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Exploring the relevance of spatial scale to life cycle inventory results using environmentally-extended input-output models of the United States

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ABSTRACT

The accuracy of direct and indirect resource use and emissions of products as quantified in life cycle models depends in part upon the geographical and technological representativeness of the production models. Production conditions vary not just between nations, but also within national boundaries. Understanding the level of geographic resolution within large industrial nations needed to reach acceptable accuracy has not been well-tested across the broad spectrum of goods and services consumed. Using an aggregate 15-industry environmentally-extended input-output model of the US along with detailed interstate commodity flow data, we test the accuracy of regionalizing the national model into two-regions (state - rest of US) versus 51 regions (all US states + DC). Our findings show the two-region form predicts life cycle emissions and resources used within 10–20% of the more detailed 51-region form for most of the environmental flows studied. The two-region form is less accurate when higher variability exists in production conditions for a product.

1. Introduction

Life cycle assessment (LCA) is an established and internationally standardized framework for estimating environmental impacts of goods and services and policies affecting their production, distribution, use, and disposal (ISO, 2006). A widely applied LCA method is environmentally-extended input-output (EEIO) analysis, which uses sector-level economic statistics in combination with various environmental data to represent sector emissions and resource use. The method has known limitations such as the lack of product-specific data, or aggregation error, and uncertainties regarding the price-quantity relationships (Heijungs and Suh, 2002). It also has many advantages, including its comprehensiveness and use of data curated by national statistical agencies such as those data collected in a census, or otherwise reported by legal mandate that are considered highly reliable.

EEIO models have been applied at national and global scales to quantify emissions associated with consumption and embodied in trade. A number of national and global EEIO models have been developed (Kerkhof et al., 2009; Lenzen, 1998; McGregor et al., 2008; Nansai, 2009; Weber et al., 2009; Wiedmann, 2009; Yang and Suh, 2011; Wood et al. 2015), including the recent USEEIO model created by the authors and others (Yang et al., 2017b). However, environmental policies within many advanced and developing economics are increasingly being developed at the regional level to account for variations in economic and environmental needs (Fredriksson and Millimet, 2002; Prager and Freese, 2009; Prasad and Munch, 2012; Zhang and Wen, 2008). Therefore, there is a growing need for the use of EEIO models at subnational levels to support analyses that can inform regional environmental decision making. For regional EEIO analysis, a state or a province might be the most proper spatial resolution, because much of the official authority with regard to industrial and economic activity, as well as environmental oversight, resides at this level for most countries. States or provinces have an interest in encouraging economic growth, protecting public environmental health within their borders, and understanding the unique regional nature of activities within their jurisdiction.

Ideally, state-based or province-based EEIO models would be similar to the environmentally-extended multiregional input-

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output (EE-MRIO) models at the global scale (Tukker et al., 2009), with each state or province differentiated and connected through interregional commodity flows (Yang, 2016; Lenzen et al. 2017). Such a detailed model fully captures regional economic and environmental situations and interregional dependences. It can be used to study the national implications of regional economic activities or policies, for example, the life cycle environmental impacts of products consumed in one or any region and how the impacts are distributed in other regions (Isard, 1951). It can also be used to study the regional implications of national activities or policies, for example, the life cycle environmental impacts of an average product consumed in different regions and how each region may be affected (Yang and Heijungs, 2017). Developing such a multiregional EEIO model within a country, however, presents numerous challenges. Most states or provinces do not produce input-output tables. And trade may not be well tracked between states or provinces, in ways it is across international borders, because commodities flow freely within a country.

In addition, for policy makers of one state or province with limited resources and whose primary interest is their own jurisdiction, a detailed multiregional model may be impractical and beyond the scope. In this case, a more practical solution may be a simplified 2-region EEIO model, with one region being the state/province of interest and the other being the rest of the country. The simplified 2-region model can be relatively easily derived from a national EEIO model. Data only need to be collected on 1) the economic and environmental aspects of the region of interest and 2) trade between the region and the rest of the country, as opposed to collecting such data for all regions in the detailed multiregional EEIO model.

The question is, how accurate is the simplified 2-region model as opposed to the detailed multiregional EEIO model? Theoretically, the loss of spatial resolution could compromise the accuracy of the results. For example, the state/province of interest may purchase its products primarily from one or several states/provinces. Under these circumstances, the aggregation of all other states/provinces into one region may lead to over- or under-estimates of its supply chain impacts. On the other hand, the extent to which the accuracy may be compromised depends on a range of factors including how different the states/provinces are and how commodities flow between them.

We address these questions in this paper. Taking the United States (US) as a case study, we present a test of the accuracy of 2-region (state-rest of the country) EEIO models by comparing their results with that of a detailed multiregional EEIO model that differentiates all states and the District of Columbia. Our goal is to improve our understanding of the level of spatial resolution necessary for accurately modeling the life cycle environmental consequences of production or consumption activities within a state/province. Our study contributes to the regional LCA literature by exploring the important question of spatial scale or spatial aggregation in life cycle inventory (LCI) analysis. That is, how the numbers of regions and their sizes and industry profiles drive differences in LCI results. This subject remains largely unexplored (Yang, 2016; Yang and Heijungs, 2017), with the exception of Su and Ang (2010) using Chinese EEIO models. Studies of regionalized LCA have focused on life cycle impact assessment (LCIA), such as developing regionalized characterization factors (Hellweg and i Canals, 2014; Potting and Hauschild, 2006). Studies covering LCI analysis often regionalized the foreground processes only (Mutel et al., 2011; O'Keeffe et al., 2016; Tessum et al., 2012; Xue et al., 2015; Yang et al., 2012), or failed to account for linkages between regions (Yang, 2016).

2. Methods and data

We first develop a 51-region EEIO model by regionalizing national input-output (IO) accounts (section 2.3). We then aggregate it into 51 unique 2-region (state-rest of the country) models. We compare the results from the 2-region models against that from the 51-region model, and calculate relative errors as an indication of how accurate the 2-region models are as a proxy for the 51-region model. The relative error is defined as:

$$RE = \frac{|m_1 - m_2|}{m_1} \tag{1}$$

where m_1 symbolizes life cycle inventory results from the 51-region model and m_2 results from the 2-region models. We explore reasons for variation of relative errors for different environmental flows. Details on computational structure and data compilation and processing are as follows.

2.1. Computational structure

The computational structure of the regionalized EEIO models is based on the use and make (UV) framework (Miller and Blair, 2009):

$$\mathbf{U} = \begin{bmatrix} \mathbf{U}^{1,1} & \mathbf{U}^{1,2} & \dots & \mathbf{U}^{1,n} \\ \mathbf{U}^{2,1} & \mathbf{U}^{2,2} & \dots & \mathbf{U}^{2,n} \\ \dots & \dots & \dots & \dots \\ \mathbf{U}^{n,1} & \mathbf{U}^{n,2} & \dots & \mathbf{U}^{n,n} \end{bmatrix} \tag{2}$$

$$\mathbf{g} = \begin{bmatrix} \mathbf{g}^1 & \mathbf{g}^2 & \dots & \mathbf{g}^n \end{bmatrix} \tag{3}$$

$$\mathbf{V} = \begin{bmatrix} \mathbf{V}^{1,1} & \mathbf{V}^{1,2} & \dots & \mathbf{V}^{1,n} \\ \mathbf{V}^{2,1} & \mathbf{V}^{2,2} & \dots & \mathbf{V}^{2,n} \\ \dots & \dots & \dots & \dots \\ \mathbf{V}^{n,1} & \mathbf{V}^{n,2} & \dots & \mathbf{V}^{n,n} \end{bmatrix} \tag{4}$$

$$\mathbf{q} = \begin{bmatrix} \mathbf{q}^1 & \mathbf{q}^2 & \dots & \mathbf{q}^n \end{bmatrix} \tag{5}$$

where $\mathbf{U}$ is the use table, reflecting commodities used by industries to produce their output. On-diagonal and off-diagonal blocks in $\mathbf{U}$ indicate intra- and inter-regional commodity flows. For example, $\mathbf{U}^{2,2}$ and $\mathbf{U}^{1,2}$ indicate commodities consumed in region 2 that are produced in region 2 and region 1, respectively. $\mathbf{V}$ is the make table, reflecting commodities produced by industries. Submatrices in $\mathbf{V}$ indicate contributions to commodities in a region. For example, $\mathbf{V}^{1,1}$ and $\mathbf{V}^{2,1}$ indicate total commodities available in region 1 that are from regions 1 and 2. $\mathbf{g}$ is a vector of total industry output, and $\mathbf{g}^i$ ($i = 1, \dots, n$) indicates total output produced by industries in region i. And $\mathbf{q}$ is a vector of total commodity, and $\mathbf{q}^i$ ($i = 1, \dots, n$) indicates total commodities available in region i.

In addition, total environmental emissions and resource use are expressed by (Suh et al., 2010):

$$\mathbf{E} = \begin{bmatrix} \mathbf{E}^1 & \mathbf{E}^2 & \dots & \mathbf{E}^n \end{bmatrix} \tag{6}$$

where $\mathbf{E}^i$ ($i = 1, \dots, n$) indicates direct emissions and resource use (per dollar) by industries in region i. To calculate the life cycle (cradle-to-gate) emissions and resources per dollar worth of a commodity (k) produced in region i:

$$\mathbf{m} = \mathbf{B}(\mathbf{I} - \mathbf{A})^{-1}\mathbf{f} \tag{7}$$