggestion to restore the land use for mitigating climate change (Chapter 5). However, such climate benefits will only materialize if land upstream in the supply chain, often in developing countries, indeed is not anymore used for agricultural activities. Without additional policies – especially support for local producers that provide most agricultural products for the international market – this could cause a massive social upheaval as livelihoods in animal agriculture face rapid and deep change. The same is also true for taxes to internalize costs related to carbon emissions or biodiversity loss, and border adjustments implemented for similar purposes. Not only is implementing such measures a challenge in view of e.g. World Trade Organisation rules, but also since such external costs will differ between agricultural products and as shown in this thesis, also between different regions for the same product [353]. But such measures may also impact competitiveness of local producers significantly. Policies aiming at realizing climate and biodiversity goals related to agriculture hence must go hand in hand with measures fostering (local) economic development and poverty eradication[423].