Going global to local: achieving agri-food sustainability from a spatially explicit input-output analysis perspective

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Chapter 1.
General Introduction

1 General Introduction

1.1 Background

In an era of increasing globalization, supply chains have become tightly interconnected and complex[1]. Given the depth of integration and the importance of international trade in sometimes helping to improve resource efficiencies, facilitating socio-economic development, and promoting human welfare, today's complex supply chains have been called the lifeblood of the global economy [2]. This is especially true in the food system where international trade plays a critical role in safeguarding nutrient and food security [3,4]. Indeed, globally traded food calories have more than doubled since the 1980s, and around one-fourth of global food production is traded on international markets [5,6]. Increasing linkages among trade partners could help mitigate climatic impacts on local food production and have knock-on impacts for reducing hunger risk and improving the resilience of the food supply chain [4,7,8].

However, international trade has not only revolutionized the way that commodities are produced, exchanged, and consumed, but has also altered the sites and scale of social and environmental impacts[1]. Depending on the indicator considered, between 10% -70% of environmental pressures (e.g. land use and greenhouse gas (GHG) emissions) or impacts (e.g. biodiversity loss) are embodied in international trade. That is, the consumption of a product in one location can lead to environmental pressures across supply chains geographically located across many distant locations on the planet [1]. The social and environmental impacts embodied in international trade have been increasing with globalization. For example, CO_2 emissions from fossil fuel embodied in the global supply chain increased from 5 Gt in 1995 to 10 Gt in 2011, and the share of embodied carbon accounting for total carbon emission increased from 27% in 1995 to 37% in 2011 [9]. Similarly, agricultural production embodied in international trade has been increasing due to globalization. For example, the area of cropland embodied in the global supply chain increased from 178 Mha in 1987 to 272 Mha in 2008, accounting for 15% and 21% of the total global cropland area respectively [10]. The amount of cropland embodied in trade increased further to 350 Mha in 2016 [11].

Affluence is a primary driver of social and environmental impacts along international supply chains [1,12–14]. While organizations such as the United Nations Environmental Program (UNEP) advocates a decoupling of economic growth from environmental impacts [15], high-income countries have been displacing environmental impacts to middle- and low-income countries [1,14,16]. Such displacement often increases overall social and environmental impacts because production in middle- and low-income nations is more environmentally intensive and faces fewer regulations[1]. Consumers, who ultimately drive economic demand and hence global trade, generally show a greater desire to reduce environmental and social impacts locally rather than distant impacts through the supply chain [14]. For example, Europe restored territorial forests by 9% (~ 13 Mha) while outsourcing 11 Mha deforestation due to crop displacement from 1990 to 2014 [17]. Furthermore, the outsourced deforestation is located in climate-vulnerable regions with incomparable biodiversity and carbon stocks [17–19].

It is important to understand how consumption and production are linked via supply chains, and how final consumption drives social and environmental impacts of production processes in these value chains. In the last 15 years, Global Multi-Regional Input-Output (GMRIO) tables have become an important tool to map such relations between production and consumption[20]. In short, a (national) input-output table divides a national economy into numerous economic sectors. A consumer demand is met by a set of production relationships between sectors which ultimately require primary natural resources. Such tables are typically available at the national level from National Statistical Institutes. By combining tables from different countries, and using the information on imports and exports by sector, a GMRIO table can be constructed that maps global value chains in the form of transactions between different economic sectors and different countries, including actors responsible for final demand. If the primary resource use and emissions are calculated for each economic sector by country, then these can be added to the GMRIO table as so-called environmental extensions. The result is an Environmentally Extended (EE) GMRIO model. Such EE GMRIO models can trace environmental impacts associated with production and consumption of commodities, following the full downstream and upstream value chain [20] (see Box 1 for more details). These GMRIO tables play a critical role in analyzing social and environmental impacts embodied in international trade [20].

Box 1. An introduction to GMRIO analysis

A global multi-regional input-output (GMRIO) table provides the input-output relationships of economic sectors within and between nations [20]. They can take two different forms: product-by-product or industry-by-industry. Product-by-product tables divide the economy into multiple products, describing the amount of a product used to produce each product regardless of the industry [21]. Similarly, industry-by-industry tables divide the economy into multiple industries, describing input-output relationships of industries irrespective of the product. The following chapters employ product-by-product tables. Adding environmental pressures (e.g. primary resource extraction, land use, water use, emissions) due to production to each economic sector generates an Environmentally Extended GMIRO (EE GMIRO) table [20]. The structure of an EE GMRIO table is illustrated below in product-by-product format. The figure shows that every product links with environmental pressures associated with its production and these pressures are then embodied in economic flows via the transaction matrix. For example, soybeans produced in Brazil, which are exported to feed cattle in China, which are then exported to South Korea for final consumption in the form of beef. The production of each intermediate product from each different country results in environmental pressures (e.g. carbon emissions) that in turn cause environmental impacts (e.g. biodiversity loss) along the supply chain. EE GMRIO can estimate all pressures related to beef consumption (a consumption-based footprint). The example is only for one product, but GMRIOs cover in a similar way all product and service categories traded between economic sectors and nations.

The structure of the global economy as depicted by a GMRIO table is shown in Figure 1.1 for a product-by-product table. In a monetary product-by-product GMRIO table, the interdependencies (i.e. input requirements per unit of output) between products and regions are expressed as a matrix (known as transaction matrix, technical coefficients matrix or matrix $\boldsymbol{A}$ in Figure 1.1). The A matrix describes the direct input-output relationship or production recipe between products and nations where products can be regarded as inputs to produce other products. However, since the products used to produce another product themselves have a production recipe, the total requirements of all upstream production has to be computed. This is calculated by a solution called the Leontief inverse matrix given by $L = (I - A)^{-1}$.

The EE GMRIO approach inherits an economic consistency from the GMRIO approach, which means direct environmental pressures generated from production cannot be "lost" in the calculation along the global supply chain [20]. The total pressures due to production shown in an EE GMRIO, by definition are equal to the total environmental footprints of consumption. Given its consistency, EE GMRIO tables are widely used to trace environmental pressures embodied in the global supply chain.

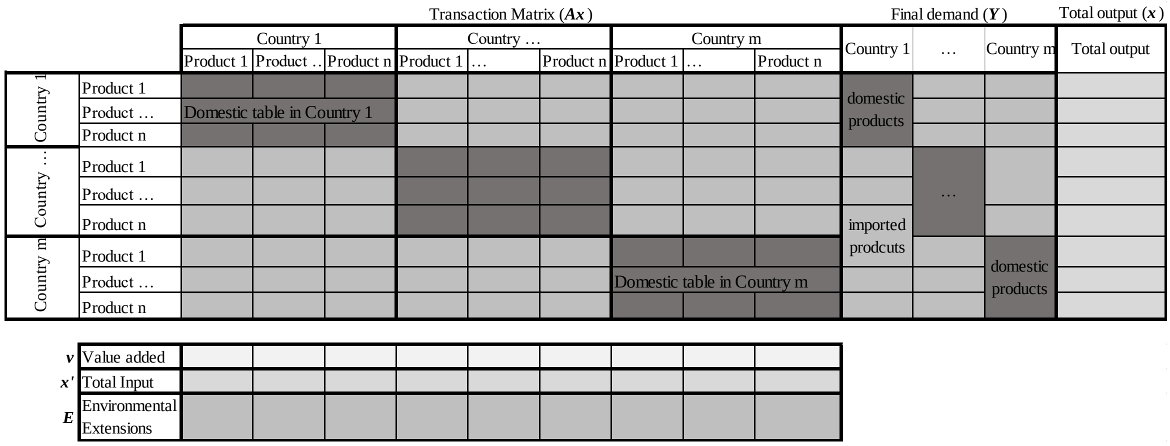

Figure 1.1. The structure of an EE GMRIO table. The transaction matrix is given by A, the final demand (the consumption of goods and services by different sectors of society) by F, the extension row vectors to the bottom of the table by E. The latter can describe economic extensions such as the value added required to produce a product, social extensions such as the hours of labor required, or environmental extensions such as emissions.

1.2 The heterogeneity of social and environmental impacts, especially in food systems

The number of EE GMRIO studies has been increasing rapidly in recent years, resulting in many country-level social and environmental footprint assessments[1]. They have focused on many different social and environmental pressures and impacts, including climate change (e.g. CO_2, N_2O, CH_4), air pollution (e.g. $PM_{2.5}$, PM_{10}, NO_x, SO_2), biodiversity loss, and employment [1]. However, as indicated, GMRIO tables are usually only available at country level and represent the average information of an economic sector for a country. The implication is that while the GMRIO approach is capable of calculating footprints of consumption, the hotspots contributing to these footprints at best can be identified at the level of sectors in a specific country. However, local social and environmental impacts of the same sector can be spatially very heterogeneous. This issue is prominent in some large countries (e.g. the US, Brazil, and China). In addition, drivers of environmental pressures from both a production and consumption perspective can be spatially concentrated. This is due the fact that different human production and consumption activities are often concentrated in specific geographical areas. For example, more than 90% of the Chinese population and most production and consumption activities of Chinese people concentrate on the east of Heihe-Tengchong Line (also known as Hu Huanyong-Line), which only accounts for 40% of China's area. Overall only 1% of China's land area accounted for three-quarters of carbon emissions driven by global consumption in China [22].

The need for spatially explicit assessments is particularly relevant for the agri-food system. The type of agricultural production in a specific area is determined by a variety of biophysical (e.g. climate conditions, land topography, and soil property) and socioeconomic variables (irrigation, population density, access to market, and cultural convention) [23]. For example, more than 90% of global oil palm is planted in Indonesia and Malaysia in relation to the specific climatic conditions in these countries [24]. In addition, there is also huge spatial heterogeneity of agricultural production and associated social and environmental impacts within a nation. For example, the US contributes to about 40% of global soybean and corn production, with 85% of this production being located in the "Corn Belt" [25]. However, agricultural production is commonly shown at provincial or country-level administrative units, which masks local diversity and spatial patterns [26].

With the development of remote sensing technologies and hyperspectral image-processing methods, an increasing number of high-resolution global land cover maps are available (e.g. Copernicus Global Land Service [27], GlobeLand30 [28], ESA-CCI-LC [29], MODIS [30], Global Food Security-Support Analysis Data[31]). These datasets are widely used to study local social and environmental impacts associated with crop and livestock production. The results of such analyses show that social and environmental impacts due to local production are spatially heterogeneous [32]. At the same time, production- and consumption-based analysis with traditional GMRIO tables misses this spatial heterogeneity, since they usually cover rather aggregated economic sectors (including agricultural sectors) with average data for whole countries.

1.3 Global spatially-explicit multi-regional input-output analysis

To trace the pathways of local social and environmental impacts along international supply chains or to identify local impact hotspots driven by global consumption, a new approach is emerging: global spatially-explicit multi-regional input-output analysis (SMRIO). There are three main options in which the spatial resolution of GMRIO models can be increased. The three options are related to the three main matrices pictured in Box 1 (***E, A, and F)***:

- Spatially explicit environmental or social extensions. That is, a spatially explicit picture is provided of the resources, emissions or land use related to production within a specific economic sector (represented by matrix ***E)***.
- Spatially explicit final demand. That is, a spatially explicit picture of the consumption of households, businesses or governments in different locations is provided, representing for example the consumption baskets of cities vs rural consumers (represented by matrix ***F***).
- Spatially explicit transaction matrices (represented by matrix ***A***). Such matrices describe value chain linkages between production and consumption activities at a high spatial resolution (and usually require information on points 1 and 2 above, too. We make this differentiation, since some SMRIO approaches just give spatially explicit information on production, or consumption, without making the transaction matrix spatially explicit).

The data requirements, already significant in the classic GMRIO approach, would be overwhelming if the approach was to include all three aspects. A more tractable approach would be to exclude points 2 and particularly 3. While in principle the intermediate inputs and outputs for a product, as given in the transaction matrix, could differ by location, as a first proxy the assumption could be made that similar production processes have similar, national average inputs and outputs. This reduces the complexity of constructing SMRIOs to combining information from GMRIOs with spatially explicit information of production activities. Such an approach would still help identify local social and environmental impacts hotspots driven by global consumption of goods and services, and which actors are involved in specific supply chains [33,34].

In the domain of agriculture and food there are several datasets that can be used in support of such a SMRIO approach. These include crop-specific land use maps such as EarthStat [35] and the Spatial Production Allocation Model [26]. Another useful dataset is the recently developed Food and Agriculture Biomass Input-Output (FABIO) table[36]. FABIO is an annual table at an unprecedented level of detail in agricultural and forestry products by country, covering 191 countries and 130 agriculture, food, and forestry products from 1986 to 2013 [36]. By linking the national data provided by FABIO to spatially explicit agricultural production maps it becomes possible to develop highly product- and location-specific details of social and environmental pressures associated with agricultural production and consumption along the international supply chain [36]. While a limitation of FABIO is that it does not cover the total economy, compared to existing GMRIOs it gives an unprecedented detail in transactions related to agriculture, food and forestry products.

1.4 Priorities in sustainable development – a focus on agriculture

The agricultural system currently occupies ~43% of global ice- and desert-free land. The food system is a major driver of biodiversity loss[37]. This is a critical issue since the earth is entering a sixth mass extinction. That is, current species extinction rates are 100-1000 times higher than the background extinction rate [38,39]. Around 25% of all species face extinction within decades, and the species extinction rate may even accelerate without any further increase in the drivers of biodiversity loss [40,41]. Around 26% of human GHG emissions are created along the global food supply chain, predominately via direct agricultural production (e.g. fertilizer use and enteric fermentation of ruminants) and indirect via land-use change (e.g. deforestation) [42]. Most GHG emissions from the food system are related to the production and consumption of animal products. For example, about one-third of global cereal production (which accounts for 40% of global cropland) is used to feed livestock [43]. This is somewhat unsurprising when we consider that the energy feed-to-food conversion efficiency of animal products is low and varies from 3% for beef to 17% for eggs within animal products [44]. In addition, consumption of animal products, especially unprocessed red meat and processed meat, increases the risk of some diseases (e.g. cancer, cardiovascular disease, diabetes, and stroke) [45,46].

Next to these significant environmental pressures we are seeing increasing concerns related to food security around the world. Yield growth has been slowing or even stagnating; average global crop yields for the 174 crops covered in FAOSTAT increased by 56% in the first stage of the Green Revolution (from 1965 to 1985), but only 20% in the post-Green Revolution (from 1985 to 2005)[47,48]. The world is off-track to achieve targets related to food security and the number of hungry and malnourished people has been increasing in past years [49]. Furthermore, agricultural production caused numerous serious social and environmental impacts because the present agricultural system is resource- and labor-intensive and consuming a large amount of natural capital [37].

On top of these issues, food systems are also highly spatially heterogeneous globally. Few studies have investigated local agricultural production and associated social and environmental impacts along the global supply chain. There are exceptions, for example studies that map local freshwater pressure driven by global consumption, but these are at a rather coarse spatial resolution (e.g. basin level) and discern just a few agricultural sectors[50]. One of the reasons is that the agricultural sectors are highly aggregated in the present GMRIO tables. Therefore, we chose the food and agricultural system as a focus in this thesis. We build an SMRIO framework to examine three key issues in sustainable food production in the following chapters—food security, biodiversity loss driven by global land use, and the carbon emission and sequestration implications of dietary changes. Each of these issues relates to different drivers and pressures or problems in the production stage, and requires hence a somewhat different approach in the SMRIO analysis.

1.5 Aims and research questions

This thesis investigates the global SMRIO method and its use in assessing environmental pressures and impacts. The thesis uses the food system as an application area, given the fact that food consumption is a driver of major environmental issues, such as biodiversity loss and carbon emissions. The analysis of such problems related to the agri-food system can benefit greatly from a spatially explicit approach. The overall research question is:

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

This main research question is addressed via the following sub-questions discussed in the following chapters (see Figure 1):

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

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? (Chapter 3)

Question 3: How does land use driven by final consumption affect global biodiversity within key biodiversity areas? (Chapter 4)

Question 4: What are the global interactions between carbon emissions and carbon sequestration driven by diets and diet changes in high-income nations? (Chapter 5)

1.6 Outline of this thesis

This thesis is composed of 6 chapters. This chapter gives a general introduction, and Chapters 2 to 5 address the above research questions. Chapter 6 summarizes and synthesizes the main findings of this thesis, and discusses limitations. In short, the principal content of each chapter is as follows:

Chapter 1 introduces recent developments in the assessment of social and environmental impacts embodied in international trade based on GMRIO analysis, and shows that GMRIOs overlook spatial heterogeneity of such pressures and impacts at local scale. It shows that SMRIO is an approach that can overcome this limitation, and that spatially explicit analyses are particularly relevant for the agri-food system. It also identifies three priorities (food security, biodiversity, climate change), which are applied to case studies in the following chapters.

Chapter 2 reviews the state of the art of spatially explicit input-output analyses, diagnoses the mechanisms connecting global consumption with local environmental impacts and identifies research gaps. It proposes a theoretical framework of the global spatially explicit multi-regional input-output approach by analyzing previous studies and provides methodological support to the following chapters.

Chapter 3 explores the importance of primary crop hotspots in international trade and food security. It uses the road network to allocate between domestic consumption and export, identifies hotspots (the most significant regions for production) for primary crops and livestock driven by international consumption, and compares per-capita primary crop and livestock consumption with an illustrative target safe operating space for every nation.

Chapter 4 assesses global biodiversity loss caused by anthropogenic land use within key biodiversity areas (KBAs) driven by final consumption. The assessment is performed by combining the Food and Agriculture Biomass Input-Output (FABIO) and EXIOBASE input-output databases with spatially explicit agricultural production maps. The biodiversity loss calculation is based on the land use area driven by global consumption and characterization factors (i.e. global species-equivalents potentially lost per area of land use) under different land use types and intensities.

Chapter 5 estimates a 'double dividend' of reduced GHG pressures by dietary changes in high-income countries from both (1) reduced direct agricultural production emissions and (2) carbon sequestration via land sparing whereby agricultural lands can revert to other uses.

Chapter 6 answers research questions, discusses broader insights, provides some policy implications, and provides recommendations for the development of spatially explicit input-output analysis.

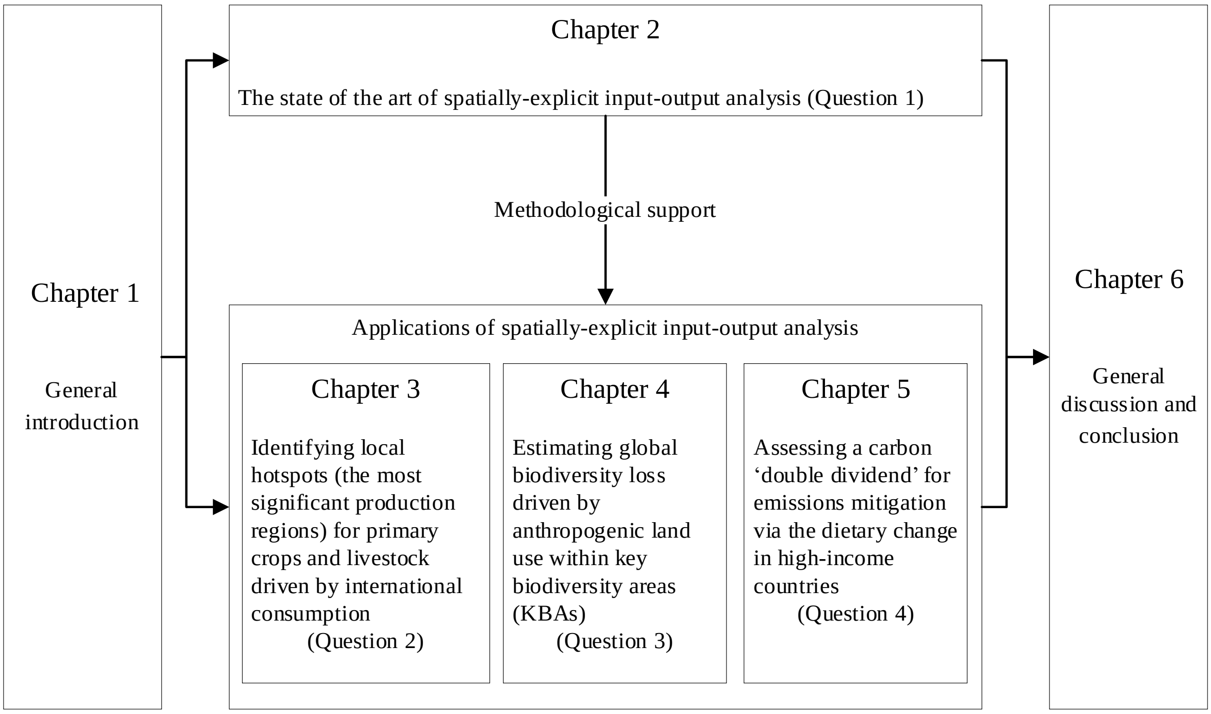

Figure 1.2. Outline of this thesis.