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Implications of a consumer-based perspective for the estimation of GHG emissions. The illustrative case of Luxembourg

Dario Caro [a,c,*], Benedetto Rugani [b], Federico Maria Pulselli [a], Enrico Benetto [b]

[a] Ecodynamics Group/DEEPS, Department of Environment, Earth and Physical Sciences, University of Siena, Via A. Moro, 2, I-53100 Siena, Italy
[b] Public Research Centre Henri Tudor (CRPHT), Resource Centre for Environmental Technologies (CRTE), 6A, avenue des Hauts-Fourneaux, L-4362 Esch-sur-Alzette, Luxembourg
[c] Department of Animal Science, University of California, Davis, CA 95616, USA

HIGHLIGHTS

- GHG emissions for Luxembourg are assessed using hybrid input–output (IO) modeling.
- Consumer and producer perspectives are compared for the period 1995–2009.
- IO-based GHG profiles are remarkably higher than traditional IPCC inventorying.
- IO-based GHG accounting presents some advantages but is limited in implementation.
- Key-aspects of IPCC and IO-based methods are extensively investigated and compared.

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ABSTRACT

The Kyoto protocol has established an accounting system for national greenhouse gas (GHG) emissions according to a geographic criterion (*producer perspective*), such as that proposed by the IPCC guidelines for national GHG inventories. However, the representativeness of this approach is still being debated, because the role of final consumers (*consumer perspective*) is not considered in the emission allocation system. This paper explores the usefulness of a hybrid analysis, including input–output (IO) and process inventory data, as a complementary tool for estimating and allocating national GHG emissions according to both *consumer*- and *producer*-based perspectives. We assess the historical GHG impact profile (from 1995 to 2009) of Luxembourg, which is taken as a case study. The country's net consumption over time is estimated to generate about 28,700 Gg CO_2e/year on average. Compared to the conventional IPCC inventory, the IO-based framework typically shows much higher emission estimations. This relevant discrepancy is mainly due to the different points of view obtained from the hybrid model, in particular with regard to the contribution of imported goods and services. Detailing the GHG inventory by economic activity and considering a wider system boundary make the hybrid IO method advantageous as compared to the IPCC approach, but its effective implementation is still limited by the relatively complex modeling system, as well as the lack of coordination and scarce availability of datasets at the national level.

1. Introduction

Greenhouse gas (GHG) inventories aim at accounting for the emission and absorption of GHGs in a given country. These inventories, upon which the binding agreements in the Kyoto protocol and all post-Kyoto commitments are based, usually adopt a producer-oriented approach, implying that the environmental effects of the production of commodities must refer to the producer country (*producer perspective* or *geographic criterion*) (IPCC, 2006). This perspective, however, disregards the influence of imported products, whose production requires somewhere else substantial amounts of energy and matter, as well as the implementation of production processes and related emission of GHGs (Statec, 2014). Significant environmental impacts, including GHG emissions, can be shifted from one country to another because impacting production processes is often delocalized and large quantities of goods are traded internationally (Su and Ang, 2011; Wiebe et al., 2012a; Caro et al., 2014b). Several studies suggest that this mechanism can result in a global increase of environmental impacts and GHG emissions (Davis and Caldeira, 2010; Peters and Hertwich, 2008a; Ackerman et al., 2007; Li and Hewitt, 2008; Wiedmann et al., 2011). At the same time, the delocalization of intensive production process, even from the point of view of GHG emission, is facilitated.

Alternative accounting procedures associated with the actual consumption of goods and services, i.e. *consumer perspective*, have been

* Corresponding author at: Ecodynamics Group/DEEPS, Department of Environment, Earth and Physical Sciences, University of Siena, Via A. Moro, 2, I-53100 Siena, Italy.
E-mail address: caro2@unisi.it (D. Caro).

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variously proposed in scientific literature (Gavrilova and Vilu, 2012; Marin et al., 2012; Nijdam et al., 2005; Weber and Matthews, 2007; Munksgaard and Pedersen, 2001; Peters and Hertwich, 2008b; Davis et al., 2011; Caro et al., 2014c). To the aim of attributing the responsibility for pollutant emissions and/or resource use to the 'final demand' actors (i.e. households, private and public national bodies and governments), environmentally extended input–output (EE-IO) analysis has long been recognized as a useful and consistent top-down technique (Kitzes, 2013; Lenzen et al., 2013; Tukker et al., 2013; Wiedmann, 2009). For instance, the integration of the National Accounting Matrix, including Environmental Accounts (NAMEA) and IO tables represents a new way to analyze the GHG emissions embodied in domestic consumption and production (Marin et al., 2012; Costantini et al., 2012). Some of the IO models have revealed that substantial CO_2e emissions can be embodied in goods and services that are internationally traded and, therefore, not typically included in traditional GHG emission inventories (Skelton et al., 2011; Ahmad and Wyckoff, 2003). As a result, GHG inventories could undergo meaningful variations if the accounting perspective was shifted from producer- to consumer-based. Hence, the question of whether a consumer perspective, based on EE-IO analysis, can have a net positive, negative, or negligible impact as compared to the traditional (IPCC-based) producer perspective becomes of global interest for the implementation of policies on GHG emission reduction.

The question is tackled in this paper, by building an hybrid inventory framework including EE-IO-process-based data, to assess historical time-series GHG emission profile (1995–2009) for the specific case of Luxembourg, which are further compared with the results of the Luxembourgish IPCC-based GHG inventory (UNFCCC, 2013b). Our ultimate goals are: i) to observe the implications beyond the application of different GHG accounting perspectives, and ii) to identify a number of key aspects that can be improved in order to allow for consistent GHG monitoring at the national level over time. Accordingly, we seek to contribute to current knowledge on EE-IO-oriented analysis to assess consumption-based country activities, providing with a novel case study analysis.

The case of Luxembourg is particularly illustrative for the present analysis because of its special socio-economic and environmental aspects. Indeed Luxembourg has one of the highest GDP per capita in the world (World Bank, 2013) and its high-income economy is mainly characterized by banking, investment and the manufacturing industry (EFAMA, 2013; Statec, 2014). The country is characterized by an important share of the import–export of goods and human resources (150,000 commuters per day from neighboring countries). The ecological footprint per capita is also among the highest in the world, bringing great attention to this country's consumption patterns and its influence on the global ecological equilibrium (Eureapa, 2013; Hild et al., 2012; Jury et al., 2013). The country shows also the highest GHG emissions per capita of the EU-28 (in 2012, 22.5 $MgCO_2e$/capita, against 8.5 $MgCO_2e$/capita for an average European citizen; EEA, 2014). Remarkably, the energy sector was able to cover about 90% of its total GHGs in 2011, and the emissions due to energy-producing industries and transportation have increased by 2697% and 151% respectively, as compared to the records from the 1990s (UNFCCC, 2013a). In 2008, Luxembourg was the latest country in Europe to adhere to the Kyoto 2012 CO_2 emission targets (EEP, 2013).

2. Methods

2.1. Hybrid inventory analysis

The use of input–output (IO) analysis in environmental accounting is constantly increasing. Numerous improvements have been achieved in recent years, such as IO-based techniques and databases for the assessment of the consumption footprint at a country's macro-level (e.g. Ewing et al., 2012; Jury et al., 2013; Lenzen et al., 2012; Minx et al., 2009; Steen-Olsen et al., 2012) and hybrid analysis using Life Cycle Assessment (LCA) at the meso- to micro-scale (e.g. Yang and Suh, 2011).

As illustrated in Fig. 1, the modeling structure for assessing GHG emissions in Luxembourg is based on the integration between modified environmental IO tables for domestic production and IO-based hybrid tables for imports in a time-series (see Tukker et al., 2009; Suh, 2004, for an in-depth overview of the definitions of different IO-based accounting frameworks). This combination has resulted in a 2-region hybrid IO-based system (hereafter HIO) "Luxembourg-RoW (Rest-of-World)", which could completely cover the country's national production and consumption boundaries, allowing the spatially differentiated analysis of technologies and environmental information. This kind of hybrid model has recently been built to account for natural capital losses and ecological deficits in Luxembourg, as illustrated in Rugani et al. (2014). A complete description of the modeling framework is also reported in the Supplementary information (SI) material, Section S1.1, while the criteria needed to manage data quality and the assumptions performed to replace missing data are included in Sections S2 and S3 of the SI, respectively.

The HIO model has utilized the World Input–Output Database—WIOD (Timmer, 2012) as the main source of environmental satellite accounts (i.e. GHG emissions). The WIOD discloses comprehensive and formerly allocated-by-sector data regarding several resource extraction sites and pollutant emissions in Luxembourg over the period 1995–2009 (according to a 35 × 35 IO model). WIOD tables, however, have less detail than the existing 39 × 39 IO tables made available by Luxembourg's statistics office STATEC (Statec, 2014), except for the 'transport and communication' sector, which specifically accounts for 'inland transport', 'water transport', 'air transport', 'other supporting and auxiliary transport activities', 'activities of travel agencies', and 'post and telecommunications' in the WIOD system. As the ability to trace GHG emissions along the various transport activities was relevant for the present investigation, we have combined the WIOD environmental data with the STATEC models to create a new 43 × 43 (product-by-product) HIO model in a time series (Fig. 1), allowing us to disaggregate the 'transport and communication' sector (see Table S4 in the SI).

The environmental extensions for domestic production included 8 air pollutant emissions (Table S3 in the SI). The IO tables for imports were built using the inter-industry transaction share available in the WIOD. The original import vector of the IO table (including 43 industry products) was then disaggregated into 67 imported goods and 15 imported services (Table S2 in the SI), and linked to the 43 × 43 IO system as indicated in Fig. 1. While the 67 goods were accounted for in physical units (i.e. kg and kWh), with annual import amounts collected from international trade statistics (e.g. Eurostat, 2013a), the annual import value of the 15 services was kept in currency units (Euro) as originally provided. Finally, each imported good or service was associated with corresponding cradle-to-grave Life Cycle Inventory (LCI) processes to encompass the upstream supply-chain in the rest of the world (LCI data retrieved from Jungbluth et al., 2011).

The combination of process-based LCI datasets and IO modeling is a common practice in IO-based hybrid studies in order to improve the granularity of the analysis. Indeed, the accuracy, representativeness and technological specificity of the process-based LCI datasets are notably higher than the ones of environmental satellite accounts associated with IO tables. In this connection, it is worth noting that the focus of this study was not in tracing the origin (imports) or destination (exports) of the commodities out of Luxembourg, but in comparing two different methodological approaches for the same system boundary. Multi-regional IO frameworks (e.g. Ewing et al., 2012; Hertwich and Peters, 2009; Steen-Olsen et al., 2012) are models capable to trace back all the intermediate steps of the supply chain and to identify the sources of impact. However, they also entail a huge time-consuming modeling work, while the added value they may provide compared to our framework is only marginal. In fact, our goal is not to allocate to the countries' sectors the responsibility for the contributions, as it could be possible by using a multi-regional IO system. Instead, we aim to stress on the