DEVELOPMENT OF A MULTI-REGION INPUT-OUTPUT DATABASE FOR POLICY APPLICATIONS

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Abstract

Countries face different problems depending on factors such as geographical position, climate, wealth, political regime, and natural resources. Given this diversity, it is important that economic, social, and environmental assessments utilise regionally detailed and comprehensive information. However, when examining a particular type of assessment, studies (in most cases) are usually conducted without any regional or sectoral specificity due to the difficulty of creating an inter-regional modelling framework at sub-national levels.

A fundamental tool for identifying specific economic characteristics of regions (either global or within a nation) is a multi-region input-output (MRIO) system. Through the understanding of regional economic distribution, sectoral contribution, and inter-regional supply chain network, input-output (I-O) based assessments are capable of providing a comprehensive picture of regional economic structures. However, the creation of an MRIO system is a time-consuming task that requires skill in handling the complexity of data compilation and reconciliation. To this end, finding an alternative method for creating an MRIO database in the most efficient way is necessary.

In this thesis, I developed new MRIO databases that utilised virtual laboratory technology: IndoLab, TaiwanLab, SwedenLab, and USLab[1], and also took part in developing the JapanLab. I then demonstrated the use of these new facilities for addressing research questions surrounding employment multipliers in Indonesia, economic impacts due to natural disasters in Taiwan, regional consumer emissions in Sweden, and the responsibility for food loss in Japan. In addition, I presented the application of a new dataset in the global MRIO database for assessing the carbon footprints of global tourism sectors.

[1] At the time of writing this thesis, the USLab is still at a finishing development stage. Therefore, it is not part of this thesis.

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List of Abbreviations

AISHA	Automated Integration System for Harmonised Accounts
ALANG	AISHA-language
ALIC	Japanese Agriculture & Livestock Industries Corporation
ARC	Australian Research Council
BPS	Biro Pusat Statistik/ Statistics Indonesia
CCPI	Climate Change Performance Index
CGE	computable general equilibrium
CHARM	Cross-Hauling-Adjusted Regionalisation Method
DBA	Destination-Based Accounting
EIA	U.S. Energy Information Administration
EPA	Swedish Environment Protection Agency
EU	European Union
FAO	Food and Agriculture Organisation
FC	fixed capital
FLQ	Flegg's Location Quotient
FTE	full time equivalent
FTE-h	full-time-equivalent hours
GDP	gross domestic product
GHG	greenhouse gas
GOS	gross operating surplus
HDI	human development index
I-O	input-output
ICAO	International Civil Aviation Organisation
ICT	information and computer technology
IDE-JETRO	Institute of Developing Economies-Japan External Trade Organisation
IDR	Indonesian rupiah
IDRm	Indonesian-rupiah million
IELab	Industrial Ecology Virtual Laboratory
IMF	International Monetary Fund
ISA	Integrated Sustainability Analysis
JSPS	Japan Society for the Promotion of Science
K-RAS	Konfliktfreies RAS
KBLI	Klasifikasi Baku Lapangan Usaha Indonesia/ Indonesian Standard Industrial Classification
KK	Kabupaten-Kota/ regency-city
LPDP	Lembaga Pengelola Dana Pendidikan/ Indonesia Endowment Fund for Education
LQ	location quotient
MAFF	Japanese Ministry of Agriculture, Forestry and Fisheries

METI	Japanese Ministry of Economy, Trade and Industry
MIC	Japanese Ministry of Internal Affairs and Communications.
MOE	Japanese Ministry of the Environment
MRIO	multi-region input-output
Mt	million tonnes
NeCTAR	National eResearch Collaboration Tools and Resources
NGO	non-government organisation
NIES	National Institute for Environmental Studies
NT$	New Taiwan Dollars
O-D	origin-destination
OECD	Organisation for Economic Co-operation and Development
RAM	Random Access Memory
RAS	bi-proportional scaling method developed by Richard Stone
RBA	Residence-Based Accounting
S&B	Steenge and Bočkarjova
Sakernas	survei tenaga kerja nasional/ labour survey
SCP	sustainable consumption and production
SDG	Sustainable Development Goal
SEEA	System of Environmental-Economic Accounts
SEK	Swedish Krona
SI	Supplemental Information
SLQ	Simple Location Quotient
Susenas	survei sosial ekonomi nasional/ socio-economic survey
TSA	Tourism Satellite Account
U.S.	United States of America
UK	United Kingdom
UN	United Nations
UNESCAP	United Nations Economic and Social Commission for Asia and the Pacific
UNWTO	United Nations World Tourism Organisation
USA	United States of America
USD	U.S. Dollars
WIOD	World Input-Output Database
WTTC	World Travel and Tourism Council

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Chapter 1
Introduction

In today's global competitive environment, production of a commodity can involve many suppliers from different countries. For example, an apparel manufacturer in China can use cotton from India, colouring materials from Turkey, machinery from Germany, and shipping services from Singapore. This supply chain network can also occur within a country, state, province, county, or even small village. No single entity can rely solely on its own resources to produce goods and services, and thanks to open economic systems that encourage trade, we can effectively create efficient prices for consumers. As trade between regions creates inter-dependency, one question arises: "how do we know the inter-connection of sectors and regions resulted from the trade transactions between them?"

It was Wassily Leontief in the late 1930s who first introduced an analytical framework for the inter-dependency between sectors: a concept called input-output (I-O) analysis. Because of his work in IO, he received a Nobel Prize in Economics in 1973. An I-O model contains information about the flow of products, i.e. from what sectors the input came (input flows) and to what sectors the products are distributed (output flows). In its basic form, an I-O model captures only one economic entity, usually a country. Most statistic offices around the world have adopted this concept and publish national I-O tables once every 1 to 5 years.

In recent years, the I-O framework has been extended to capture not only single economic entities but also multiple regions. This concept, known as the multi-region input-output (MRIO) framework, is able to track the movement of products between their origin and destination. MRIO analysis is extensively applied throughout the world and has helped address a wide range of research questions surrounding economic, social, and environmental issues (see Miller and Blair 2010). For example, MRIO frameworks have supported research that has impacted policy at high levels, such as with the UK's consumer-based carbon emissions (Barrett *et al.* 2013), global material resource efficiency and decoupling (Wiedmann *et al.* 2013), as well as economic and productivity losses due to disease-related disasters (Santos *et al.* 2013).

Countries face different problems depending on factors such as geographical position, climate, wealth, political regime, and natural resources. Given this diversity, it is important that economic, social, and environmental assessments utilise regionally detailed and comprehensive information. However, when examining a particular type of assessment, studies (in most cases) are usually conducted without any regional or sectoral specificity due to the difficulty of creating MRIO databases at sub-national levels. Making matters even more challenging, the creation of an MRIO model is a time-consuming task that requires skill in handling the complexity of data compilation and reconciliation (Geschke and Hadjikakou 2017). To this end, finding an alternative method for creating an MRIO database in the most efficient way is necessary.

1.1 History and applicability of virtual laboratory

In 2014, Australian researchers introduced a so-called virtual laboratory (Lenzen *et al.* 2014). This virtual laboratory is an online workstation equipped with a data processing engine that is powered by ultra-high-capacity computer storage located at the University of Sydney, Australia. The virtual laboratory allows integration and reconciliation of large data sets into a harmonised framework and automatic system, meaning that working in it can significantly speed up the process of creating MRIO tables. The virtual laboratory offers flexibility in the choice of MRIO years, as well as sectoral and regional classifications to suit the users' research questions. The virtual laboratory also allows non-monetary satellite data (such as employment, carbon emissions, and food production) to be attached to the MRIO tables. These features mean that using the virtual laboratory will likely lead to significant cost reductions and accelerated work outcomes in MRIO-related research.

In the last 5 years, the virtual laboratory has enabled a wide range of MRIO-based applications in economics, social, and environmental studies. Table 1.1 shows various published articles undertaken with the virtual laboratory (Wiedmann 2017; ielab.info 2019).

Table 1.1. Applicability of virtual laboratory, 2014-2019.

Topic	Case study	Reference
Environment	carbon footprint analyses of Australian cities and/or their industries	Chen *et al.* 2016; Wiedmann *et al.* 2016; Wolfram *et al.* 2016; Malik *et al.* 2018
	analysis of energy intensity and embodied energy flows	Lam *et al.* 2019; He *et al.* 2019
	sustainability assessments of biofuel industries	Malik *et al.* 2014; Malik *et al.* 2015
	environmental impact assessment of household food consumption	Reynolds *et al.* 2015b
	refining waste input–output calculations	Lenzen and Reynolds 2014
	analysis of embodied waste flows	Reynolds *et al.* 2014; Fry *et al.* 2016a; Fry *et al.* 2018
	analysis of water footprints	Ridoutt *et al.* 2018; Reutter *et al.* 2018
	assessment of alternative water supply options	Hadjikakou *et al.* 2019
	hybrid life-cycle assessment of construction materials	Rodríguez-Alloza *et al.* 2015; Teh *et al.* 2015
	construction of a time series of physical input–output tables (PIOTs) and analysing the flows of construction materials	Fry *et al.* 2016b
Economics	strategic transport appraisals	Robson and Dixit 2017
	economic complexity analysis to assess competitiveness and innovation at the sub-national level	Reynolds *et al.* 2017
	investigation of the economic cost of a good night's sleep	Reynolds *et al.* 2015a
Social	assessment of spillovers resulted from cyclone Debbie on value-added and employment	Lenzen *et al.* 2019
	decoupling between human development and energy consumption	Akizu-Gardoki *et al.* 2018
Others	optimising MRIO construction	Geschke *et al.* 2014; Geschke *et al.* 2019
	improving non-survey methods	Többen and Kronenberg 2015
	replication of MRIO datasets at global level	Lenzen *et al.* 2017; Rahman *et al.* 2017; Reyes *et al.* 2017

Source: Wiedmann 2017; ielab.info 2019

1.2 Novelty of thesis

I developed four new MRIO databases that utilised virtual laboratory technology: IndoLab, TaiwanLab, SwedenLab, and USLab[2], and also took part in developing the JapanLab. I then demonstrated the use of these new facilities for addressing research questions surrounding employment multipliers in Indonesia, economic impacts due to natural disasters in Taiwan, regional consumer emissions in Sweden, and the responsibility for food loss in Japan. In addition, I presented the application of a new dataset in the global MRIO database for assessing the carbon footprints of global tourism sectors.

At the time of writing, no such databases had been available, thus preventing MRIO-based analyses of the aforementioned case studies. The key novelty of this thesis therefore:

1. The IndoLab is the first regionally and sectorally highly detailed MRIO database for Indonesia, able to capture 495 regions down to the city and regency level represented by up to 1,148 sectors for the period 1990–2016.
2. The TaiwanLab is the first database capable of constructing detailed sub-national MRIO tables for 22 Taiwan's city-counties distinguished up to 267 sectors for the period 1990-2016 that can be tailored to a set of specific disaster analysis questions.
3. The SwedenLab is the first sub-national MRIO database with up to 821 sectors across Swedish 291 municipalities for the years 2008–2016.
4. The JapanLab is the first database able to generate MRIO tables for up to 47 Japanese prefectures that can be tailored to specific sectors (e.g. 14 types of vegetables) and data constraints (e.g. agricultural trade data).
5. Tourism dataset in the GlobalLab is the first database covering both the direct and indirect, supply chain contributions of tourist activities across 189 countries from 2009 to 2013. In addition, it includes not only emissions of CO2 but also those of CH4, N2O, HFCs, CFCs, SF6 and NF3.

[2] See footnote 1

1.3 Overview of thesis

The thesis is organised as follows. **Chapter 2** describes the capability of the IndoLab for measuring regional employment multipliers in Indonesia. **Chapter 3** explores the use of the TaiwanLab for assessing the economic impacts of natural disasters (earthquakes and typhoons) in Taiwan. **Chapter 4** introduces a new virtual laboratory, the SwedenLab, able to evaluate consumption-based emissions in 21 Swedish counties. **Chapter 5** describes the utilisation of the JapanLab for assessing regional responsibility for food loss in Japan. **Chapter 6** presents the application of the global MRIO virtual laboratory for assessing the carbon footprints of global tourism sectors. **Chapter 7** presents the conclusions.

Connecting Page

The second chapter describes utilising the IndoLab for measuring regional employment multipliers.

Indonesia has a large labour force, amounting to more than 125 million people in 2016 (BPS 2016). As the labour force holds a significant role in driving national economic development, policymakers have to focus on strategies to direct them in order to deliver long-term economic growth. Policymakers can use a so-called 'employment multiplier' to determine which investments provide high labour productivity and create an above-average number of jobs (Domański and Gwosdz 2010; Gretton 2013). Given Indonesia's economic diversity, the employment multipliers are likely to vary across regions. However, prior studies on Indonesian employment multipliers only relied on national-scale information.

A fundamental tool for measuring regional employment multipliers is sub-national MRIO tables. I-O based assessments are capable of identifying specific characteristics of employment at the regional level.

In Chapter 2, I introduce the IndoLab: a new virtual laboratory capable of generating highly detailed time series of regional and sectoral MRIO databases for Indonesia. This new database was then applied to reveal regional employment multipliers in Indonesia.

Chapter 2

A new sub-national multi-region input-output database for Indonesia

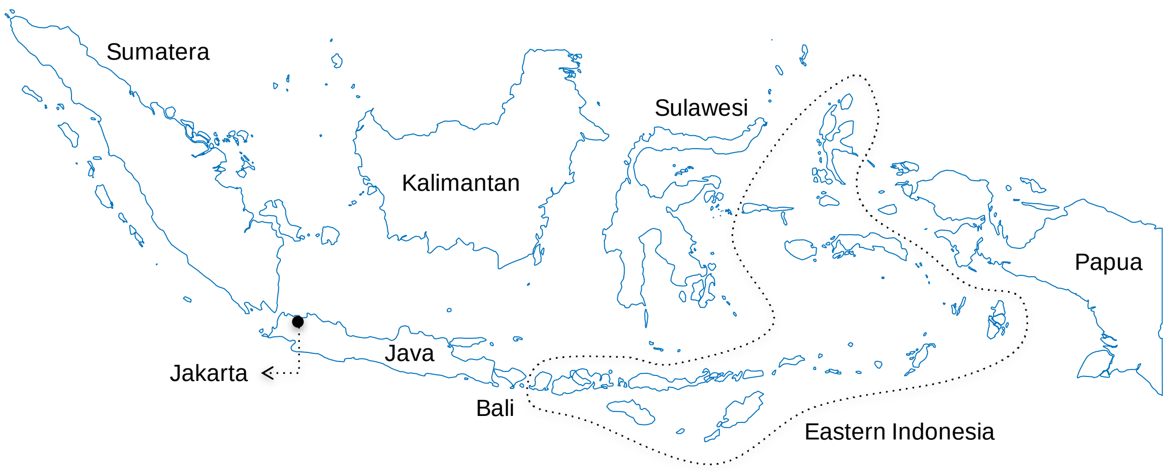
Abstract

As a large archipelago with significant geographical variation and economic diversity, Indonesia requires detailed regional information when subjected to economic modelling. While such information is available, it however has not been integrated and harmonised into a comprehensive I-O database, thus preventing economic, social and environmental modelling for investigating sub-national regional policy questions. We present the new *IndoLab*, a collaborative research platform for Indonesia, enabling I-O modelling of economic, social and environmental issues in a cloud-computing environment. Within the IndoLab researchers are for the first time able to generate a time series of regionally and sectorally detailed and comprehensive, sub-national MRIO tables for Indonesia. By integrating a multitude of economic, social and environmental data into a single standardised processing pipeline and harmonised data repository, the IndoLab is able to generate MRIO tables capturing up to 1,148 sectors, and 495 cities and regencies. Researchers can freely choose from this detail to construct tables with customised classifications that suit their own research questions. First results from the IndoLab clearly demonstrate the unique characteristics of regions in terms of their sectors' employment intensity. Thus, the IndoLab has great potential for investigating policy questions that cannot be comprehensively addressed using a single national database.

2.1 Introduction

Indonesia is an archipelago comprised of 5 main islands (**Figure 2.1**) and more than 17,000 small islands (BPS 2014). In 2014 more than 250 million people lived in 34 provinces, with half of the population on Java Island alone. As a result, almost 60% of economic activity is concentrated in Java (BPS 2015c), with manufacturing and services as the main sectors, leaving the other parts of Indonesia as the suppliers of agricultural and energy commodities. More generally, Indonesia is a country with comparatively high geographical variation in terms of climate, topography, population density, urban and transport infrastructure, and therefore features highly diverse production regimes.

Figure 2.1. Map of Indonesia.



Given Indonesia's geographical size and economic diversity, it is important that economic, social and environmental assessments make use of regionally detailed and comprehensive information. However, when examining a particular type of assessment—using I-O methods—, studies are usually conducted without any regional specificity, based solely on a national I-O database.[3] Only a small number of studies employ region-specific data, such as analyses of renewable energy and waste treatment options in Kupang City (Amheka *et al.* 2014), or tollroad investment in Bandung District

[3] Lange *et al.* 1993, Resosudarmo and Thorbecke 1996, Lange 1998, Hamilton 1997, Zuhdi *et al.* 2014, Rohman and Bohlin 2014.

(Anas *et al.* 2015). A limited number of attempts have been made at generating a sub-national MRIO system for Indonesia. Hulu and Hewings (1993) created an inter-regional model consisting of 11 sectors and connecting 5 main regions of Indonesia: Sumatera, Java and Bali, Kalimantan, Sulawesi, and Eastern Indonesia. This model was subsequently used for structural analyses (Sonis *et al.* 1997; Achjar *et al.* 2006). Resosudarmo *et al.* (2009a) extended a similar model to 35 sectors, and embedded the resulting information into a Computable General Equilibrium model (Resosudarmo *et al.* 2009b).

Although this prior MRIO work captured sub-national regions, it did so at a relatively crude level of regional and sectoral detail, with corresponding limitations for economic modelling. In addition, and this is a particular focus of our work, these databases were one-off exercises that did not allow users to customise and update the data to match specific research questions and analytical purposes. At the time of writing, therefore, no detailed, comprehensive and easily accessible sub-national MRIO database for Indonesia had been available, thus preventing economic and environmental modelling of national and sub-national issues, such as the impact of inter-regional trade, return on investment of social spending among regions, and individual income disparity and taxability.

It is this gap in terms of research capability, and hence knowledge, that our study is aimed at filling. To this end, we follow the concept of the Australian Industrial Ecology Virtual Laboratory (IELab, Lenzen *et al.* 2014) in introducing the *IndoLab*, a collaborative research platform for Indonesia, enabling I-O modelling of economic, social and environmental activities in a cloud-computing environment. The IndoLab is able to generate a time series of the most comprehensive sub-national MRIO tables[4] for Indonesia. As with the Australian IELab, regional and sectoral detail is flexible and can be chosen by the user, and the IndoLab permits databases with unprecedented detail: up to 1,148 economic sectors and 495 regions (down to the city and regency level).

[4] As with the Australian IELab, the IndoLab's MRIO database is actually in supply-use table form. For the sake of brevity, we will refer to the multi-region supply-use tables (MR-SUT) simply as "MRIOs", and treat the entire supply-use block $\begin{bmatrix} \mathbf{0} & \mathbf{V} \\ \mathbf{U} & \mathbf{0} \end{bmatrix}$ as a compound transaction matrix $\mathbf{T}$ that can be turned into a coefficients matrix and inverted (see Lenzen and Rueda-Cantuche 2012).

In the following, we will first give a brief review of the virtual laboratory concept and technology for sub-national MRIO applications. We then describe our method and data sources for constructing sub-national MRIO tables for Indonesia. We present actual results for the year 2012, including regional employment multipliers derived from our database. We finish by discussing the utility of the new research capability for contemporary policy questions in Indonesia.

2.2 Methods and data

2.2.1 MRIO analysis

An I-O table is a matrix that represents the inter-dependency among industries within an economy, and depicts the flows of money and output from suppliers to users. In the beginning of its development era in 1930s, an I-O table only consisted of a single economic entity. However, during its further development, an I-O became able to capture multiple regions in a single matrix (Leontief 1953; Leontief and Strout 1963). Tukker and Dietzenbacher 2013 provide overviews and introductions to the current state of knowledge related to global MRIO frameworks, including EXIOBASE (Tukker 2013; Tukker *et al.* 2013), WIOD (Dietzenbacher *et al.* 2013a; Dietzenbacher *et al.* 2013b), Eora (Lenzen *et al.* 2012a; Lenzen *et al.* 2013; Moran 2013), OECD (Yamano 2012; OECD 2015), and IDE-JETRO (Inomata and Meng 2013; Meng *et al.* 2013), but also sub-national MRIO databases, for example for Indonesia (Hulu and Hewings 1993; Resosudarmo *et al.* 2009b), Spain (Cazcarro *et al.* 2013a; Cazcarro *et al.* 2013b), Australia (Gallego and Lenzen 2009; Lenzen *et al.* 2014), Germany (Többen and Kronenberg 2011; Schulte in den Bäumen *et al.* 2015), China (Feng *et al.* 2012; Feng *et al.* 2013), or the UK (Yu *et al.* 2010; Minx *et al.* 2013). More recently, international/sub-national nested MRIO databases have been completed, for example for China (Wang *et al.* 2015) and Canada (Bachmann *et al.* 2015). MRIO databases have supported research that has impacted policy at high-levels, such as on the UK's carbon footprint (Barrett *et al.* 2013) and global material resource efficiency and decoupling (Wiedmann *et al.* 2013).

2.2.2 Virtual laboratory technology

We build on prior sub-national MRIO work, and apply the construction principles developed in the Australian IELab (Lenzen *et al.* 2014) to creating a new MRIO database (in supply-use format) for Indonesia. The IELab integrates a multitude of economic, social and environmental data into a single, standardised system, generating time series of MRIO databases at high regional and sectoral detail. The use of a cloud-computing environment allows multiple users to create customised MRIO tables fit for their particular research aims. This novel approach to MRIO database-making offers many advantages for users: saving the cost of handling data, reducing the time of processing data, and high specificity to the user's specific research question.

As the Australian predecessor, the IndoLab functions in a cloud-computing environment. It contains a web-based user access portal, repositories and processing functionality for standardising raw data into data feeds that can be understood by a reconciliation engine belonging to either the RAS or quadratic programming families (Geschke *et al.* 2011; Geschke *et al.* 2014). There exist data feeds for assembling the initial estimate, the point of departure of the underdetermined constrained optimisation task. Data feeds for constraints form the backbone information for "pinning down" as many areas of the MRIO table as possible. Finally, a particularly useful output of the reconciliation process is a matrix of standard deviations accompanying the MRIO table (Lenzen *et al.* 2010; Lenzen *et al.* 2012b).

2.2.3 Regionalisation

To construct MRIO tables for Indonesia, we use a technique known as regionalisation (Oosterhaven *et al.* 1986; Oosterhaven *et al.* 2008). This technique is performed when a (set of) regional I-O (or supply-use) table(s) is derived from a national I-O (or supply-use) table (Sargento *et al.* 2012), to serve as the initial estimate for the constrained-optimisation reconciliation step. To this end the national I-O table needs to be proportionally split using a proxy quantity representing the size of regional economies. In the IndoLab, labour survey data is chosen as the proxy quantity since it is available for all 495 Indonesian cities and regencies, and for 1,148 sectors.[5] The actual split of the national I-O table is accomplished through so-called non-survey methods (Hewings 2007; Bonfiglio and Chelli 2008). In the IndoLab, users currently have the flexibility to select their preferred regionalisation method from a choice of eleven different non-survey methods, more specifically location quotient and cross-hauling approaches.

In our work we chose a variant of Kronenberg's cross-hauling method developed by Vogt (2011), because this method performed best in terms of representing the entire set of primary data in an overall sense (see the method in Gallego and Lenzen 2009), using a number of matrix distance measures (Wiebe and Lenzen 2016).

2.2.4 Regional and sectoral classification

Within the IndoLab, users are able to choose regional and sectoral subsets of a so-called root classification that acts as a classification "feedstock". These subsets form the so-called base-table[6] classification into which the user's MRIO database will be cast. Theoretically, base tables can be expressed in terms of as many individual regions and sectors as the root classification allows, however limits are likely posed by available computer RAM. Typically, a root classification is a consolidation of various classifications from selected high-detail data sources[7] into a single classification, so that as many user-specific classifications as possible can be derived from one and the same root.[8] For the root classification in our work, we utilise the 2005 Indonesian Standard Industrial Classification (Klasifikasi Baku Lapangan Usaha Indonesia/KBLI, BPS 2006) consisting of 1,148 economic sectors and the 2010 Regencies and Cities classification (Kabupaten-Kota, KK) covering 495 regions. Employment data expressed in both classifications are available from the 2010 labour survey (Sakernas, BPS 2016b) published by Indonesian Bureau of Statistics (Badan Pusat Statistik/BPS). This regional and sectoral detail however acts only as a feedstock for a variety of smaller MRIO variants. Generating a full MRIO table using this root detail would produce a matrix sized 1.1 million by 1.1 million

[5] Value-added would have been another proxy quantity candidate, but this was not chosen because data are only available for 185 sectors.
[6] Previously "mother" table.
[7] In Australia these are input-output product details (1284 sectors) and the Census (2214 regions).
[8] This idea was conceived at the Project Réunion's 2012 meeting at L'Hermitage-les-Bains on Réunion Island.

elements, requiring 2.3 terabytes of RAM for each time series year and valuation layer. At the time of writing, such amounts of information were beyond existing computer capacity.

Although the IndoLab provides flexibility in choosing regional and sectoral classifications, users must consider the availability of primary data. If, say, data were only available at the provincial regional level, users should not attempt a classification capturing individual cities and regencies, unless they are in possession of additional high-detail data on these regional entities. In such cases, the IndoLab allows users to upload additional information and data sets, with the choice of read protection for a select user group in case of confidentiality. The definition of a classification suited to data sources as well as research aims, therefore, is entirely the user's responsibility.

2.2.5 Data sources

The IndoLab offers time series of MRIO tables, currently spanning the period 1990-2015. The initial estimate is constructed for 2010, because data availability is best for this year. The selection of the 2010 national supply-use table as the main data source for intermediate transactions determines some attributes of the IndoLab's MRIO tables. First, the currency unit is 1 million 2010 Indonesian Rupiah (IDR), and data from all other years and sources must be adjusted to this unit. Second, final demand has six fixed components: consumption expenditure by households, consumption expenditure by the government, gross fixed capital formation, changes in inventories, export of goods, and export of services. Third, primary inputs have five fixed components: compensation of employees, gross operating surplus, depreciation, taxes less subsidies on production, and taxes less subsidies on products. Fourth, the tables feature six valuations: basic price, wholesale margin, retail margin, transport margin, taxes, and subsidies (**Figure 2.2**).

At the time of writing, a number of data sources have been used simultaneously as constraints for the reconciliation step. For the sake of transparency information from these sources is fed into the optimisation process without any scaling, adjustment or other alteration. As these data sources are conflicting, they require the use of optimisation algorithms such as KRAS (Lenzen *et al.* 2009) or quadratic programming (van der Ploeg 1984) that are not affected by the type of convergence problems that afflicts traditional RAS-type methods. **Table 2.1** shows the data used in our work.

Table 2.1. Primary data employed for IndoLab constraints.

No	Data	Years	Regions	Sectors	Constraining	Source
1.	National I-O Tables					
	a. 66 sectors	1990, 1995, 2000	1	66	T, y, v	BPS 1994, 1999, 2002b
,	b. 78 sectors	1990, 1995	1	78	T, y, v	IDE-JETRO 2015
	c. 76 sectors	2000, 2005	1	76	T, y, v	IDE-JETRO 2015
	d. 175 sectors	2005	1	175	T, y, v	BPS 2008b
	e. 185 sectors	2010	1	185	T, y, v	BPS 2015e
2.	National Accounts					
	a. by sectors	1990-2014	1	43	v	Bank Indonesia 2016a; BPS 2016a
	b. by expenditure	1990-2014	1	6	y	BPS 2011; 2015a; Bank Indonesia 2016b
3.	Provincial Accounts					
	a. by sectors	1998-2014	34	17	v	BPS 2002a, 2004, 2009, 2012a, 2015c
	b. by expenditure	2003-2014	34	6	y	BPS 2008a, 2012b, 2015d
4.	Cities and Regencies Accounts	2010-2014	495	17	v	BPS 2015b
5.	Labour Survey					
	a. 1148 sectors	2007-2010	495	1148	v	(Sakernas) BPS 2016b
	b. 63 sectors	2011-2015	495	63	v	(Sakernas) BPS 2016b
6.	Socio-economic Survey	2010-2015	495	311	y	(Susenas) BPS 2016c

Note: BPS=Badan Pusat Statistik (Statistics Indonesia), T= intermediate demand matrix, y= final demand matrix, v= value-added matrix.

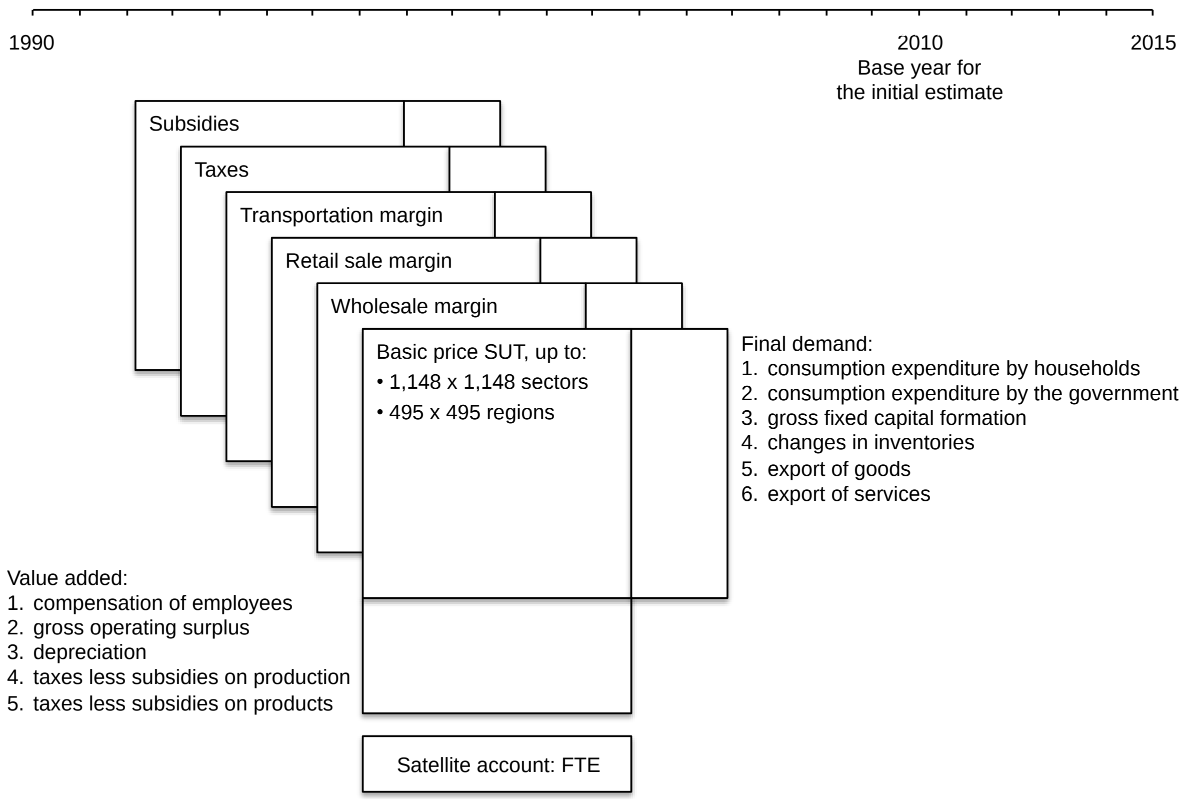
Since the primary data listed above adhere to different classifications, concordance matrices are needed to connect these data to the MRIO structure. These concordance matrices were assembled manually.

2.3 Results

2.3.1 Multi-region supply-use structure

Figure 2.2 shows the structure of the IndoLab's MRIO tables in supply-use format, distinguishing the basic price tables, wholesale margins, retail margins, transportation margins, taxes and subsidies, all summing up to the purchasers' prices. The IndoLab is able to provide information beyond the monetary I-O transactions. Satellite accounts accompanying the value-added matrix, social and environmental indicators can be integrated into the MRIO tables. In this study we present multipliers derived from an employment satellite account expressed in units of Full-Time Equivalents (FTE), complied on the basis of the Labour Survey (Sakernas).

Figure 2.2. Structure of IndoLab MRIO tables in supply-use format.



The IndoLab is able to construct time-series MRIO tables, at the time of writing from 1990 to 2015, capturing up to 1,148 sectors and 495 regions[9] and consisting of 5 value-added and 6 final-demand categories. For illustrative purposes we present here an MRIO version with the root classification aggregated

- into 9 economic sectors: agriculture, forestry and fishery; mining and quarrying; manufacturing; utilities; construction; trade, hotels and restaurants; transportation and communication; finance; and other services,
- and into 8 regions: Sumatera, Jakarta, rest of Java, Bali, Kalimantan, Sulawesi, Papua, and the rest of Eastern Indonesia.

The choice of 9 sectors for the MRIO table relates to the availability of the cities and regencies data for the year 2012, with the original service sectors aggregated into one.

2.3.2 Database for 2012

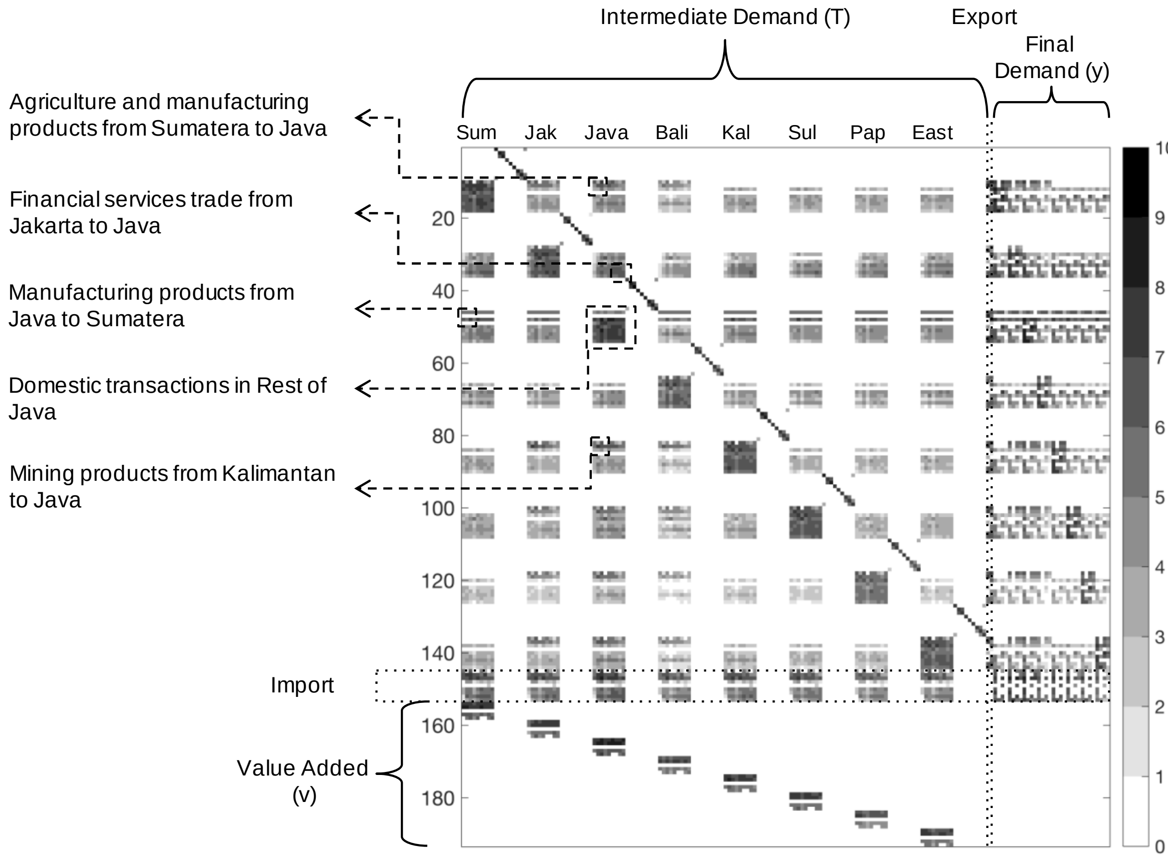
The heat map in **Figure 2.3** shows a visualisation of the monetary transaction flows within the Indonesian economy. Such visualisations are useful tools providing immediate understanding about regional attributes, such as regional economic size, interregional trade transactions, and sectoral contribution of a region.

The heat map in **Figure 2.3** allows a quick inspection of Indonesian regional economies. The high intra-regional transactions among sectors in Java (excluding Jakarta) show that Java's economy dominates national economic activities. In fact, Java's gross domestic products (GDP), workforce and population amount to 41%, 54% and 53% of the national totals, respectively (**Table 2.2**). Java is the prime location in Indonesia for manufacturing industries (61% of the national manufacturing total). Hi-tech industries such as electronics equipment, vehicles, machinery, and textiles manufacturing are mainly located in West Java, while food and tobacco products are mainly produced in Central Java and East Java. Chemical and metal industries are the leading sectors in Banten, the western part of Java. To support their large manufacturing industries, about 64% of utilities such as electricity, gas, and water supply are situated in Java. Java also dominates

[9] Not 1,148 sectors and 495 regions simultaneously, but for example 1,148 sectors and 5 regions, computer RAM permitting.

the Indonesian trade, hotel, and restaurant sector (48% of the national total), and transportation and communication (41% of the national total).

Figure 2.3. Heat map of the Indonesian MRIO table in supply-use format for the year 2012.



Note: The cell colours indicate the logarithm of the transaction values scaled in millions of Indonesian Rupiah. A value of 2 represents a transaction value of IDR100m, and a value of -2 represents a transaction value of minus IDR100m. The Indonesian MRIO table can be distinguished as 3 separate parts: the intermediate demand **T** (MR-SUT) matrix, the final demand **y** matrix, and the value-added **v** matrix. The diagonal blocks of the **T** matrix and the **y** matrix represent intra-transactions of all provinces, while the off-diagonal blocks are the inter-regional trade transactions. The block immediately below the **T** matrix indicates the import **M** matrix, and two vertical columns next to the **T** matrix indicate exports of goods and services. Since primary inputs are not traded, the value-added **v** matrix only contains diagonal blocks.

The heat map also allows a quick evaluation of trade transactions among regions. The Java-Sumatera off-diagonal blocks show that each island relies on the manufacturing products of the other. In particular, Sumatera exports food products such as sugar, cooking oil and other (semi-) processed agricultural products to Java, for example from its large sugar cane plantations in Lampung and palm plantations in Riau and North Sumatera. On the other hand, Java exports consumer items such as foods and beverages, apparels, cosmetics, vehicles, and household appliances to Sumatera and other part of Indonesia.

Table 2.2. Characteristics of Indonesian regions.

No	Region	Gross Domestic Product[1] (%)	Population[2] (%)	Employees[2] (%)	Human Development Index[2] (average)	Dominant sectors[1]
1.	Sumatera	23.0	21.5	20.4	74.3	Agg (22%), Min (20%)
2.	Jakarta	15.8	4.0	4.3	78.3	Fin (24%), Trade (21%)
3.	Java	40.9	53.1	54.3	73.5	Man (35%), Trade (19%)
4.	Bali	1.4	1.6	2.0	73.5	Trade (29%), Agg (16%)
5.	Kalimantan	9.7	5.9	6.0	73.4	Min (42%), Man (16%)
6.	Sulawesi	5.4	7.3	6.8	72.5	Agg (26%), Ser (14%)
7.	Papua	1.8	1.6	1.6	68.0	Min (37%), Ser (12%)
8.	Eastern Indonesia	1.9	5.0	4.6	69.4	Agg (27%), Ser (22%)

Source:
[1] BPS, 2015c
[2] BPS, 2014

Sumatera and Kalimantan boast significant mining sectors, especially for crude petroleum and natural gas representing 75% of the national total. High volumes of mining products from Kalimantan, especially coal, are exported to Java.

Jakarta dominates the national economy with its large financial sector, contributing 47% to the national total. The dark grey highlights of the trade matrix between Jakarta and Java, and Jakarta and other regions confirm that Jakarta's large financial sector sells its products to all regions in Indonesia.

2.3.3 Data conflict and uncertainty

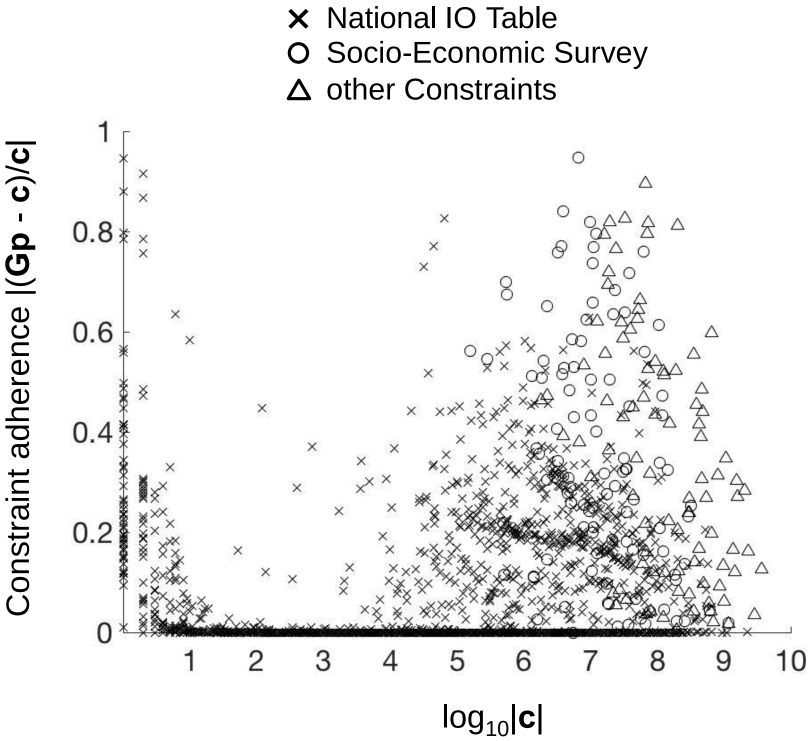
The use of multiple primary data sources as constraints for the reconciliation of the Indonesian MRIO tables involves data conflict. In other words, there is often a mismatch between different sets of primary data, and between primary data and their realisation in the MRIO database. National statistics offices often resolve data conflict manually, for example by choosing one data source over another, which is very time-consuming. We maintain all primary information unmodified, and let the reconciliation engine (e.g. KRAS) find the MRIO table that best adheres to all data points.

The IndoLab is transparent in that it retains the original source data, and lets the user choose which data source they consider most reliable. For example, due to the well-known problem of incomplete representation of high-income classes in income surveys (Sumner and Edward 2014), household consumption information from the Indonesian socio-economic survey likely underestimates national expenditure. Including these survey data can cause deviations of MRIO elements from any data source that also provides household consumption, as differing pieces of information on the same accounting items distort the reconciliation process (see Figure 1 in Lenzen *et al.* 2012a). However, as each primary data set comes with accompanying standard deviations, the reconciliation engine chooses a compromise solution between conflicting data points, adhering more to any data that are tagged with relatively low standard deviations. As a consequence, in our optimisation runs, we have assigned a much higher standard deviation to the socio-economic survey data set than to other census-type data sources.

In order to evaluate the performance of the constrained-optimisation reconciliation process of primary data with the MRIO structure, we undertake a diagnostic test (**Figure 2.4**). In this test, primary data **c** are compared with their realisations **Gp** in the MRIO matrix, and relative constraint adherences $|[(\mathbf{Gp})_i - c_i]/c_i|$ are enumerated. Here, **p** is a vectorised MRIO table and **G** is the constraints address matrix linking primary data and MRIO elements (see page 8375 in Lenzen *et al.* 2012a).

The result of this performance test for the Indonesian MRIO table is depicted in **Figure 2.4**, showing that adherence tends to improve towards larger primary data items. This circumstance occurs because large MRIO elements undergo relatively few adjustments during reconciliation process (Lenzen *et al.* 2012a). These adherence characteristics are satisfactory, given that Jensen has demonstrated with his concept of holistic accuracy (Jensen 1980; Jensen and West 1980) that the accuracy of individual small elements in an I-O table is relatively unimportant for the accuracy of multipliers used for policy analysis.

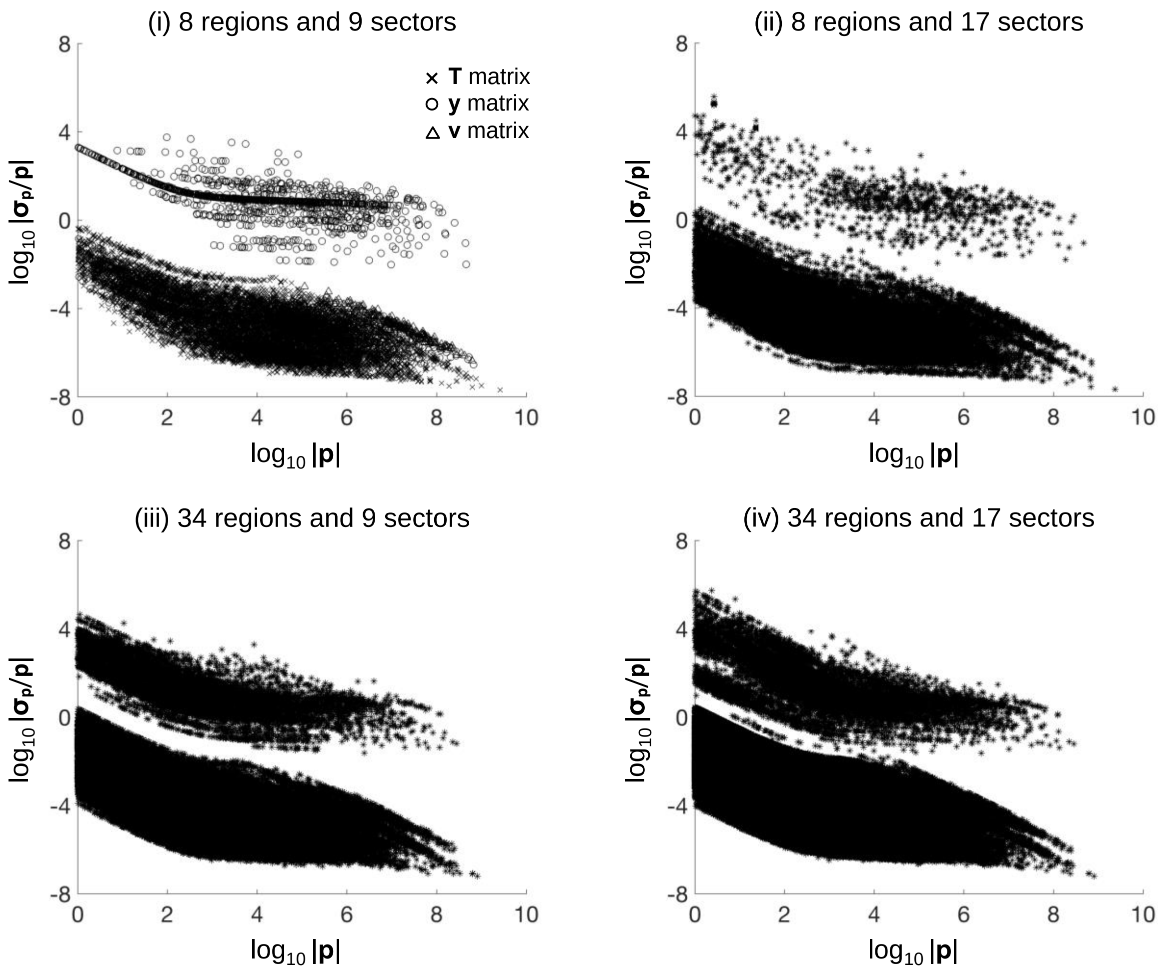
Figure 2.4. Relative constraint adherence $|\mathbf{Gp} - \mathbf{c}|/\mathbf{c}$ for constraints imposed on the 2012 Indonesian MRIO table from primary data **c** (in Millions of IDR).



Note: The variable **p** holds the vectorised MRIO table, and **G** is the constraint coefficients matrix that links the MRIO elements **p** to the constraints **c**. Each constraint point c_i is realised in the MRIO by a value $(\mathbf{Gp})_i$, which is usually different from c_i. *For each data source*, the points follow a distinct "hockey stick" curve, indicating that large primary data items c_i are represented more accurately in the MRIO table, because they deviate less from constraint realisations $(\mathbf{Gp})_i$. Note also that socio-economic survey data carry more uncertainty than national I-O table data.

It is important to equip MRIO tables with estimates of data uncertainty. Standard deviations are a suitable measure for evaluating the magnitude of estimation errors of MRIO entries. We present standard deviations of four 2012 MRIO variations with different regional and sectoral details (**Figure 2.5**). As with constraint violations, larger MRIO items are associated with smaller relative standard deviations, because these elements undergo only minor adjustments during the reconciliation. Panel (i) shows an estimate of uncertainty at the broad classification used in this work. We found that the 8-region 9-sector Indonesian MRIO table generated in the IndoLab is characterised by standard deviations of less than 1%, but around 10% for some large elements in the order of 10^8 million Rupiah and above, and more than 100% for some final demand transactions worth 10^7 million Rupiah and less. However, when we increased the number of regions and sectors of MRIO tables, standard deviations of more than 100% occurred more often (panels ii – iv). This result highlights the principle that in order to estimate an MRIO table with sufficiently low uncertainty, primary data must be available that constrains the MRIO elements at the respective level of detail. If the chosen MRIO classification is more detailed than the data, standard deviations increase. Estimating standard deviations thus provides an effective check on table reliability.

Figure 2.5. Standard deviations for 2012 Indonesian MRIO table variants.



Note: The x-axis shows the magnitude of MRIO elements p_i, and the y-axis shows their relative standard deviation $\sigma_{\mathbf{p},i}$ / p_i.

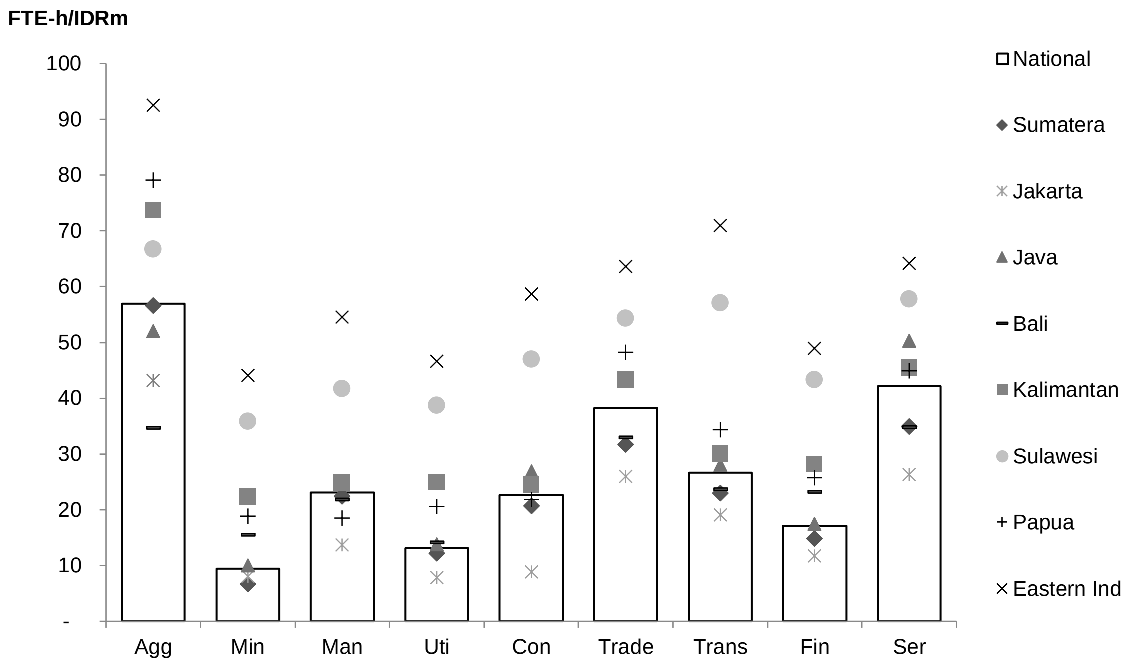
2.3.4 Utility for policy applications

The I-O approach can be a powerful tool for businesses that can, for example, utilise employment multipliers for determining which investments can provide high labour productivity and can create above-average number of jobs (Domański and Gwosdz 2010, Gretton 2013). In addition, governments can use income multipliers in order to formulate individual taxes policies and poverty reduction programs (World Bank 2014). Prior studies on Indonesian economic I-O multipliers, however, only relied on national-scale information, for example a study on creative industries by Zuhdi (2015), and on coal utilisation by Winarno and Drebenstedt (2016). As a consequence, valuable information about regional specific-industry characteristics was not being utilised.

To demonstrate the utility of the new Indonesian MRIO database over current single-region national I-O tables for analysing regional economics, we compute regional employment multipliers measuring the impact of one unit of final demand on regional employment expressed in full-time-equivalent hours worked (FTE-h). Information for populating the corresponding satellite account was taken from the 2012 Labour Survey (Sakernas, BPS 2016b). FTE-hours were calculated by converting the surveyed number of hours worked into annual full-time equivalents.

Employment multipliers vary among sectors, as expected (**Figure 2.6**). Agriculture, forestry, and fishery features the highest employment multiplier at a national average of 57 FTE-h/IDRm. The second and third largest employment multiplier belongs to the services sector, and the trade, hotel, and restaurant sector, at 42 FTE-h/IDRm and 38 FTE-h/IDRm, respectively. These three sectors are the most labour-intensive in the Indonesian economy. The employment multipliers for the mining sector, the utilities sector, and the financial sector are relatively low, at between 9 and 17 FTE-h/IDRm, reflecting their status as capital-intensive sectors. More importantly, we are able to inspect the employment multipliers from a regional point of view. First of all, the regional employment multipliers show a consistent trend across sectors, as expected aligned with the national labour-intensity pattern.

Figure 2.6. Employment multipliers for the year 2012, in units of FTE-h/IDRm.



Second, the employment multipliers in Jakarta and Sumatera are lower than national multipliers, for all sectors, indicating that stimulating demand in these regions will likely not result in significant additional employment, compared to other Indonesian regions. We believe that this is due to the relatively high level of human and socio-economic development in Jakarta and Sumatera (see the human development index (HDI) and other data in **Table 2.2**), and consequently to the relatively high wages. Highly-paid labour means that a fixed amount of additional demand will translate into relatively little employment in terms of FTE-h. In contrast, the employment multipliers in Kalimantan, Sulawesi and Eastern Indonesia, and to a degree also Papua, are higher value than the national averages. Here, the reverse argument applies: Relatively low human and socio-economic development means that wages are low, and hence a fixed amount of additional final demand translates into relatively high FTE employment.

The regional employment multipliers imply that new investment should be located in Kalimantan, Sulawesi, Papua, and Eastern Indonesia since it will impact wider economy. The government then could allocate greater public spending in these areas to improve the quality of local infrastructure including roads, harbors, airports, and electricity networks. Good-quality infrastructure is vital in order to offer a more attractive business and investment climate. Moreover, the employment multipliers imply that the government should direct the new investment in labour intensive sectors (agriculture, services, and trade). Government bodies across different areas then could improve sector-specific facilities, such as cold storage for fishery businesses, and workshop for local traders and service providers in order to boost local economy.

Most importantly, **Figure 2.6** shows that the range of employment multipliers around the national average is sufficiently large to cause regional policy assessments to lead to inaccurate results if a surrogate national I-O table is used for the region. These circumstances underscore the significant of being able to regionalise I-O and satellite data, offered by the IndoLab.

2.4 Conclusions

We have described the creation of the IndoLab, a collaborative research platform operating on a cloud-computing environment, capable of generating time series of regionally and sectorally highly detailed MRIO databases for Indonesia, with users being able to freely choose the classification of the MRIO tables to suit their particular research aims. This is the first time that such a detailed I-O database exists for Indonesia, able to capture 495 regions of Indonesia down to the city and regency level represented by up to 1,148 sectors. In addition, the IndoLab enables the construction of a timely update of MRIO tables, which is otherwise a costly process. These capabilities, as the authors' knowledge, cannot be found in any other existing MRIO tables for Indonesia, such as the works by Hulu and Hewings (1993) and Resosudarmo *et al.* (2009a).

The Indonesian MRIO database has numerous policy applications. For example, Indonesia has implemented significant and massive decentralisation, known in Indonesia as the "big bang approach to decentralisation" (Bahl and Martinez-Vazquez 2006). Despite Indonesia's socio-economic diversity and large population, the authorities moved from central to local government within a relatively short period and without major disruption to public services (World Bank 2003, Firman 2009, White and Smoke 2005). This rapid change altered both inter-regional performance and central-local relationships. For example, central duties have shrunk to cover only foreign affairs, defence, security, justice, monetary and fiscal policies, and religious affairs (Law 32 of

2004), leaving substantial responsibility to local governments, such as public works, health, education, culture, agriculture, communication, industry, trade, investment, environment, land, and labour. It is useful, therefore, to utilize the Indonesian MRIO to compare Indonesia's economic structures during pre- and post-decentralisation eras in order to evaluate regional developments. This research-based analysis can provide a credible reference to policymakers in reformulation the central and local government duties.

The Indonesian MRIO is also useful as a tool for verifying whether investment in natural-resource-endowed regions outside Java is more successful after the implementation of decentralisation. Referring to Law 28 of 2009, local governments are now allowed to grant investment licenses for exploration of coal and other mineral products, thus providing more flexibility for local governments in directing their own investment towards revenue-maximising activities. The IndoLab's MRIO, therefore, can be used to examine the capacity of local governments to boost particularly profitable regional sectors.

Furthermore, having successfully identified specific employment characteristics of the Indonesian regions, it is of interest to use the Indonesian MRIO for analysing a wide range of other social issues such as corruption and gender inequality, as well as environmental issues such as climate change and deforestation (Hamilton 1997). As with employment, such social and environmental indicators are likely to vary across regions, thus requiring a regional MRIO for their assessment.

Summarising, the use of the IndoLab's MRIO capability has great potential for solving national and regional research questions that cannot be comprehensively addressed using a single and/or aggregated national database. As an online cloud-based platform, the IndoLab offers many benefits. Its openness enables interested parties to become involved in collaborative work and address common research questions. Through its standardised MRIO construction pipeline, it allows researchers to integrate a wide variety of raw data from third-party sources with their own data. These features mean that work in the IndoLab will likely lead to significant cost reduction and accelerated work outcomes in MRIO-related research.

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Connecting Page

The third chapter describes employing the TaiwanLab for assessing the economic impacts of natural disasters (earthquakes and typhoons) in Taiwan.

Taiwan is a country frequently hit by severe natural disasters; a total of 96 catastrophic earthquakes have occurred since 1990 and an average of 3 to 4 typhoons per year make landfall in the country (Central Weather Bureau 2017). These frequent and severe natural disasters often interrupt Taiwan's economy. The 1999 Chichi earthquake, for example, caused extensive damage to buildings, public infrastructure, road and electricity networks, and eventually resulted in a 0.5% correction to the 1999 economic growth (Dong *et al.* 2000). Taiwan's vulnerability to such devastating natural disasters necessitates comprehensive disaster impact assessments to support damage prevention and economic recovery. However, existing databases are not necessarily detailed enough to allow meaningful disaster analysis.

An essential method for undertaking disaster impact assessment is using a sub-national MRIO table. I-O based analysis is able to reveal the economic losses resulting from supply chain interruptions.

In this chapter, I present the TaiwanLab: a new virtual laboratory able of capturing the links between specific disaster-hit sectors and regions, and the remainder of the economy. The MRIO database was then used for assessing the economic losses that resulted from 4 major natural disasters in Taiwan between 1999 to 2016.

Chapter 3

Using Virtual Laboratories for disaster analysis—A case study of Taiwan

Abstract

Due to its geographic location, Taiwan frequently experiences severe natural disasters (for example earthquakes and typhoons) that significantly interrupt business operations and subsequently cause extensive financial losses. Prior work on economic losses resulting from such natural disasters in Taiwan has not considered regional and sectoral spillover effects. In this work, we estimate the economic impacts resulting from the 1999 Chichi earthquake, the 2009 typhoon Morakot, the 2016 Tainan earthquake, and the 2016 typhoon Megi. We do so in the new TaiwanLab, a collaborative virtual laboratory that is capable of generating a time-series of sub-national MRIO tables, capturing interregional transactions among 267 sectors across Taiwan's 22 city-counties. We identify critical economic sectors in regions of high vulnerability to natural disasters. Our research is, thus, a credible reference to decision-making that determines regional and sectoral prioritisation for damage mitigation, improved resiliency, and faster recovery schedules.

3.1 Introduction

The rapid industrialisation of Taiwan during the 1950s and 1960s created a prosperous industrial economy and transformed Taiwan into one of Asia's economic miracles, alongside Hong Kong, South Korea and Singapore. Since then Taiwan became a crucial part of the world economy, especially in high-tech manufacturing. In 2016, Taiwan was a key supplier in the world market for semiconductor manufacturing equipment, with roughly 25% of the market share (Blouin 2017). For many years, Taiwan also lead the world in contract manufacturing of information and computer technology (ICT) equipment. High-tech manufacturing sites sprang up in many areas of Taiwan—Taipei, New Taipei, Taoyuan, Miaoli, Hsinchu, Taichung, Tainan and Kaohsiung—ultimately comprising about a third of Taiwan's GDP. Manufacturing, thus, replaced agriculture as the island's leading sector. In fact, in 2016 the latter contributed only 2% of GDP (National Statistics 2017e).

Taiwan's prosperous economy is often interrupted by severe natural disasters. The 1999 Chichi earthquake, for example, damaged many business facilities and resulted in extensive financial loss across the breadth of the island's economy. Ultimately, 100,000 people become homeless, 9,000 industrial sites were damaged, and 4 million households lacked water supply; a power blackout covered north and central Taiwan for ten days. The Chichi earthquake resulted in a 0.5% correction in the island's 1999 GDP growth (Dong *et al.* 2000).

Taiwan frequently experiences natural disasters. This results from its geographic position within the circum-Pacific seismic zone. Indeed, record show that 20,000 earthquakes occurred there between 1604 to 1988 (Chang 1996). Seismic activity on Taiwan was particularly high from 1991 to 2014 at 18,000 earthquakes per year (Central Weather Bureau 2017a). On 6 February 2018, an earthquake that hit 6.4 on the Richter scale struck Hualien, injuring more than 100 people (The Guardian 2018).

From 1911 to 2015, a total of 360 typhoons made landfall in Taiwan—an annual average of 3 to 4 typhoons (Central Weather Bureau 2017b). Taiwan's vulnerability to such devastating natural disasters necessitates comprehensive disaster impact assessments to support damage prevention and economic recovery.

3.1.1 Review of prior work on I-O based disaster analysis

I-O based disaster assessments enable the quantification of both the direct and the indirect supply chain impacts of a disaster. Since Cochrane (1974) a plethora of publications has focussed on disaster analysis using I-O tables and I-O analysis, specifically. In the last decade, *Economic Systems Research* has featured two special issues on the topic (Okuyama 2007; Okuyama and Santos 2014). Many variants of IO-based models have emerged that extend the fundamental IO calculus to incorporate temporal and spatial scales (Santos and Haimes 2004; Haimes *et al.* 2005; Donaghy *et al.* 2007; Yamano *et al.* 2007). But most published IO disaster studies use a single-region IO model; they thus omit the assessment of interregional and international spillover and feedback effects (Miller and Blair 2010). This is largely due to the inherent difficulties in constructing sub-national MRIO tables; intra-national interregional trade data tend not to be collected.

The availability of a global/sub-national multiregional IO (MRIO) table is needed to depict the interactions between different regions. At a global level, for example, the construction of MRIO databases (Tukker and Dietzenbacher 2013) enabled Schulte in den Bäumen *et al.* (2014) to assess the multi-country economic impact of Coronal mass ejections (CMEs) on electrical grids. MacKenzie *et al.* (2012) and Arto *et al.* (2015) used the OECD I-O table and WIOD, respectively, for measuring the global economic impacts of the 2011 Japanese earthquake and tsunami. At a sub-national level, researchers used multiregional models to analyse the spillover effects of three floods in Rotterdam, The Netherlands (Koks and Thissen 2016), flooding in eastern and southern Germany (Schulte in den Bäumen *et al.* 2015), Hurricane Katrina's landfall in Louisiana, USA (Hallegatte 2008), and a tropical cyclone in Queensland, Australia (Lenzen *et al.* 2019).

In this work, we demonstrate the functionality of MRIO framework for the assessment of spillover effects resulted from natural disasters using a case study of Taiwan. There have been prior attempts to quantify the effects and impacts of natural disasters in Taiwan.

Most of the research that touches upon the social and economic dimensions of post-disaster human behaviour. It discusses the consequent reduction in worker productivity (Tsai *et al.* 2012), the psychological and behavioural change as embodied in fear and risk (Huan *et al.* 2004), the loss and recovery of tourism (Liu 2014), and the assessment of risk and management on the hospitality sector and high-tech manufacturing (Tsai and Chen 2010). Lin *et al.* 2012) used an MRIO model of Taiwan to estimate the economic impacts of two scenario earthquakes for a year.

Despite all of the above, a comprehensive, detailed assessment of natural disasters in Taiwan remains lacking. The importance of this gap cannot be overemphasized due to the high rate of disaster occurrence, as well as the tremendous economic losses and uncertainty that accompany each event. The sheer mass of the above work points to the importance of understanding intersectoral consequences in a disaster context, in particular for communities and/or organisations that need public assistance and policy attention. The indirect losses of sectors and regions can only be understood well through the interregional modelling frameworks. Hsu *et al.* (2013), for example, estimate the earthquake vulnerability of hi-tech manufacturing in Taiwan; but they fail to assess economic losses emanating from disaster-generated supply chain disruptions.

3.1.2 This study

The occurrence and consequences of disasters tend to be highly localised. Combine this with an equally differentiated regional economy, and it becomes clear that assessing indirect effects from disasters in Taiwan requires a regionally and sectorally detailed data foundation. The specific regional and sectoral nature of disaster impacts necessitate a particular sub-national MRIO table that features a) very recent data, and b) detail where disaster impacts are expected to be significant. But in Taiwan, and elsewhere, existing MRIO databases tend to be insufficiently spatially detailed to enable meaningful disaster analyses, not to mention the required sectoral resolution and vintage. Moreover, whilst studies on losses resulting from natural disasters usually focus on leftover capacity (UNESCAP 2018), we examine alternative definitions of loss in terms of value-added. This is the key novelty of our work: We develop[10] a new virtual laboratory—the *TaiwanLab*—, which is capable of constructing detailed sub-national MRIO tables for Taiwan for the period 1990-2016 that can be tailored to a set of specific disaster analysis questions. A virtual lab is an innovative and compelling solution to the current gap of flexible and timely MRIO tables for disaster analysis. Taiwan is a great illustration of this innovation, but also interesting one, because the country is small and unexpectedly varied, especially with regard to the vulnerability of its regions to disasters and their impacts.

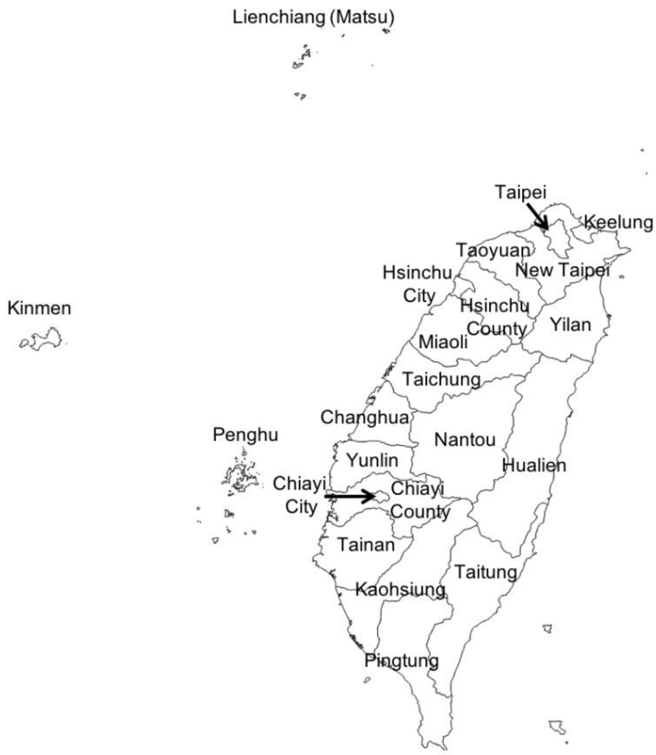
A virtual laboratory is a collaborative research platform that enables the: a) timely update of (multiregional) IO tables, a process that is otherwise a tedious and an expensive, b) development of sub-national IO tables that can be used for studying disaster-related spillovers and feedback effects across regions in a country; and c) construction of a time-series of IO tables, which allows the study of disasters across time (Lenzen *et al.* 2017). A virtual laboratory also allows users to customise their MRIO tables to specific regions or sectors, and integrate additional region- and sector-specific information. These capabilities assist users in adapting their modelling framework to specific natural disasters, as these can occur in specific, varying regions, and hit only particular sectors. The TaiwanLab is built at high regional and sectoral detail, generating a time-series of MRIO tables consisting of 22 city-counties (see **Figure 3.1**) and 267 economic sectors (see **Appendix 1** and **2.2**). Because of this unsurpassed detail, the TaiwanLab is able to capture linkages between disaster-hit sectors and regions, and the remainder of the economy. At the time of this writing, no such MRIO database exists for Taiwan.

Herein, we describe how using the TaiwanLab advances comprehensive regional assessments of disaster impacts. To this end, we apply the TaiwanLab to four case studies of natural disasters in Taiwan that have so far not been analysed. We include Taiwan's deadliest earthquake as well as its deadliest typhoon in modern history—the 1999 Chichi earthquake and the 2009 typhoon Morakot. We add to those the most recent earthquake and typhoon at the time of this writing—the 2016 Tainan earthquake and the 2016 typhoon Megi. These four cases are diverse in the way they affected regions and sectors. The earthquakes usually hit western Taiwan where the island's financial and industrial

[10] Based on a collaboration between the University of Sydney in Australia and the National Cheng Kung University in Taiwan.

centre are located, while the typhoons land mostly in the agricultural locations in eastern Taiwan. This diversity is meant to showcase the utility of the TaiwanLab. Our contribution to disaster analysis is therefore twofold: a) using a virtual lab to achieve the regional and sectoral detail necessary to undertake disaster analysis at sufficient resolution, and b) analysing four disasters in Taiwan that have never been studied before. We use a method proposed by Steenge and Bočkarjova (2007) to determine regional and sectoral spillover effects.

Figure 3.1. Map of Taiwan.



3.2 Methods

3.2.1 MRIO database

3.2.1.1 Virtual laboratory technology

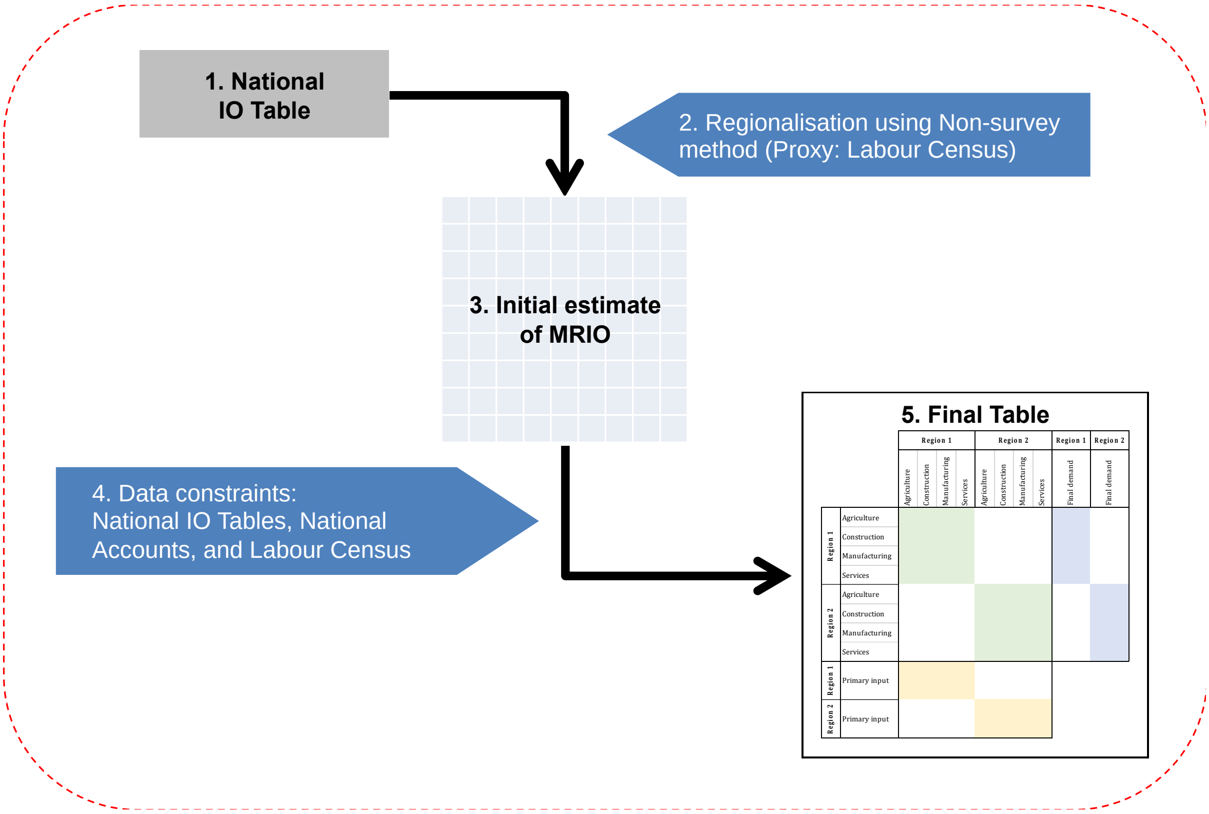
The TaiwanLab is a virtual laboratory built in a cloud-computing environment, similar to those hosting the Australian IELab (Lenzen *et al.* 2017), the Indonesian IELab (Faturay *et al.* 2017), the Chinese IELab (Wang 2017) and the Japanese IELab (Wakiyama *et al.* 2019). As with other virtual laboratories, the TaiwanLab supports remote access, harmonized data storage, automatic data processing, and flexible regional and sectoral classifications. Lab users are able to access, update or integrate a number of data sources, and choose their preferred regional and sectoral classifications, to suit their specific disaster case studies. These characteristics overcome the difficulty and time-consuming process of developing sub-national MRIO tables.

The first step in constructing a sub-national MRIO database in the TaiwanLab (see **Figure 3.2**) is to obtain national IO tables at the highest possible detail. Second, these national IO tables are then disaggregated into sub-national MRIO tables using non-survey regionalisation methods (Sargento *et al.* 2012), which are widely-used techniques for generating sub-regional MRIO tables using national IO tables as a starting point. The TaiwanLab is currently equipped with ten different non-survey methods that can be flexibly selected by users (see *SI* 3.6). We choose the cross-hauling-adjusted regionalisation method (CHARM) over the traditional method (e.g. the simple location quotient, SLQ) to regionalise the Taiwan national IO table. CHARM allows simultaneous export and import of a commodity (cross-hauling) and avoids some downward bias in interregional trade transactions (Többen and Kronenberg 2015). Cross-hauling is the rule rather than the exception, as implicitly assumed by SLQs. The MRIO tables are tailored into 267 sectors, yet the industrial groups are sufficiently large to accommodate heterogeneous products. For example, manufacture of textile includes the conversion of fibre into yarn, and yarn into fabric.

The regionalisation of the national IO tables into sub-national MRIO tables is accomplished using a proxy quantity describing the economic structure of a region in comparison to the nation. Labour data are the preferred candidate for this proxy quantity since they are available at a satisfactory level of disaggregation for all cities and counties, and for all sectors. Taiwan's regional employment data capture 22 city-counties and 267 sectors. This detail is used as the root classification serving as a feedstock during the MRIO reconciliation process. The use of a root classification aims to consolidate various data classifications into a single classification so that all user-specific classifications can be derived from one and the same feedstock. To tailor the MRIO table to the users' specific questions, lab users select application-specific sectors and regions to be represented individually in the MRIO table, and aggregate other sectors and regions. For example, to investigate the effects of the 2016 Tainan earthquake, the important sectors are agriculture, livestock, forestry, and fishery products, whilst the important regions are Tainan, Kaohsiung and Pingtung. The tailoring process then proceeds via the user setting up concordance matrices that cast the root classification into the earthquake-specific classification. Detailed regional employment and Census data for agricultural industries in Tainan, Kaohsiung and Pingtung are then used to support the regionalisation of the MRIO table. In this way, the geography of Taiwan can be "used" to inform specific disaster-related questions. In this study, four disasters are simultaneously examined, impacting virtually the entire Taiwanese economy, and every city/county. Therefore, we generated full MRIO tables at root classification, and then investigated the spillover effects of Taiwan natural disasters to all possible sectors and regions.

Third, based on the user's choice of sectors, regions and the non-survey regionalisation method, we extract the national and specific regional data that are needed to regionalize the national table. Most non-survey regionalisation methods, such as the location quotients and cross-hauling variants available to the TaiwanLab, apply regional weights—here derived from the labour census—to regionalise a national table. The user's choice of regionalisation method is independent of their choice of sectoral and regional classifications.

Figure 3.2. Steps to construct MRIO tables in the TaiwanLab.



Fourth, the outcome of this regionalisation process is an initial estimate of the MRIO table. It is a preliminary estimate or prior to start a reconciliation process, in which balance conditions and a set of constraints are enforced. Reconciliation is carried out using an automatic system, known as AISHA (Automated Integration System for Harmonised Accounts, Geschke *et al.* 2014). A number of data sources are then used to simultaneously constrain the Taiwan MRIO tables, such as the series of national IO tables, national accounts, and the labour census (see **Section 3.2.1.2** and **Table 3.1**).

Fifth, the final MRIO table for one year is used as the initial estimate for the following year, and the procedure repeats. This multistep process allows us to construct regionally and sectorally detailed MRIO tables for any given year between 1990 and 2016. To this end, we obtained the balanced MRIO tables tailored to specific datasets for the years 1999, 2009, and 2016. These years correspond to those in which the four natural disaster case studies occurred.

3.2.1.2 Data sources

Table 3.1 shows the raw data used for the development of Taiwan's MRIO tables. The 2011 national IO tables obtained from National Statistics of Taiwan are the main source for the construction of the initial estimate (National Statistics 2017b). A number of data items are used to constrain MRIO elements, namely the 2001 and 2006 national IO tables (National Statistics 2017b), a set of national accounts from 1990 to 2016 (National Statistics 2017e), and detailed regional employment data at the city-county level. The latter contain 241 sectors in the Industry and Service Census (National Statistics 2017d), 20 sectors in the Agriculture, Forestry, Fishery, and Animal Husbandry Census (National Statistics 2017a), and 6 sectors in the Public Services and Education Census (National Statistics 2017c).

Table 3.1. Primary data for the TaiwanLab.

	Data	Years	Regions	Sectors	MRIO part constrained	Source
1.	National I-O Tables					National Statistics 2017b
	162 sectors	2001, 2006	1	162	ID, FD, VA	
	166 sectors	2011	1	166	ID, FD, VA	
2.	National Accounts					National Statistics 2017e
	GDP by expenditure	1990-2016	1	6	FD, Exp, Imp	
	GDP by sector	1990-2016	1	63	VA	
	Gross output	1990-2016	1	63	GO	
	Intermediate consumption	1990-2016	1	63	ID	
3.	Census					
	Industry and Service Census	2001, 2006, 2011	22	241	Proxy for regionalisation	National Statistics 2017d
	Agriculture, Forestry, Fishery and Animal Husbandry Census	2000, 2005, 2010	22	20	Proxy for regionalisation	National Statistics 2017a
	Public Services and Education Census	2001, 2006, 2011	22	6	Proxy for regionalisation	National Statistics 2017c

Note: ID = Intermediate Demand, FD = Final Demand, VA = Value-Added, Imp = Import, Exp = Export, and GO = Gross Output. The text under column header "MRIO part constrained" describes the specific MRIO elements that are constrained by the respective data source. The text "Proxy for regionalisation" means that the respective data source was used in the non-survey approach for disaggregating the national IO tables into sub-national MRIO tables.

3.2.2 Disaster case study of Taiwan

3.2.2.1 Disaster events in Taiwan

Since 1990, a total of 96 catastrophic earthquakes have occurred in Taiwan, most had their epicentre in open sea off the island's east coast (Central Weather Bureau 2017a). The Chichi earthquake in Nantou County on 21 September 1999 was the deadliest in modern Taiwanese history. It measured 7.3 on Richter scale with tremors felt across the island and killing at least 2,400 people. It caused extensive damages to buildings, public infrastructure, and electricity and water networks. The total damage was estimated at 300 billion New Taiwan Dollars (NT$; 1 US$ ≈ 31 NT$) or about 3% of Taiwan's GDP in 1999 (Tsai *et al.* 2013). After the 1999 Chichi earthquake, the next most deadly earthquake occurred in Tainan on 6 February 2016. It measured 6.4 in moment magnitude, caused 114 casualties, and resulted in NT$ 1 billion in damage (Vervaeck and Daniell 2016).

Taiwan is also vulnerable to typhoon landings, which bring excessive rainfall and severe flooding. Morakot, the deadliest typhoon to strike Taiwan in modern history, battered the island on 8 August 2009. At least 677 people were killed, 1,612 houses were destroyed and financial losses reached NT$ 90 billion (Yang *et al.* 2014). Despite crossing the central regions, the strong winds and heavy rain accompanying the typhoon triggered a massive landslide and severe flooding throughout southern Taiwan. On 25 September 2016, typhoon Megi made landfall in Hualien County in eastern Taiwan. The 1,015 mm of rainfall from typhoon Megi caused NT$ 1 billion in agriculture losses (Hsu-min *et al.* 2016).

3.2.2.2 Methods

We use the method proposed by Steenge and Bočkarjova (2007) to study post-disaster consumption possibilities resulting from four selected disasters that hit Taiwan between 1999 and 2016, as described in **Section 3.2.2.1** Roughly speaking, we may divide the literature on disaster analysis within an interindustry setting into three strands. On the one hand, the computable general equilibrium (CGE) approach (see e.g. Okuyama 2007) allows modelling some behavioural aspects. But such models can take enormous amounts of time and labour to build. On the other hand, IO (see e.g. Okuyama and Santos 2014) yields simple and somewhat more tractable model that is relatively easy to build. A third is systems econometric time-series models (see West and Lenze 1994) showing how recovery will likely roll out over time in the case of smaller disasters. But there is no a single "one size fits all" approach exists. Different (types of) disasters induce different economic behaviour that require different modelling approaches.

For example, within the IO approach, the inoperability model has been widely applied (see Greenberg *et al.* 2012, for its importance). Recently, however, Dietzenbacher and Miller (2015) as a mild variation on the supply-side model conceived by Ghosh (1958). In a similar vein, Oosterhaven (2017) points at other shortcomings, including the inability of the inoperability model to handle supply disruptions.

In the present paper, we take supply shocks as our starting point. Instead of building a supply-driven model (Ghosh 1958) or using nonlinear programming techniques (Oosterhaven and Bouwmeester 2016), we use a linear programming model in connection with the so-called event matrix as proposed by S&B (2007). In principle, their idea is simple. A disaster or disruption leads to damages and a reduction in production capacity. To this end, S&B (2007) introduce the concept of a so-called event matrix that identifies the reduction in production capacity that results from some event. They assume that capacity if fully employed, which then yields the immediate post-disaster output levels. A consequence can be that the sum of final demands and intermediate inputs (necessary to produce the post-disaster output) are larger than the post-disaster outputs. In other words, total demands are larger than total supply and the economy cannot self-reproduce. They then discuss possibilities for the recovery process.

In our paper, we follow S&B (2007) and assume that production capacity is reduced due to damages from a disaster. But we do *not* assume the production capacity is fully employed[11] as they originally propose. Rather we require that outputs are not larger than

[11] Oosterhaven and Többen 2017) show in an I-O context that full capacity utilisation leads to substantially higher indirect disaster impacts. A similar finding was reported by Hallegatte and Ghil (2008) using a systems time-series macroeconomic model.

the production capacity. Secondly, we do not start from given final demands. Rather we require that the intermediate input demands do not exhaust outputs. That is, the net output, i.e. output that is used to meet final demands, must be nonnegative. These two requirements define a set of feasible solutions (i.e. output levels) from which we select the one that maximises the sum of outputs[12]. That is, we adopt a linear programming approach. After we obtain the optimal post-disaster output levels, we calculate the loss in value-added as an indicator of the impact of a disaster[13]. We focus on a single year of impacts and ignore any dynamics of post-disaster period.

3.2.2.2.1 Technical details

S&B (2007) require information about reductions in production that can result directly from a disaster, such as damages to public facilities, agriculture, manufacturing sites, and utilities. This information is assembled in the so-called event matrix $\hat{\boldsymbol{\gamma}}$ that quantifies the relative loss in total output by specific region and sector. We follow this approach by defining a diagonal event matrix $\hat{\boldsymbol{\gamma}}$ with elements γ_i ,which indicate the share of the output in industry *i* that is lost. In addition to the event matrix $\hat{\boldsymbol{\gamma}}$, our method requires known the pre-disaster total output vector $\mathbf{x}_0$ and the matrix $\mathbf{A}$ with the economy's production recipe. The outcomes of our method are the post-disaster outputs $\tilde{\mathbf{x}}$ and the net outputs for final demand purposes $\tilde{\mathbf{y}} = (\mathbf{I} - \mathbf{A})\tilde{\mathbf{x}}$.

We determine the post-disaster output by maximising economy-wide total output $\max(\sum \tilde{x}_i)$, subject to two conditions. First, $\tilde{\mathbf{x}} \leq (\mathbf{I} - \hat{\boldsymbol{\gamma}})\mathbf{x}_0$, where $\mathbf{I}$ is an identity matrix. Our second condition is that post-disaster net outputs are nonnegative, $\tilde{\mathbf{y}} \geq 0$. Since coefficients in $\mathbf{A}$ remain the same as pre-disaster, the economic structure is unchanged. Thus, we assume businesses are unable to recover their original production status through import substitution and factor substitution (capital vs. labour) at least in the short run. The overall linear programming problem becomes $\max(\sum \tilde{x}_i)$ subject to $\tilde{\mathbf{x}} \leq (\mathbf{I} - \hat{\boldsymbol{\gamma}})\mathbf{x}_0$ and $\tilde{\mathbf{y}} = (\mathbf{I} - \mathbf{A})\tilde{\mathbf{x}} \geq 0$.

[12] In the context of underutilised capacities, excess demand (households can consume less than desired due to the disaster) and prices fixed (as always in the quantity I-O model), maximising output implies profit maximisation.
[13] Natural disasters can yield positive impacts to regions or sectors that are not directly affected (cf. Carrera *et al.* 2015; Koks and Thissen 2016; Oosterhaven and Többen 2017).

To measure the severity of the disaster one usually adopts the loss of capacity. This would be $\mathbf{e}'(\mathbf{I}-\hat{\boldsymbol{\gamma}})\mathbf{x}_0 - \mathbf{e}'\tilde{\mathbf{x}} = \sum_i[(1-\gamma_i)x_{0,i} - \tilde{x}_i]$, where $\mathbf{e}$ indicates the summation vector of ones. In the present study we use the value-added loss, which is determined by the difference between the post-disaster value-added $\tilde{q}$ and the pre-disaster value-added q_0. In order to estimate the value-added loss $q_0 - \tilde{q}$, we need the vector of value-added coefficients (i.e. value-added per unit of output). Let the vector of pre-disaster values-added be given by $\mathbf{q}_0$. The vector of value-added coefficients then yields $\mathbf{v} = \hat{\mathbf{x}}_0^{-1}\mathbf{q}_0$. Vectors are columns by definition, row vectors are transposed column vectors. The estimate for the total post-disaster value-added is $\tilde{q} = \mathbf{v}'\tilde{\mathbf{x}}$ and the loss in value-added yields $q_0 - \tilde{q} = \mathbf{v}'(\mathbf{x}_0 - \tilde{\mathbf{x}})$.

3.2.2.2.2 An example of spillover calculation

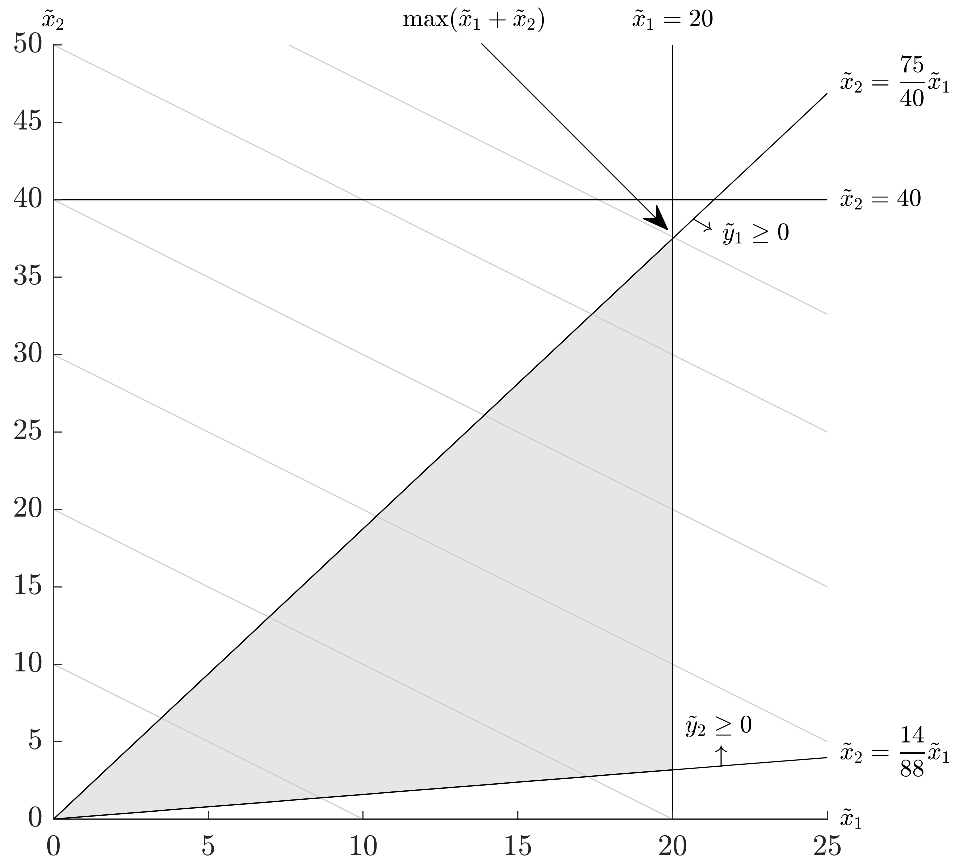
Take the numerical example in S&B (2007), where the event matrix has been adapted. That is, $\mathbf{A} = \begin{bmatrix} 0.25 & 0.4 \\ 0.14 & 0.12 \end{bmatrix}$, $\mathbf{x}_0 = \begin{bmatrix} 100 \\ 50 \end{bmatrix}$, $\mathbf{y}_0 = \begin{bmatrix} 55 \\ 30 \end{bmatrix}$, and $\mathbf{I}-\hat{\boldsymbol{\gamma}} = \begin{bmatrix} 0.2 & 0 \\ 0 & 0.8 \end{bmatrix}$.

The condition $\tilde{\mathbf{x}} \le (\mathbf{I}-\hat{\boldsymbol{\gamma}})\mathbf{x}_0$ implies that $\tilde{x}_1 \le 20$ and $\tilde{x}_2 \le 40$, and the condition $(\mathbf{I}-\mathbf{A})\tilde{\mathbf{x}} \ge 0$ implies that $0.75\tilde{x}_1 \ge 0.4\tilde{x}_2 \Leftrightarrow \tilde{x}_2 \le (75/40)\tilde{x}_1$, and $0.14\tilde{x}_1 \le 0.88\tilde{x}_2 \Leftrightarrow \tilde{x}_2 \ge (14/88)\tilde{x}_1$. In **Figure 3. 3**, we have the shaded area with feasible solutions. Anything below the line $\tilde{x}_2 = (75/40)\tilde{x}_1$ gives values $\tilde{y}_1 > 0$ and anything above $\tilde{x}_2 = (14/88)\tilde{x}_1$ gives $\tilde{y}_2 > 0$. The solution for maximising total output $\max(\sum \tilde{x}_i)$, where both $\tilde{\mathbf{x}} \le (\mathbf{I}-\hat{\boldsymbol{\gamma}})\mathbf{x}_0$ and $\tilde{\mathbf{y}} = (\mathbf{I}-\mathbf{A})\tilde{\mathbf{x}} \ge 0$ is $\tilde{\mathbf{x}} = \begin{bmatrix} 20 \\ 38 \end{bmatrix}$ and $\tilde{\mathbf{y}} = \begin{bmatrix} 0 \\ 30.2 \end{bmatrix}$.

Note that the optimal outputs do not absorb the maximum available capacity. If the output levels would equal capacity the net output of industry 1 would become negative. That is, if $\tilde{\mathbf{x}} = (\mathbf{I}-\hat{\boldsymbol{\gamma}})\mathbf{x}_0 = \begin{bmatrix} 20 \\ 40 \end{bmatrix}$, then $\tilde{\mathbf{y}} = (\mathbf{I}-\mathbf{A})\tilde{\mathbf{x}} = \begin{bmatrix} -1 \\ 32.4 \end{bmatrix}$.

If we set $\mathbf{I}-\hat{\boldsymbol{\gamma}} = \begin{bmatrix} 0.25 & 0 \\ 0 & 1 \end{bmatrix}$, industry 2 does not experience a direct disaster hit. The optimal solution is $\tilde{\mathbf{x}} = \begin{bmatrix} 25 \\ 47 \end{bmatrix}$ and $\tilde{\mathbf{y}} = \begin{bmatrix} 0 \\ 37.75 \end{bmatrix}$. Observe that although industry 2 is not affected directly by the disaster, it is in an indirect way. This shows that industry spillovers may occur despite the disaster being restricted to one industry. If a multiregional model is used, this finding extends to regional spillovers.

Figure 3.3. Feasible solution space for $\tilde{\mathbf{x}} \leq (\mathbf{I} - \hat{\boldsymbol{\gamma}})\mathbf{x}_0$ and $\tilde{\mathbf{y}} = (\mathbf{I} - \mathbf{A})\tilde{\mathbf{x}} \geq 0$, for the example in **Section 3.2.2.2.2**.



3.2.2.2.3 Alternative objective functions

In the example above and in the empirical application in **Section 3.3**, we maximise the sum of the gross outputs. It should be stressed though that our linear programming approach is very flexible and allows for many alternative objective functions. As the term indicates, the function one chooses depends on one's objective. It may reflect economic behaviour or the goals of policy makers, it may also be normative and based on political viewpoints.

In what follows, we describe several examples of alternative objective functions. The objective function depends on the question(s) one would like to answer and should be chosen very carefully. Therefore, we illustrate some of the more plausible and more common objective functions. First, the aim might be to keep the post-disaster outputs closest to the pre-disaster outputs. The objective function then becomes $Z = \sum_i (\tilde{x}_i - x_{0,i})^2$. The optimisation problem is to find the values $\tilde{x}_i$ that minimise Z, subject to the constraints.

Second, Oosterhaven and Bouwmeester (2016, p. 586) "simulate the *back to business-as-usual* behaviour of economic actors … [and] minimise the difference in the information value of the post-event compared to the pre-event market equilibrium as measured by the … input-output table". As an alternative, one may consider firms that try to stick to their pre-disaster business patterns as close as possible. This might be modelled by requiring that the new outputs are proportional to the original outputs. This implies an additional set of constraints, i.e. $\tilde{x}_i = \lambda x_{0,i} \forall i$. The optimisation problem then would be to find the maximum value of λ, subject to the constraints.

Third, the objective function might be defined in terms of the consumption possibilities $\tilde{y}_i$. Recall that the model is such that the output levels are chosen (or given) exogenously. This means that also the intermediate inputs $\mathbf{A}\tilde{\mathbf{x}}$—that producers need—are predetermined for any given $\tilde{\mathbf{x}}$. Post-disaster final demand is then determined endogenously as the residual, i.e. $\tilde{\mathbf{y}} = (\mathbf{I} - \mathbf{A})\tilde{\mathbf{x}}$; it is what is left of the outputs after the intermediate deliveries have been satisfied. These leftovers are to satisfy consumption. We may choose to maximise total consumption ($\sum_i \tilde{y}_i$) or we may attach weights to the consumption of separate goods. Natural disasters destroy homes, agriculture, and business assets. At the same time, people require basic goods (like food, clothing, housing) to survive. Therefore, we might give basic goods large weights and luxury goods (like cars or traveling for touristic purposes) small weights. In that case, the objective function becomes $Z = \sum_i w_i \tilde{y}_i$, which can be rewritten as $Z = \sum_i \mu_i \tilde{x}_i$ with $\mu_i = w_i - \sum_j w_j a_{ji}$.

Fourth, the measure for the severity of the disaster might be adopted as the objective function. If the loss of capacity is used, we might use as the objective to minimise this loss.

That is, minimise $Z = \sum_i [(1-\gamma_i)x_{0,i} - \tilde{x}_i]$, which can be rewritten as maximise $Z = \sum_i \tilde{x}_i$. Note that this is exactly the same as the objective function that we are currently using. If the value-added loss is chosen as the evaluation criterion, we might use to minimise that measure. That is, minimise $Z = \sum_i v_i(x_{0,i} - \tilde{x}_i)$, which is the same as maximise $Z = \sum_i v_i \tilde{x}_i$.

3.2.2.2.4 Event matrix $\hat{\boldsymbol{\gamma}}$

In order to populate the event matrix $\hat{\boldsymbol{\gamma}}$ for the four disasters, we use information on financial damages from public sources such as government and non-government organisation (NGO) reports, academic journal articles, and government statements in online media. To give an example, in the case of the 1999 Chichi Earthquake, the information of the direct losses includes:

- electric power outages lasted for 1-2 weeks mostly in central and northern Taiwan and caused severe business interruptions (Chang 2000);
- farmers in central Taiwan experienced significant losses in their facilities, and the reconstruction costs were estimated at NT$ 26.2 billion (Low 1999);
- tourism lost revenue worth NT$ 1 billion (Chuang 1999);
- transportation and communications infrastructure needed repairs valued at NT$ 10 billion across all areas (Chang 2000); and
- general damages to communities, estimated using the post-disaster reconstruction funds (e.g. public and community reconstruction), costed NT$ 212.4 billion to the Taiwan government budget (Tsai *et al.* 2013).

Some of the above information was not available by region, but instead as a total only. We dealt with such circumstances as follows. In the absence of detailed information about economic impacts in specific regions, we used data on the region-specific damages to buildings (Tsai *et al.* 2000) to disaggregate the direct economic effects of the earthquake to all cities and counties. In addition, we used data on the length of city-county highways to allocate total damages to regions as incurred by the transportation and communication sectors.

Table 3.2. Event matrix $\hat{\mathbf{y}}$ for the 1999 Chichi Earthquake.

	Agr	Min	Man	Uti	Con	Trade	Trans	Fin	Ser
Hsinchu County	0.0099	-	-	0.0241	-	0.0001	0.0016	-	0.0002
Taoyuan	0.0038	-	-	0.0230	-	0.0000	0.0002	-	0.0000
Yilan	-	-	-	-	-	-	-	-	-
Hsinchu City	0.0880	-	-	0.0335	-	0.0001	0.0004	-	0.0002
Keelung	-	-	-	-	-	-	-	-	-
New Taipei	0.2361	-	-	0.0296	-	0.0002	0.0029	-	0.0006
Taipei	0.0786	-	-	0.0324	-	0.0000	0.0000	-	0.0002
Changhua	0.0153	-	-	0.0248	-	0.0003	0.0235	-	0.0007
Miaoli	0.0942	-	-	0.0313	-	0.0022	0.0482	-	0.0031
Nantou	0.6154	-	-	0.0310	-	0.0270	0.4047	-	0.0400
Yunlin	0.0153	-	-	0.0326	-	0.0008	0.0330	-	0.0011
Taichung	0.3762	-	-	0.0305	-	0.0020	0.0280	-	0.0053
Chiayi County	0.0007	-	-	0.0245	-	0.0001	0.0034	-	0.0001
Penghu	-	-	-	-	-	-	-	-	-
Pingtung	-	-	-	-	-	-	-	-	-
Chiayi City	0.0035	-	-	0.0302	-	0.0000	0.0001	-	0.0000
Kaohsiung	-	-	-	-	-	-	-	-	-
Tainan	-	-	-	-	-	-	-	-	-
Hualien	-	-	-	-	-	-	-	-	-
Taitung	-	-	-	-	-	-	-	-	-
Kinmen	-	-	-	-	-	-	-	-	-
Lienchiang	-	-	-	-	-	-	-	-	-

Note: It is possible some manufacturing firms also directly experienced facility damages, however we do not include any losses for the manufacturing sectors since these stems mostly from electric power outages, which we already capture in our supply chain calculus. For sector names see *SI* 3.7.

It is less straightforward to estimate the production shortfalls, which might arise due to damaged infrastructure. The input of fixed capital (*FC*)—in form of depreciation— into production is part of value-added. *FC* is often—most certainly so in Taiwan—lumped together with Gross Operating Surplus (*GOS*). Since $FC \leq GOS$, the ratio $g_i = x_i/GOS_i \leq x_i/FC_i$ provides a lower limit for the industrial output of sector *i* enabled by the annual input of fixed capital. To estimate the reduction in sectoral total output due to infrastructure damages, we utilise an approach outlined in Lenzen *et al.* (2019). Here, we follow Hallegatte (2008) in assuming that a) the infrastructure loss is equivalent to a loss of fixed capital inputs, annualised over a 25-year time-frame, and that b) the reduced output of the damaged industries is approximated by the value of this loss multiplied by the output-enabling ratio g_i. Thus, we arrive at a lower limit—i.e. a conservative estimate—for the production shortfalls due to damaged infrastructure, which we enter as a separate component of the event matrix $\hat{\mathbf{y}}$ for capital losses (representing around 20% of total losses for the four disasters investigated). An event matrix $\hat{\mathbf{y}}$ containing both direct and capital damage components is shown for the 1999 Chichi Earthquake for 22 regions and 9 sectors in **Table 3.2**.

We apply the aforementioned methods to construct the event matrices $\hat{\mathbf{y}}$ for other natural disaster covered in this paper, including the 2009 typhoon Morakot, the 2016 Tainan earthquake, and the 2016 typhoon Megi (see *SI* 3.8).

3.2.2.2.5 Production-layer decomposition

Production-layer decomposition analysis (Lenzen *et al.* 2019) is then performed to decompose losses in value-added across upstream layers of production resulting from the case studies. Recall that we have defined $\tilde{\mathbf{y}} = (\mathbf{I} - \mathbf{A})\tilde{\mathbf{x}}$. This implies $\tilde{\mathbf{x}} = (\mathbf{I} - \mathbf{A})^{-1}\tilde{\mathbf{y}} = \mathbf{L}\tilde{\mathbf{y}}$. We can do the same for the pre-disaster values. That is, $\mathbf{y}_0 = (\mathbf{I} - \mathbf{A})\mathbf{x}_0$ or $\mathbf{x}_0 = \mathbf{L}\mathbf{y}_0$. The production-layer decomposition is determined by $q_0 - \tilde{q} = \mathbf{v}'(\mathbf{x}_0 - \tilde{\mathbf{x}}) = \mathbf{v}'\mathbf{L}(\mathbf{y}_0 - \tilde{\mathbf{y}}) = \mathbf{v}'(\mathbf{I} + \mathbf{A} + \mathbf{A}^2 + \cdots)(\mathbf{y}_0 - \tilde{\mathbf{y}})$. Here, $(\mathbf{y}_0 - \tilde{\mathbf{y}})$ is the reduction in consumption possibilities (S&B, 2007). Specifically, we quantify value-added losses broken down by sectors and by regions of the upstream supply chain. Upstream production-layers are shown on the x-axis, with 0 representing the value-added loss in sectors affected immediately by the reduction of consumption possibilities $(\mathbf{y}_0 - \tilde{\mathbf{y}})$, 1 being the value-added loss experienced by the suppliers of sectors in layer 0, and so on.

3.3 Results

Before delving into the description of the results for our disaster impact assessment, we should briefly describe the multiregional economic features that emerge from our Taiwan MRIO database. This description should aid in understanding the characteristics and significance of the distribution of regional disaster impacts and their relationships with Taiwan's economic geography. Therefore, we first present Taiwan's economic structure as represented by the TaiwanLab's MRIO, and then refer to these features when describing the regional and sectoral impacts—including spillovers—of the four disasters.

3.3.1 Taiwan's economic structure

The TaiwanLab has built-in data repositories and tools for constructing a time-series of MRIO tables for the Taiwan economy from 1990-2016, distinguishing up to 267 industry sectors for 22 city-counties. The tables are valued in millions of NT$. To demonstrate the capability of virtual laboratories for disaster analysis, we use the TaiwanLab to construct MRIO tables for years 1999, 2009, and 2016, which correspond to the years of our natural disaster case studies. For the sake of conciseness in presenting our findings only, we aggregate the 267 industry sectors represented in the MRIO tables into 9 broad categories: agriculture (including livestock, forestry, and fishery); mining and quarrying; manufacturing; utilities; construction; trade, hotels and restaurants; transportation and communication; financial services (including real estate, and business services); and other services.

Table 3.3 shows detailed outputs of 9 economic sectors in 22 Taiwan's city-counties. The leading manufacturing hubs are mainly Taoyuan (16% of the national total), New Taipei (14%), Taichung (14%), Tainan (10%), and Kaohsiung (10%), while agricultural output mainly stems from Tainan (12%), Kaohsiung (11%), Changhua (11%), Yunlin (9%), and Taichung (9%). Taipei is the core of the nation's economy. Along with New Taipei (formerly Taipei County) and Taoyuan, Taipei has become the primary host for national financial services, and transportation and communication sectors with a combined output of more than 60% of the island's total output. Taipei also produces significant outputs in trade, hotel, and restaurant sectors, and other services, representing a national share of 24% and 21%, respectively. Northern Taiwan's regions (Taipei, New Taipei, Taoyuan, Keelung, Hsinchu, and Miaoli) maintain 50% of the national manufacturing. It is the island's main home for high-tech manufacturing such as electronic components, computer and optical products, and electrical equipment, which is facilitated by the presence of science parks and easy access to international ports.

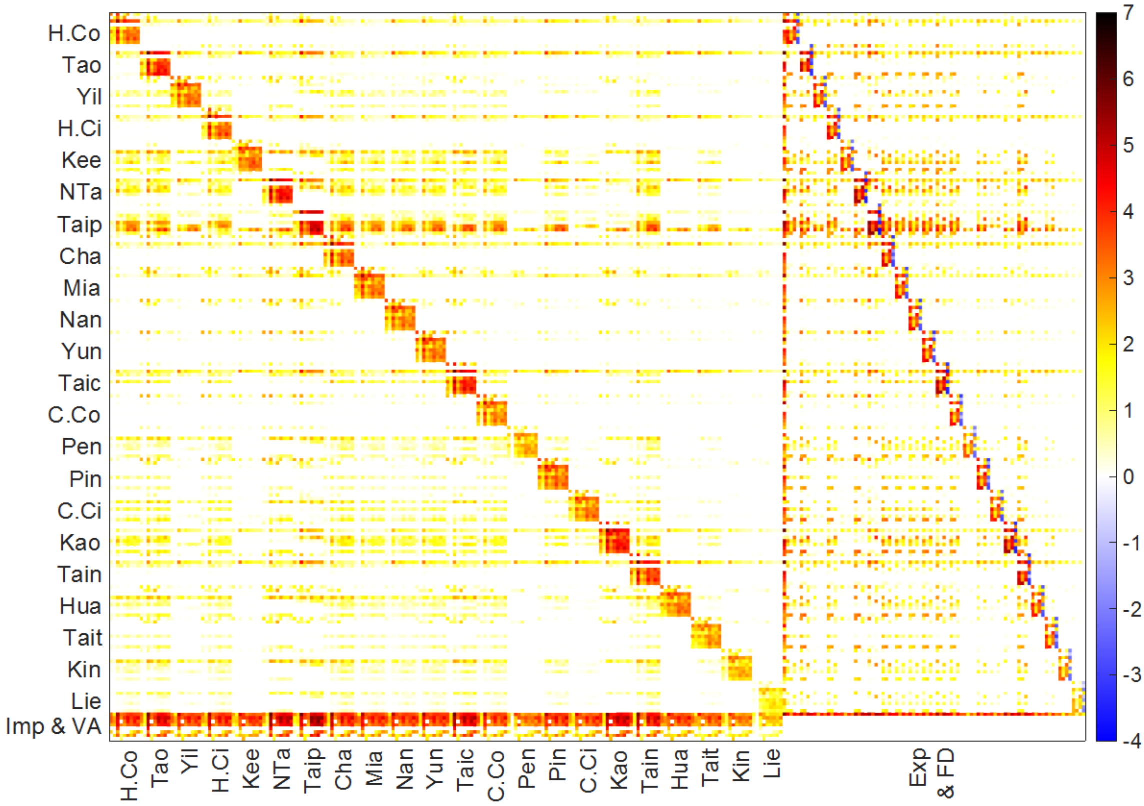
Table 3.3. Taiwan's regional output for the year 2016 (in NT$ billion).

	Agr	Min	Man	Uti	Con	Trade	Trans	Fin	Ser
Hsinchu County	22.2	2.2	659.1	12.0	36.0	91.6	34.2	75.3	80.4
Taoyuan	18.1	0.6	2,461.5	33.1	119.3	394.1	195.7	305.5	172.6
Yilan	19.0	1.4	203.2	32.6	38.3	70.5	25.4	42.4	86.7
Hsinchu City	8.3	0.9	761.7	17.5	41.9	108.8	37.6	113.8	89.6
Keelung	2.3	0.6	93.1	73.8	23.2	46.4	59.3	29.3	76.7
New Taipei	12.7	0.4	2,759.6	41.5	280.5	708.1	279.1	515.3	437.1
Taipei	6.5	0.9	1,360.6	63.5	85.9	1,130.8	765.3	1,714.2	872.8
Changhua	65.8	0.6	1,145.1	14.4	36.6	184.3	47.7	106.0	174.6
Miaoli	29.0	6.7	424.2	34.4	35.0	77.1	27.8	57.2	85.5
Nantou	40.0	1.4	236.2	42.1	27.5	71.9	21.9	39.3	89.5
Yunlin	57.2	0.6	381.9	52.4	39.3	89.3	30.7	50.7	99.9
Taichung	57.2	1.0	2,499.3	39.7	186.3	581.8	173.6	441.2	508.1
Chiayi County	43.7	0.4	290.8	12.4	28.5	62.6	19.8	37.5	79.6
Penghu	2.3	0.0	13.3	27.1	6.7	12.9	8.0	7.6	19.4
Pingtung	54.0	2.0	274.8	62.6	40.8	117.5	27.8	58.4	144.9
Chiayi City	4.6	0.4	80.7	33.5	14.6	54.3	16.0	39.0	76.4
Kaohsiung	67.3	0.7	1,765.0	184.4	233.7	526.6	238.7	435.6	543.7
Tainan	70.8	0.6	1,780.4	28.0	31.4	324.8	84.9	231.3	311.8
Hualien	14.5	2.6	85.6	54.9	23.4	55.1	23.8	31.7	78.8
Taitung	13.4	1.6	37.7	17.0	11.5	33.5	10.4	15.9	49.2
Kinmen	1.7	0.1	19.2	32.8	7.2	9.5	6.9	6.2	11.1
Lienchiang	0.1	0.0	2.3	4.2	1.9	1.4	1.9	1.0	2.8

Central and southern Taiwan each contribute around 20% of Taiwan's total economic activity. These regions produce a range of commodities: For example, city-counties in central Taiwan (Taichung, Changhua, Nantou, and Yunlin) are the main producers of leather, rubber, wood, and furniture. Regions in southern Taiwan (Chiayi, Tainan, Kaohsiung, and Pingtung) and also the aforementioned central regions are the main hubs for agriculture, livestock, forestry, and fishery products. Producing two-thirds of Taiwan's agricultural output, city-counties in central and southern Taiwan have comparative advantages in agriculture-related manufactured products, such as food and beverage manufacturing. The central and southern regions have also significant mining-related industries such as petroleum refineries, and basic metal manufacturing. The eastern regions of Yilan, Hualien, and Taitung and the offshore regions of Penghu, Kinmen, and Lienchiang contribute less than 4% to Taiwan's economic activities.

In **Figure 3.4**, we display a heat map of the 2016 Taiwan MRIO table. The heat map allows for a visual assessment of Taiwan's inter-regional supply chain structure. For example, the dark row of matrices for Taipei indicate a high dependence of the other regions on Taipei. The row of matrices of city-counties in northern Taiwan—Taipei (Taip), New Taipei (NTa), Taoyuan (Tao), and Keelung (Kee)—show relatively large interregional trade flows, again indicating how much the rest of Taiwan depends on this region.

Figure 3.4. Heat map of the 2016 Taiwan MRIO table.



Note: The diagonal blocks of the intermediate demand and the final demand matrices show intra-regional trade within the 22 city-counties; the off-diagonal blocks represent interregional trade between different regions; and the blocks below the intermediate demand matrix are the imports and the value-added matrices. Exports of goods and services are placed in a vertical column to the right of the intermediate demand matrix. The cell colours indicate the magnitude of the trade transactions on a log-scale. The Taiwan MRIO tables are valued in NT$1 million, hence the colour tone against a value of 2 represents a transaction of NT$100m. Imp = Import, VA = Value-Added, Exp = Export, and FD = Final Demand. For sector, FD, and VA names see *SI* 3.3 and 3.4.

The heat map in **Figure 3.4** shows how a disaster focused on agricultural production can indirectly affect other industries in Taiwan. Assume a cyclone or a flood hitting Changhua, Pingtung, and Yunlin (green), which are the main interregional exporters of agricultural products (see the top rows in green boxes in the heat map). Whilst Tainan and Kaohsiung (grey) have relatively high agricultural outputs, New Taipei, Taoyuan, and Taichung (grey) depend on imports of agricultural products from the disaster-hit Changhua, Pingtung, and Yunlin to supply the raw inputs for their food manufacturing sectors. Taipei is highly dependent on food manufacturing industries, and so is likely to face shortages in (semi-) processed food products that are normally imported from New Taipei, Taoyuan, Taichung, Tainan, and Kaohsiung. These shortages would affect businesses (grey boxes in the heat map) and households (brown boxes in the heat map) alike. These regional inter-linkages demonstrate the importance of using MRIO tables for disaster analysis.

3.3.2 Regional impact of natural disasters

The IO structure and data shown in **Table 3.3** and **Figure 3.4** clearly demonstrate that Taiwan's economy is highly diversified and interconnected. In the following description of the regional and sectoral impacts of the four disasters, we will refer to **Table 3.3** and **Figure 3.4** to highlight regional and sectoral spillover effects. Such spillovers occur, for example, when a natural disaster occurs in a region with a high concentration of agricultural output and, facilitated by interregional supply chains, the economic impact spreads to other regions that depend on agricultural products as their inputs.

3.3.2.1 Total output losses

The literature on economic losses resulting from the four natural disasters in Taiwan that we examine does not mention any regional and sectoral spillover effects (Hsu *et al.* 2013). Spillover effects occur when sectors and regions, which do not experience any direct effects of the disaster, are negatively affected by supply chain interruptions. In particular, these reports only document the direct impacts, i.e. impacts in directly affected regions. Reports by the Taiwan's Directorate General of Budget, Accounting and Statistics (Lin 1999) and the Risk Management Solutions (Dong *et al.* 2000), for example, estimated the economic loss of the 1999 Chichi earthquake to be NT$ 290-380 billion. But these reports provided no information about the economic spillover effects, whereas we suggest the 1999 Chichi earthquake caused a total loss on the order of NT$ 508.3 billion (including an indirect loss due to the upstream spillover effects of NT$ 177.7 billion). These total losses result directly out of our maximisation of post-disaster total output $\tilde{\mathbf{x}} \leq (\mathbf{I} - \hat{\boldsymbol{\gamma}})\mathbf{x}_0$. By comparing $\tilde{\mathbf{x}}$ and $\mathbf{x}_0$, we can already identify the significance of regional spillovers. However, in the following we will concentrate on our measure $\mathbf{v}'(\mathbf{x}_0 - \tilde{\mathbf{x}})$ of value-added loss.

3.3.2.2 Value-added losses

In **Figure 3.5**, we show the magnitude of the value-added losses resulting from the 1999 Chichi earthquake, the 2009 typhoon Morakot, the 2016 Tainan earthquake, and the 2016 typhoon Megi.

The 1999 Chichi earthquake resulted in the loss of NT$ 508.3 billion of value-added, 40% of which occurred as sectoral and regional spillovers. Initially, the earthquake damaged transportation links and the power plants, particularly around Taichung which is close to the earthquake's epicentre. The electricity outages affected the operation of many businesses nation-wide, and consequently, manufacturing and trade sectors encountered a total loss of NT$ 159.5 billion and NT$ 123.2 billion, respectively. Almost half of the losses in both sectors were felt in Taipei, New Taipei, Taoyuan, and Hsinchu, despite the distance of these city-counties from the earthquake's epicentre, because of the grid-wide effects of power generation and transmission outages. Our MRIO-based analysis shows that the loss of the northern manufacturing sectors, especially those producing computers, electronic equipment, and motor vehicles, reduced interregional demand from Taichung's machinery, Tainan's basic metal, and Kaohsiung's chemical products. As a result, Taichung and the southern regions of Kaohsiung and Tainan also experienced significant spillover loss in the manufacturing sectors (worth NT$ 58.3 billion) and the trade sectors (worth NT$ 38.3 billion).

The spillover effects from the damage of transportation links also triggered a drastic reduction in the output of manufacturing and the trade sectors in the north. Based on the

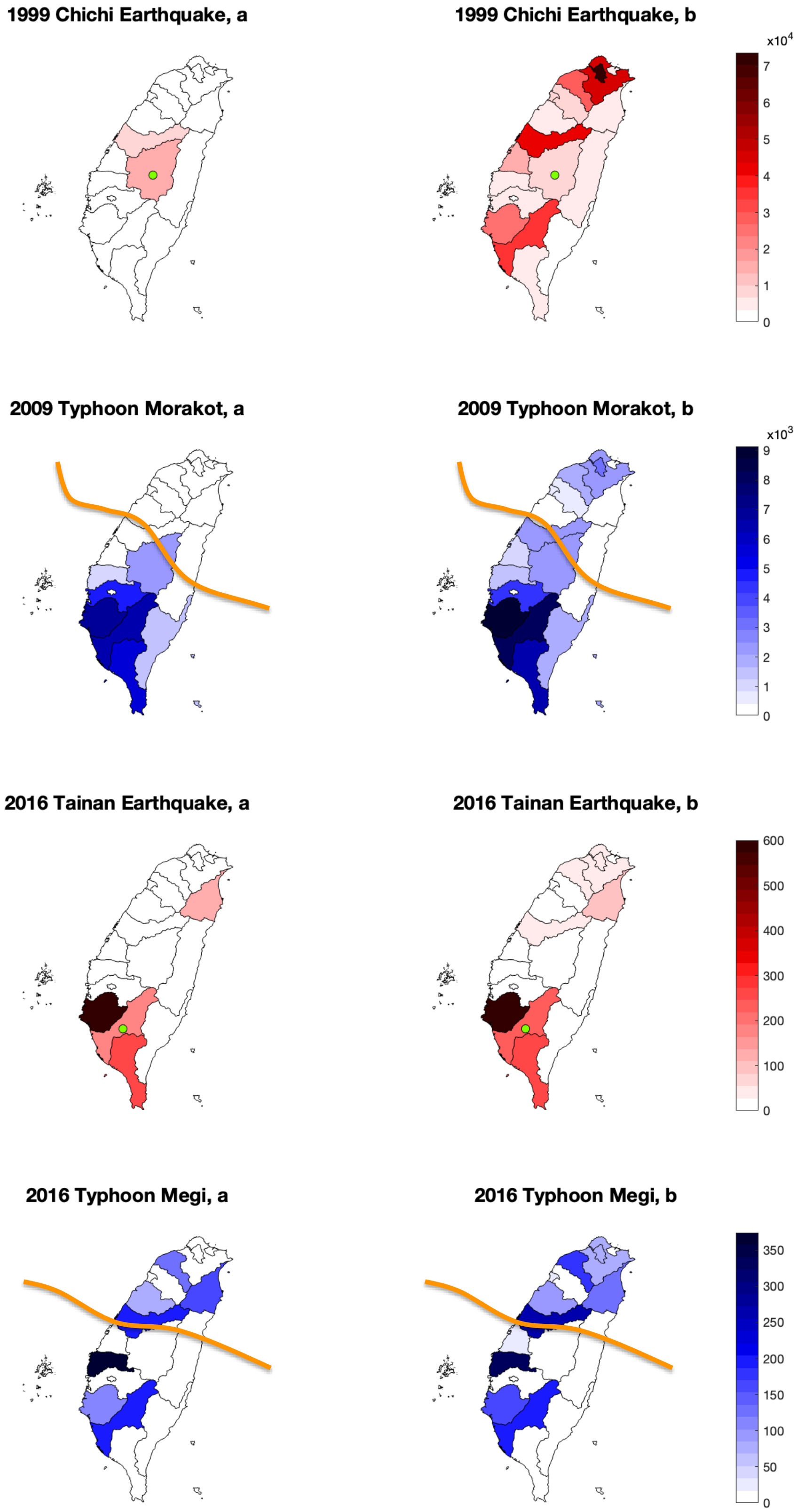
MRIO structure, spillovers due to transportation and communication losses, such as in airports, seaports, and telephone networks, amounted to NT$ 38.3 billion. Approximately two-thirds of these losses were felt in New Taipei and other northern manufacturing hubs. In this case, extensive damages to roads and bridges throughout Nantou, Taichung, Chiayi, and Yunlin, and the railway tracks near Taichung (Dong *et al.* 2000) cut access to the north for several weeks. This affected the freight delivery of critical inputs from Taoyuan and New Taipei's manufacturing sectors to their central and southern customers, and vice versa.

The financial, real estate, and business services sectors suffered substantial losses of NT$ 95.4 billion following the week-long closure of the Taiwan Stock Exchange, the increase of property insurance claims to NT$ 15.4 billion, and the payment reschedule of the mortgage debts (Chang 2000). Most of the insurance claims and the bad credits occurred in Nantou, Yunlin, Changhua, Taichung, and Tainan. However, Taipei and New Taipei carried most of the spillover effect in the financial sectors (worth NT$ 53.4 billion) because these cities are the centre of the financial, real estate, and business services activities in Taiwan.

The 1999 Chichi earthquake caused serious damage to public facilities such as schools and hospitals. The total loss in public services was valued at NT$ 62 billion, and the effects were felt across all regions. In particular, city-counties with a high seismicity experienced higher loss than other city-counties.

The loss in agriculture, livestock, forestry, and fishery sectors were equivalent to NT$ 11 billion, 60% of which was felt in the central regions of Changhua, Yunlin, Taichung, and Nantou, where the earthquake's epicentre was located. Since these cities and counties supplied around 40% of the Taiwan's agricultural outputs (see **Table 3.3**), the losses borne by these regions spread to the downstream food and beverage factories in Taoyuan, New Taipei, and Tainan, which in turn reduced the (semi-)processed food products supply to restaurants in Taipei. Based on our MRIO database, the restaurant sectors in Taipei suffered a value-added loss of NT$ 2 billion.

Figure 3.5. Regional value-added losses (direct plus spillovers) from four natural disasters in Taiwan.



Notes: "a" and "b" refer to direct and indirect losses, respectively. The dots represent the earthquakes' epicenters, and the lines represent the typhoon paths. The Taiwan MRIO tables are valued in NT$ 1 million, hence a value of 600 in the legend represents a value-added loss of NT$ 600m.

The 2009 typhoon Morakot resulted in a value-added loss of NT$ 71.9 billion. As the typhoon triggered extreme flooding in the south, the majority of the losses (about 60%) were felt in city-counties throughout southern Taiwan. Tainan experienced the largest loss of all regions, approximately NT$ 13.4 billion, mostly in the agriculture, livestock, forestry, and fishery sectors. Based on our MRIO data, Tainan's agricultural damages reduced the supply of raw agricultural products to Taoyuan and New Taipei's food and beverage industries, leading to a value-added loss of NT$ 5.1 billion. The extreme flooding also caused a combined loss of NT$ 13.6 to the agricultural sectors in southern regions of Pingtung, Kaohsiung, and Chiayi, and central regions of Nantou, Taichung, and Yunlin. This in turn affected the sizable agriculture-related manufacturing in all city-counties in central and southern Taiwan: our results show that the typhoon caused an indirect loss of about NT$ 6.9 billion in the manufacturing sectors of these regions.

Typhoon Morakot resulted in a combined loss of NT$ 18.5 billion for trade, hotel, and restaurants, transportation and communication, and other services. Typhoon-triggered damage to public facilities reduced tourism activities, passenger delivery, and education services in Tainan, Kaohsiung, Pingtung, and Chiayi. As manufacturing activities, such as supply delivery from Chiayi to Taoyuan, were also disrupted, the damage on public infrastructures spilled over to the manufacturing sectors in Taoyuan and New Taipei. In addition, the typhoon indirectly hit Taipei's financial, real estate, and business services with a loss worth NT$ 2.2 billion. This indirect loss mainly resulted from the spillover effects of the increase in the insurance claims in Tainan, Chiayi, Pingtung, and Kaohsiung.

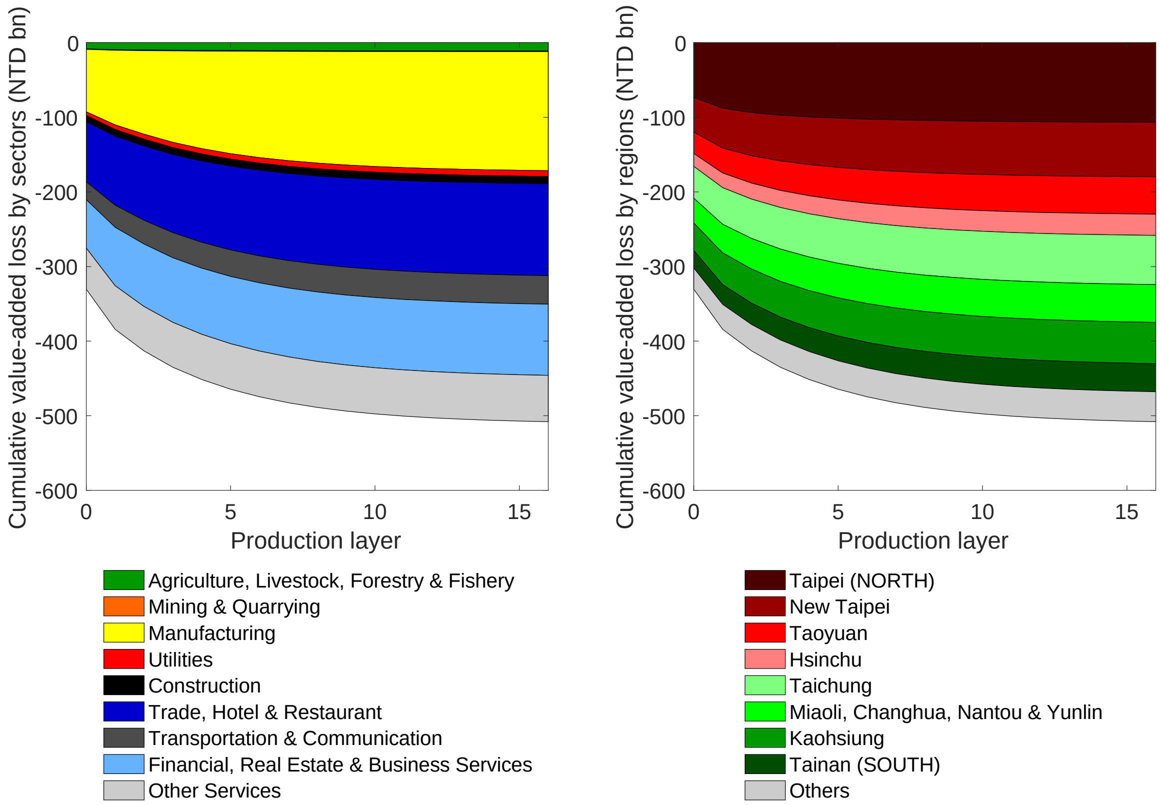
In the case of the 2016 Tainan earthquake, the value-added loss was about NT$ 1.9 billion. Since the epicentre of the earthquake was in the south, the southern city-counties suffered approximately 80% of the total value-added losses. Most of the losses were felt by education and recreation services sectors due to damages on local schools and tourism monuments, and agricultural sectors due to damages on farming and livestock facilities. In contrast to the 1999 Chichi earthquake, the spillover effects of the 2016 Tainan earthquake were relatively small since the earthquake caused no damage to essential business facilities. While no structural damages were found on the national railway (Shu-Fen and Liu 2015), the manufacturing activities in the high-tech factories in the Southern Taiwan Science Park remained normal after the earthquake (Ya-Chen and Hsu 2015).

The value-added loss resulting from the 2016 typhoon Megi amounted to NT$ 2.5 billion, about 40% of which was felt in agriculture, livestock, forestry, and fishery sectors. Yunlin and Taichung were the hardest-hit regions as the typhoon passed through these city-counties. The shortage of agricultural products from Yunlin, Taichung, Kaohsiung, Tainan, and Yilan triggered a loss in the agriculture-related manufacturing sectors in Taoyuan, and New Taipei, which our MRIO data allow estimating at about NT$ 0.2 billion. Similarly, Typhoon Megi also caused flooding in the south, in turn damaging farm fields, public infrastructures and business sites, and resulting in an indirect loss of NT$ 0.2 billion in Kaohsiung and Tainan's manufacturing sectors.

3.3.2.3 Production-layer decomposition of value-added losses

In what follows we present detailed results for the value-added losses resulting from 1999 Chichi Earthquake, particularly, since this disaster was the most destructive of the four selected natural disasters. Results from the production-layer decomposition analysis reveal that the 1999 Chichi earthquake resulted in NT$ 177.6 billion loss in value-added in the upstream supply chain, in addition to NT$ 330.4 billion value-added losses. The manufacturing sectors, the trade, hotel, and restaurant, the financial services, and the transportation and communication had the biggest fraction of this upstream supply chain effect, equal to NT$ 75.7 billion, NT$ 42.8 billion, NT$ 30.5 billion and NT$ 14.3 billion loss, respectively (**Figure 3.6**, left panel). Meanwhile, the northern regions of Taipei, New Taipei, and Taoyuan suffered high regional upstream supply chain effect worth NT$ 32.9 billion, NT$ 26.9 billion, NT$ 21.4 billion, respectively (**Figure 3.6**, right panel). Such upstream supply chain effects are inevitable in the event of a disaster, since a likely shut-down of one particular business results affects other establishments that depend on its outputs, or that supply its inputs. As a result, the output of these dependent establishments will also be reduced. The MRIO tables depict this inter-relationship between sectors across multiple regions, and therefore serve as a comprehensive analytical tool for disaster assessments.

Figure 3.6. Cumulative value-added loss resulting from the 1999 Chichi Earthquake (in NT$ billion).



In the case of the 2009 typhoon Morakot, the 2016 Tainan earthquake, and the 2016 typhoon Megi, a further value-added loss in the supply chain was worth NT$ 25.4 billion, NT$ 0.5 billion, and NT$ 0.9 billion, respectively. As manufacturing and trade involved relatively high supply chain activities, approximately two-thirds of the value-added loss occurred in these sectors.

In **Table 3.4**, we summarise the results of value-added losses of each natural disaster in this study. The upstream supply chain effect is approximately half of the magnitude of value-added losses, leading to a multiplier of 1.4~1.5. This means that for each NT$ of value-added directly lost due to reduced consumption possibilities in the wake of a natural disaster earthquake or typhoon in Taiwan, a loss of 0.4~0.5 NT$ in value-added should be expected due to regional and sectoral spillovers. The Taiwan impact multipliers are slightly below the global multipliers (Okuyama and Sahin 2009), which range from

1.8 to 2.0 depending on the type of natural disasters: meteorological 2.0, geophysical 1.9, hydrological 1.8, and climatological 1.8.

Table 3.4. Estimation of value-added losses.

	1999 Chichi earthquake	2009 typhoon Morakot	2016 Tainan earthquake	2016 typhoon Megi
Total loss (NT$ billion)	508.0	71.9	1.9	2.5
a) Directly losses as a result of reduced consumption possibilities	330.4	46.5	1.4	1.6
b) Indirect supply chain losses resulting from a)	177.6	25.4	0.5	0.9
Main sector affected	Manufacturing	Agriculture	Services	Agriculture
Main region affected	Taipei City	Tainan City	Tainan City	Yunlin County

3.4 Discussion

In this study we reveal economic impacts of four selected natural disasters in Taiwan, in particular resulting from business and public facility damages, as well as supply chain interruptions—two areas that researchers have found difficult to model in the case of Taiwan (Hsu *et al.* 2013). We assess the new TaiwanLab, a collaborative virtual laboratory that is able to generate a time-series of sub-national MRIO tables so analysts can capture interregional transactions between 267 economic sectors across Taiwan's 22 city-counties.

The Taiwan MRIO database appears to be able to enable comprehensive disaster impact assessments. By yielding an understanding of the regional economic income distribution, sectoral contributions, and interregional trade flows, the Taiwan MRIO database provides a comprehensive picture of Taiwan's regional economic structure, and how the interconnections within it expose different parts of the nation to natural disasters differentially. Using the Taiwan MRIO database, we identify critical economic sectors in regions with high vulnerability to natural disasters. The analysis could not have been achieved without sub-national MRIO tables, and these can be tailored to disaster-analysis-specific questions using a virtual lab.

We subsequently estimate that the 1999 Chichi earthquake, the 2009 typhoon Morakot, the 2016 Tainan earthquake, and the 2016 typhoon Megi caused a total value-added loss of NT$ 508.0 billion, NT$ 71.9 billion, NT$ 1.9 billion, and NT$ 2.5 billion, respectively. In particular, the losses that resulted from upstream linkages were large, amounting to about half of value-added lost. Since Taiwan's economy is highly interconnected, no single region is unaffected by such disasters. In some cases, a region located far from the disaster's epicentre or path suffered important economic losses. Taipei's and New Taipei's powerful financial and trade sectors, for example, experienced a relatively high value-added loss due to the repercussions of disaster damage in other regions, making these sectors vulnerable regardless of their physical distance from the natural disasters. We also find regional economic impact multipliers of the four natural disasters in Taiwan range between 1.2 and 2.0 (**Table 3.5**). These multipliers are the ratio of total impacts $\sum_{n=0}^{\infty} \mathbf{v}'(\mathbf{I} + \mathbf{A}^n)(\mathbf{y}_0 - \tilde{\mathbf{y}})$ to direct losses caused by reduced consumption possibilities $q_0 - \tilde{q}$. The financial and industrial centre of Taipei, New Taipei, and Taoyuan has higher multiplier than do agricultural locations of Yilan, Yunlin, and Nantou. This confirms the work of Kellenberg and Mobarak (2008), who indicates that higher-income regions are more vulnerable to natural disasters than are middle- and lower-income regions. The range of regional multipliers could not have been captured without considering the economic interdependence of the affected areas, as offered by the Taiwan MRIO tables.

In addition, an MRIO-based disaster framework can serve as an early-warning and resilience planning system for regions likely affected by natural disasters. Our analysis of the 1999 Chichi earthquake shows that a relatively small disruption of a vital industrial input, such as electricity, can cause significant economic losses. Such insight can help governments evaluate the national electric grid, and perhaps suggest the construction of power plants or the storage of back-up transformers nearer essential economic locations, such as high-tech manufacturing and financial markets. Similarly, to ensure the seamless distribution of goods and services, transportation networks connecting west Taiwan could be re-designed to assure more resilience near emergency facilities and important industrial complexes.

Table 3.5. Regional impact multiplier

	1999 Chichi Earthquake	2009 Typhoon Morakot	2016 Tainan Earthquake	2016 Typhoon Megi
Hsinchu County	1.6	2.0	1.9	1.9
Taoyuan	1.7	2.0	2.0	1.6
Yilan	1.4	1.9	1.3	1.3
Hsinchu City	1.7	2.0	1.9	1.9
Keelung	1.5	2.0	1.9	1.9
New Taipei	1.6	2.0	2.0	2.0
Taipei	1.4	2.0	2.0	2.0
Changhua	1.6	2.0	2.0	2.0
Miaoli	1.6	1.9	1.9	1.4
Nantou	1.3	1.4	1.9	1.9
Yunlin	1.5	1.4	1.9	1.3
Taichung	1.5	1.9	2.0	1.5
Chiayi County	1.5	1.3	1.9	1.9
Penghu	1.4	1.7	1.8	1.7
Pingtung	1.4	1.3	1.1	1.9
Chiayi City	1.4	1.9	1.9	1.9
Kaohsiung	1.5	1.4	1.4	1.5
Tainan	1.6	1.5	1.2	1.5
Hualien	1.4	1.9	1.9	1.9
Taitung	1.3	1.3	1.7	1.8
Kinmen	1.5	1.8	1.8	1.8
Lienchiang	1.3	1.4	1.5	1.2
National	1.5	1.5	1.4	1.5

3.5 Conclusions

Disasters are highly localised. Even in a relatively small country like Taiwan, small breaks in supply chains can cause major economywide losses. Therefore, regionally- and sectorally-detailed MRIO databases are needed to undertake disaster analysis at sufficient resolution. Since disasters can affect agriculture in one region and manufacturing industries in another region, either at the same time or at different times, flexible, adaptive MRIO databases can be quite beneficial. For this reason, we chose to establish a virtual laboratory for Taiwan, the TaiwanLab.

The TaiwanLab provides flexibility to users so they can obtain customised regional and sectoral classifications for MRIO tables, and incorporate a wide variety of primary data. The lab also can update or add additional data to suit specific research questions, so that it allows a wide range of international users to undertake IO modelling on various economic, social, and environmental topics.

Whilst this paper demonstrates the TaiwanLab as a case study for disaster analysis, this innovation can be and is being transferred to other countries such as Australia (Lenzen *et al.* 2014; Lenzen *et al.* 2017), Indonesia (Faturay *et al.* 2017), China (Wang *et al.* 2015; Wang 2017), Japan (Wakiyama *et al.* 2019), Sweden (Faturay *et al.* 2019a), and the USA (Faturay *et al.* 2019b). The hope is for the virtual lab technology to become a blueprint for aforementioned countries to assess the regional economic impacts of natural disasters.

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Connecting Page

Chapter 4 describes applying the SwedenLab for evaluating consumption-based emissions in 21 Swedish counties.

Economic development and industrialisation result in negative environmental effects. One of the environmental issues is related to the increase of carbon dioxide in the atmosphere, a side-effect of which is commonly known as climate change. Sweden has been one of the countries producing the lowest levels of GHG emissions per capita. However, a complete picture of the direct and indirect (embodied) greenhouse gas (GHG) emissions resulting from consumption at regional levels is currently unavailable. This requires the complete depiction of emissions released throughout inter-regional activities as well as international trades across Sweden's 21 counties.

A fundamental technique for undertaking assessment of consumption-based emissions is utilising a sub-national MRIO table. I-O based assessments enable the quantification of emissions embodied in the supply chain network.

In what follows, I present the SwedenLab: a new virtual laboratory able to depict the inter-regional interactions across all counties in Sweden. The MRIO database was then employed for assessing the current status of regional carbon emissions from the consumer perspective in Sweden between 2008 and 2016.

Chapter 4

Demand-driven GHG emissions of Swedish regions: 2008–2016

Abstract

Sweden is one of the most sustainable countries in the world and has become the best-performing country regarding reducing GHG emissions. In 2016, Sweden's GHG emissions amounted to 6.2 tonnes per capita, the lowest among European Union (EU) countries, which averaged 8.7 tonnes per capita. However, looking at the emissions from the perspective of consumption, the figures look very different, with emissions amounting to 10.1 tonnes per capita in 2016. In this study, we go a step further in the analysis of Swedish consumption-based emissions by looking at the carbon flows between regions. That is, we look at which regions (through their consumption) are driving the emissions in other regions. We do this through MRIO analysis utilising a new virtual laboratory, the SwedenLab. This new database is able to quantify regional consumption of GHG emissions for 59 sectors across Sweden's 21 counties for the years 2008–2016.

4.1 Introduction

GHG emissions have raised the earth's temperature by at least 1.2 degrees since the beginning of the 20th century (Amadeo 2019). As was concluded in the Paris Agreement, increasing efforts are needed to decrease GHG emissions and to substantially mitigate climate change. One country that is a pioneer in mitigating the effects of climate change is Sweden. Based on the Climate Change Performance Index (CCPI), Sweden is the best-performing country in combating climate change (Burck *et al.* 2018). The CCPI has tracked countries' efforts to meet the global goals of the Paris Agreement by considering the current levels in energy use, renewable energy, and GHG emissions. The CCPI has been an important tool for evaluating countries' progress on climate policy.

The Swedish Government has implemented a number of initiatives to boost carbon-efficiency in governments, industries, and households. The National climate policy framework in 2017 sets out the long-term conditions for business and society. Even earlier, in 1999 the Environmental Quality Objective was accepted by the Swedish Parliament. These environmental objectives are covering 16 areas, of which climate change one such objective. The basic goal of the environmental objectives are to leave a society to the next generation where the major environmental problems are solved, without causing increased environmental and health related problems to the rest of the world (Swedish EPA 2017). Since adopting these policies, a substantial carbon emission reduction has been achieved.

In 2016, Sweden was one of the countries producing the lowest levels of GHG emissions per capita. The country's GHG emissions per capita amounted to 6.2 tonnes, the lowest among EU countries, which averaged 8.7 tonnes. Sweden also successfully lowered its GHG emissions by 26% compared to 1990 levels (OECD Stat 2019). The Swedish Government introduced a more ambitious emissions target in June 2017. In order to achieve the Paris Agreement's goal (aiming to limit the global temperature increase to only 1.5°C), the Government plans to cut GHG emissions by 40% of 1990 levels by the year 2020, and to have zero net GHG emissions by 2045 (5 years earlier than the previous plan). To accomplish this goal, the Government has to come up with more drastic measures so that by 2045, GHG emissions will have declined by at least 80% below 1990 levels.

The country's pivotal role in climate mitigation efforts requires having a complete picture of the emissions resulting from domestic consumption in order to provide better assessments of the country's responsibility on climate change. Global trade links consumption patterns in one country attributed to the emissions in another country. This is popularly known as a 'carbon footprint', which measures the emissions embodied in the consumption of goods and services. The traditional approach for accounting for carbon emissions takes a territorial perspective; however, this does not reflect the full impacts of climate change (Wiedmann *et al.* 2010). The carbon footprint approach adjusts production-based emissions—how much emissions are produced by the national economy—by subtracting export-related and adding import-related emissions.

Since the end of the 2000s, there has been a rise in the demand for such data that can measure the impact of trade on emission consumption (Minx 2009). A fundamental tool for undertaking a consumption-based emissions assessment is the use of a MRIO modelling framework. I-O based assessments enable the quantification of emissions embodied in trade, as an MRIO model is able to depict the inter-regional interactions between different sectors across multiple regions. There have been prior studies undertaken to quantify consumer-based emissions using I-O analysis. At the global level, I-O analysis has been applied to estimate carbon emissions in 189 countries (Malik and Lan 2016), 13,000 cities (Moran *et al.* 2018), 177 EU regions (Ivanova *et al.* 2017), and China's global trade partners (Qi *et al.* 2012). The MRIO framework has also supported the assessment of carbon footprints at sub-national levels, such as in the UK (Minx *et al.* 2013), Scotland (Hermannsson and McIntyre 2014), China (Feng *et al.* 2012; Mi *et al.* 2017), and Australia (Wiedmann *et al.* 2016; Guangwu *et al.* 2016), among others.

In the Swedish context, emissions by industry are regularly reported, followed by an analysis of emissions embodied in final consumption (Minx *et al.* 2008; Swedish EPA 2010; Swedish EPA 2012). Based on the reports, Sweden is clearly a net importing country of carbon emissions. However, a comprehensive assessment of the emissions resulting from consumption at sub-national levels remains lacking.

The dangers of the effects of climate change—such as floods, landslides and erosion—are predicted to be intense in many local areas in Sweden (Swedish Government 2007). The regional diversity means that different areas require different policies, and as Sweden has a decentralised system with self-autonomy in the municipalities the climate policy will differ locally (Olsson 2018). Hence, it becomes clear that assessing responsibility of climate change at regional levels is necessary. To this end, a comprehensive sub-national model is needed to capture the unique characteristics of Sweden's counties, in particular, focussing on very recent data and detailed supply chain distribution in all sectors and regions. Albeit there exists an I-O based model, it is not yet able to take into account inter-regional trade.

Here, we present the SwedenLab, which can generate regionally and sectorally detailed MRIO tables for Sweden's 21 counties from 2008–2016. The MRIO database is then applied to reveal the effects of international trades on regional emissions, the driver for national emissions, and the changes in inter-regional emission flows from 2008–2016. Understanding these details is critical in forming the basis for local policymakers' long-term planning, as they are the ones responsible for future climate policies.

The remainder of this study is organised as follows. We will first describe how we constructed the MRIO database in a virtual laboratory, so-called the SwedenLab. We then present our empirical results utilising this new database. We finish by concluding our results.

4.2 Methods and Data

4.2.1 I-O basic equation

The basic I-O relationship can be expressed as (UN 1999):

$$\mathbf{x} = (\mathbf{I} - \mathbf{A})^{-1}\mathbf{Y} = \mathbf{LY}$$

where $\mathbf{x}$ is the gross output, $\mathbf{A}$ is the domestic input coefficients of matrix, $\mathbf{Y}$ is the final demand, and $\mathbf{L}$ is the Leontief inverse matrix representing structural interdependencies.

The satellite accounts of GHG emissions[14] is then linked to the I-O model to form a so-called environmentally extended I-O analysis (Leontief 1966; Leontief and Ford 1970; UNSD 2017). By applying an emission intensity matrix $\mathbf{q}$ (kg/SEK) to the equation above, the carbon footprint Q can be formulated as:

$$Q = \mathbf{qLY}.$$

Emissions embodied in imported commodities Q_M resulting from domestic consumption are handled separately. In this study, we use an imported emission intensity matrix $\mathbf{q}_M$ from the PRINCE project (Palm 2018) which utilised the EXIOBASE model (Tukker 2013).

4.2.2 Virtual laboratory

Constructing MRIO tables can be time-consuming and labour intensive, but in recent years, the use of virtual laboratory technology for compiling sub-national I-O tables has become an alternative solution, reducing costs related to MRIO table development (Faturay *et al.* 2017). Virtual laboratories started in Australia (Lenzen *et al.* 2014), and since then have spread to other countries, such as Indonesia (Faturay *et al.* 2017), China (Wang 2017), Japan (Wakiyama *et al.* 2018), Taiwan (Faturay *et al.* 2018) and the USA (Faturay *et al.* 2019). The applications from these labs have resulted in various analyses, including of regional employment multipliers in Indonesia, carbon emissions in China, food loss in Japan, disaster impact assessments in Taiwan, and renewable energy in the USA. Since work in a virtual laboratory significantly accelerates outcomes in MRIO-related research, we, therefore, chose to build a time-series of sub-national MRIO tables for Sweden in a virtual laboratory, called the SwedenLab.

The SwedenLab offers flexibility in customising regional and sectoral classifications, incorporating data constraints, and selecting particular years of MRIO tables. As with other labs, constructing a sub-national MRIO database in the SwedenLab requires

[14] The satellite accounts refer to data from the System of Environmental-Economic Accounts (SEEA) that was established in the revision of the System of National Accounts in 1993 at global level to link the environment to the economy in the same framework. Sweden started producing data from the SEEA in 1993.

national I-O tables. These national I-O tables are then disaggregated into sub-national MRIO tables using non-survey regionalisation methods (Sargento *et al.* 2012), which is a widely used technique for generating sub-regional MRIO tables. A total of 10 different non-survey methods, such as the location quotients (LQ) and cross-hauling variants, are available in the SwedenLab. The user's choice of non-survey method may have an impact on the results. In this study, we chose Flegg's Location Quotient[15] (FLQ, Flegg and Webber 2000) to regionalise the Sweden national I-O table due to the superior performance of the FLQ over basic regionalisation methods (such as Simple LQ and Cross Industry LQ) for estimating inter-regional input coefficients (Bonfiglio and Chelli 2008). The regionalisation of the national I-O tables into sub-national MRIO tables is accomplished using regional weights, describing the relative size of industries of a region in comparison to the nation.

At this stage, the MRIO table can be tailored using specific classifications. The available sectoral classifications for SwedenLab are 21 sectors, 59 sectors, and 821 sectors, and the regional classifications are available for 8 regions, 21 regions, and 291 regions. However, the current data is not quality assured at the maximum level of detail. It is also possible to construct MRIO tables beyond these classifications by creating a concordance matrix connecting their own classifications with the root classification. The use of a root classification is the key to the lab's flexibility since it captures the maximum regional and sectoral classifications. From this root, more aggregated sectors and regions can be selected to represent the final table. The root classifications are extracted from labour data that is available at a satisfactory level of disaggregation for all regions and sectors. Labour data also becomes the proxy quantity for the regionalisation process. The outcome of this regionalisation process is used as an initial estimate for the MRIO table.

The initial estimate is a preliminary user-specific MRIO table that serves as an input into a reconciliation process, where a set of constraints and balanced conditions are enforced. Reconciliation is carried out using a code system known as AISHA (Geschke *et al.* 2014). The MRIO tables need constraints to control elements in the final demand, value-added, and trade blocks. For example, the detailed GDP for Stockholm are used for constraining

[15] Tests have also been done using CHARM and SLQ methods which indicate different results.

elements in the Stockholm's final demand block. Users must also consider the availability of data constraints. If the data are available at the county level, users should not attempt to create MRIO tables capturing municipalities. In this study, the MRIO tables consist of 59 sectors (at the county level) of 21 regions for the years from 2008 to 2016, due to data only being available up to that point.

It should be noted that the SwedenLab allows users to integrate new datasets and update existing constraints. Incorporating new data into a virtual laboratory, however, requires an in-depth understanding of programming workflow (Geschke and Hadjikakou 2017). For example, users have to be familiar with Matlab software, and ALANG files. Given the complexity of the virtual laboratory framework, working collaboratively with researchers who are already familiar with the lab's environments is preferable. The collaborative work undertaken within the virtual laboratory community has resulted in at least 30 published articles (see Wiedmann 2017 for complete list).

4.2.3 Data sources

All data for this study come from Statistics Sweden (Statistics Sweden 2019). National I-O tables for Sweden are available for 2008–2016, consisting of 59 sectors. The currency unit is 1 million Swedish Krona (SEK), the final demand has eight fixed components[16], and the primary inputs have twelve fixed categories[17]. Statistics Sweden publishes national input-tables on a regular basis, once a year. In addition, we utilise labour survey data to regionalise national I-O tables. **Table 4.1** shows the primary data for the SwedenLab.

Two regional datasets are available to use: disposable income (for constraining the consumption expenditure by households in the final demand matrix), and aggregated value-added (for constraining the value-added matrix). Moreover, regional GHG

[16] Final consumption expenditure by households; Final consumption expenditure by non-profit organisations serving households (NPISH); Final consumption expenditure by government; Gross fixed capital formation by industry; Gross fixed capital formation by government; Changes in inventories; Acquisitions less disposals of valuables; and Export.
[17] Wages and salaries; Employers' social security contributions; Consumption of fixed capital; Operating surplus and mixed income, net; Other taxes on production; Other subsidies on production; Customs; Taxes; Subsidies; Value-added tax (VAT); Direct purchases abroad by residents; and Purchases on the domestic territory by non-residents.

emissions presented in CO_2 equivalents are used as satellite accounts. Since all regional data consist of 21 counties, we generated Sweden MRIO tables at this level of detail.

To measure the effects of international trade on Sweden's regional emissions, we utilise carbon intensity information from PRINCE project (Palm 2018).

Table 4.1. Primary data for the SwedenLab.

	Data	Years	Regions	Sectors	MRIO part constrained
1.	National I-O tables	2008-2016	1	59	ID, FD, VA, Imp, Exp, GO
2.	Disposable income	2008-2016	291	1	FD
3.	Value-added	2008-2016	291	2	VA
4.	Labour survey	2008-2016	291	821	Proxy for regionalisation
5.	GHG emissions	2008-2016	21	17	Satellite accounts

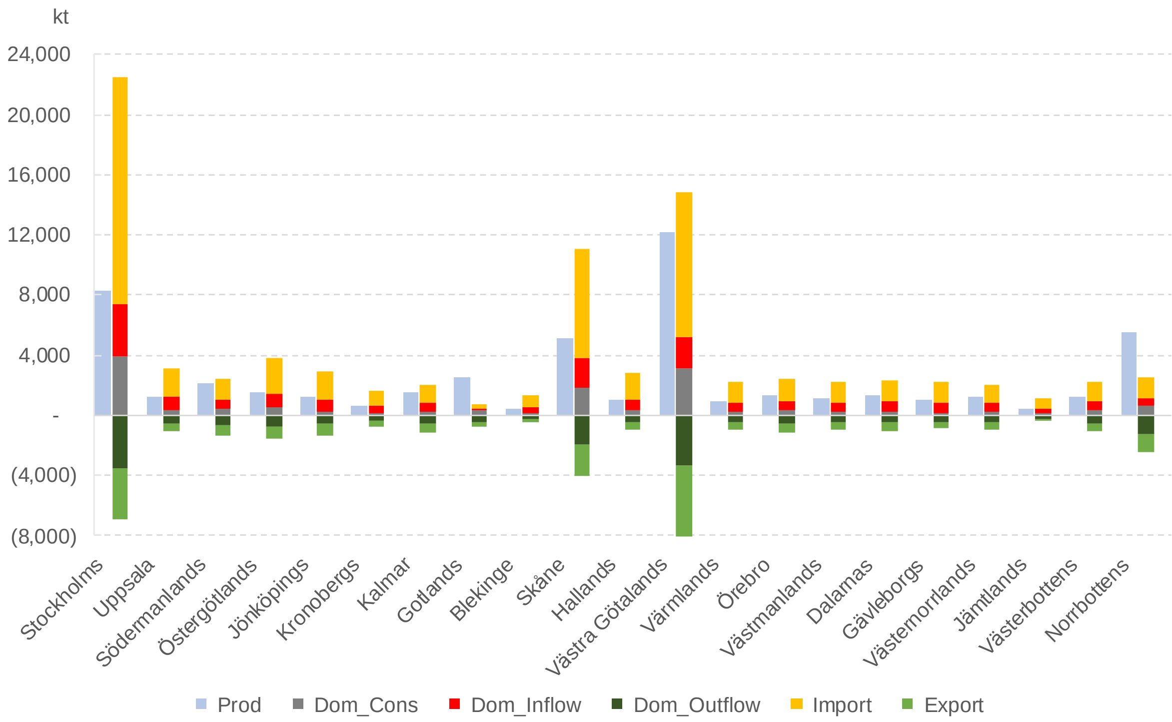
Note: All data comes from Statistics Sweden. ID = Intermediate Demand, FD = Final Demand, VA = Value-Added, Imp = Import, Exp = Export, and GO = Gross Output. The text under column header "MRIO part constrained" describes the specific MRIO elements that are constrained by the respective data source. The text "Proxy for regionalisation" means that the respective data source was used in the non-survey approach for disaggregating the national I-O tables into sub-national MRIO tables.

4.3 Results

4.3.1 Regional production-based emissions in Sweden

In 2016, Sweden emitted a total of 52.0 million tonnes (Mt) of GHG emissions (excluding households). **Figure 4.1** shows regional GHG emissions for Sweden's 21 counties in 2016. The production of GHG emissions from the economy are the largest in Västra Götaland due to its sizeable heavy manufacturing industries and transportation service activities. The capital city of Stockholm is the second largest emitter, following by Skåne in third place. Stockholm's large emissions volume is mainly the result of transportation sectors, while Skåne's agriculture activities caused the emissions high for this county. Västra Götaland, Stockholm, and Skåne produced a combined 23.7 million tonnes (Mt) of GHG emissions in 2016, just short of 50% of the national emissions. Norrbotten, Gotland, and Södermanland county also produced significant amounts of GHG emissions due to the presence of high-carbon-intensive industries, such as pulp-and paper, steel industries and electricity power generators in Norrbottens county, extraction of minerals in Gotland, and waste services in Södermanland. The other 15 counties combined produced less than 30% of national emissions. In particular, counties with the lowest population, such as Kronoberg, Blekinge, Värmland, and Jämtland, emitted the smallest production-based GHG emissions in Sweden.

Figure 4.1. Regional GHG emissions in 2016



4.3.2 Regional GHG emissions due to inter-regional and international trade

Using information about Sweden's interconnected MRIO structure, we can calculate consumption-based emissions for 59 sectors in 21 counties. In total, around 62% of the 52.0 Mt of emissions produced in Sweden in 2016 was consumed by domestic markets, while the rest amounted to 20.4 Mt was exported to other countries. More than 70% of the 20.4 Mt of exported emissions from Sweden was from manufacturing industries, such as motor vehicles, paper, machinery, and chemical products. In the same period, total imported emissions were significant, amounting to 56.2 Mt. Therefore, the net imported emissions amounted to 35.8 Mt or approximately 70% of the production-based emissions.

Sweden's consumption of foods, clothing, electronics, and household appliances is to a large extent produced in other countries. As a result, high-carbon-intensive commodities from abroad are consumed by Swedish citizens. In 2016, the emissions embodied in manufacturing products amounted to 45.8 Mt or approximately 80% of the total emissions from abroad. The emissions from food, motor vehicles, furniture, textiles, machinery, and electronic products dominated imported emissions. A large amount of emissions was also attached to agricultural products, air transportation, electricity, metal, and rubber products.

Stockholm is the biggest consumer of the imported emissions, amounting to 15 Mt. With a population of 2.3 million people, or approximately one-fourth of the total population, Stockholm's GDP contributed to one-third of the national total. Given this large population, Stockholm imports abundant commodities from other countries, and consequently, GHG emissions embedded in the imported products were consumed in Stockholm. Food products, cars, furniture, clothing, and air travel dominated the imported emissions in Stockholm. The imported emissions were also significant in Västra Götaland and Skåne, amounting to 9.6 Mt and 7.2 Mt, respectively. Västra Götaland and Skåne are the second and third largest economic contributors to the Swedish GDP, with a combined contribution of 30% of the national economy. After Stockholm, those counties are also the most populous regions in Sweden and therefore consume large amounts of the emissions embodied in imported products.

4.3.3 GHG emissions per capita

In per capita terms, the production based GHG emissions per capita for Sweden amounted to 6.2 tonnes in 2016. However, using consumption-based estimation, per capita GHG emissions increased by 70% to 8.9 tonnes. **Table 4.2** shows Sweden's per capita GHG emissions for 21 counties in 2016. The emissions per capita of Gotland and Norrbotten declined drastically from 43.4 tonnes to 13.1 tonnes, and from 21.8 tonnes to 10 tonnes, respectively. This is because most of the high-carbon-intensive products in those regions are consumed by people elsewhere, especially high-carbon-intensive products such as steel and cement. **Figure 4.1** shows that the production-based emissions in Gotland and Norrbotten are higher than consumption-based emissions due to the presence of high-carbon-intensive industries in those regions. In contrast, Stockholm's emissions per capita rose significantly to 10 tonnes due to the city's high consumption. The calculation of consumption-based emissions increases the emissions per capita for most regions and demonstrates less variation than the production-based emissions. The results also show that consumer per capita emissions tend to be higher in metropolitan cities than in the less populated counties.

Table 4.2. Per capita GHG emissions in 2016.

Counties	Production-based GHG emission per capita (tonnes)	Consumption-based GHG emission per capita (tonnes)
Stockholms	3.7	10.0
Uppsala	3.3	8.6
Södermanlands	7.4	8.4
Östergötlands	3.5	8.4
Jönköpings	3.5	8.3
Kronobergs	3.5	8.6
Kalmar	6.2	8.4
Gotlands	43.4	13.1
Blekinge	2.7	8.3
Skåne	3.9	8.4
Hallands	3.3	8.8
Västra Götalands	7.3	9.0
Värmlands	3.5	8.0
Örebro	4.6	8.2
Västmanlands	4.2	8.4
Dalarnas	4.7	8.2
Gävleborgs	3.6	7.9
Västernorrlands	4.8	8.3
Jämtlands	3.7	8.9
Västerbottens	4.6	8.5
Norrbottens	21.8	10.0
Sweden	5.2	8.9

4.3.4 Trend of regional consumption-based emissions in Sweden 2008–2016

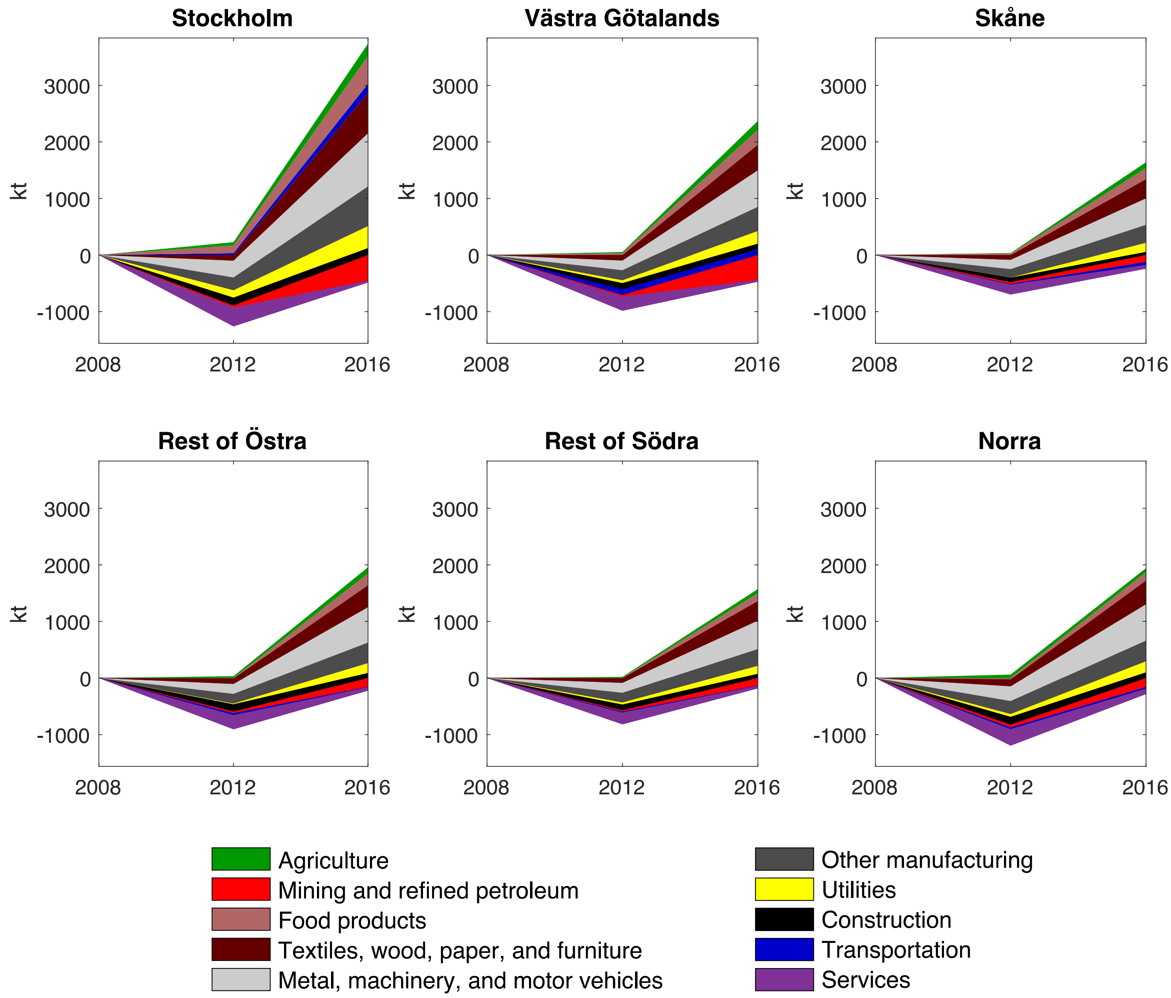
Figure 4.2 shows the change of consumption pattern of GHG emissions in Sweden's regions between 2008 and 2016. For comparability and ease of presentation, we aggregate the results to six regions (Stockholm, Västra Götalands, Skåne, the rest of Östra, the rest of Södra, and Norra) and 10 sectors (agriculture; mining and refined petroleum; food products; textiles, wood, paper, and furniture; metal, machinery, and motor vehicles; other manufacturing; electricity; construction, transportation; and services).

For the period 2008–2012, almost all sectors in all regions successfully reduced the consumption of GHG emissions. Air travel and forestry products, however, experienced an increase in consumption of GHG emissions following the rise of demand for those products. The increase in imported emissions from air travel and forestry products was relatively small, and was therefore offset by the reduction in consumer emissions in all other sectors. In total, the net reduction in consumer emissions in 2012 amounted to 6.6 Mt. This impressive decrease was derived from the energy efficient methods implemented in business, public services, and households.

From 2012 to 2016, while the consumption of GHG emissions embodied in service sectors still showed a substantial reduction, all other sectors bounced back and increased sharply, especially in manufacturing sectors. In total, there was an increase of 10.8 Mt of GHG emissions during the period 2012–2016. Motor vehicles, foods, textile, furniture, and machinery are the most significant contributors to the increase in GHG emission consumption in 2016. Emissions embodied in electricity also increased significantly due to the rise in demand for similar products in domestic markets.

The consumer-based emissions in Stockholm outperformed other regions. Between 2012 and 2016, there was an additional 3 Mt of GHG emissions consumed by Stockholm, especially embodied in manufacturing sectors. Combined with Västra Götaland and Skåne, additional emissions consumed by Stockholm amounted to 60% of the national total. It is clear that the emissions consumed by those counties drive GHG emissions at the national level. In comparison, the emissions embodied in consumption in the other 18 counties added another 4 Mt to Sweden's GHG emissions.

Figure 4.2. Change of consumption pattern of GHG emissions

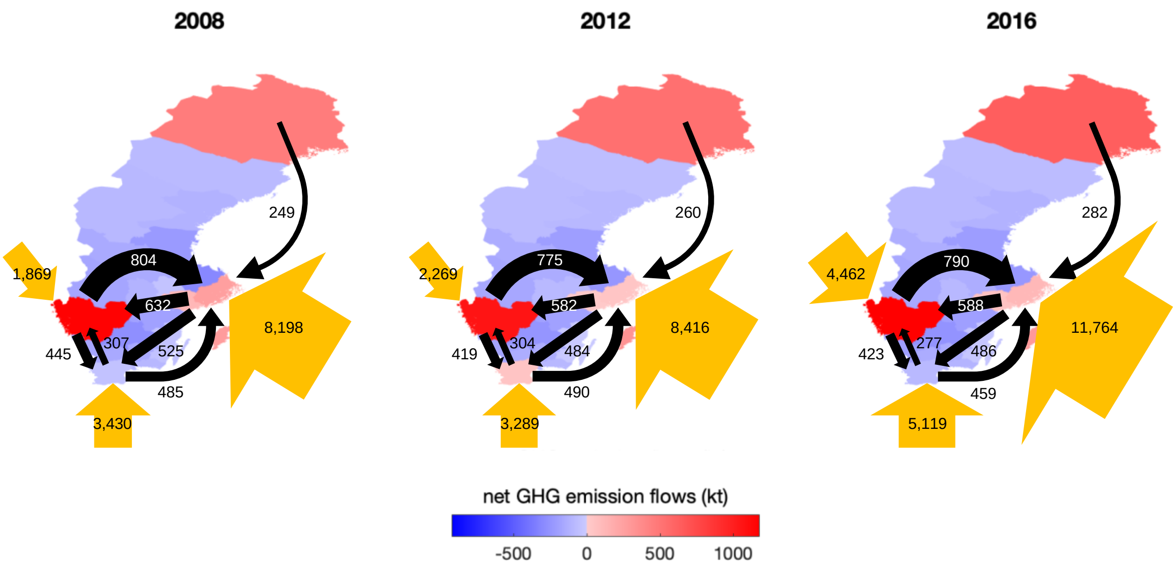


4.3.5 Carbon emission flows

Figure 4.3 (yellow arrows) shows the net imported emissions from abroad in Sweden. For the period 2008–2012, the average net imported emissions grew by 4%. However, the average net imported emissions for the period 2012–2016 grew by more than 50%. This is attributed to the significant growth of domestic consumption. As a result, the dependence of the counties' industries on high-carbon-intensive products from abroad increased dramatically during the period 2012–2016. **Figure 4.3** (black arrows) shows the emission flows within Sweden in 2008, 2012, and 2016. Stockholm, Västra Götaland, Norrbottens, and Gotlands consistently become net emitter counties in domestic economy, meaning that their emissions outflow is larger than their emissions inflow.

Västra Götalands has the most significant net emissions outflow, amounting to 1.2 Mt. The county exported approximately 3.3 Mt emissions, embodied particularly in agriculture and forestry products, electricity, sewerage, and shipping services, but only imported 2.1 Mt emissions, attributed to its food products, construction, and business services. The flow pattern of inter-regional emissions in Västra Götalands also applied to Stockholm. Stockholm exported approximately 3.6 Mt GHG emissions to other regions, mostly embodied in high-carbon-intensive commodities such as agricultural products, utilities, and transportation services. At the same time, Stockholm imported 3.4 Mt GHG emissions, mainly going to its high-value-added industries such as construction, and business and public services.

Figure 4.3. Emission flows within Sweden.



Note: Yellow arrows represent the net imported GHG emissions

The pattern of the inter-regional emissions flow between 2008 and 2016 shows there is an increase in carbon emissions flow from Norrbotten to Stockholm. The northern county of Norrbotten exports a significant amount of emissions through its electricity. This rise represents the increase in purchasing power in Stockholm. In contrast, the GHG emissions outflows from Skåne gradually reduced, which is attributed to the shifting of the county's economic activities to low-carbon-intensive technology.

Figure 4.3 also shows counties surrounding Stockholm (such as Uppsala, Västmanland, and Örebro, and ones in northern Sweden such as Dalarna, Gävleborg, Västernorrland, and Jämtland) usually have net domestic emissions inflows. Those counties become net emissions importers due to their import of high-value-added products of manufacturing and services from Stockholm, Västra Götaland, and Skåne.

4.4 Discussion

In this study, we have investigated consumption-based GHG emissions for 21 counties in Sweden. We conducted our assessment in the new SwedenLab, a collaborative virtual laboratory that is capable of generating a time-series of sub-national MRIO tables for the period 2008–2016.

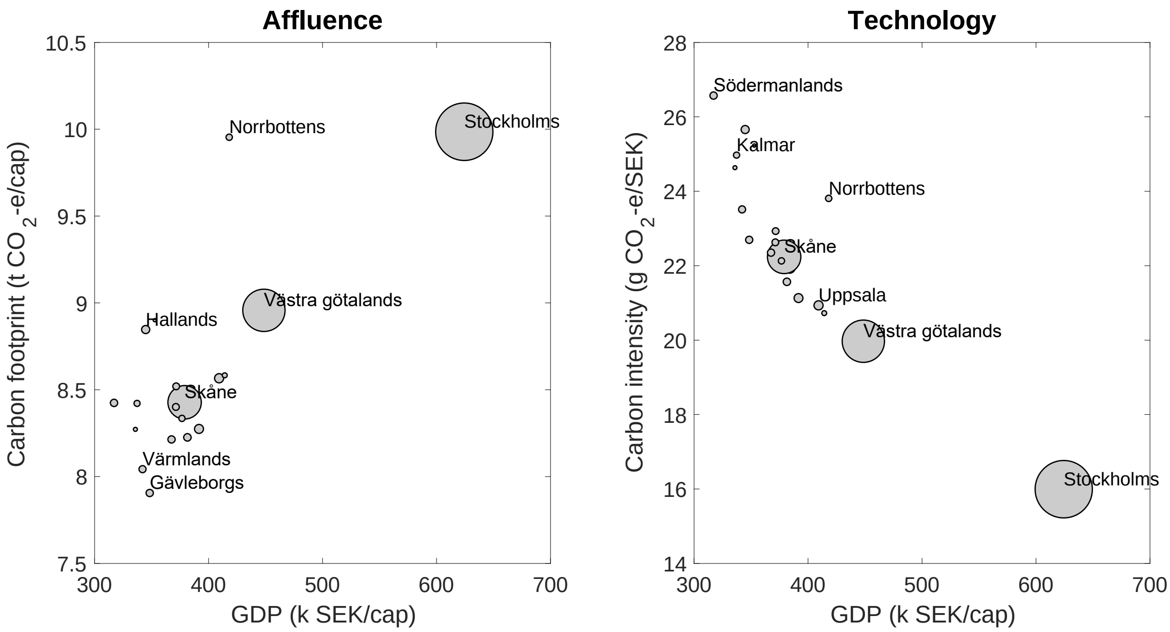
Due to international and inter-regional trade, the consumption of emissions goes beyond basic economic boundaries. Using an MRIO modelling framework, we are able to identify the emission flows between counties in Sweden and the effect of international trade on domestic consumption patterns. Our findings highlight the importance of inter-regional modelling for assessing consumer emissions at the sub-national level.

Consumption-based GHG emissions in our model showed an increase over time, verifiable with the national data. While production-based emissions decreased by 14% between 2008 and 2016, emissions from abroad increased by 18% over the same period. The increase can be partly explained by the 17% increase in value of imports from 2008 to 2016. However, trade is not the only factor causing the increased carbon footprint.

To investigate the drivers behind the increase in consumer emissions in Sweden, we compared regional GDP per capita with carbon footprint per capita and carbon intensity. We found that the per capita carbon footprint increased when GDP per capita increased (**Figure 4.4**, left). This means that more affluent regions emit more emissions than poorer ones. Such a strong positive correlation is because wealthier people can afford more products, which therefore increases their consumption of emissions embodied in those commodities. It is clear that high consumption in Sweden's big counties (Stockholm, Västra Götaland, and Skåne) is driving national emissions. For policies that aim at reducing GHG emissions, therefore, the implications could include directing consumption patterns in the main emission-consumer counties: Stockholm, Västra Götalands, and Skane.

We also found that carbon intensity is lower when per capita GDP is higher (**Figure 4.4**, right), which is to be expected since carbon footprints decrease with improving technology (Lenzen *et al.* 2006). This result implies that mitigating climate change could also be achieved by improving technology, targeting both private sector and the industries. The Government then could encourage the implementation of new technology that is capable of reducing substantial carbon emissions by e.g. levying taxes on fossil fuels and giving subsidies on geothermal, wind power and solar power. This policy intervention could provide avenues for better preparing all counties to combat climate change in the future.

Figure 4.4. Driver of consumption pattern of GHG emissions in 2016.



Note: Circle size represents population.

4.5 Conclusions

Our results show that consumption-based emissions are able to capture real consumption patterns since they include emissions embodied in international and inter-regional trade. The consumption-based method, therefore, provides insight into the consumption patterns of GHG emissions at the regional level. The range of regional emissions could not have been deduced without considering the economic interdependencies, as offered by the Swedish MRIO database.

The SwedenLab is capable of overcoming the difficult and time-consuming process of developing sub-national MRIO tables. By storing various sets of raw data and processing tools into a cloud system, users are able to access, update or integrate a number of data sources. This approach provides flexibility for users to customise their MRIO tables to suit their specific constraints and preferred regional and sectoral classifications.

Despite Sweden's contribution to global emissions being low, the country is vulnerable to long-term climate change and extreme weather events. The Swedish Government predicted that if the trend of global warming continues at its current rate, temperatures in Sweden will rise by 3 to 5 degrees by 2080, in comparison to average temperature in the period from 1960 to 1990. This means that Sweden will experience a greater temperature increase than the global average (Swedish Government 2007).

Consequently, the increased risk of climate change gives the Government greater impetus to initiate a more proactive climate policy. Swedish policymakers then require a modelling framework that is able to provide a comprehensive picture of regional economic structures and identify unique characteristics of different regions. The inter-regional supply chain flows in the MRIO framework are a great benefit since they are able to track the consumption patterns in one region that are attributed to another region. Utilising virtual laboratories, as was done with the SwedenLab, could be a part of the solution, providing research-based assessments for both national and local policymakers.

4.6 Acknowledgements

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Connecting Page

The fifth chapter describes employing the JapanLab for assessing regional responsibility for food loss in Japan.

Overproduction and non-standard agricultural products can lead to food loss. Due to Japan's high market standards, approximately 25% of food waste is categorised as food loss (MOE 2017). In term of the carbon emissions, food loss generates the same environmental effects as 'normal' foods. Since the amount of carbon emissions embodied in food loss is substantial, reducing food loss contributes to a significant decline in carbon emissions. However, a comprehensive picture of the environmental impacts resulting from food loss in Japan does not currently exist.

A vital tool for measuring the environmental effects of food loss are sub-national MRIO tables. Through the supply chain network, I-O based assessments are able to measure the intended demands for food loss from the consumers' perspective, and eventually the environmental responsibility for food loss at a regional level.

In this chapter, I present the calculation for food loss from the perspective of Japanese consumers. This valuation was a result of the new virtual MRIO laboratory, capable of quantifying regional characteristics and the environmental responsibility for the food loss in Japan.

Chapter 5

Responsibility for food loss from a regional supply-chain perspective

Abstract

Reducing food waste and food loss generated through the whole food supply chain has, in actuality, become a global requirement. A Sustainable Development Goal (SDG) aims to ensure sustainable consumption and production patterns. The government in a nation strives efforts to reduce the amount of the wasted edible food to achieve the SDG target. This paper examines edible food loss at the stage of vegetable production in Japan. Vegetables are not delivered to a market, but are instead discarded in the field. As described herein, we identify the amount of food loss at the regional level in Japan, and elucidate relations between production and consumption by examining multi-regional trading within Japan. Using a footprint analysis particularly addressing vegetables that are discarded in fields, we identify where food loss occurs and where agricultural products that are discarded in fields are presumed to be delivered and consumed. Clarifying the linkage of the food loss from production sites to intended consumers by prefecture helps farmers to make a crop production and distribution plan and to cooperate with other farmers to reduce annual food losses. Our food loss footprint analysis can provide opportunities for consumers to realize their own responsibilities and to raise awareness about food loss. Furthermore, it identifies environmental burdens by producing the crops discarded in a field. The findings from our analysis can facilitate producer-consumer communication to avoid overproduction and to highlight alternative destinations for overproduced agricultural products to markets with a shortage of agricultural crops.

5.1 Introduction

Food security is one of several key global issues related to sustainability (UN 2015). A certain amount of food is disposed of annually worldwide. According to the United Nations Food and Agriculture Organisation (FAO), every year, 1.3 billion tonnes of food is wasted or lost in supply chains, equivalent to one-third of all food produced for human consumption (FAO, 2011). According to the FAO, food that is lost at production, post-harvest and processing stages is designated as 'food loss', whereas food that is ready for human consumption but discarded by retailers or consumers is recorded as 'food waste' (FAO 2011; Gustavsson et al. 2013).

Reducing food waste and food loss generated through the whole food supply chain has become a global requirement. One of the SDGs accepted by the 193 member states of the United Nations (UN) aims to ensure sustainable consumption and production (SCP) patterns. The Goal aims at *"by 2030, halving per capita global food waste at the retail and consumer level, and reduce food losses along production and supply chains, including post-harvest losses"* (UN, 2015, page 22).

To confront this global challenge, the Japanese government has promoted the reduction of food waste generated in food-related industries by introducing a recycling policy for food waste under the 'Act on Promotion of Recycling and Related Activities for the Treatment of Cyclical Food Resources'. According to an estimate by the MOE (Ministry of the Environment, Japan) and the MAFF (Ministry of Agriculture, Forestry and Fisheries), 27.75 million tonnes of food is wasted per year in Japan as of 2014 (MOE 2017). Of this, 6.21 million tonnes is edible but discarded before consumption. Of the wasted edible food, 3.39 million tonnes are generated from food-related business, and 2.82 million tonnes come from households. The Japanese government is striving to reduce the amount of wasted edible food to achieve the SDG target (MOE 2017).

Edible food that is discarded before reaching consumers includes food loss categorized by the FAO as food disposed of in the agricultural production stage, not only food waste discarded during distribution and consumption (Johnson *et al*., 2018). In fact, as noted earlier, the SDG target 'to ensure sustainable SCP patterns' includes reducing *"post-*

harvest losses". Therefore, Japan could also aim at reducing food loss in the post-harvest stages of the supply chain as a contribution toward achieving the SDG target. Reducing food loss also helps to enhance food security by increasing food self-sufficiency (Clapp 2017). Furthermore, water, cropland, energy, and fertilizers are used for food production, so reducing food loss provides a benefit in mitigating CO2 and nitrogen emissions, and soil degradation through reduced use of energy and fertilizers (FAO, 2008; Gruber and Galloway, 2008; Rockström *et al.*, 2009; Bobbink *et al.*, 2010; FAO, 2011; Mekonnen and Hoekstra, 2011; Kummu *et al.*, 2012).

However, the amount of food lost at the agricultural production and post-harvest stages of the supply chain has not been quantified in Japan. Few studies have specifically examined food loss during agricultural production (Kimura 2013; Kodera and Isobe 2016; Engström and Carlsson-Kanyama 2004). Policies and measures to reduce food loss have not been actively implemented. Therefore, there is currently no concrete action or target for tackling the food loss issue in Japan. In contrast, food loss at the agricultural production stage, categorized by the FAO as the first system boundary of food loss and waste in the overall supply chain, is not treated as actual loss of food but as an amount of depletion (MAFF 2007a; Kimura 2013). This means that crops disposed of in the field are counted as losses during the delivery of food from production sites to consumers, similar to losses during transportation and storage. In Japan, allowing food loss at the agricultural production stage is a practice supported by the government to maintain ready access to food and to secure a sufficient stock in case of emergency (MAFF 2007a). Its intent is to cope with surplus volumes of production incurred in good weather to keep prices of agricultural crops constant and to stabilize the supply (MAFF, 2007a; Kurasaka *et al.*, 2010). The practice is called 'field disposal', wherein agricultural products, specifically vegetables, are disposed of on site at the field during times of oversupply.

The main causes of food loss include not only oversupply caused by overproduction, but also nonstandard products that cannot be sold in a market (Kurasaka *et al.,* 2010). Some agricultural products are not delivered to consumers because they do not meet market standards for acceptable size and shape or are not of a certain quality (Mattsson 2014). If they do not meet the standards, they are not delivered. However, issues of overproduction and nonstandard products might be resolved by increasing communication that occurs among producers, buyers and consumers (MAFF 2007a, 2007c). Although nonstandard products are discarded before reaching consumers, various needs and markets exist for such agricultural products (Tsuruta *et al.*, 2007; Tamura 2015). For instance, an Australian grocery chain, Harris Farm Markets, has sold over 15 million kilograms of imperfect vegetables and fruit over three years via a campaign (Harris Farm 2018; Australian Government 2017) that aims to reduce the amount of farmers' crops discarded at the farm and not delivered to market because they do not meet such standards.

One measure to reduce food loss generated by not using non-standard agricultural products and overproduction is to reveal how much food is lost at the point of agricultural production (producer's responsibility), and to identify potential demand for crops that do not reach markets (consumers' responsibility). This intended demand comes from industries that require agricultural crops to produce their products or provide their services, such as food manufacturing, food- related business, and the social service industry. By quantifying food loss at production sites and identifying intended markets, producers' and consumers' needs can be visualized, and the distribution channels for such products can be re-examined (Hobbs and Young 2000). A coordination of the producers and consumers' need might help to reduce the amount of agricultural products discarded in fields.

Furthermore, enhancing and sharing information on food loss could help consumers as well as producers to make efforts to reduce food loss. There is usually an information gap between producers and consumers, especially related to issues such as environmental burdens (Poore and Nemecek 2018; Grunert *et al.*, 2014). Pollution is emitted during the production of agricultural crops and its impacts are evident in the fields. Consumers are unaware of such pollution related to the products they purchase (Zaks et al. 2009). Similar to such environmental bur- dens, food loss is not recognized by consumers, although both producers and consumers bear responsibility for it. Thus, revealing the amount of food lost and identifying both producers' and consumers' responsibility for that loss is the first step to reductions. It also helps the government to set up targets and investment plans for policies and measures to avoid overproduction (Australian Government 2017).

Footprint analysis has been widely used to fill in the information gaps about the environmental burdens occurring throughout supply chains, (Hoekstra and Wiedmann 2014; Lenzen et al. 2007; Gruber and Galloway 2008). MRIO analysis is a particularly useful approach to quantifying the footprints of both producers and consumers across different countries or regions. In fact, MRIO analyses are used globally to calculate the environmental, economic and social footprints of a product or activity at the international and sub-national level (Wiedmann, 2009; Lenzen *et al.*, 2012; Lenzen *et al.*, 2018; Wiedmann and Lenzen, 2018). Footprints calculated using MRIO analysis track the impacts of local consumption on the environment through the whole supply chain. For instance, carbon footprint analysis quantifies the amount of CO_2 emitted over the full life cycle of a product from its raw materials, through manufacturing to consumption (Lenzen *et al.*, 2004; Cu Cek *et al.*, 2012; Lenzen, 2013). A sub-national MRIO analysis can track inter-regional trade for cities, counties or states within a country (Hitomi and Bunditsakulchai, 2008; Zhang and Anadon, 2014; Wu and Liu, 2016; Lenzen *et al.*, 2018). Therefore, a footprint analysis conducted using an MRIO database can help fill in information gaps between producers and consumers on the issue of food loss and can enhance their mutual communication to bring about loss reductions.

Being aware of the issues described above, in this paper, we conduct a food loss analysis, aiming to estimate the amount of food loss at the regional level in Japan. We examine food loss not only from a production perspective (producers' responsibility), but also from a demand-side perspective (consumers' responsibility). To analyse consumers' responsibility, we infer the markets for vegetables to which the vegetables would have been delivered had they not been discarded in the field. We quantify regional food loss footprints using a sub-national MRIO database to ascertain where the food loss occurs and where the agricultural products discarded in fields would presumably be delivered and consumed. Moreover, we estimate the environmental burdens caused by agricultural production that is harvested but not delivered to market.

This study comprises five sections. Following the introduction, **Section 5.2** presents our methods and the data used for estimating regional food loss and our footprint analysis. **Section 5.3** presents the results of our footprint assessment by identifying inter-regional supply chain relations in terms of food loss. We conclude with a discussion in **Section 5.4**.

5.2 Methods and data

5.2.1 Estimating regional food loss

The main issue hindering food loss estimation is a lack of data related to food loss. We do not know the degree to which vegetables and fruit are discarded annually in fields. Therefore, we first collect annual vegetable and fruit production and shipment data by production site and by crop. Those data are published by the MAFF (MAFF 2015e, 2015c, 2015d). Then, we calculate any differences in the data between production and shipment to estimate the amount of field disposal by region and by crop. We assume the differences to be food loss. We collect data for 139 types of domestic vegetables and fruit including local specialty crops by prefecture as of 2014. Then we estimate the total amount of food loss. Japanese annual vegetable and fruit production data are estimated by multiplying crop yields per 10 acres by planted areas. Such data are collected through online and mail surveys, and complemented by patrols and information-gathering by governmental official staff and statisticians (MAFF 2015c). Shipping data are collected through invoices from shipping associations, and display labels that show the quantities recorded in shipping registers.

Field disposal of agricultural products occurs mainly for vegetables such as potatoes, carrots, onions, and white radishes since they are perishable goods produced especially through outdoor cultivation. Yields are strongly influenced by weather. The market price fluctuates considerably along with supply and demand (MAFF 2007b; Dixie 2005). In our analysis, we estimated food loss for 14 vegetables (out of 139 types of vegetables and fruit) for 47 prefectures[18]. These include white radishes, carrots, potatoes, taro, Chinese cabbage, cabbage, spinach, lettuce, Japanese leeks, onions, cucumbers, eggplants, tomatoes, and green peppers. These make up 60% of the total annual production in Japan (MAFF 2015e). Furthermore, these vegetables are designated by the Japanese government as vegetables that are traded nationwide and annually consumed in large quantities (MAFF 2015e). The Japanese government has strived to stabilize the price of

[18] Japan has a two-tier local authority system; prefecture as regional government unit and municipality (cities) as basic local government unit. Prefectures are 47 areas constituting the first level of jurisdiction and administrative division.

these 14 vegetables by supporting the formation and maintenance of their production sites under a law called 'Act on Stabilisation of Production and Shipment of Vegetables' (ALIC 2017).

5.2.2 Sub-national level MRIO addressing the food supply system

To identify the amount of agricultural products discarded in the field, where this occurs, and how much are otherwise sold and consumed, we analyse the supply chain of agricultural products ending up discarded in fields by constructing a Japanese sub-national MRIO table including 47 prefectures and 19 sectors. The MRIO table is constructed using the same framework used by the Australian MRIO database compiled by Lenzen *et al.* (2014). We disaggregate Japan's I-O table (one region (national), 518 × 397 sectors) (MIC 2015) using laboursurvey data from the Economic Census for Business Activity (Stat 2014a) to make an MRIO table with 47 regions and 19 sectors. The 19 sectors consist of the 14 vegetables, other agricultural products including fruit and vegetables beside those 14, three major stakeholders of food supply chains (food manufacturing, food-related business and the social service industry, and the restaurant and food service industry), and other remaining sectors (the classification of these sectors are listed in *SI* 5.1). The main aim of our analysis is to examine the supply chain of the 14 subject vegetables. Thus, we examine their production sites, their demand by sector, which indicates where they are intended to be used, and their final demand, which indicates where they are intended to be finally consumed. We identify sectors that use vegetables as inputs for their production, and then classify them into eighteen food-related sectors. Other remaining sectors are aggregated as not being related to a food business. We do not examine the food loss of vegetables and fruit other than the 14 types, because as described in **Section 5.2.1**, we focus on the footprints of food loss for those officially designated vegetables. In addition, the trade flow of vegetables and fruit other than those 14 is not clear and they are not distributed countrywide.

In order to construct a sub-national inter-regional MRIO table, we estimated inter-regional transactions using a non-survey method because of the lack of reliable survey data underpinning inter-regional trade coefficients (Miyagi *et al.*, 2003; Yamada, 2011; Hasegawa *et al.*, 2011; Hagiwara, 2012). Many researchers have used non-survey methods for inter-regional trade estimation, finding these to be a useful alternative in the absence of data (Sargento, Nogueira Ramos, and Hewings, 2012). For our analysis, we use a CHARM variant, which is a combination of the commodity-based method and the cross-hauling method (Kronenberg 2009; Többen and Kronenberg 2015). In contrast to a single-country I-O table, an MRIO table includes trade transactions between multi-regions, as described by Hasegawa et al. (2011) and Lenzen et al. (2017) for a sub-national MRIO table, and Lenzen et al. (2013) and Hiramatsu et al (2016) for a global MRIO table. Our sub-national MRIO table includes intermediate demand (19 sectors, 47 prefectures), final demand such as household consumption, government spending and inventory (18 sectors[19], 47 prefectures), value-added (11 sectors[20], 47 prefectures) and exports (1 sectors, 1 rest-of-world region). To increase the reliability of entries regarding inter-regional trade of vegetables described in our MRIO table, we incorporated agricultural trade data from the 'Vegetable wholesale market research report' (MAFF 2015b). These market data cover 80% of the annual transaction volume of the total vegetable wholesale market (MAFF 2015b). Using these data, we can trace how many tonnes of the 14 types of vegetables are delivered from production sites to markets at the prefecture level. In addition, we use agricultural wholesale market data (MAFF 2015a) that indicate how much of each are traded in the wholesale market in quantities (tonnes) and by monetary value (Japanese Yen) at the prefecture level.

5.2.3 Sub-national level MRIO calculations

Using the 47-region 19-sector MRIO table including the 14 chosen vegetables, the agricultural food supply chain network can be enumerated using the Leontief demand-pull model (Leontief 1970). In this model, the amount of production is determined by final demand. For instance, agricultural commodities are distributed to markets where demand exists.

Using the Leontief inverse matrix, we calculate food loss footprints for the 14 vegetables. First, we calculate multipliers $\mathbf{m} = \mathbf{q} \times (\mathbf{I} - \mathbf{A})^{-1}$, where the 1 x N matrix $\mathbf{q} = \mathbf{Q}\hat{\mathbf{x}}^{-1}$ holds the food loss coefficients in units of tonne/million yen (t/¥), with $\mathbf{Q}$ being a 1 x N food

[19] The 18 sectors in final demand is the same with sectors in final demand of Japan input output table 2011.
[20] The 11 sectors in value-added is the same with sectors in value-added of Japan input output table 2011.

loss matrix and **x** being the 1 x N total output. In our work N = 893, the product of 19 sectors by 47 regions. The N x N matrix $\mathbf{A} = \mathbf{T}\hat{\mathbf{x}}^{-1}$ holds economic input coefficients, derived by dividing I-O transactions T_{ij} by total output x_j. $\mathbf{L} = (\mathbf{I} - \mathbf{A})^{-1}$ is the Leontief inverse. The multiplier captures the ripple effects of food loss starting with the consumption of the 14 vegetables and progressing over the entire product supply chain. Supply chain coverage is aided by the Japanese sub-national MRIO database, as it includes all monetary transactions occurring in Japan. We post-multiply the multiplier with the final demand (**y**) to calculate the consumers' responsibility for food loss. Instead of applying a matrix product (**my** or **qLy**), we use an element-wise product (**m#y** or **qL#y**) that retains the N region-sector detail.

We calculated the consumers' responsibility for food loss in two different ways; by intermediate demand sectors and by final demand categories (agents).

5.2.4 Environmental satellite data

Our analysis also estimates the environmental burden of producing agricultural products that are disposed of without reaching consumers. Reducing food loss can make more food available for human consumption without additional farm input. To assess the environmental impact, we prepare a dataset of pollutants (GHG, nitrogen, potassium oxide and phosphorus pentoxide) emitted by producing vegetables. To calculate each burden, we use the intensity of each type of pollution generated by the use of energy and agricultural fertilizers. To calculate the GHG emissions of each type of vegetable produced, we use emission factors (t CO2eq per million JPY) published by the National Institute for Environmental Studies, called "Embodied Energy and Emission Intensity Data (3EID)" (NIES 2018). The 3EID provides the embodied environmental burden intensities of CO2 emissions generated directly and indirectly by production activities of a sector. Therefore, for vegetables, the emissions from the use of fertilizers, agrochemicals, electricity, transportation and packaging are included. The emission intensity data is available by sector at the national level. For our analysis, we apply the national emission intensity to data on the vegetables discarded in fields by calculating **total emissions = Q_m*3 EID CO2 intensity (vegetables).** Q_m is the market value of the discarded vegetables of the subject 14 types. One limitation of the analysis is that we do not consider regional differences in the emission factors and do not use different emission factors for different types of vegetables, due to data unavailability. At the same time, the 3EID data includes emissions generated through the entire supply chains from production to transportation to and sale in a market although we analyse vegetables discarded in fields before being delivered to market. We include all the emissions because it is difficult to separate the emission attributable to activities before the vegetables are delivered to market, from the total generated in the entire supply chain.

The amount of nitrogen, potassium oxide, and phosphorus pentoxide generated from the use of agricultural fertilizers are estimated using absorption factors (kilograms per 1000 kilograms of production of vegetable) published by the MAFF (MAFF 2016).

5.3 Results

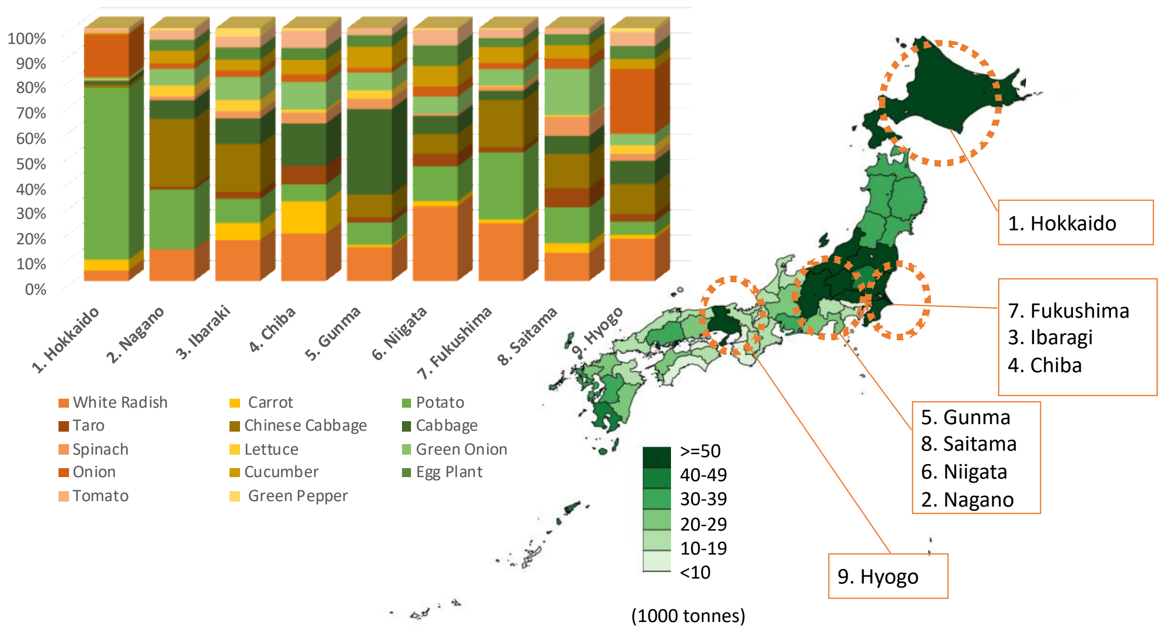
5.3.1 Regional characteristics of food loss

We quantify food loss of vegetables in Japan by comprehensively examining the whole supply chain. Then, we conduct a food loss analysis by quantifying the amount of agricultural products discarded in the fields, locating where this occurs, and identifying intended buyers and consumers.

While the total production of vegetables and fruit in 2012 in Japan was about 16.7 million tonnes, approximately 2.31 million tonnes were discarded in the field without being delivered to market. We estimate food loss of vegetables and fruit using the difference between production and shipment data. We regard this difference as edible food loss although some crops might be damaged by extreme weather such as storms or heat and drought. 2.31 million tonnes is a significant amount, comparable to the 3.39 million tonnes of edible food waste annually generated from food-related businesses. Of that 2.31 million tonnes, 1.68 million tonnes (73% of the total field-disposed vegetables and fruit) are the 14 types of vegetables that we examine for our footprint analysis. That 1.68 million tonnes of production require the use of 497,000 ha of land.

In our analysis, it is apparent that potatoes, white radishes, Chinese cabbage, cabbage, and onions are the most discarded of the vegetables. They are grown outdoors and are exposed to weather conditions. **Figure 5.1** depicts where and how much food loss occurs in different regions on a prefecture level. The map shows that more food loss at production sites is observed in large agricultural production regions such as Hokkaido, Nagano, Fukushima, and Gunma prefectures. The food loss in these prefectures respectively accounts for 18%, 6%, 5%, and 4% of the total loss of the 14 types of vegetables. Hokkaido has the highest food loss of any prefecture, alone accounting for more than 200,000 tonnes. In fact, Hokkaido has a large cultivated land area per farm household, about 13.4 times greater than other prefectures, and a large area of cultivated acreage, which accounts for 25% of Japan's total cultivated areas (Hokkaido Government 2018).

Figure 5.1. Food loss of 14 types of vegetables at production sites (tonnes).

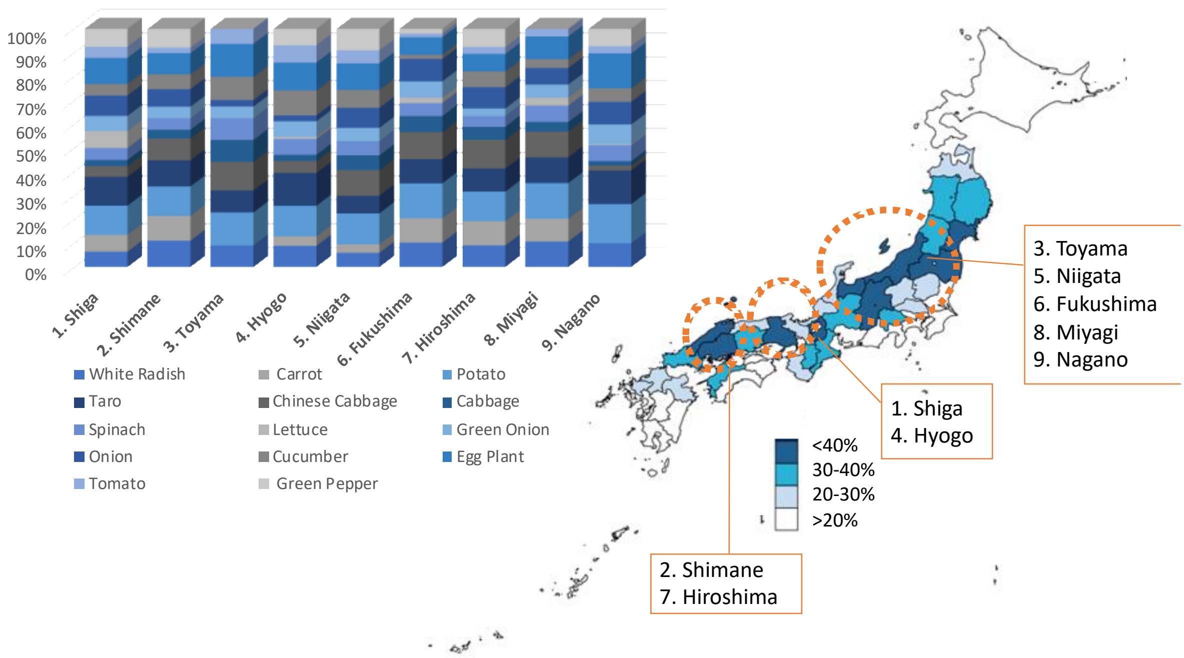


Note: Darker colours denote prefectures with higher food losses.

The bar chart in the upper-left side of **Figure 5.1** presents food loss broken down by vegetable crop type at production sites by prefecture. It specifically examines the regions where the total food loss is more than 50,000 tonnes. The proportion of losses clearly differs by region. For instance, in Hokkaido, the food loss of potatoes and onions are markedly larger than those of other regions. Many potatoes and onions are disposed of in the fields without being delivered to market.

In our analysis of food loss at production sites, we also examine how much of food loss per production is generated at a regional level (**Figure 5.2**). Identifying this intensity of loss is important for stakeholders, including governments, as they tackle food loss issues by region. Al- though the absolute amount of food loss is high in Hokkaido (**Figure 5.1**), the intensity in Hokkaido is lower than other regions at less than 20% (**Figure 5.2**). On the other hand, while some regions have a low total food loss, their intensity is significant with more than 50% of regional pro- duction being lost. The proportion of food loss per production by crop type varies by region as depicted in the bar chart in the upper-left side of **Figure 5.2**. That of potatoes is relatively large across regions. In 27 of the 47 prefectures, more than 50% of the tonnage of potatoes produced is lost. In Hokkaido the loss intensity for potatoes is only approximately 10% while in Nagano it is more than 80%. Some of these potatoes might be used for animal feed or seed. However, according to the ALIC (2018), only 6% of the total production of potatoes is used for animal feed and 0.4% is used for seed potatoes as of 2014.

Figure 5.2. Food loss per production at production site.



Note: Regions with intensities of more than 40% are listed in the bar chart inset.

5.3.2 Structure of food loss footprints by regions

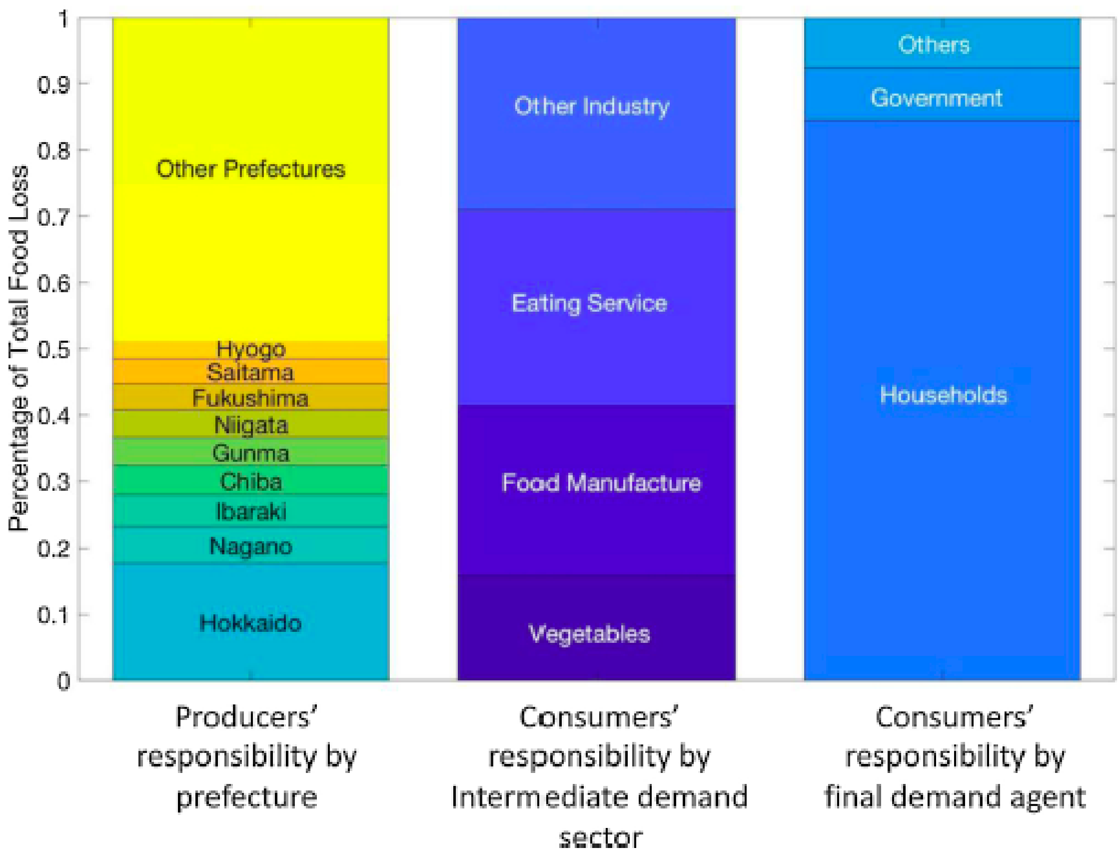
To examine the linkages between consumption and production of the 1.68 million tonnes of food that is lost, we conduct a food loss footprint analysis using vegetable production, shipment, and market data. First, by building a sub-national MRIO table particularly addressing losses of the 14 chosen types of vegetables, we map the losses from three layers of the supply chain: food loss at production sites, intended demand by sector, and intended consumers by agent (final demand sectors).

The total of the food losses at each layer of the supply chain is equal to the total vegetable food loss (1.68 million tonnes). The left-hand bar in **Figure 5.3** indicates the proportion of the total food loss (q) of vegetables in agricultural production layer, determined by differences in production and shipment (Producers' responsibility by prefecture). The results indicate that a large amount of the food lost at production sites is generated in Hokkaido, as described in **Section 5.3.1**.

The middle bar in **Figure 5.3** indicates how much of the vegetables discarded at production sites could be presumed to be delivered to the following categories (consumers' responsibility by intermediate demand sector): direct demand for the 14 types of vegetables, other agricultural sectors, food manufacturing, food-related business and social service industry, restaurant and food service industry, and other sectors. The demand for vegetables by the 19 sectors is estimated by "**my**" (see the details of the calculation in **Section 5.2.3**). Then, we calculate the proportion of total food loss in the demand by sector to make the graph. The graph reveals that sales of vegetables in markets for direct consumption contribute only 3.6% of the total food loss while more than 90% of the vegetables discarded in fields are intended to be used for industrial purposes in the supply chain. About 46% are intended for use by restaurants and food services while about 31% are intended to be used for manufacturing meat products, seasonings, noodles, breads and confectioneries, as well as canned and processed vegetable foods. Food-related businesses and the social service industry, including accommodation services and social service providers such as hotels, and medical, health care and welfare facilities where food is served as one of their services, contribute 14% of the total food loss.

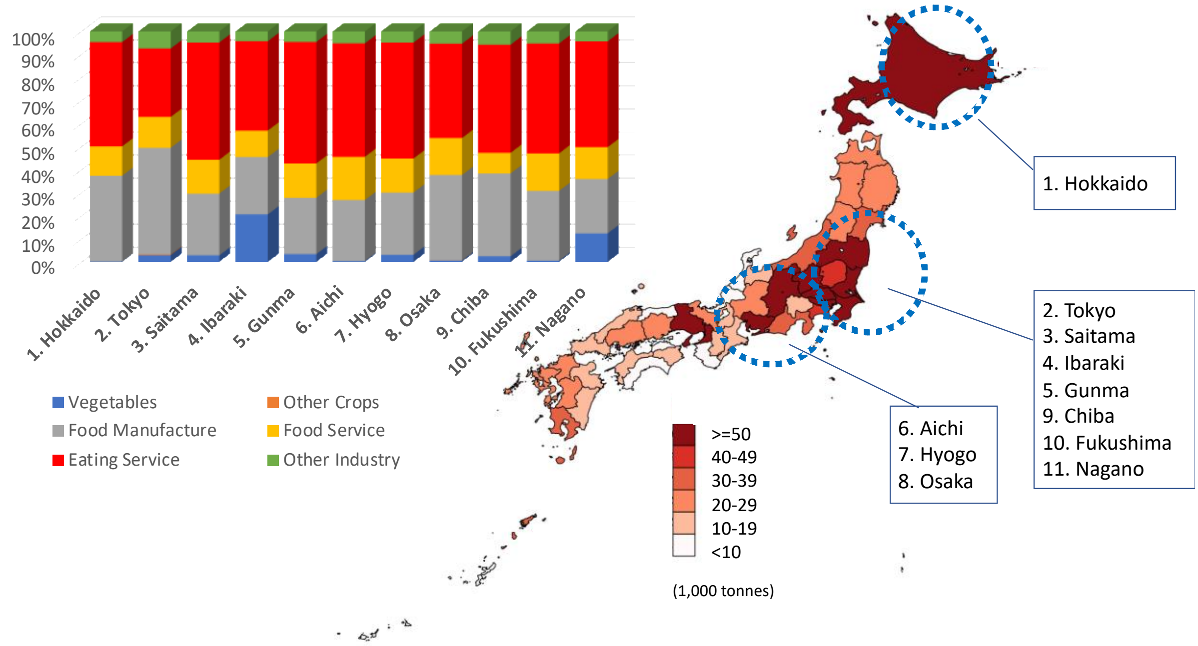
The right-hand bar is estimated by post-multiplying the multiplier (**m**) by the following three components of final demand (consumers' responsibility by agent) (see the details of the calculation in **Section 5.2.3**); households (**y** of households); government (**y** of government spending); and other (**y** of inventory) (**Figure 5.3**). The results indicate that almost all the vegetables discarded in the field are intended to be consumed by domestic households through sales, or to be used in processed and prepared foods made in food manufacturing and pro- vided through food-related service industries, or for the restaurant and food service industry. 13% of the total food loss is linked to government expenditures on food-related social services to the community including education-related and medical services (hospitalisation) and social welfare. Final demand in other sectors indicates expenses for stocks of food manufacturing products such as preserved agricultural foods, lunch boxes and prepared frozen foods.

Figure 5.3. Food loss at three stages of the supply chain.



Although we identify which sectors have responsibility for food loss for the 14 vegetables from both a production perspective and a demand-side perspective in the bar graph above (**Figure 5.3**), it remains unclear which sectors bear responsibility for food losses at the regional level. Therefore, we break down the responsibility for (contribution to) food loss by prefecture and by supply chain, and map the consumers' responsibility (**Figure 5.4**). Tokyo, Osaka, Aichi and Saitama prefectures have four of the five largest population in Japan (Stat 2014b), share high responsibility for the food loss, as shown in dark red in **Figure 5.4**. Hokkaido, Saitama and Aichi, the top three food manufacturing prefectures as of 2012 (METI 2014) also contribute a certain amount to the food loss. The 14 types of vegetables are intended to be delivered to those regions for use in producing or serving food-related products, or to be sold for vegetable consumption. The bar chart in the upper-left side in **Figure 5.4** shows the proportion of food loss by supply chain. We select regions responsible for more than 50,000 tonnes of food loss for inclusion here. The graph demonstrates that consumption of vegetables through restaurants and food services is high in those regions.

Figure 5.4. Consumers' responsibility for food loss of 14 types of vegetables (tonnes).



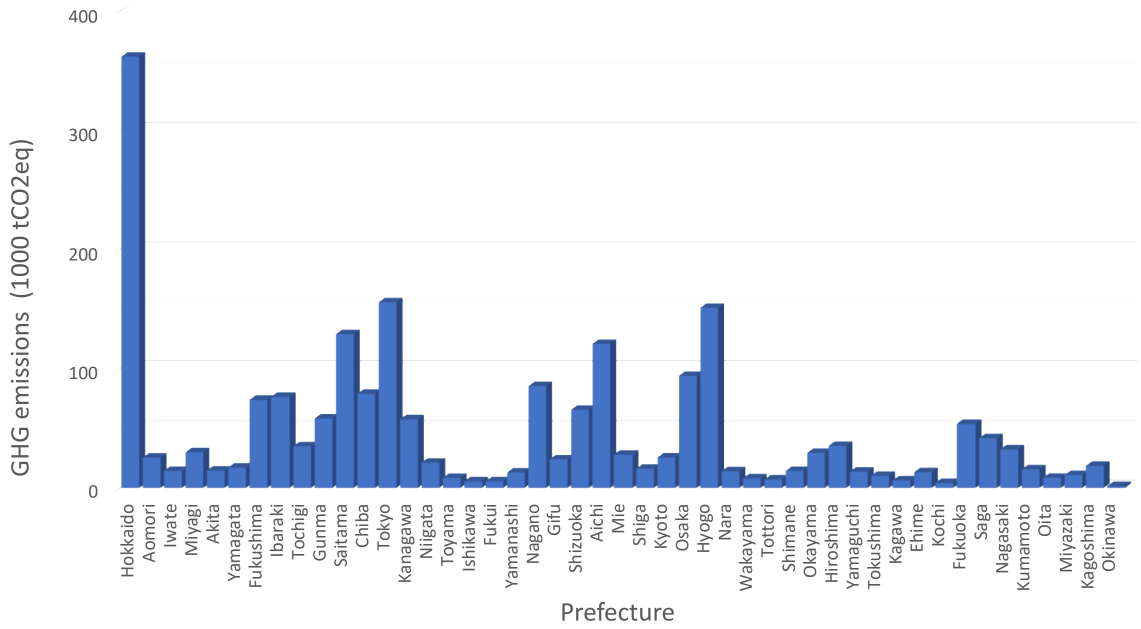
Note: Darker colours denote prefectures with higher contributions to food loss.

To examine in more detail which layers of the supply chain are the intended destinations where the vegetables could be consumed, we analyse the multipliers and final demand by prefecture and commodity. Consumers' responsibility for food loss in restaurants and the food service industry is larger in Hokkaido, Saitama, Gunma, Aichi, Tokyo and Osaka than in other regions. Tokyo, Osaka, Aichi, Saitama and Chiba are the top five areas of Japan in gross revenue for restaurants and the food service industry as of 2012 (Stat 2014a). While Gunma prefecture has a high multiplier and low final demand in the industry, the multipliers for Tokyo, Aichi and Osaka are low, although large amounts of final demand exist in those regions. The multiplier indicates the amount of food loss embodied in a value unit of commodity produced. The result also indicates that their multipliers for the 14 types of vegetables is larger than any of the other sectors although there is low final demand. This implies that overproducing vegetables with high yields results in a significant amount of food loss.

5.3.3 Environmental burdens related to the food loss footprint

As described in this paper, we identify the responsibility of consumers as well as producers for food losses of 14 types of vegetables. One of the aims of our analysis is to identify the responsibility for food loss both from a producer perspective and a demand-side perspective, and at the same time, to raise awareness of consumers role in food loss. Production of vegetables emits GHG, uses energy, and introduces nitrogen, potassium oxide and phosphorus pentoxide into soil through the use of agricultural fertilizers. Such pollution is emitted where the vegetables are grown, although the production would be required for industries and consumers in other regions. The vegetables discarded in fields are also produced for the benefit of consumers. **Figure 5.5** depicts the GHG emissions from a consumption perspective. Consequently, the figure indicates the degree to which environmental burdens are borne by consumers. As one might expect, Hokkaido shoulders a large amount of the burden for GHG emissions compared to other areas (**Figure 5.5**). That is true because a large proportion of those vegetables are intended to be consumed through production or provision of food-related products in regions with high population, production of food manufacturing products, and gross revenue in restaurants and the food service industry. The results also demonstrate that the amounts of nitrogen, potassium oxide, and phosphorus pentoxide are high in Hokkaido because agricultural crops such as potatoes and carrots require higher amounts of these fertilizers than other agricultural crops (MAFF 2016). Overall, our results demonstrate that avoiding the food loss and producing only the amounts that consumers' need would reduce 2,133,736 tCO_2eq of GHG. By reducing the food loss, absorption of 6,145 tonnes of nitrogen, 2,301 tonnes of potassium oxide, and 9,185 tonnes of phosphorus pentoxide could be avoided. In our analysis, we only consider the emissions generated by cultivating 14 types of vegetables, and do not consider those from other crops. This is because in this paper, we aim to identify the responsibility for the emissions attributable to the 14 subject vegetables that are discarded in the fields.

Figure 5.5. GHG emissions generated via consumption of 14 subject vegetables discarded in the fields.



5.4 Discussion

Prevention of food loss is a key issue for sustainability and food security, as it requires efficient utilisation of resources such as land, water, and energy. We analyse production-based food loss for 14 vegetables types in Japan and establish consumers' responsibility for those food losses using a Japan MRIO database. Footprint analysis using MRIO data is able to quantify the impact exerted by the entire supply chain. Through our analysis, we identify where the food that ends up lost is produced, and where that food's potential consumers reside. Japanese people have reduced the amount of food they waste by introducing recycling policies. As the next step, the Japanese government must consider adopting measures and policies to reduce food loss. Although a discussion of the supply and demand adjustment for vegetable production was conducted in 2007 (MAFF 2007b), there is no concrete policy or current action to reduce food loss. In fact, while 17% of the total production of the 14 types of vegetables were discarded in fields in 2007, only a two percent reduction was achieved for field disposal from 2007 to 2014.

Target setting for achieving the SDG of sustainable production and consumption is one measure toward reducing food loss. For instance, farmers, food businesses, and consumers together can discuss how to reduce losses by making use of vegetables that are otherwise disposed of by setting a clear reduction target. Then, the progress toward achieving the target can be measured by establishing baselines and methodologies (Australian Government 2017). To establish baselines, a comprehensive picture of the amount of food loss and the trade flow of agricultural crops are required. Consequently, the first step to reducing food loss is to identify where and how much food is lost (Buzby and Hyman 2012; Johnson *et al*., 2018), and to enhance communication and cooperation between farmers (FAO 2011), buyers, and consumers throughout the supply chain (Seminar 2016).

Our analysis identifies that a significant amount of vegetables is harvested but not delivered to markets. Some reasons for this food loss are overproduction, lowering demand, or nonstandard shapes of vegetables. These issues could be solved by enhancing communication and the transparency of mutual linkages among producers, industries, and consumers. By revealing the linkages of stakeholders in food loss, farmers, buyers, consumers, and policymakers can find measures to reduce that loss by region and by stakeholder. In fact, food waste and loss in medium/high-income countries occurs mainly due to *"consumer behaviour as well as the lack of coordination between different actors in the supply chain"* (FAO, 2011, page v), and because of the difficulty in predicting the numbers of buyers and consumers (Buzby and Hyman 2012).

In our study, to identify such linkages between production and consumption, we conduct a food loss footprint analysis. The food loss footprint can reveal intended transactions for agricultural crops that are presumed to be delivered to the market, but which are discarded in fields without being consumed. Such transactions extend from Hokkaido at the north end of Japan to Okinawa, Japan's southernmost prefecture. One finding from our agricultural food loss footprint analysis is that densely populated regions such as

Tokyo, Osaka and Saitama have more responsibility for agricultural food loss than less-populated regions, because of their higher demand for those crops. However, less-populated regions also bear a high burden of consumers' responsibility for the food loss, because such regions have a high multiplier and/or high demand for vegetables. For instance, if factories making processed foods are located in a region, then this region bears responsibility for agricultural food loss because it exerts intermediate demand for the agricultural crops to produce the foods. In this way, tracing a supply chain of food loss using a footprint analysis helps to elucidate where such loss is generated and where it is intended to be delivered. Identifying how much and what types of vegetables are discarded in fields could help farmers plan crop production and distribution, cooperate with other farmers to reduce food loss, identify potential markets for crops such as nonstandard vegetables, and investigate alternative destinations of overproduced agricultural crops to markets with a shortage of the crops. Such information can also help consumers, industry and policymakers to raise awareness of food loss (Buzby and Hyman 2012).

Mutual communication and coordination involving producers, buyers, and consumers will be more necessary than ever before whilst climate change intensifies. As described earlier, food loss occurs in part because of unpredictable weather. Therefore, if climate change comes to pose severe difficulties, field disposal may have to be implemented more frequently because of increasing uncertainty about annual and seasonal agricultural production (Lobell *et al.*, 2011; Campbell *et al.*, 2016). That could occur because "*a changing climate engenders changes in the frequency, intensity, spatial extent, duration and timing of extreme weather and climate events, and can result in unprecedented extreme weather and climate events*" (IPCC, 2012, page 5). It affects the annual agricultural production. Moreover, farmers tend to produce excess quantities of crops beyond the quantity likely to be demanded to cope with unexpected weather events as well as pest damage (Kodera and Isobe 2016). Therefore, food loss is expected to become a more important issue to tackle in terms of food security and reducing environmental burdens, along with achieving the SDG targets.

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Connecting Page

Chapter 6 describes utilising the global MRIO virtual laboratory for assessing the carbon footprints of global tourism sectors.

Global tourism is a booming industry worth over USD 7 trillion and is responsible for the employment of almost 300 million people around the world (WTTC 2017). Given its potential long-term growth, development strategies on tourism must be reassessed. However, prior calculations on the environmental effects of global tourism—especially those related to carbon emissions—do not cover all the commodities used by the tourism industry. As a result, the contribution of tourism sectors to climate change is often underestimated.

The tourism sectors' carbon footprints have to be evaluated using methods that cover the supply chain emissions of tourism-related goods and services. The global MRIO database is able to cover not only the carbon emitted directly during tourism activities (for example, through combusting petrol in vehicles) but also the carbon embodied in the commodities purchased by tourists (such as food, accommodation, transport, fuel, and shopping).

This chapter describes the capability of the global virtual MRIO laboratory (Lenzen *et al.* 2017a) to integrate a new dataset that covers both the direct and indirect supply chain contributions of tourist activities across 159 countries from 2009 to 2012. The MRIO modelling framework applied to this database led to new estimates on the global tourism sectors' carbon footprints.

Chapter 6

The carbon footprint of global tourism

Abstract

Tourism contributes significantly to global GDP, and is forecast to grow at an annual 4%, thus outpacing many other economic sectors. However, the global carbon emissions related to tourism are currently not well quantified. Here, we quantify tourism-related global carbon flows between 160 countries, and their carbon footprints under origin and destination accounting perspectives. We find that between 2009 and 2013, tourism's global carbon footprint has increased from 3.9 to 4.5 Gt CO2-e, four times larger than previously estimated, accounting for about 8% of global greenhouse gas emissions. Transport, shopping and food are significant contributors. The majority of this footprint is exerted by and in high-income countries. The rapid increase in tourism demand is effectively outstripping decarbonisation of tourism-related technology. We project that, due to its high carbon intensity and continuing growth, tourism will constitute a growing part of the world's GHG emissions.

6.1 Introduction

Global tourism is a trillion-dollar industry, representing in the order of 7% of global exports and contributing significantly to global GDP (WTTC 2017). International arrivals and tourism receipts have been growing at an annual 3-5%, outpacing the growth of international trade, and in 2016 exceeded 1 billion and $1.2 trillion, respectively (UNWTO 2016; WTTC 2017). Clearly, economic activity at this scale has a significant impact on the environment (Gössling 2002). In particular transport, a key ingredient of travel, is an energy- and carbon-intensive commodity, rendering tourism a potentially potent contributor to climate change. The sensitivity and vulnerability of destinations (such as winter and coastal recreation) to weather and climate change also implies that, as a result of climate change, the tourism industry will in turn undergo drastic future change and will need to adapt to increasing risk (Scott *et al.* 2012). Given future projections of an unabated 4% growth beyond 2025 (UNWTO 2016; WTTC 2017), the continuous monitoring and analysis of carbon emissions associated with tourism is becoming more pressing.

By definition, the carbon footprint of tourism should include the carbon emitted directly during tourism activities (for example combusting petrol in vehicles), as well as the carbon embodied in the commodities purchased by tourists (food, accommodation, transport, fuel, shopping; *SI 6.*1). Tourism carbon footprints therefore need to be evaluated using methods that cover the life-cycle, or supply chain emissions of tourism-related goods and services (*SI 6.*1.2). Life-Cycle Assessment (El Hanandeh 2013; Pereira *et al.* 2017; Puig *et al.* 2017) and I-O analysis (Becken and Patterson 2006; Dwyer *et al.* 2010; Munday *et al.* 2013; Sun 2014a; Cadarso *et al.* 2015a; Cadarso *et al.* 2016; Sharp *et al.* 2016) have been used for quantifying the carbon footprint of specific aspects of tourism operations such as hotels (Puig *et al.* 2017), events (El Hanandeh 2013) and transportation infrastructure (Pereira *et al.* 2017; Luo *et al.* 2018), and in particular countries (or regions thereof) such as Spain (Cadarso *et al.* 2015a; Cadarso *et al.* 2016; Puig *et al.* 2017), the UK (Munday *et al.* 2013), Taiwan (Sun 2014a), China (Luo *et al.* 2018), Saudi Arabia (El Hanandeh 2013), Brazil (Pereira *et al.* 2017), Iceland (Sharp *et al.* 2016), Australia (Dwyer *et al.* 2010) and New Zealand (Becken and Patterson 2006).

Prior estimates of global CO_2 emissions from selected tourism sectors arrive at 1.3 and 1.17 Gt CO_2 for 2005 (UNWTO *et al.* 2008; Peeters and Dubois 2010), and 1.12 Gt for 2010 (Gössling and Peeters 2015), amounting to about 2.5-3% of global CO_2-equivalent emissions. However, these analyses do not cover the supply chains underpinning tourism and do therefore not represent true carbon footprints. A WTO-UNEP-WMO report (UNWTO *et al.* 2008) states that (p. 134) "*[t]aking into account all lifecycle and indirect energy needs related to tourism, it is expected that the sum of emissions would be higher, although there are no specific data for global tourism available*". Similarly, Gössling and Peeters (2015) state that (p. 642) "*… a more complete analysis of the energy needed to maintain the tourism system would also have to include food and beverages, infrastructure construction and maintenance, as well as retail and services, all of these on the basis of a life cycle perspective accounting for the energy embodied in the goods and services consumed in tourism. However, no database exists for these and the estimate thus must be considered conservative*".

This work fills an important knowledge gap by offering a comprehensive calculation of the carbon footprint of global tourism. We source the most detailed compendium of Tourism Satellite Accounts (TSAs) available to date (55 countries with individual TSAs and 105 countries with UNWTO data; *SI 6.*2.2 and 6.3.1.2), integrate this into a comprehensive global MRIO database (*SI 6.*2.5), and use Leontief's standard model (*SI 6.*1.2) to establish carbon footprint estimates that cover both the direct and indirect, supply chain contributions of tourist activities. In addition, we advance current knowledge by a) including not only emissions of CO_2 but also those of CH_4, N_2O, HFCs, CFCs, SF_6 and NF_3 (*SI 6.*3.2), b) presenting an annual carbon footprint time series from 2009 to 2013, c) analysing drivers of change, d) providing details about carbon-intensive supply chains, and e) comparing two accounting perspectives.

The two accounting perspectives mentioned in the final point e) are Residence-Based Accounting (RBA) and Destination-Based Accounting (DBA). Both perspectives are variants of the well-known Consumption-Based Accounting principle (Kander *et al.* 2015), however whilst RBA allocates consumption-based emissions to the country of the tourist residence, DBA allocates them to the country of the tourist destination (Dwyer *et al.* 2010; Sun and Lenzen 2017). The two perspectives serve clear and distinct purposes:

RBA can shed light on the determinants of travel choices, such as travel frequency, distance, and transportation modes, reflecting the GHG responsibility borne by travellers. RBA-based emissions therefore match the scope and definition of the conventional carbon footprint. DBA is required to assess options for managing the carbon footprint of tourism operations at the destination, for example through improving the carbon efficiency of the local technology, or imposing market-based measures for international aviation (ICAO 2016). Ultimately, RBA and DBA can be used to evaluate the progress of mitigation strategies proposed by the United Nations World Tourism Organisation (UNWTO), aiming at changing travel behaviour at departure points and at encouraging technology improvement at destinations.

6.2 Methods

6.2.1 Methods summary

We combine detailed TSAs (UNWTO 2017) with a detailed global MRIO and greenhouse gas emissions database of N = 14,838 country/industry sector pairs (Lenzen *et al.* 2012a; Lenzen *et al.* 2013), covering the 2009-2013 period (*SI 6*.2). We subject this system to Leontief's demand-pull formalism (Leontief and Strout 1963) (*SI 6*.1.2.1), matching previous high-level research that applies MRIO techniques to carbon and nitrogen emissions, groundwater depletion, biodiversity threats, aerosol forcing and health impacts from air pollution (Lenzen *et al.* 2012b; Steinberger *et al.* 2012; Feng *et al.* 2015; Kander *et al.* 2015; Lin *et al.* 2016; Oita *et al.* 2016; Dalin *et al.* 2017; Zhang *et al.* 2017). More specifically, we convert TSA data into an N×1 matrix $\tilde{\mathbf{y}}$ acting as the final demand block of the MRIO system (WTTC and Oxford Economics 2017), and determine carbon footprints of tourism $\tilde{Q}$ through Leontief's fundamental I-O equation $\tilde{\mathbf{Q}} = \mathbf{q}(\mathbf{I} - \mathbf{T}\hat{\mathbf{x}}^{-1})^{-1}\tilde{\mathbf{y}}$, where $\mathbf{q}$ is a 1×N matrix of carbon emissions intensities (in kg CO_2-e/US$), $\mathbf{I}$ is an N×N identity matrix, $\mathbf{T}$ is an N×N MRIO matrix listing international trade transactions between countries, where $\mathbf{x} = \mathbf{T}\mathbf{1}^{\mathbf{T}} + \mathbf{y}\mathbf{1}^{\mathbf{y}}$ is total economic output, with $\mathbf{1}^{\mathbf{T}} = \underbrace{\{1,1,\dots,1\}}_{N \text{ elements}}$ and $\mathbf{1}^{\mathbf{y}} = \underbrace{\{1,1,\dots,1\}}_{M \text{ elements}}$ being suitable summation operators, and where $\mathbf{y}$ is an N×M matrix of final demand by M global agents (households, governments, the capital sector, stocks) of N products. We slice the resulting tensor $\tilde{Q}_{ij}^{rst}$ to generate carbon footprints for two perspectives of Consumption-Based Accounting: a) Resident-Based Accounting (RBA; $\tilde{Q}^{t}_{\mathrm{RBA},j} = \tilde{Q}^{\cdot\cdot t}_{\cdot j1}$) and b) Destination-Based Accounting (DBA; $\tilde{Q}^{s}_{\mathrm{DBA},j} = \tilde{Q}^{\cdot s \cdot}_{\cdot j1}$), as well as for c) Production-Based Accounting ($\tilde{Q}^{t}_{\mathrm{PBA},j} = \tilde{Q}^{r\cdot\cdot}_{i\cdot 1}$). We use these tensor representations to reveal the global footprint's detailed country and commodity content (*SI 6.*1.2.1), and to prepare a global map of embodied carbon flows. We employ Production Layer Decomposition $\tilde{\mathbf{Q}} = \mathbf{q}(\mathbf{I} + \mathbf{A} + \mathbf{A}^2 + \cdots)\tilde{\mathbf{y}}\mathbf{1}^{\mathbf{y}}$ to unravel the aggregate carbon footprint into contributions from various layers of the supply chain network (*SI 6.*1.2.2). We use multiple regression to investigate trends and drivers of the global tourism carbon footprint over time (*SI 6.*1.3).

6.2.2 I-O theory

Let $\mathbf{T}$ be an $N \times N$ MRIO matrix listing international trade transactions (so-called intermediate demand) between countries, and let $\mathbf{y}$ be an $N \times M$ matrix of final demand by M global agents (households, governments, the capital sector, stocks) of N products. Both matrices are expressed in units of money. The sum of intermediate and final demand equals total economic output $\mathbf{x} = \mathbf{T}\mathbf{1}^{\mathbf{T}} + \mathbf{y}\mathbf{1}^{\mathbf{y}}$, with $\mathbf{1}^{\mathbf{T}} = \underbrace{\{1,1,\ldots,1\}'}_{N\text{ elements}}$ and $\mathbf{1}^{\mathbf{y}} = \underbrace{\{1,1,\ldots,1\}'}_{M\text{ elements}}$ being suitable summation operators, and with the $'$ symbol denoting vector transposition. This accounting identity can be transformed into the fundamental I-O equation $\mathbf{x} = (\mathbf{I} - \mathbf{T}\hat{\mathbf{x}}^{-1})^{-1}\mathbf{y}\mathbf{1}^{\mathbf{y}}$, where $\mathbf{I}$ is an $N \times N$ identity matrix. This equation represents Leontief's demand-pull model of the economy (Leontief 1966), where the provision of final demand $\mathbf{y}$ requires–directly and indirectly via international trade routes throughout a global supply chain network–total output $\mathbf{x}$ to be produced (Dixon 1996). The matrix $(\mathbf{I} - \mathbf{T}\hat{\mathbf{x}}^{-1})^{-1}$ is Leontief's inverse.

The integration of the monetary I-O calculus with CO_2 emissions data is straightforward: Let $\mathbf{Q}$ be a $1 \times N$ matrix listing CO_2 emissions (in units of tonnes) by country and industry sector. Let $\mathbf{q} = \mathbf{Q}\hat{\mathbf{x}}^{-1}$be a $1 \times N$ matrix of carbon emissions intensity (in tonnes per monetary unit) by country and industry sector. Then $Q = \mathbf{q}\mathbf{x} = \mathbf{Q}\hat{\mathbf{x}}^{-1}(\mathbf{I} - \mathbf{T}\hat{\mathbf{x}}^{-1})^{-1}\mathbf{y}\mathbf{1}^{\mathbf{y}}$ is called the global carbon footprint. The elements of the $1 \times N$ vector $\mathbf{m} = \mathbf{Q}\hat{\mathbf{x}}^{-1}(\mathbf{I} - \mathbf{T}\hat{\mathbf{x}}^{-1})^{-1}$ are called emissions multipliers, because they characterise the CO_2 emissions embodied in a unit of final demand, rather than the coefficients $\mathbf{q}$ which describe CO_2 emissions per unit of industrial output. Thus, I-O analysis provides the so-called producer perspective ($\mathbf{qx}$) and consumer perspective ($\mathbf{my}$) of global CO_2 emissions (Munksgaard and Pedersen 2001). Note here that $\mathbf{Q}$ and therefore also $\mathbf{q}$ do not distinguish between tourism-related and non-tourism related activities, because such detail is not available in the data. This means that all tourism-specific activities are treated within the broader industry: For example, a coach transporting tourists is assumed to have the same fuel-use and embodied-emissions characteristics as a coach transporting school children.

6.2.2.1 MRIO analysis of tourism expenditures

MRIO analysis is a straightforward extension of conventional (single-region) I-O analysis (Leontief and Strout 1963). MRIO databases feature a number of regions and/or countries, with each country's economy represented by a number of economic sectors (Kanemoto and Murray 2010). As a result, final demand is a four-dimensional tensor with elements y_{ik}^{rs}, where the index r counts regions of final sale, s regions of final demand, i the commodities consumed, and k the consuming agents (households etc). In fact, in an MRIO context, $\mathbf{x}$, $\mathbf{T}$ and $\mathbf{y}$ are all four-dimensional tensors.

Expenditures on tourism enter Leontief's model as final demand $\tilde{\mathbf{y}}$, which in turn drives economic output $\tilde{\mathbf{x}} = (\mathbf{I} - \mathbf{T}\hat{\mathbf{x}}^{-1})^{-1}\tilde{\mathbf{y}}\mathbf{1}^{\mathbf{y}}$, which then causes the carbon footprint of tourism, $\tilde{Q} = \mathbf{q}\tilde{\mathbf{x}}$.[21] Writing out the tensor products in this aggregate relationship for the scalar $\tilde{Q}$ allows unraveling carbon footprints into supplying and demanding regions, commodities and agents (Kanemoto *et al.* 2012). The most general breakdown of the carbon footprint in an MRIO setting is achieved by an element-wise product $\mathbf{q}\#\mathbf{L}\#\tilde{\mathbf{y}}$, or $\tilde{Q}_{ijk}^{rst} = q_i^r L_{ij}^{rs} \tilde{y}_{jk}^{st}$, where $\mathbf{L} = (\mathbf{I} - \mathbf{T}\hat{\mathbf{x}}^{-1})^{-1}$ is the Leontief inverse, and where r counts regions of production and therefore emissions, s regions of final sale (eg of airfares and food services, often the tourist destinations), t the regions of final demand (the residence of the visitors), i the commodities produced during emission, j the commodities consumed (airfares, hotels etc), and k the consuming agents (practically only households, k=1).

[21] The ~ symbol denotes a particular final demand stressor $\tilde{\mathbf{y}}$ for the Leontief model. This stressor does not normally satisfy the national accounting identity.

The tensor $\tilde{Q}_{ij1}^{rst}$ can now be sliced in various ways, using tensor contraction (denoted by a dot '.'), to provide various types of information. For example, $\tilde{Q}_{.j1}^{.st} =: \sum_{r,i} q_i^r L_{ij}^{rs} \tilde{y}_{j1}^{st}$ sums over emitting entities and shows the final-commodity content and regions of visitor residence (t) and location of final sale (s). Another option is $\tilde{Q}_{i.1}^{r.t} =: \sum_{s,j} q_i^r L_{ij}^{rs} \tilde{y}_{j1}^{st}$, showing the carbon footprint by region and industry of emission, and region of visitor residence. $\tilde{Q}_{..1}^{r.t} =: \sum_{i,s,j} q_i^r L_{ij}^{rs} \tilde{y}_{j1}^{st}$ and $\tilde{Q}_{..1}^{.st} =: \sum_{r,i,j} q_i^r L_{ij}^{rs} \tilde{y}_{j1}^{st}$ simply map bilateral embodied CO_2 flows (Kanemoto *et al.* 2012). The terms $\tilde{Q}_{..1}^{.st}$ link locations of final sale and residence and might therefore more or less resemble actual visitor movements. In contrast, the $\tilde{Q}_{..1}^{r.t}$ link visitor residence with country of emission, and thus provide a measure of the ultimate regional spread of a country's carbon footprint of tourism.

In our work, we will use two particular way of slicing $\tilde{\mathbf{Q}}$: RBA and DBA (Sun and Lenzen 2017). Both perspectives are variants of the well-known Consumption-Based Accounting principle (Kander *et al.* 2015), however whilst RBA allocates consumption-based emissions to the country of the visitor residence, DBA allocates them to the country of the tourist destination (Sun and Lenzen 2017).

Specifically,

$$\tilde{Q}_{\mathrm{RBA},j}^{t} = \tilde{Q}_{.j1}^{..t} \text{ and } \tilde{Q}_{\mathrm{RBA},i}^{t} = \tilde{Q}_{i.1}^{..t} \qquad (SI\ 6.1.1)$$

are residence-based carbon footprints of visitors from countries *t*, broken down either by commodities *j* purchased by the visitor, or by emitting industries *i*. Similarly,

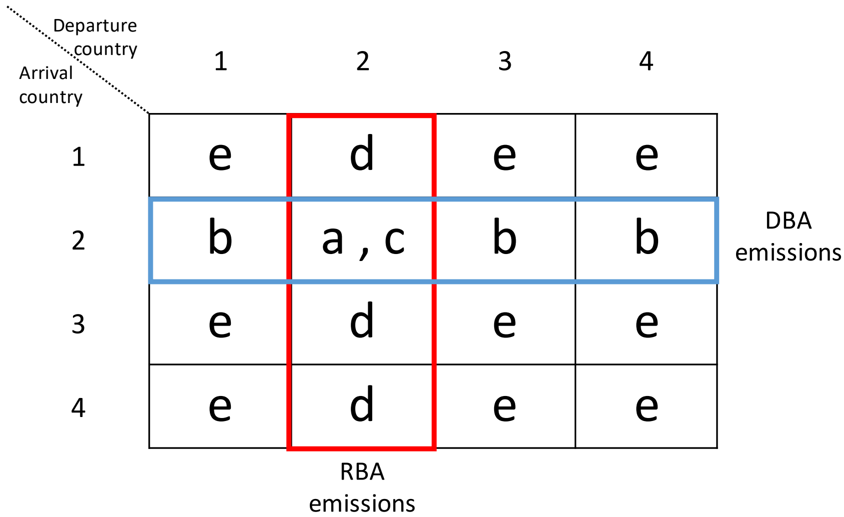
$$\tilde{Q}_{\mathrm{DBA},j}^{s} = \tilde{Q}_{.j1}^{.s.} \text{ and } \tilde{Q}_{\mathrm{DBA},i}^{s} = \tilde{Q}_{i.1}^{.s.} \qquad (SI\ 6.1.2)$$

are destination-based carbon footprints of tourism operations in countries *s*, broken down either by commodities *j* sold to the visitor, or by emitting industries *i*.

Calculating $\tilde{Q}_{\mathrm{RBA}}^{t}$ and $\tilde{Q}_{\mathrm{DBA}}^{s}$ involves slicing the stressor $\tilde{y}_{j1}^{st}$ in two different ways (see **Figure 6.1**), so that

$$\tilde{y}^{t}_{\mathrm{RBA},j} = \tilde{y}^{:t}_{j1} \text{ and } \tilde{y}^{t}_{\mathrm{DBA},j} = \tilde{y}^{s:}_{j1} \, . \tag{SI 6.1.3}$$

Figure 6.1. Schematic of the tourism expenditure matrix $\tilde{\mathbf{y}}$ for a hypothetical 4-region world, with destinations s in rows and visitor origins t in columns.



Note: The RBA perspective $\tilde{Q}^{t}_{\mathrm{RBA}}$ sums over rows for each column (red column), whilst the DBA perspective $\tilde{Q}^{s}_{\mathrm{DBA}}$ sums over columns for each row (blue row). Taking country 2 as an example, segments of $\tilde{\mathbf{y}}$ are labelled a-d to link with data items in TSAs where a: domestic tourist expenditure in country i, b: inbound visitor expenditure in country i, c: spending that occurs in the domestic region (country i) for residents travelling abroad (such as domestic transportation), and d: residents' outbound spending in foreign countries (country j).

6.2.2.2 Production Layer Decomposition

A further option for carbon footprint analysis is production layer decomposition. Utilising the series expansion of the Leontief inverse (Waugh 1950) $\mathbf{L} = (\mathbf{I} - \mathbf{T}\hat{\mathbf{x}}^{-1})^{-1} =: (\mathbf{I} - \mathbf{A})^{-1} = \sum_{n=0}^{\infty} \mathbf{A}^n = \mathbf{I} + \mathbf{A} + \mathbf{A}^2 + \cdots$, where $\mathbf{A} = \mathbf{T}\hat{\mathbf{x}}^{-1}$ is the input coefficients matrix. The terms $\mathbf{A}^n$ correspond to contributions from supply chains of n^{th} order, that is with n nodes. The sum of all contributions from supply chains of n^{th} order is called the n^{th} production layer.

For example, total output $\tilde{\mathbf{x}} = (\mathbf{I} - \mathbf{T}\hat{\mathbf{x}}^{-1})^{-1}\tilde{\mathbf{y}}\mathbf{1}^{\mathbf{y}}$ can be unravelled as $\tilde{\mathbf{x}} = (\mathbf{I} + \mathbf{A} + \mathbf{A}^2 + \cdots)\tilde{\mathbf{y}}\mathbf{1}^{\mathbf{y}}$. The first production layer $\mathbf{A}\tilde{\mathbf{y}}\mathbf{1}^{\mathbf{y}}$ contains production inputs of the direct suppliers to final demand, the second layer $\mathbf{A}^2\tilde{\mathbf{y}}\mathbf{1}^\mathbf{y}$ production inputs of the suppliers of the direct suppliers to final demand, the third layer $\mathbf{A}^3\tilde{\mathbf{y}}\mathbf{1}^\mathbf{y}$ production inputs of the suppliers of the suppliers of the direct suppliers to final demand, and so on. In carbon terms, a production layer decomposition reads $\tilde{Q} = \mathbf{q}(\mathbf{I} + \mathbf{A} + \mathbf{A}^2 + \cdots)\tilde{\mathbf{y}}\mathbf{1}^\mathbf{y}$, with 0th-order terms being $\mathbf{q}\tilde{\mathbf{y}}\mathbf{1}^\mathbf{y}$, 1st-order terms $\mathbf{qA}\tilde{\mathbf{y}}\mathbf{1}^\mathbf{y}$, 2nd-order terms $\mathbf{qA}^2\tilde{\mathbf{y}}\mathbf{1}^\mathbf{y}$, and so on.

Separating the 0th-order term and the remainder of the expansion, and considering that $\mathbf{A} + \mathbf{A}^2 + \cdots = \mathbf{A}(\mathbf{I} + \mathbf{A} + \cdots) = \mathbf{AL}$, carbon footprints can be split into a sum of direct and indirect effects: $\tilde{Q}_{ij1}^{rst} = q_i^r \tilde{y}_{i1}^{rt} + q_i^r (\mathbf{AL})_{ij}^{rs} \tilde{y}_{j1}^{st}$. The term $q_i^r \tilde{y}_{i1}^{rt}$ holds what consumers usually associate with their carbon responsibility when traveling, including for example the emissions from the plane they board.

6.2.2.3 I-O data

The quantities $\mathbf{Q}$, $\mathbf{T}$ and $\mathbf{x}$, and therefore also $\mathbf{q}$, $\mathbf{A}$ and $\mathbf{L}$, are computed using the Eora global MRIO database (Lenzen *et al.* 2012a; Lenzen *et al.* 2013), as constructed in the Global MRIO Virtual Laboratory (Lenzen *et al.* 2017). The final demand stressor $\tilde{y}_{j1}^{st}$ needs to be specified by purchased commodity *j*, country of visitor residence *s*, and tourist destination *t*. This information is sourced primarily from TSA reports published by individual countries. Where TSA reports are not available, a visitor expenditure total for individual countries reported by UNWTO is adopted. **Section** Error! Reference source not found. provides a detailed description of the tourism data compilation process.

6.2.3 Multiple regression

Multiple regression can be used to reveal drivers of the carbon footprint F, by optimising the parameters p_j of functions $f_j(x_{ji}, p_j)$ of explanatory variables $x_j(i)$, so that $g(F_i) = p_0 + \sum_j f_j(x_{ji}, p_j) + \varepsilon_i$, where g is a function, p_0 is the regression intercept, and where the ε_i are called residuals of observations i. To estimate the regression equation for $g(F_i)$, we use the ordinary least squares method in which the parameters p_j are adjusted so that the sum of squared residuals $SSE = \sum_i \varepsilon_i^2$ is minimised.

In our work, we follow Wier *et al.* (2001) and Lenzen *et al.* (2006), and formulate a multiplicative relationship for per capita carbon footprints F as

$$F = k\, x^{\eta_x}\, \mathrm{e}^{\varrho_q q}\, \mathrm{e}^{\varrho_t t}\,, \qquad (SI\ 6.1.4)$$

where the explanatory variables are a) per capita GDP x, carbon intensity of production q, and time t. Equation *SI 6.*1.4 is parametrised by a regression constant k, and so-called elasticities η and ϱ. To transform equation *SI 6.*1.4 into additive form for multiple regression we take natural logarithms

$$\ln(F) = \ln(k) + \eta_x \ln(x) + \varrho_q q + \varrho_c t\,. \qquad (SI\ 6.1.5)$$

Here it can be seen that $\ln(k)$ is the regression intercept. Calculating derivatives of F is equation *SI 6.*1.4 yields for example

$$\frac{\partial F}{\partial x} = k\, \eta_x x^{\eta_x - 1}\, \mathrm{e}^{\varrho_q q}\, \mathrm{e}^{\varrho_t t} = \eta_x \frac{F}{x} \Leftrightarrow \eta_x = \frac{\partial F/F}{\partial x/x}\,. \qquad (SI\ 6.1.6)$$

This relationship shows that the parameter η_x describes the relative change in carbon footprint F as a result of a relative change in GDP x. Similarly,

$$\frac{\partial F}{\partial q} = \varrho_q F \Leftrightarrow \varrho_q = \frac{\partial F/F}{\partial q} \text{ and } \frac{\partial F}{\partial t} = \varrho_t F \Leftrightarrow \varrho_t = \frac{\partial F/F}{\partial t} \qquad (\text{SI } 6.1.7)$$

describes the relative change in carbon footprint F as a result of a unit change (one kg CO_2-e/$ and one year) in carbon intensity and time.

Preliminary findings showed that using equation *SI 6.*1.4 as the basis for regressing tourism carbon footprints showed that there exists no uniform relationship across the entire international per capita GDP range, and that the regression form must allow for a GDP-elasticity of the carbon footprint that varies with per capita GDP:

$$\eta_x = \eta_{x,0} + \theta x \,, \qquad (SI\ 6.1.8)$$

where θ describes the change in the elasticity η_x as a result of change in per capita GDP. Inserting equation *SI 6.*1.8 into equation *SI 6.*1.4 yields the linear regression form

$$\ln(F) = \ln(k) + \eta_x \ln(x) + \theta x \ln(x) + \varrho_q q + \varrho_t t \,. \qquad (SI\ 6.1.9)$$

Differentiating

$$\begin{aligned} \frac{\partial F}{\partial x} &= \frac{\partial\left(k\, x^{\eta_{x,0}+\theta x}\, \mathrm{e}^{\varrho_q q}\, \mathrm{e}^{\varrho_t t}\right)}{\partial x} = k\, \mathrm{e}^{\varrho_q q}\, \mathrm{e}^{\varrho_t t} \frac{\partial\left(x^{\eta_{x,0}} x^{\theta x}\right)}{\partial x} \\ &= k\, \mathrm{e}^{\varrho_q q}\, \mathrm{e}^{\varrho_t t} \left[x^{\theta x} \frac{\partial\left(x^{\eta_{x,0}}\right)}{\partial x} + x^{\eta_{x,0}} \frac{\partial\left(x^{\theta x}\right)}{\partial x}\right] \\ &= k\, \mathrm{e}^{\varrho_q q}\, \mathrm{e}^{\varrho_t t} \left[x^{\theta x} \eta_{x,0} x^{\eta_{x,0}-1} + x^{\eta_{x,0}} \theta x^{\theta x} \left(\ln(x) + 1\right)\right] \\ &= \eta_{x,0} \frac{F}{x} + F\theta \left(\ln(x) + 1\right) \\ &= \frac{F}{x}\left(\eta_{x,0} + \theta x \left(\ln(x) + 1\right)\right) \end{aligned} \qquad (SI\ 6.1.10)$$

yields a modified expression for the GDP-elasticity of the carbon footprint

$$\frac{\partial F/F}{\partial x/x} = \eta_{x,0} + \theta x \left(\ln(x) + 1\right) . \qquad (SI\ 6.1.11)$$

6.3 TSAs, data processing and uncertainty

6.3.1 Compiling a set of TSAs

TSA concept was proposed by the UN and other multi-lateral organisations in 1993 to provide a comprehensive and consistent evaluation framework for documenting the economic contribution of tourism consumption to a national economy (United Nations 1993). To compile a global visitor expenditure database, our search for the individual TSA reports starts with a list from the UNWTO, identifying around 60 countries that in 2010 had produced or were currently developing a TSA exercise (World Tourism Organisation 2010). Electronic resources from the UNWTO, OECD, EU, governmental reports, or journal articles were searched in order to locate national TSA consumption data. Finally, we identified 55 full TSA reports from major tourism countries, covering around 88% (2009 – 87.2%, 2010 – 88.3%, 2011 – 88.3%, 2012 – 88.1%, 2013 – 88.1%) of the global tourism consumption. Further details see *SI 6.*2.

6.3.2 Estimate inbound visitor consumption by country of departure

After compiling a global longitudinal visitor expenditure database, the next step is to establish the origin-destination (O-D) pattern for inbound travel. Inbound tourism expenditure reported by the standard TSA only report one aggregate number without identifying point of origin (departure country) of foreigners or their associated spending. To estimate inbound spending to destination s from individual countries t, we use origin- and destination-specific data from the World Tourism Organisation (UNWTO 2009-2013) containing "*arrivals of non-resident visitors at national borders by country of residence*", as a proxy to allow us to estimate normalized weights w^{st} for allocating the inbound tourism expenditure $\tilde{y}_{j1}^{st} = w^{st}\left(\tilde{y}_{j1}^{s.}\right)$ across countries of residence t of inbound visitors. While UNWTO data are complete for about 80% total visitor movements (2009 – 79.8%, 2010 – 94.5%, 2011 – 95.6%, 2012 – 95.8%, 2013 – 95.6%), additional steps are taken to estimate the bilateral travel flows. First, official inbound/outbound data published by individual tourism authority are manually searched online for important destinations countries across five continents. Secondly, for the remaining missing component, the bilateral travel flow is estimated based on the gravity model assumption

(Chasapopoulos *et al.* 2014; Morley *et al.* 2014), which allocates the undistributed inbound visits to the remaining departure countries in a direct proportion to the gross national GDP of the visitor's country (approximating purchasing power for tourism activities), and in inverse proportion to the distance between two countries (approximating cost of journey).

6.3.3 Integrating TSA and MRIO data

A TSA captures economic transactions within the national boundary for visitors taking trips within, towards or from the country of reference. It does not reflect economic activities at foreign destinations from outbound travel nor airfares paid to foreign-based airlines. TSAs have been used before as the basis for consumption-based accounting (CBA) and for establishing I-O based tourism carbon footprints, for example for Wales, UK (Munday *et al.* 2013), Taiwan (Sun 2014b), Australia (Dwyer *et al.* 2010), Spain (Cadarso *et al.* 2015b), and Switzerland (Perch-Nielsen *et al.* 2010). Integrating a TSA into the final-demand block of an MRIO database offers several advantages. First, the TSA conceptual framework and data compliance are comprehensive and consistent across nations, allowing inter-country comparisons on tourism economic significance, GHG emissions, and tourism eco-efficiency. Second, both the TSA and MRIO databases comply with the System of National Accounts, allowing individual destinations to benchmark their tourism development against other sectors in the economy in terms of both economic and environmental performance. Third, adopting the TSA concept offers a straightforward treatment of the international aviation issue. Aviation emissions are only attributable to the tourism sector of a country when the transaction of the air transportation creates an economic significance at the geographic territory.

Technically, TSA data enter Leontief's model as final demand $\tilde{\mathbf{y}}$, where the 39 classifications of the original TSAs (Tab. *SI 6.*1) and the MRIO database are bridged using concordance matrices. A concordance matrix $\mathbf{C}$ shows an entry C_{ij} = 1 where TSA class i corresponds to MRIO class j, and 0 elsewhere.

6.3.4 Uncertainty

To assess the influence of allocation and parametrical uncertainty on our carbon footprint results, we carry out a detailed uncertainty analysis using error propagation (Lloyd and Ries 2007; Imbeault-Tétreault *et al.* 2013). The calculation of carbon footprints based on I-O analysis involves a matrix inversion, and as a consequence analytical error propagation is not possible (Lenzen 2011). I-O researchers have overcome this difficulty by resorting to Monte Carlo approaches (Bullard and Sebald 1977; Bullard and Sebald 1988; Yoshida *et al.* 2002). Here, uncertainty is propagated using standard deviations (Lenzen *et al.* 2010) [sourced from the same MRIO database, Eora (Lenzen *et al.* 2012a; Lenzen *et al.* 2013)], as constructed in the Global MRIO Virtual Laboratory) for perturbing the basic data items Q, T and y, calculating perturbed carbon footprints and then gathering these for a large number of perturbation runs. Standard deviations of derived carbon footprint measures are then taken from the statistical distribution of the perturbations. For further technical details, and details on our uncertainty calculus, see *SI* 6.4.3.

6.4 Results

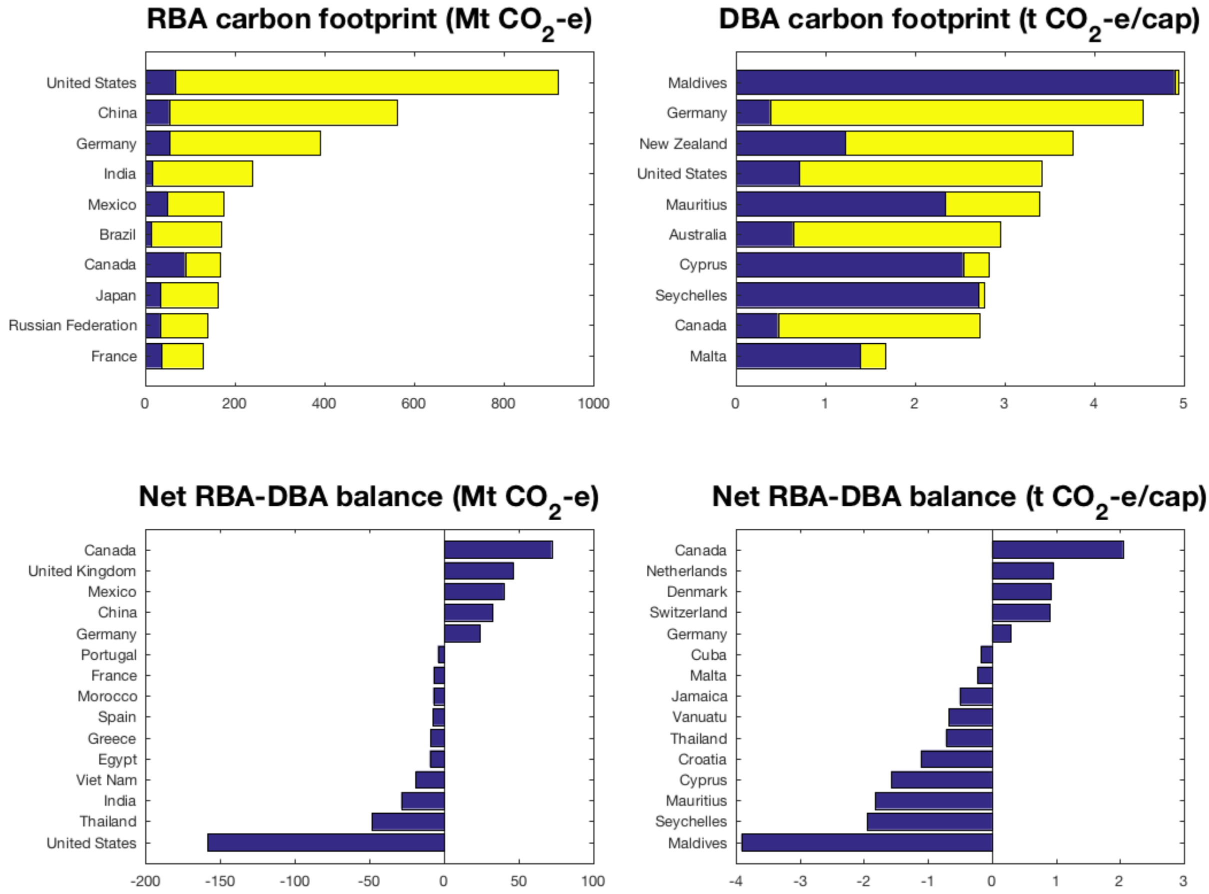
On the back of a growth in tourist expenditure from 2.5 $tr in 2009 to 4.7 $tr in 2013, the global carbon footprint increased rapidly from 3.9 to 4.5 Gt CO_2-e during the same period (*SI 6.*4.1), representing about 8% of global greenhouse gas emissions (certain within ±7% at the 95%-level of confidence, *SI 6.*2.6 and *SI 6.*4.3). Using production layer decomposition (*SI 6.*4.5), we estimate 2013 *direct* emissions from tourism operations to be about 2.9 Gt CO_2-e (exceeding previous estimates (UNWTO *et al.* 2008; Peeters and Dubois 2010; Gössling and Peeters 2015) because of our more complete scope; *SI 6.*4.4), demonstrating that including all upstream supply chains leads to the addition of at least another 1-2 Gt CO_2-e that have so far been absent from global tourism studies (*SI 6.*4.4 & *SI 6.*4.5).

The US tops the carbon footprint ranking (**Figure 6.2** top left) under both DBA (1060 Mt CO_2-e) and RBA (909 Mt CO_2-e) accounting perspectives, followed by China (528/561 Mt CO_2-e), Germany (305/329), and India (268/240). The majority of these carbon footprints are caused by domestic travel. In per capita terms, small-island destinations feature some of the highest destination-based footprints per capita (**Figure 6.2** top right), mostly due to international visitors. In countries such as the Maldives, Mauritius, Cyprus and the Seychelles, international tourism represents between 30% and 80% of national emissions.

6.4.1 International travel footprints

When taking the difference between RBA and DBA footprints, domestic travel cancels out, and the resulting net balance reflects only international travel. This means that the US and India are "net destinations", and that China and Germany are "net origins" (**Figure 6.2** bottom left). On a per capita basis, "net travelers" such as Canadians, Swiss, Dutch, Danish and Norwegians exert a much higher carbon footprint elsewhere than others in their own country. In contrast, "net hosts" such as Islanders and residents of popular tourist destinations such as Croatia, Greece and Thailand shoulder much higher footprints from their visitors than they exert elsewhere (**Figure 6.2** bottom right).

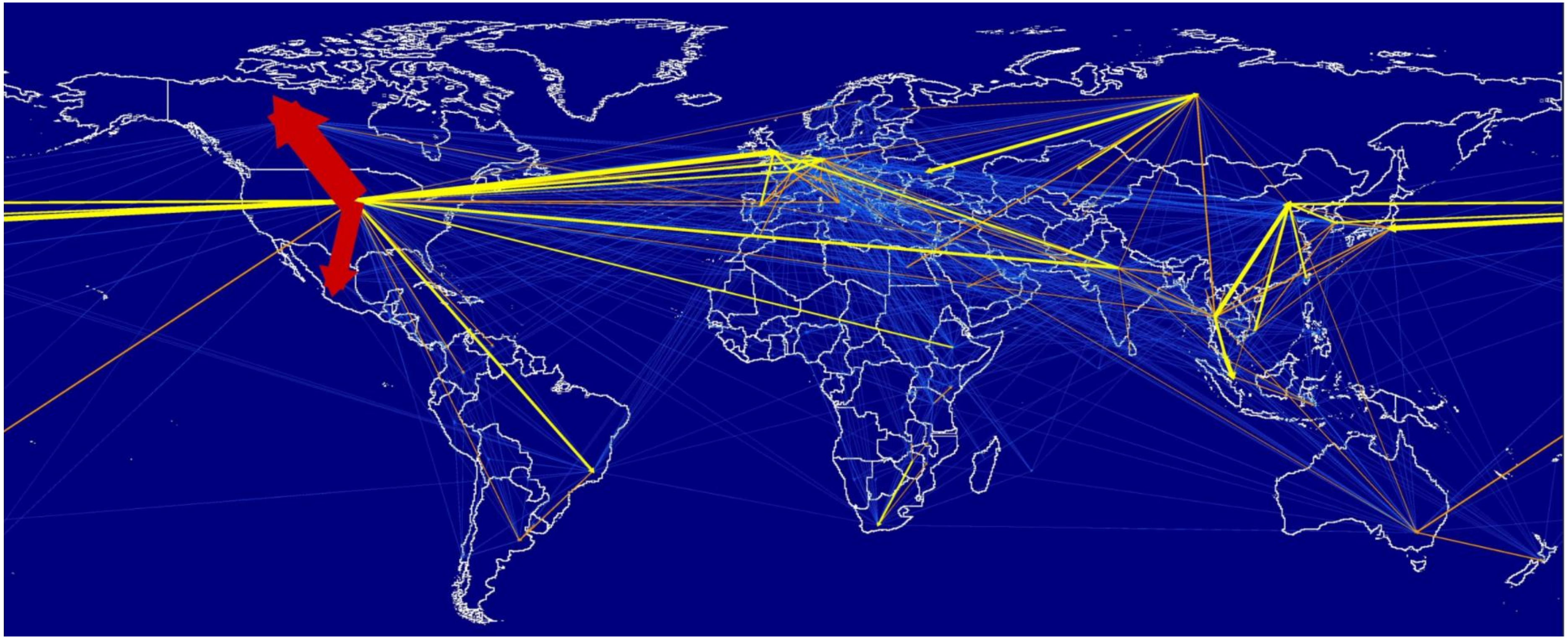
Figure 6.2: Carbon footprint measures of selected top-ranking countries, for 2013.



Note: Top left: RBA carbon footprint by nationality of visitor, blue international travel, yellow domestic travel; bottom left: net RBA-DBA balance, positive for “net origins”, negative for “net destinations”; top right: per capita DBA carbon footprint by destination, blue international travel, yellow domestic travel; bottom right: per capita net RBA-DBA balance, positive for “net travelers”, negative for “net hosts”.

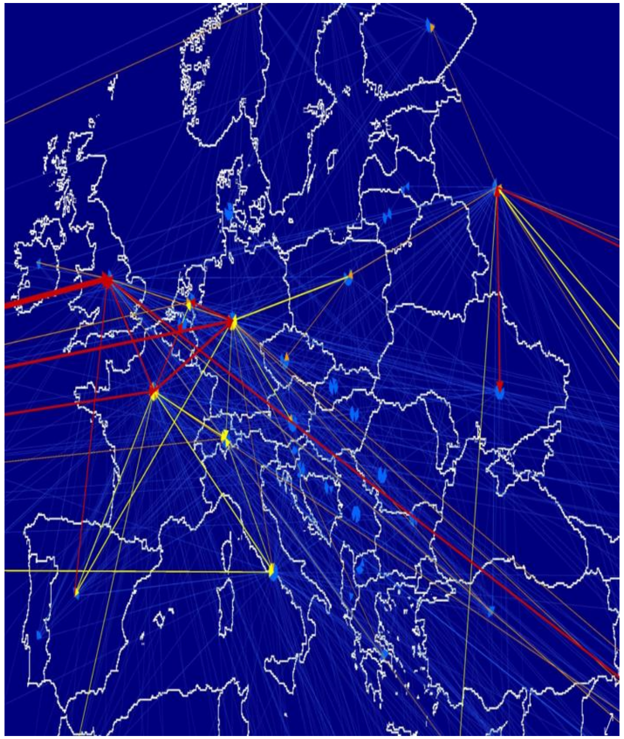
Further unraveling footprints into bilateral movements of embodied carbon shows that Canadians and Mexicans traveling to the US are the two largest individual contributions, making up 2.7% of the global total (**Figure 6.3**). The map of global carbon movements shows that travelling is largely a high-income affair, and as a result carbon embodied in tourism flows mainly between high-income countries acting both as traveler residence and destinations (**Figure 6.4**, **Table 6.1**). About half of the global total footprint was caused by travel between countries with a per capita GDP of more than 25,000 US$ (further details in *SI 6*.4.1).

Figure 6.3. Top bilateral embodied carbon movements.



Note: In 2013, international travel caused a carbon footprint of about 1 Gt CO_2-e, or 23% of the global carbon footprint of tourism. Arrows point in the direction of embodied carbon flow, which – in accordance with the literature – is the direction of commodity trade, and which is opposite to the movement of people. Red arrows: bilateral international movements belonging to the top 10% of the total 1 Gt CO_2-e; yellow arrows: top 10-30%; orange arrows 30-50%; blue arrows: remainder.

Figure 6.4. Top bilateral embodied carbon movements to and/or from Europe.



Note: Arrows point in the direction of embodied carbon flow, which – in accordance with the literature – is the direction of commodity trade, and which is opposite to the movement of people. Top flows are

Table 6.1. Top 15 global carbon movements and Top 15 carbon movements into and/or from Europe.

Top 15 global flows	Carbon footprint (Mt)	Top 15 flows into and/or from Europe	Carbon footprint (Mt)
United States → Canada	75.0	United States → United Kingdom	12.0
United States → Mexico	47.0	Russian Federation → Ukraine	7.8
United States → United Kingdom	12.0	France → Germany	6.2
United States → Japan	12.0	United States → Germany	6.1
Canada → United States	12.0	Ukraine → Russian Federation	5.9
Thailand → China	11.0	France → United Kingdom	5.8
Malaysia → Singapore	10.0	Spain → United Kingdom	5.3
Russian Federation → Ukraine	7.8	India → United Kingdom	5.2
Mexico → United States	7.3	United States → France	4.8
Thailand → Malaysia	7.0	France → Belgium	4.3
India → United States	7.0	Russian Federation → Kazakhstan	4.3
United States → Brazil	6.6	Germany → Netherlands	4.1
Viet Nam → China	6.3	Thailand → Russian Federation	4.0
United States → China	5.8	France → Italy	3.6
Republic of Korea → China	5.3	Spain → Germany	3.6

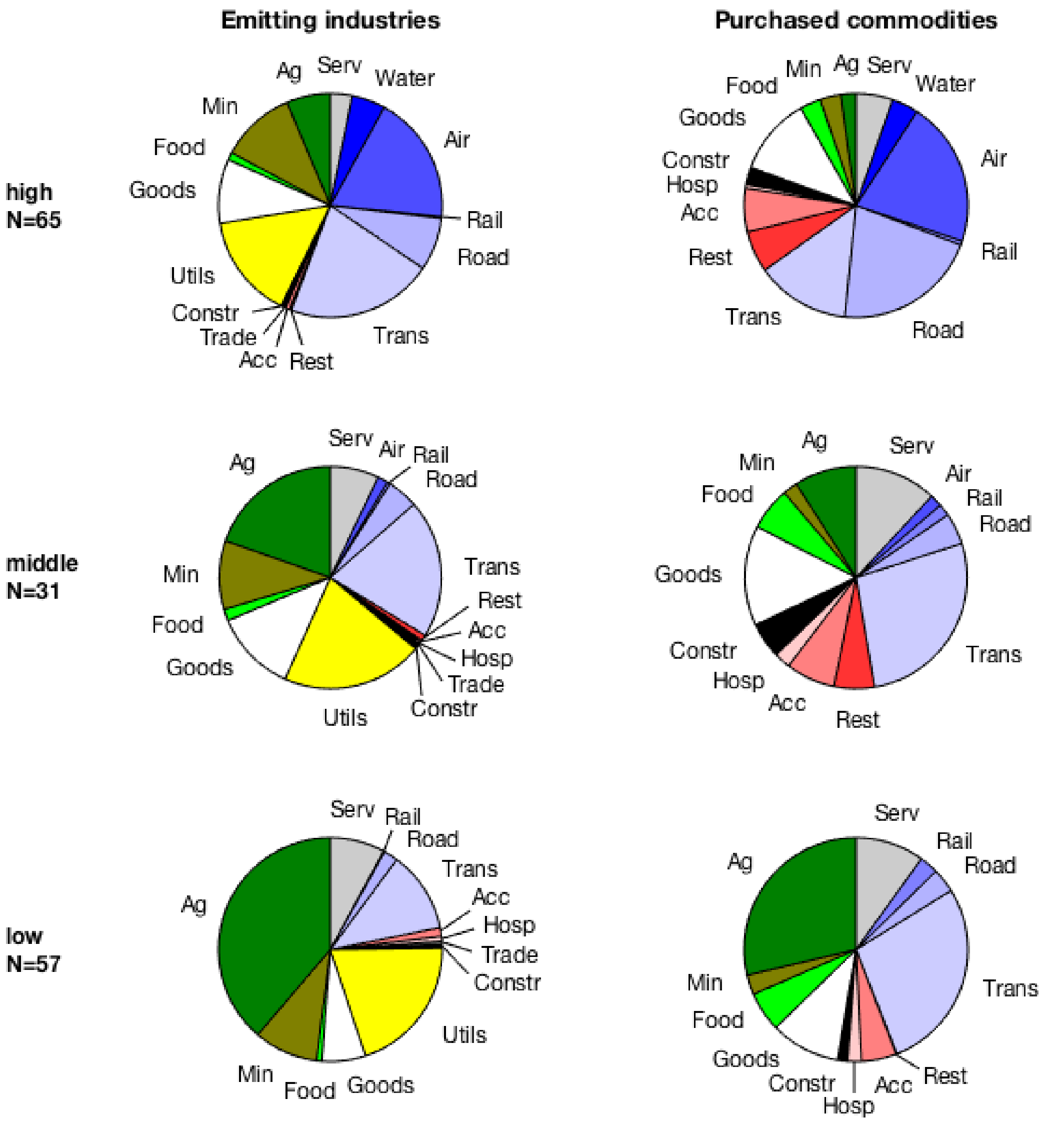
Note: The arrows represent flows of carbon; people move into opposite directions.

6.4.2 Gas species and supply chains

About 72% of the global footprint, or 3.6 Gt CO_2-e are in form of CO_2 stemming mostly from the combustion of fuels and land use changes, with most of the remainder being CH_4 emitted from livestock (enteric fermentation and manure management) and during oil and gas extraction (venting and flaring; *SI 6.*4.6). Emissions of N_2O and other greenhouse gases were not found to be significant.

The proportion of CO_2 and CH_4 emitted during production is ultimately determined by the basket of commodities purchased for consumption. Sectoral breakdown of tourism's carbon footprint at the production and consumption sides are quite different: For example, mining and utilities operate mainly at the production side to produce inputs into the downstream provision of tourism-related goods and services (**Figure 6.5**). Visitors from and in high-income countries demand a high proportion of transport (especially by air), goods (shopping) and hospitality (accommodation and restaurants), reflecting their travel expectations (**Figure 6.5**, top right). Visitors from and in low-income countries consume a high proportion of unprocessed food (listed under 'Ag') and road transport, and little commercial hospitality services (**Figure 6.5**, bottom right), demonstrating that for this income group, travel mostly involves the bare necessities. Such consumer behavior translates into different upstream emission profiles: Whilst high-income visits are linked with mostly energy-related CO_2 emissions of transport operators (especially by air) and goods manufacturers, low-income visits include a high proportion of CO_2 from road transport, and non-energy CO_2 emissions and CH_4 emissions from farms. In this assessment, the contribution of air travel emissions amounts to 20% (0.9 Gt CO2-e) of tourism's global carbon footprint (*SI 6.*4.4 and 6.4.6), which is due to our inclusion of a) food and shopping, b) upstream supply chains that are relatively insignificant for air travel, and c) non-CO_2 greenhouse gas emissions, rendering especially food consumption equally carbon-intensive.

Figure 6.5: Breakdown of the tourism carbon footprint into purchased commodities and emitting industries, and into high-, middle- and low-income countries.



Note: "Purchased commodities" represent the consumers' end of the supply chain network, "emitting industries" the producers' end. Due to many I-O tables of low-income countries not distinguishing modes, 'Trans' represents unspecified transport, which includes air transport. The three per capita GDP brackets are L <\$3k, M \$3k-\$10k, and H >\$10k, and *N* represents the number of countries in the income group. 2013 tourist volumes from the three groups are 53.9m (L), 281.5m (M), and 656.7m (H). For further details and an explanation of sector acronyms see *SI* 6.3.3.

These findings need to be qualified. First, we have not included direct non-CO2 emissions from aviation into our assessment. Especially contrails and aircraft-induced cloudiness could potentially play a significant role that could well alter air travel's contribution (Lee *et al.* 2010). However, the effects on radiative forcing of short-lived greenhouse gases emitted from sub-sonic aircraft remain impossible to quantify, and we have been made aware of only one carbon footprint study (Perch-Nielsen *et al.* 2010) that includes these. Second, it could be argued that food, shopping and ground transport be counted net of what tourists would have eaten, purchased or travelled had they stayed at home. If only additional emissions were counted with reference to a stay-home scenario, air travel may well come out as the dominant emissions component. We do not attempt to quantify additionality, for a number of reasons (*SI 6.*1), most importantly, because food, shopping and transport by international visitors increase the carbon footprint of destinations, as opposed to the carbon footprints of the visitors' home country. These activities matter for international embodied-carbon transfers (Peters *et al.* 2011).

6.4.3 Drivers and projections

The carbon footprint of global tourism is mainly determined by two factors: Demand for, and carbon intensity of tourism-related goods and services. Trends of these two factors are known to counteract (Malik *et al.* 2016). In the case of tourism, an annual 7% or 5-year 30% increase in tourism-related expenditure during 2009-2013 has cancelled out all carbon intensity reductions (-2.7%/-12.9%), and caused the carbon footprint of global tourism to increase by 3.3% annually or 14% over the period (Tab. *SI 6.*6). Half of the 540 Mt CO_2-e carbon footprint growth occurred in high-income countries and due to high-income visitors (*SI 6.*4.7), however middle-income countries – notably China – recorded the highest growth rate (17.4% p.a., *SI 6.*4.7).

At around 1 kg CO_2-e per dollar of final demand (Tab. *SI 6.*6c), the carbon multiplier (*SI 6.*1.2) of global tourism is higher than those of global manufacturing (0.8 kg CO_2-e/$) and construction (0.7 kg CO_2-e/$), and higher than the global average (0.75 kg CO_2-e/$). Growth in tourism-related expenditure is therefore a stronger accelerator of emissions than growth in manufacturing, construction or services provision.

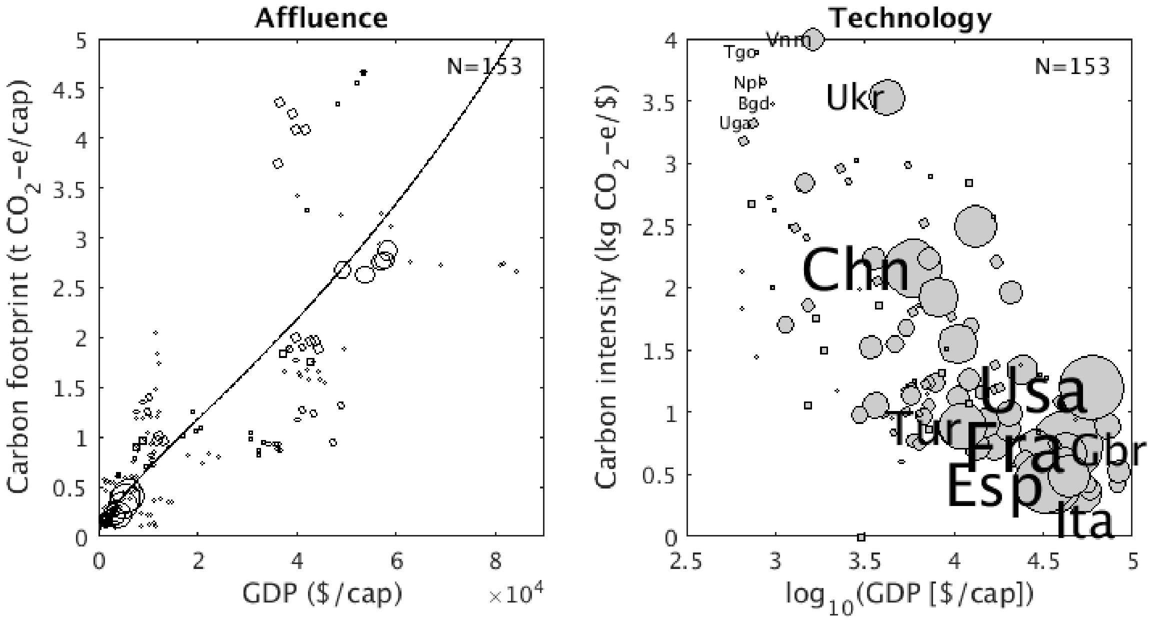
The International Monetary Fund (IMF) projects the world's average per capita GDP to increase by 4.2% annually, from 10,750 US$/year in 2017 to 13,210 US$/year in 2022 (IMF 2017), which if true would squarely outpace the 2.2-3.2% average carbon intensity decline projected by the OECD and EIA (OECD and PBL 2011; EIA 2017). What influence are such developments likely to have on the carbon footprint of global tourism? To obtain an indication of possible future trends we carry out a multiple regression of 2009-2013 per capita carbon footprints (RBA) against three explanatory variables – per capita GDP ("affluence"), carbon intensity ("technology"), and time (*SI 6.*4.8) – and use the regression results for projecting the global carbon footprint to 2025.

We find that the per capita carbon footprint increases strongly with increasing affluence (wealthier people travel more), decreases weakly with improving technology (saving energy means emitting less), and that time has no significant bearing (*SI 6.*4.8.3 & 6.4.8.4).

Whilst a positive relationship between footprint and affluence can be expected (Wier *et al.* 2001; Lenzen *et al.* 2004; Lenzen *et al.* 2006) – after all, wealth determines the ability to travel – the relative weakness of the connection between footprint and technology seems surprising at first. If under any accounting perspective, technology had a significant influence on carbon footprints, the latter should saturate towards higher per capita GDP where the carbon intensity is low (Lenzen *et al.* 2006) (**Figure 6.6**, right panel). However, we do not observe such a saturation in the RBA perspective, where carbon footprints increase as travelers' per capita GDP increases (**Figure 6.6**, left panel). At affluence levels beyond 40,000 $/cap the GDP relationship becomes so strong that a 10% increase in wealth brings about a carbon footprint increase of up to 13% (*SI 6.*4.8.3). Expressed in economics parlance, the GDP-elasticity of the carbon footprint is higher than 1, reflecting that tourism a luxury good the consumption of which a) is largely enjoyed by the wealthy segment of the global population, and b) does not appear to satiate as incomes grow (*SI 6.*4.8.3).

Above-unity elasticities are reported in prior work on international tourism demand (Garin-Munoz and Amaral 2000; Song and Wong 2003; Lim *et al.* 2008), and on Brazilian households (Cohen *et al.* 2005), whose propensity to consume fuel for mobility increased more than proportionally with income as Brazil went through a rapid socio-economic development phase. A similar process may be at work here, as wealthy citizens in emerging economies such as Brazil, Russia, India, China and Mexico – who are amongst those nationalities recording the strongest growth in RBA-based footprints (Figure *SI 6.*5) – find new opportunities for enhancing quality of life and expressing socio-economic status. These aspirations motivate desires to visit countries that offer exotic experiences combined with luxury and comfort, leading people to use aviation to travel further (especially internationally) (Wong *et al.* 2016; Mishra and Bansal 2017). Previous work confirms this view in that travel distance and transportation modes were found to be the most critical factors in determining the magnitude of direct tourism emissions (Gössling *et al.* 2005; Dubois and Ceron 2006; Filimonau *et al.* 2014; Gössling *et al.* 2015).

Figure 6.6. Affluence and technology as drivers of the carbon footprint of global tourism (RBA).



Note: Affluence is measured as per capita GDP (left, including regression curve from *SI 6*.4.8.3) and technology is measured as carbon efficiency (right). Circle size represents population, and *N* represents the number of countries in the sample.

Our finding provides both an explanation for the rapid growth of the carbon footprint of global tourism, and an indication of the growth it is likely to experience over the next five years. Extrapolating our 2009-2013 multiple regression (*SI 6*.4.8, DBA and RBA perspectives yield similar results) to 2025, we estimate that under very optimistic assumptions (2% p.a. per capita GDP increase and -4% p.a. technology-driven carbon intensity decline (Hatfield-Dodds *et al.* 2015; Lenzen *et al.* 2016), the latter brought about by unprecedented afforestation) the carbon footprint of global tourism can be limited to about 5 Gt CO_2-e (Figure *SI 6.*13). In contrast, business as usual (4.2% p.a. per capita GDP increase and -2.7% p.a. carbon intensity decline) would likely continue the current 3% annual growth pattern, and lead to tourism-related emissions of 6.5 Gt CO_2-e.

6.5 Conclusions

Travel is highly income-elastic and carbon-intensive. As global economic development progresses, especially among high-income countries and regions experiencing rapid economic growth, consumers' demand for travel has grown much faster than their consumption of other products and services. Driven by the desire for exotic travel experiences and an increasing reliance on aviation and luxury amenities, affluence has turned tourism into a carbon-intensive consumption category. Global demand for tourism is outstripping the de-carbonisation of tourism operations, and as a result is accelerating global carbon emissions. At the same time, at least 15% of global tourism-related emissions are currently under no binding reduction target as emissions of international aviation and bunker shipping are excluded from the Paris Agreement. In addition, the USA, as the most significant source of tourism emissions, does not support the Agreement.

There exists a popular mindset assuming that "tourism is a low-impact and non-consumptive development option" (Gössling 2000). This belief has compelled countries to pursue rapid and large-scale tourism development projects, in cases attempting to double visitor volume over a short time period (Citrinot 2012; Murai 2016; Hungary Today 2017). We have shown that such pursuit of economic growth comes with a significant carbon burden, as tourism is significantly more carbon-intensive than other potential areas of economic development. Developing tourism has therefore been – at least on average – not instrumental in reducing national greenhouse inventories. This finding should be considered in future deliberations on national development strategies and policies. In particular, the results of this study could serve to inform the work of the UNWTO (which advocates further tourism growth, even in already highly developed tourism economies) and World Travel and Tourism Council (WTTC) in creating awareness of the carbon burden faced by tourism-stressed areas.

Residence- and destination-based accounting perspectives amply demonstrate the unequal distribution of tourism impacts across citizens of traveler and host nations. In particular island destinations face an enormous additional carbon burden as they host a significant number of inbound tourists (McElroy 2006). These islands benefit substantially from the incomes from tourists, hence their governments face a challenge of how to impose national mitigation strategies without reducing tourism income (Sun 2014a). Switching from high-volume to high-revenue marketing (Gössling *et al.* 2015), and developing local income streams (Lenzen 2008) can assist in decoupling income and local emissions. Because of many islands' remoteness, international air travel will remain a critical component in the DBA carbon footprint (de Bruijn *et al.* 2014; Gössling *et al.* 2015; Sun 2016; Wong *et al.* 2016). The issue is complex, but channeling financial and technical assistance from major and wealthy tourism departure countries to disadvantaged island destinations could provide avenues for better preparing the island nations for the future (Wilkinson 2012).

Recognizing the global significance of tourism-related emissions, the UNWTO proposed two mitigation strategies: a) to encourage travelers to choose short-haul destinations with an increased use of public transportation and less aviation; and b) to provide market-based incentives for tourism operators to improve their energy and carbon efficiency (UNWTO *et al.* 2008). Our findings provide proof that so far these mitigation strategies have yielded limited success. Neither responsible travel behaviour nor technological improvements have been able to reign in the increase of tourism's carbon footprint. Carbon taxes or carbon trading schemes (especially for aviation services) may be required to curtail unchecked future growth in tourism-related emissions (ICAO 2016).

6.6 Acknowledgements

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Chapter 7

Conclusions

I have demonstrated the capability of virtual laboratories in adapting to specific regional and sectoral classifications. Through the understanding of regional economic distribution, sectoral contribution, and inter-regional supply chain flow, MRIO analysis that is implemented in a virtual laboratory is able to cover various analyses on economic, social, and environmental issues. The application of an MRIO database can provide a comprehensive analysis of employment multipliers in Indonesia through the IndoLab, economic impacts due to natural disasters in Taiwan through the TaiwanLab, regional consumer emissions in Sweden through the SwedenLab, responsibility of food loss in Japan through the JapanLab, and carbon footprints of global tourism sectors through the global MRIO lab. Since those case studies require specific regional and sectoral details, flexibility in constructing adaptive MRIO databases is of great benefit. Therefore, virtual laboratory technology provides essential tools for MRIO-related studies.

As an online platform, the virtual laboratory is open to new users. Users have two options: one, to use the existing database and classifications, or two, to incorporate their own data to suit specific research questions. **Table 7.1** shows various regional and sectoral classifications, data constraints, and a time-series selection for each virtual laboratory. If the existing database and classifications are not suitable for their research requirements, users should choose option two.

The virtual laboratory allows users to upload additional information and datasets. Incorporating new data to the virtual laboratory, however, requires an in-depth understanding of programming workflow (Geschke and Hadjikakou 2017). For example, users have to be familiar with concordance matrices, Matlab software, and ALANG files. Given the complexity of the virtual laboratory framework, working collaboratively with researchers who are already familiar with the virtual laboratory environment is preferable. The collaborative works undertaken within the virtual laboratory have resulted in at least 30 published articles, addressing issues such as economic complexity

(Reynolds *et al.* 2017), the gender pay gap (Reyes *et al.* 2018), and waste flows (Fry *et al.* 2016), among others (see Wiedmann 2017 for complete list).

Table 7.1. Existing database for each virtual laboratory

	Virtual Laboratory	Years	Regions	Sectors	Data constraints	Satellite Accounts
1.	IndoLab	1990–2016	495, 34, 8	1148, 185, 52, 17, 9	National IO tables, Provinces GDP, Cities GDP, Socio-economic survey	Employment
2.	TaiwanLab	1990–2016	22	267, 19, 9	National IO tables, GDP, Outputs, Intermediate consumption	Employment, Carbon emissions
3.	SwedenLab	2008–2016	291, 21, 8	821, 59, 21, 9	National IO tables, Disposable Income, Value-added	Employment, Carbon emissions
4.	JapanLab	1990–2016	47	4266, 19	National IO tables, Regional IO tables, Regional GDP, Regional statistics of industry	Employment, Carbon emissions
5.	USLab	2000–2016	52, 9	1058, 72, 21	National IO tables, States GDP, Export/import, Personal consumption expenditure, Commodity flow survey	Employment

Work in a virtual laboratory can also significantly accelerate outcomes in MRIO-related research. Policymakers are often under pressure to act quickly to solve urgent problems, such as climate change, disaster relief, and resource allocation (O'Dwyer 2007). The consequences of being slow to respond may worsen the impacts. Allowing users to incorporate timely data into a virtual laboratory is, therefore, of great benefit for formulating urgent research-based analyses. For example, the impact assessment of Cyclone Debbie hitting Queensland, Australia, in March 2017 was done within two months after the event (Lenzen *et al.* 2017b). Such research-based analysis can provide a credible reference for policymakers when formulating disaster relief policy in the impacted sectors and regions.

Meanwhile, the innovation of virtual laboratories is being transferred to other countries such as Germany, India, Brazil, and Malaysia. As with other virtual laboratories, a new MRIO database will utilise the same data processing engine and computer infrastructure. A new laboratory developer can then replicate the existing construction process, which eventually leads to significant cost reductions. The hope is that the virtual laboratory will benefit a vast number of people, including academics, researchers, and policymakers, around the world.

Chapter 8

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Supplementary Information

Table of Contents

Supplementary Information for Chapter 2

A new sub-national multi-region input-output database for Indonesia

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2.1 List of root regions

	Code	Region Name
1	1101	Kab. Simeulue
2	1102	Kab. Aceh Singkil
3	1103	Kab. Aceh Selatan
4	1104	Kab. Aceh Tenggara
5	1105	Kab. Aceh Timur
6	1106	Kab. Aceh Tengah
7	1107	Kab. Aceh Barat
8	1108	Kab. Aceh Besar
9	1109	Kab. Pidie
10	1110	Kab. Bireuen
11	1111	Kab. Aceh Utara
12	1112	Kab. Aceh Barat Daya
13	1113	Kab. Gayo Lues
14	1114	Kab. Aceh Tamiang
15	1115	Kab. Nagan Raya
16	1116	Kab. Aceh Jaya
17	1117	Kab. Bener Meriah
18	1118	Kab. Pidie Jaya
19	1171	Kota Banda Aceh
20	1172	Kota Sabang
21	1173	Kota Langsa
22	1174	Kota Lhokseumawe
23	1175	Kota Subulussalam
24	1201	Kab. Nias
25	1202	Kab. Mandailing Natal
26	1203	Kab. Tapanuli Selatan
27	1204	Kab. Tapanuli Tengah
28	1205	Kab. Tapanuli Utara
29	1206	Kab. Toba Samosir
30	1207	Kab. Labuhanbatu
31	1208	Kab. Asahan
32	1209	Kab. Simalungun
33	1210	Kab. Dairi
34	1211	Kab. Karo
35	1212	Kab. Deli Serdang
36	1213	Kab. Langkat
37	1214	Kab. Nias Selatan
38	1215	Kab. Humbang Hasundutan
39	1216	Kab. Pakpak Bharat
40	1217	Kab. Samosir
41	1218	Kab. Serdang Bedagai
42	1219	Kab. Batu Bara
43	1220	Kab. Padang Lawas Utara
44	1221	Kab. Padang Lawas
45	1222	Kab. Labuhanbatu Selatan
46	1223	Kab. Labuhanbatu Utara
47	1224	Kab. Nias Utara
48	1225	Kab. Nias Barat
49	1271	Kota Sibolga
50	1272	Kota Tanjung Balai
51	1273	Kota Pematang Siantar
52	1274	Kota Tebing Tinggi
53	1275	Kota Medan
54	1276	Kota Binjai
55	1277	Kota Padang Sidempuan
56	1278	Kota Gunung Sitoli
57	1301	Kab. Kepulauan Mentawai
58	1302	Kab. Pesisir Selatan
59	1303	Kab. Solok
60	1304	Kab. Sijunjung
61	1305	Kab. Tanah Datar
62	1306	Kab. Padang Pariaman
63	1307	Kab. Agam
64	1308	Kab. Limapuluh Koto
65	1309	Kab. Pasaman
66	1310	Kab. Solok Selatan
67	1311	Kab. Dharmasraya
68	1312	Kab. Pasaman Barat
69	1371	Kota Padang
70	1372	Kota Solok
71	1373	Kota Sawahlunto
72	1374	Kota Padang Panjang
73	1375	Kota Bukittinggi
74	1376	Kota Payakumbuh
75	1377	Kota Pariaman
76	1401	Kab. Kuantan Singingi
77	1402	Kab. Indragiri Hulu
78	1403	Kab. Indragiri Hilir
79	1404	Kab. Pelalawan
80	1405	Kab. Siak
81	1406	Kab. Kampar
82	1407	Kab. Rokan Hulu
83	1408	Kab. Bengkalis
84	1409	Kab. Rokan Hilir
85	1410	Kab. Kepulauan Meranti
86	1471	Kota Pekanbaru
87	1473	Kota Dumai
88	1501	Kab. Kerinci
89	1502	Kab. Merangin
90	1503	Kab. Sarolangun
91	1504	Kab. Batang Hari
92	1505	Kab. Muaro Jambi
93	1506	Kab. Tanjung Jabung Timur
94	1507	Kab. Tanjung Jabung Barat
95	1508	Kab. Tebo
96	1509	Kab. Bungo
97	1571	Kota Jambi
98	1572	Kota Sungai Penuh
99	1601	Kab. Ogan Komering Ulu
100	1602	Kab. Ogan Komering Ilir
101	1603	Kab. Muara Enim
102	1604	Kab. Lahat
103	1605	Kab. Musi Rawas
104	1606	Kab. Musi Banyuasin
105	1607	Kab. Banyuasin

106	1608	Kab. Ogan Komering Ulu Selatan
107	1609	Kab. Ogan Komering Ulu Timur
108	1610	Kab. Ogan Ilir
109	1611	Kab. Empat Lawang
110	1671	Kota Palembang
111	1672	Kota Prabumulih
112	1673	Kota Pagar Alam
113	1674	Kota Lubuk Linggau
114	1701	Kab. Bengkulu Selatan
115	1702	Kab. Rejang Lebong
116	1703	Kab. Bengkulu Utara
117	1704	Kab. Kaur
118	1705	Kab. Seluma
119	1706	Kab. Mukomuko
120	1707	Kab. Lebong
121	1708	Kab. Kepahiang
122	1709	Kab. Bengkulu Tengah
123	1771	Kota Bengkulu
124	1801	Kab. Lampung Barat
125	1802	Kab. Tanggamus
126	1803	Kab. Lampung Selatan
127	1804	Kab. Lampung Timur
128	1805	Kab. Lampung Tengah
129	1806	Kab. Lampung Utara
130	1807	Kab. Way Kanan
131	1808	Kab. Tulang Bawang
132	1809	Kab. Pesawaran
133	1810	Kab. Pringsewu
134	1811	Kab. Mesuji
135	1812	Kab. Tulang Bawang Barat
136	1871	Kota Bandar Lampung
137	1872	Kota Metro
138	1901	Kab. Bangka
139	1902	Kab. Belitung
140	1903	Kab. Bangka Barat
141	1904	Kab. Bangka Tengah
142	1905	Kab. Bangka Selatan
143	1906	Kab. Belitung Timur
144	1971	Kota Pangkal Pinang
145	2101	Kab. Karimun
146	2102	Kab. Bintan
147	2103	Kab. Kepulauan Anambas
148	2104	Kab. Lingga
149	2105	Kab. Natuna
150	2171	Kota Batam
151	2172	Kota Tanjung Pinang
152	3101	Kab. Kepulauan Seribu
153	3171	Kota Jakarta Selatan
154	3172	Kota Jakarta Timur
155	3173	Kota Jakarta Pusat
156	3174	Kota Jakarta Barat
157	3175	Kota Jakarta Utara
158	3201	Kab. Bogor

159	3202	Kab. Sukabumi
160	3203	Kab. Cianjur
161	3204	Kab. Bandung
162	3205	Kab. Garut
163	3206	Kab. Tasikmalaya
164	3207	Kab. Ciamis
165	3208	Kab. Kuningan
166	3209	Kab. Cirebon
167	3210	Kab. Majalengka
168	3211	Kab. Sumedang
169	3212	Kab. Indramayu
170	3213	Kab. Subang
171	3214	Kab. Purwakarta
172	3215	Kab. Karawang
173	3216	Kab. Bekasi
174	3217	Kab. Bandung Barat
175	3271	Kota Bogor
176	3272	Kota Sukabumi
177	3273	Kota Bandung
178	3274	Kota Cirebon
179	3275	Kota Bekasi
180	3276	Kota Depok
181	3277	Kota Cimahi
182	3278	Kota Tasikmalaya
183	3279	Kota Banjar
184	3301	Kab. Cilacap
185	3302	Kab. Banyumas
186	3303	Kab. Purbalingga
187	3304	Kab. Banjarnegara
188	3305	Kab. Kebumen
189	3306	Kab. Purworejo
190	3307	Kab. Wonosobo
191	3308	Kab. Magelang
192	3309	Kab. Boyolali
193	3310	Kab. Klaten
194	3311	Kab. Sukoharjo
195	3312	Kab. Wonogiri
196	3313	Kab. Karanganyar
197	3314	Kab. Sragen
198	3315	Kab. Grobogan
199	3316	Kab. Blora
200	3317	Kab. Rembang
201	3318	Kab. Pati
202	3319	Kab. Kudus
203	3320	Kab. Jepara
204	3321	Kab. Demak
205	3322	Kab. Semarang
206	3323	Kab. Temanggung
207	3324	Kab. Kendal
208	3325	Kab. Batang
209	3326	Kab. Pekalongan
210	3327	Kab. Pemalang
211	3328	Kab. Tegal
212	3329	Kab. Brebes

213	3371	Kota Magelang
214	3372	Kota Surakarta
215	3373	Kota Salatiga
216	3374	Kota Semarang
217	3375	Kota Pekalongan
218	3376	Kota Tegal
219	3401	Kab. Kulon Progo
220	3402	Kab. Bantul
221	3403	Kab. Gunung Kidul
222	3404	Kab. Sleman
223	3471	Kota Yogyakarta
224	3501	Kab. Pacitan
225	3502	Kab. Ponorogo
226	3503	Kab. Trenggalek
227	3504	Kab. Tulungagung
228	3505	Kab. Blitar
229	3506	Kab. Kediri
230	3507	Kab. Malang
231	3508	Kab. Lumajang
232	3509	Kab. Jember
233	3510	Kab. Banyuwangi
234	3511	Kab. Bondowoso
235	3512	Kab. Situbondo
236	3513	Kab. Probolinggo
237	3514	Kab. Pasuruan
238	3515	Kab. Sidoarjo
239	3516	Kab. Mojokerto
240	3517	Kab. Jombang
241	3518	Kab. Nganjuk
242	3519	Kab. Madiun
243	3520	Kab. Magetan
244	3521	Kab. Ngawi
245	3522	Kab. Bojonegoro
246	3523	Kab. Tuban
247	3524	Kab. Lamongan
248	3525	Kab. Gresik
249	3526	Kab. Bangkalan
250	3527	Kab. Sampang
251	3528	Kab. Pamekasan
252	3529	Kab. Sumenep
253	3571	Kota Kediri
254	3572	Kota Blitar
255	3573	Kota Malang
256	3574	Kota Probolinggo
257	3575	Kota Pasuruan
258	3576	Kota Mojokerto
259	3577	Kota Madiun
260	3578	Kota Surabaya
261	3579	Kota Batu
262	3601	Kab. Pandeglang
263	3602	Kab. Lebak
264	3603	Kab. Tangerang
265	3604	Kab. Serang
266	3671	Kota Tangerang
267	3672	Kota Cilegon
268	3673	Kota Serang
269	3674	Kota Tangerang Selatan
270	5101	Kab. Jembrana
271	5102	Kab. Tabanan
272	5103	Kab. Badung
273	5104	Kab. Gianyar
274	5105	Kab. Klungkung
275	5106	Kab. Bangli
276	5107	Kab. Karangasem
277	5108	Kab. Buleleng
278	5171	Kota Denpasar
279	5201	Kab. Lombok Barat
280	5202	Kab. Lombok Tengah
281	5203	Kab. Lombok Timur
282	5204	Kab. Sumbawa
283	5205	Kab. Dompu
284	5206	Kab. Bima
285	5207	Kab. Sumbawa Barat
286	5208	Kab. Lombok Utara
287	5271	Kota Mataram
288	5272	Kota Bima
289	5301	Kab. Sumba Barat
290	5302	Kab. Sumba Timur
291	5303	Kab. Kupang
292	5304	Kab. Timor Tengah Selatan
293	5305	Kab. Timor Tengah Utara
294	5306	Kab. Belu
295	5307	Kab. Alor
296	5308	Kab. Lembata
297	5309	Kab. Flores Timur
298	5310	Kab. Sikka
299	5311	Kab. Ende
300	5312	Kab. Ngada
301	5313	Kab. Manggarai
302	5314	Kab. Rote Ndao
303	5315	Kab. Manggarai Barat
304	5316	Kab. Sumba Barat Daya
305	5317	Kab. Sumba Tengah
306	5318	Kab. Nagekeo
307	5319	Kab. Manggarai Timur
308	5320	Kab. Sabu Raijua
309	5371	Kota Kupang
310	6101	Kab. Sambas
311	6102	Kab. Bengkayang
312	6103	Kab. Landak
313	6104	Kab. Pontianak
314	6105	Kab. Sanggau
315	6106	Kab. Ketapang
316	6107	Kab. Sintang
317	6108	Kab. Kapuas Hulu
318	6109	Kab. Sekadau
319	6110	Kab. Melawi
320	6111	Kab. Kayong Utara

321	6112	Kab. Kubu Raya
322	6171	Kota Pontianak
323	6172	Kota Singkawang
324	6201	Kab. Kotawaringin Barat
325	6202	Kab. Kotawaringin Timur
326	6203	Kab. Kapuas
327	6204	Kab. Barito Selatan
328	6205	Kab. Barito Utara
329	6206	Kab. Sukamara
330	6207	Kab. Lamandau
331	6208	Kab. Seruyan
332	6209	Kab. Katingan
333	6210	Kab. Pulang Pisau
334	6211	Kab. Gunung Mas
335	6212	Kab. Barito Timur
336	6213	Kab. Murung Raya
337	6271	Kota Palangkaraya
338	6301	Kab. Tanah Laut
339	6302	Kab. Kotabaru
340	6303	Kab. Banjar
341	6304	Kab. Barito Kuala
342	6305	Kab. Tapin
343	6306	Kab. Hulu Sungai Selatan
344	6307	Kab. Hulu Sungai Tengah
345	6308	Kab. Hulu Sungai Utara
346	6309	Kab. Tabalong
347	6310	Kab. Tanah Bumbu
348	6311	Kab. Balangan
349	6371	Kota Banjarmasin
350	6372	Kota Banjarbaru
351	6401	Kab. Paser
352	6402	Kab. Kutai Barat
353	6403	Kab. Kutai Kertanegara
354	6404	Kab. Kutai Timur
355	6405	Kab. Berau
356	6406	Kab. Malinau
357	6407	Kab. Bulungan
358	6408	Kab. Nunukan
359	6409	Kab. Penajam Paser Utara
360	6410	Kab. Tana Tidung
361	6471	Kota Balikpapan
362	6472	Kota Samarinda
363	6473	Kota Tarakan
364	6474	Kota Bontang
365	7101	Kab. Bolaang Mongondow
366	7102	Kab. Minahasa
367	7103	Kab. Kepulauan Sangihe
368	7104	Kab. Kepulauan Talaud
369	7105	Kab. Minahasa Selatan
370	7106	Kab. Minahasa Utara
371	7107	Kab. Bolaang Mongondow Utara
372	7108	Kab. Kep. Siau Tagulandang Biaro
373	7109	Kab. Minahasa Tenggara
374	7110	Kab. Bolaang Mongondow Selatan
375	7111	Kab. Bolaang Mongondow Timur
376	7171	Kota Manado
377	7172	Kota Bitung
378	7173	Kota Tomohon
379	7174	Kota Mobagu
380	7201	Kab. Banggai Kepulauan
381	7202	Kab. Banggai
382	7203	Kab. Morowali
383	7204	Kab. Poso
384	7205	Kab. Donggala
385	7206	Kab. Tolitoli
386	7207	Kab. Buol
387	7208	Kab. Parigi Moutong
388	7209	Kab. Tojo Una-Una
389	7210	Kab. Sigi
390	7271	Kota Palu
391	7301	Kab. Kepulauan Selayar
392	7302	Kab. Bulukumba
393	7303	Kab. Bantaeng
394	7304	Kab. Jeneponto
395	7305	Kab. Takalar
396	7306	Kab. Gowa
397	7307	Kab. Sinjai
398	7308	Kab. Maros
399	7309	Kab. Pangkajene Kepulauan
400	7310	Kab. Barru
401	7311	Kab. Bone
402	7312	Kab. Soppeng
403	7313	Kab. Wajo
404	7314	Kab. Sidenreng Rappang
405	7315	Kab. Pinrang
406	7316	Kab. Enrekang
407	7317	Kab. Luwu
408	7318	Kab. Tana Toraja
409	7322	Kab. Luwu Utara
410	7325	Kab. Luwu Timur
411	7326	Kab. Toraja Utara
412	7371	Kota Makassar
413	7372	Kota Parepare
414	7373	Kota Palopo
415	7401	Kab. Buton
416	7402	Kab. Muna
417	7403	Kab. Konawe
418	7404	Kab. Kolaka
419	7405	Kab. Konawe Selatan
420	7406	Kab. Bombana
421	7407	Kab. Wakatobi
422	7408	Kab. Kolaka Utara
423	7409	Kab. Buton Utara
424	7410	Kab. Konawe Utara
425	7471	Kota Kendari
426	7472	Kota Baubau

427	7501	Kab. Boalemo
428	7502	Kab. Gorontalo
429	7503	Kab. Pohuwato
430	7504	Kab. Bone Bolango
431	7505	Kab. Gorontalo Utara
432	7571	Kota Gorontalo
433	7601	Kab. Majene
434	7602	Kab. Polewali Mandar
435	7603	Kab. Mamasa
436	7604	Kab. Mamuju
437	7605	Kab. Mamuju Utara
438	8101	Kab. Maluku Tenggara Barat
439	8102	Kab. Maluku Tenggara
440	8103	Kab. Maluku Tengah
441	8104	Kab. Buru
442	8105	Kab. Kepulauan Aru
443	8106	Kab. Seram Bagian Barat
444	8107	Kab. Seram Bagian Timur
445	8108	Kab. Maluku Barat Daya
446	8109	Kab. Buru Selatan
447	8171	Kota Ambon
448	8172	Kota Tual
449	8201	Kab. Halmahera Barat
450	8202	Kab. Halmahera Tengah
451	8203	Kab. Kepulauan Sula
452	8204	Kab. Halmahera Selatan
453	8205	Kab. Halmahera Utara
454	8206	Kab. Halmahera Timur
455	8207	Kab. Pulau Morotai
456	8271	Kota Ternate
457	8272	Kota Tidore Kepulauan
458	9101	Kab. Fakfak
459	9102	Kab. Kaimana
460	9103	Kab. Teluk Wondama
461	9104	Kab. Teluk Bintuni
462	9105	Kab. Manokwari
463	9106	Kab. Sorong Selatan
464	9107	Kab. Sorong
465	9108	Kab. Raja Ampat
466	9109	Kab. Tambrauw
467	9110	Kab. Maybrat
468	9171	Kota Sorong
469	9401	Kab. Merauke
470	9402	Kab. Jayawijaya
471	9403	Kab. Jayapura
472	9404	Kab. Nabire
473	9408	Kab. Kepulauan Yapen
474	9409	Kab. Biak Numfor
475	9410	Kab. Paniai
476	9411	Kab. Puncak Jaya
477	9412	Kab. Mimika
478	9413	Kab. Boven Digoel
479	9414	Kab. Mappi
480	9415	Kab. Asmat
481	9416	Kab. Yahukimo
482	9417	Kab. Pegunungan Bintang
483	9418	Kab. Tolikara
484	9419	Kab. Sarmi
485	9420	Kab. Keerom
486	9426	Kab. Waropen
487	9427	Kab. Supiori
488	9428	Kab. Mamberamo Raya
489	9429	Kab. Nduga
490	9430	Kab. Lanny Jaya
491	9431	Kab. Mamberamo Tengah
492	9432	Kab. Yalimo
493	9433	Kab. Puncak
494	9434	Kab. Dogiyai
495	9471	Kota Jayapura

2.2 List of root sectors

	ISIC code	Sector name
1	1111	Growing of rice
2	1112	Growing of other grains
3	1113	Growing of sugar cane
4	1114	Growing of tobacco
5	1115	Growing of rubber
6	1116	Growing of cotton
7	1117	Growing of medical / pharmaceuticals plant
8	1118	Growing of essential oil plant
9	1119	Growing of other plants n.e.c.
10	1121	Growing of vegetables (harvested once)
11	1122	Growing of vegetables (harvested more than once)
12	1123	Growing of flowers
13	1124	Growing of other ornamental plants
14	1125	Seed production of vegetables and flowers
15	1131	Growing of fruits (seasonal)
16	1132	Growing of fruits (all season)
17	1133	Growing of coconut
18	1134	Growing of palm
19	1135	Growing of beverage plants
20	1136	Growing of cashew
21	1137	Growing of pepper
22	1138	Growing of clove
23	1139	Growing of other spices
24	1211	Farming of beef cattle
25	1212	Farming of dairy cattle
26	1213	Farming of buffalo (meat)
27	1214	Farming of buffalo (dairy)
28	1215	Farming of horses
29	1216	Farming of goats (meat)
30	1217	Farming of goats (dairy)
31	1218	Farming of sheep
32	1221	Farming of pigs
33	1222	Farming of rooster
34	1223	Farming of chicken
35	1224	Farming of ducks
36	1225	Farming of quails
37	1226	Farming of pigeons
38	1227	Farming of turkey
39	1228	Farming of other livestock
40	1229	Farming of other poultry
41	1300	Mixed farming
42	1401	Site processing services
43	1402	Fertilisation, seed production and pest control services
44	1403	Harvesting and post harvesting services
45	1404	Other crop services
46	1405	Livestock health care services
47	1406	Livestock breeding services
48	1407	Egg hatchery services
49	1408	Other livestock services
50	1501	Hunting and trapping of wild animal
51	1502	Capturing of wild animal
52	2011	Forestry of teak
53	2012	Forestry of pine
54	2013	Forestry of mahogany
55	2014	Forestry of sonokeling
56	2015	Forestry of albasia / jeunjing
57	2016	Forestry of sandalwood
58	2017	Forestry of acacia
59	2018	Forestry of eucalyptus
60	2019	Other forestry
61	2020	Rain forestry
62	2031	Logging of rattan
63	2032	Logging of pine sap
64	2033	Logging of white wood leaves
65	2034	Logging of silkworm cocoon
66	2035	Logging of damar
67	2039	Logging of other forest products
68	2041	Forestry services of site inventory and classification
69	2042	Forestry services of forest protection and conservation
70	2043	Forestry services of reforestation and rehabilitation
71	2049	Other forestry services
72	2051	Gathering of wood
73	2052	Gathering of others beside wood
74	2059	Other forestry activities
75	5011	Marine fishing
76	5012	Fishing of sea crustacean
77	5013	Fishing of sea molluscs
78	5014	Gathering of sea plants
79	5015	Gathering of sea life seeds
80	5021	Sea life aquaculture
81	5022	Seed production of sea life
82	5031	Public water fishing
83	5032	Public water fishing of crustaceans, molluscs, and others life
84	5041	Freshwater life aquaculture
85	5042	Saltwater life aquaculture
86	5043	Seed production of freshwater life
87	5044	Seed production of saltwater life
88	5051	Production facility services (saltwater fish)
89	5052	Production services (saltwater fish)
90	5053	Post harvesting services (saltwater fish)

91	5054	Production facility services (freshwater fish)
92	5055	Production services (freshwater fish)
93	5056	Post harvesting services (freshwater fish)
94	10101	Mining of coal and quarrying of peat
95	10102	Gasification of coal
96	10200	Manufacture of coal briquette
97	11101	Mining of crude oil and natural gas
98	11102	Utilisation of geothermal
99	11200	Crude oil and natural gas mining services
100	12000	Mining of uranium and thorium ores
101	13101	Mining of iron sand
102	13102	Mining of iron ores
103	13201	Mining of tin ores
104	13202	Mining of bauxite ores
105	13203	Mining of copper ores
106	13204	Mining of nickel ores
107	13205	Mining of manganese ores
108	13206	Mining of gold and silver
109	13207	Mining of lead ores
110	13209	Quarrying of other minerals not containing iron ores
111	14101	Quarrying of ornamental and building stones
112	14102	Quarrying of manufacturing material stones
113	14103	Quarrying of soil and clay
114	14104	Quarrying of gips
115	14105	Quarrying of sand
116	14106	Quarrying of gravel
117	14211	Mining of sulphur
118	14212	Mining of phosphate
119	14213	Mining of nitrate
120	14214	Mining of iodine
121	14215	Mining of potash (potassium carbonate)
122	14219	Mining of other chemicals and fertilizer minerals
123	14220	Extraction of salt
124	14291	Mining of natural asphalt
125	14292	Quarrying of asbestos
126	14299	Other mining and quarrying n.e.c.
127	15111	Cutting of meat
128	15112	Processing and preserving of meat
129	15121	Canning of fish and other water life
130	15122	Preserving of fish and other water life (salting/ drying)
131	15123	Preserving of fish and other water life (smoking)
132	15124	Preserving of fish and other water life (freezing)
133	15125	Preserving of fish and other water life (fumigation)
134	15129	Other processing and preserving of fish and other water life
135	15131	Canning of fruit and vegetable
136	15132	Preserving of fruit and vegetable (salting/ sweetening)
137	15133	Preserving of fruit and vegetable (digestion)
138	15134	Preserving of fruit and vegetable (drying)
139	15139	Other processing and preserving of fruit and vegetable
140	15141	Manufacture of vegetable and animal edible oils
141	15142	Manufacture of margarine
142	15143	Manufacture of cooking oils (coconut)
143	15144	Manufacture of cooking oils (palm)
144	15145	Manufacture of other vegetable and animal cooking oils
145	15149	Manufacture of other vegetable and animal oils and fats
146	15201	Manufacture of milk
147	15202	Manufacture of dairy products
148	15203	Manufacture of ice cream
149	15311	Milling and cleaning of rice
150	15312	Milling and cleaning of other grain
151	15313	Peeling, cleaning and sorting of coffee
152	15314	Peeling, cleaning and drying of cocoa
153	15315	Peeling and cleaning other grains of coffee and cocoa
154	15316	Peeling and cleaning of nuts
155	15317	Peeling and cleaning of tubers (including rhizomes)
156	15318	Manufacture of copra
157	15321	Manufacture of wheat flour
158	15322	Manufacture of various flour from grain, grains, nuts, tubers, and the like
159	15323	Manufacture of cassava starch
160	15324	Manufacture of various starch palm
161	15329	Manufacture of other starches
162	15331	Manufacture of livestock/ fish feed
163	15332	Manufacture of livestock concentrated feed
164	15410	Manufacture of bakery products
165	15421	Manufacture of sugar

166	15422	Manufacture of sugarcane
167	15423	Manufacture of other sugar
168	15424	Manufacture of syrup
169	15429	Manufacture of other sugar products besides syrup
170	15431	Manufacture of cocoa powder
171	15432	Manufacture of chocolate products and candy
172	15440	Manufacture of macaroni, noodles, spaghetti, vermicelli, rice noodles and the like
173	15491	Manufacture of tea and coffee
174	15492	Manufacture of ice
175	15493	Manufacture of soy sauce
176	15494	Manufacture of tempeh and tofu
177	15495	Manufacture of other soybean and nuts products besides soy sauce, tempeh and tofu
178	15496	Manufacture of crackers, chips, peyek
179	15497	Manufacture of food seasonings and flavorings
180	15498	Manufacture of pastries
181	15499	Manufacture of food n.e.c.
182	15510	Manufacture of liquors
183	15520	Manufacture of wines
184	15530	Manufacture of malt liquors and malt
185	15541	Manufacture of soft drinks
186	15542	Manufacture of bottled water
187	16001	Drying and processing of tobacco
188	16002	Manufacture of cigarettes
189	16003	Manufacture of white cigarettes
190	16004	Manufacture of other cigarettes
191	16009	Manufacture of cigarette seasonings and other stuffs
192	17111	Preparation of textile fibres
193	17112	Spinning of textile fibres
194	17113	Spinning of yarn
195	17114	Weaving of textile (except jute sacks and others)
196	17115	Manufacture of woven tie
197	17121	Completion of yarn
198	17122	Completion of fabrics
199	17123	Printing of fabrics
200	17124	Manufacture of batik
201	17211	Manufacture of finished textile (for household purposes)
202	17212	Manufacture of finished textile (for health purposes)
203	17213	Manufacture of other finished textiles
204	17214	Manufacture of jute sacks
205	17215	Manufacture of other sacks
206	17220	Manufacture of carpets
207	17231	Manufacture of rope
208	17232	Manufacture of goods from rope
209	17291	Manufacture of narrow fabrics
210	17292	Manufacture of manufacturing fabrics
211	17293	Manufacture of embroidery
212	17294	Manufacture of non-woven
213	17295	Manufacture of tire fabrics
214	17299	Manufacture of other textiles n.e.c.
215	17301	Manufacture of knitted fabrics
216	17302	Manufacture of knitted garment
217	17303	Manufacture of knitted socks
218	17304	Manufacture of other knitted garments
219	17400	Manufacture of kapok
220	18101	Manufacture of wearing apparel made-up textile and appliances
221	18102	Manufacture of wearing apparel made-up leather and appliances
222	18201	Manufacture of imitation fur
223	18202	Manufacture of wearing apparel made-up fur leather or accessories
224	18203	Dyeing of fur
225	19111	Preserving of leather
226	19112	Tanning of leather
227	19113	Manufacture of imitation leather
228	19121	Manufacture of leather/ imitation leather products (for personal purposes)
229	19122	Manufacture of leather/ imitation leather products (for industry purposes)
230	19123	Manufacture of leather/ imitation leather products (for animal purposes)
231	19129	Manufacture of leather/ imitation leather products (for other purposes)
232	19201	Manufacture of footwears for daily activities
233	19202	Manufacture of sport shoes
234	19203	Manufacture of outdoor shoes/ for manufacturing activities
235	19209	Manufacture of other footwears
236	20101	Sawmilling of wood
237	20102	Preserving of wood
238	20103	Preserving of rattan, bamboo, and the like
239	20104	Processing of rattan
240	20211	Manufacture of plywood
241	20212	Manufacture of laminated plywood, including decorative plywood
242	20213	Manufacture of other panel woods

243	20214	Manufacture of veneer
244	20220	Manufacture of moulding and building material components
245	20230	Manufacture of wooden container, except coffin
246	20291	Manufacture of rattan and bamboo plaiting
247	20292	Manufacture of plant plaiting, except rattan and bamboo
248	20293	Manufacture of wooden carving crafts, except furniture
249	20294	Manufacture of kitchen equipment made-up wood, rattan and bamboo
250	20299	Manufacture of wood, rattan, and cork products n.e.c.
251	21011	Manufacture of pulp
252	21012	Manufacture of culture paper
253	21013	Manufacture of valuable paper
254	21014	Manufacture of special paper
255	21015	Manufacture of manufacturing paper
256	21016	Manufacture of tissue paper
257	21019	Manufacture of other papers
258	21020	Manufacture of paper and paperboard containers
259	21090	Manufacture of paper and paperboard products n.e.c.
260	22110	Publishing of books, brochures, music books and other publications
261	22120	Publishing of newspapers, journals, tabloid, and magazines
262	22130	Publishing of recorded media
263	22140	Special publishing
264	22190	Other publishing
265	22210	Printing
266	22220	Printing support services
267	22301	Reproduction of recorded media
268	22302	Reproduction of film and video
269	23100	Manufacture of coal products
270	23201	Purification and refinery of petroleum
271	23202	Purification and processing of natural gas
272	23203	Manufacture of refined petroleum products
273	23204	Manufacture of lubricant
274	23205	Remanufacture of used lubricant
275	23300	Processing of nuclear fuel
276	24111	Manufacture of basic inorganic chemical (chlorine and alkali)
277	24112	Manufacture of basic inorganic chemical (manufacturing gas)
278	24113	Manufacture of basic inorganic chemical (pigment)
279	24114	Manufacture of other basic inorganic chemicals
280	24115	Manufacture of basic organic chemical, from agricultural products
281	24116	Manufacture of basic organic chemical, dye and pigment raw materials, dyes and pigments
282	24117	Manufacture of basic organic chemical, from crude oil, gas and coal
283	24118	Manufacture of basic organic chemical, producing of special chemicals
284	24119	Manufacture of other basic organic chemicals
285	24121	Manufacture of natural fertilizer/ non-synthetic primary macronutrient
286	24122	Manufacture of synthetic fertilizer, individual primary macronutrient
287	24123	Manufacture of synthetic fertilizer, compound primary macronutrient
288	24124	Manufacture of synthetic fertilizer, mixed primary macronutrient
289	24125	Manufacture of secondary macronutrient fertilizer
290	24126	Manufacture of micronutrient fertilizer
291	24127	Manufacture of complementary fertilizer
292	24129	Manufacture of other fertilizers
293	24131	Manufacture of synthetic resin and plastic raw materials
294	24132	Manufacture of synthetic rubber
295	24211	Manufacture of pest eradication raw materials (active ingredients)
296	24212	Manufacture of pesticides (formulations)
297	24213	Manufacture of plant growth controller
298	24214	Manufacture of ameliorant products
299	24221	Manufacture of paints
300	24222	Manufacture of varnishes
301	24223	Manufacture of coatings
302	24231	Manufacture of pharmaceutical materials
303	24232	Manufacture of pharmaceutical products
304	24233	Manufacture of herbal medicine ingredients
305	24234	Manufacture of herbal medicine
306	24235	Manufacture of toner drinks

307	24241	Manufacture of soap and cleaning products for households, including toothpaste
308	24242	Manufacture of cosmetic materials and cosmetics
309	24291	Manufacture of adhesives / glue
310	24292	Manufacture of explosive products
311	24293	Manufacture of ink
312	24294	Manufacture of essential oil
313	24295	Manufacture of wooden lighter
314	24299	Manufacture of other chemicals and chemical products
315	24301	Manufacture of fibres/ synthetic filaments yarn
316	24302	Manufacture of synthetic staple fibres
317	25111	Manufacture of rubber tyres and tubes
318	25112	Manufacture of rubber tyres
319	25121	Curing of rubber
320	25122	Manufacture of rubber milling
321	25123	Manufacture of crumb rubber
322	25191	Manufacture of rubber products (for household)
323	25192	Manufacture of rubber products (for industry)
324	25199	Manufacture of other rubber products n.e.c.
325	25201	Manufacture of plastics pipes and hoses
326	25202	Manufacture of plastics sheets
327	25203	Manufacture of plastics recorded media
328	25204	Manufacture of household plastics equipment and appliances, not included furniture
329	25205	Manufacture of plastics containers
330	25206	Manufacture of plastics engineering equipment
331	25209	Manufacture of other plastics products
332	26111	Manufacture of glass sheets
333	26112	Manufacture of safety glass
334	26119	Manufacture of other glass
335	26121	Manufacture of household glass equipment and appliances
336	26122	Manufacture of laboratory equipment, pharmaceuticals and healthcare made-up glass
337	26123	Manufacture of glass products for book cover
338	26124	Manufacture of glass containers
339	26129	Manufacture of other glass products
340	26201	Manufacture of household porcelain appliances
341	26202	Manufacture of porcelain building materials
342	26203	Manufacture of laboratory equipment, and electric appliances made-up porcelain
343	26209	Manufacture of other porcelain products
344	26311	Manufacture of refractory bricks
345	26319	Manufacture of refractory clay/ ceramic products
346	26321	Manufacture of clay/ ceramic products (for household)
347	26322	Manufacture of clay/ ceramic bricks
348	26323	Manufacture of clay/ ceramic tile
349	26324	Manufacture of clay/ ceramic building materials, except bricks and tile
350	26329	Manufacture of other clay/ ceramic products
351	26411	Manufacture of cement
352	26412	Manufacture of lime
353	26413	Manufacture of gypsum
354	26421	Manufacture of cement products
355	26422	Manufacture of lime products
356	26423	Manufacture of cement and lime products for construction
357	26429	Manufacture of other cement and lime products
358	26501	Manufacture of marble and granite products (for household and displays)
359	26502	Manufacture of marble and granite products (for building materials)
360	26503	Manufacture of stone products (for household and displays)
361	26509	Manufacture of other marble, granite and stone products
362	26601	Manufacture of asbestos products (for building materials)
363	26602	Manufacture of asbestos products (for industry)
364	26609	Manufacture of other asbestos products
365	26900	Manufacture of other non-metallic mineral products
366	27101	Manufacture of basic iron and steel
367	27102	Rolling of steel
368	27103	Manufacture of steel and iron pipe and connection pipe
369	27201	Making of non-ferrous metals
370	27202	Rolling of non-ferrous metals

371	27203	Extraction of non-ferrous metals
372	27204	Manufacture of pipe and pipe connection made-up non-ferrous metals
373	27310	Casting of iron and steel
374	27320	Casting of non-ferrous metals
375	28111	Manufacture of structural metal products other than aluminium
376	28112	Manufacture of structural aluminium products
377	28113	Manufacture of heavy structural steel products
378	28119	Manufacture of other structural metal products
379	28120	Manufacture of metal tanks, reservoirs, and containers
380	28910	Forging, pressing, and roll-forming of metal
381	28920	Metalworking service activities
382	28931	Manufacture of metal agricultural equipment
383	28932	Manufacture of metal carpentry equipment
384	28933	Manufacture of cutlery and other household equipment
385	28939	Manufacture of other metal equipment
386	28991	Manufacture of metal kitchen equipment
387	28992	Manufacture of metal office equipment, except furniture
388	28993	Manufacture of nails, nuts and bolts
389	28994	Manufacture of various metal containers
390	28995	Manufacture of metal wires and wire products
391	28996	Making of profile
392	28997	Manufacture of metal lights
393	28998	manufacture of other metal household equipment
394	28999	Manufacture of other metal products n.e.c.
395	29111	Manufacture of steam engines, turbines and windmills
396	29112	Manufacture of combustion engines
397	29113	Manufacture of components and parts of primary engines
398	29114	Supporting services for primary engines industry
399	29120	Manufacture of pumps and compressors
400	29130	Manufacture of mechanical transmission other than vehicles
401	29141	Manufacture of non-electric furnace (not for household purposes)
402	29142	Manufacture of electric furnace, oven, other similar heating equipment
403	29150	Manufacture of lifting and handling equipment
404	29191	Manufacture of machinery for packaging, bottling, and canning
405	29192	Manufacture of scale machinery
406	29193	Manufacture of cooling machinery (not for household purposes)
407	29199	Manufacture of other general-purpose machinery
408	29211	Manufacture of agricultural and forestry machinery
409	29212	Supporting services for agriculture and forestry machinery industry
410	29221	Manufacture of machinery/ equipment for metal processing
411	29222	Manufacture of machinery/ equipment for wood processing
412	29223	Manufacture of machinery/ equipment for processing of other materials other than metal and wood
413	29224	Manufacture of electric machinery/ equipment for welding
414	29230	Manufacture of machinery for metallurgy
415	29240	Manufacture of machinery for mining, quarrying and construction
416	29250	Manufacture of machinery for food, beverages and tobacco processing
417	29261	Manufacture of sewing machine cabinet
418	29262	Manufacture of sewing and washing machine, and dryers for commercial purposes
419	29263	Manufacture of machinery for textile production
420	29264	Manufacture of needles and knitting needles
421	29270	Manufacture of weapons and ammunition
422	29291	Manufacture of machinery for printing
423	29292	Manufacture of machinery for paper factory
424	29299	Manufacture of other special-purpose machinery
425	29301	Manufacture of non-electric stove, heating and room heater equipment
426	29302	Manufacture of household electric appliances

427	29309	Manufacture of other household electric appliances
428	30001	Manufacture of manual office and accounting machinery
429	30002	Manufacture of electric office and accounting machinery
430	30003	Manufacture of electronic office, accounting and computing machinery
431	30004	Manufacture of photocopier machinery
432	31101	Manufacture of electric engines
433	31102	Manufacture of power plant machinery
434	31103	Manufacture of voltage converter, rectifier and stabilizer
435	31201	Manufacture of electric panel and switch gear
436	31202	Manufacture of electricity distribution and control apparatus
437	31300	Manufacture of electric and phone cable
438	31401	Manufacture of dry batteries (primary batteries)
439	31402	Manufacture of electric accumulator (secondary batteries)
440	31501	Manufacture of incandescent light bulbs, centralized lamps and ultra violet lights
441	31502	Manufacture of gas tube lights (electric waster lights)
442	31509	Manufacture of electric light components
443	31900	Manufacture of other electric equipment n.e.c.
444	32100	Manufacture of electronic tubes and valves and other electronic components
445	32200	Manufacture of communication transmitters equipment
446	32300	Manufacture of radio, television, voice recording equipment
447	33111	Manufacture of surgical, nursing, and dentist equipment
448	33112	Manufacture of x-ray equipment and appliances
449	33113	Manufacture of medical and dentist equipment, orthopaedic and prosthetic appliances
450	33119	Manufacture of other medical equipment and orthopaedic appliances
451	33121	Manufacture of manual measuring, controlling, and testing equipment
452	33122	Manufacture of electric measuring, controlling, and testing equipment
453	33123	Manufacture of electronic measuring, controlling, and testing equipment
454	33130	Manufacture of industrial process control equipment
455	33201	Manufacture of eye glasses
456	33202	Manufacture of binoculars and optical equipment
457	33203	Manufacture of photography camera
458	33204	Manufacture of cinematographic projector camera and appliances
459	33300	Manufacture of watches, bells, and the like
460	34100	Manufacture of four wheels or more motor vehicles
461	34200	Manufacture of bodies for four wheels or more motor vehicles
462	34300	Manufacture of parts and accessories for four wheels or more motor vehicles
463	35111	Manufacture of ships/ boats
464	35112	Manufacture of ship equipment and accessories
465	35113	repair of ships
466	35114	Breaking of ships
467	35115	Manufacture of offshore buildings
468	35120	Building and maintaining cruise, recreational and sport boats
469	35201	Manufacture of railway, parts and accessories
470	35202	Supporting services for railway
471	35301	Manufacture of aircraft and accessories
472	35302	repair and maintaining services for aircraft
473	35911	Manufacture of two and three wheels motor vehicles
474	35912	Manufacture of parts and accessories for two and three wheels motor vehicles
475	35921	Manufacture of bicycles and tricycles
476	35922	Manufacture of bicycles and tricycles accessories
477	35990	Manufacture of other vehicles n.e.c.
478	36101	Manufacture of furniture made-up wood
479	36102	Manufacture of furniture made-up rattan and/or bamboo
480	36103	Manufacture of furniture made-up plastics
481	36104	Manufacture of furniture made-up metal

482	36109	Manufacture of furniture n.e.c.
483	36911	Manufacture of gem
484	36912	Manufacture of precious metal jewellery (for personal purposes)
485	36913	Manufacture of precious metal jewellery (not for personal purposes)
486	36914	Manufacture of precious metal equipment (for technical or laboratory purposes)
487	36915	Manufacture of non-precious metal equipment (for personal purposes)
488	36921	Manufacture of traditional musical instruments
489	36922	Manufacture of non-traditional musical instruments
490	36930	Manufacture of sports goods
491	36941	Manufacture of games
492	36942	Manufacture of toys
493	36991	Manufacture of writing and drawing equipment, including accessories
494	36992	Manufacture of writing and drawing tape
495	36993	Manufacture of other crafts n.e.c.
496	36999	Other manufacturing n.e.c.
497	37100	Recycling of metal waste
498	37200	Recycling of non-metal waste
499	40101	Production of electricity
500	40102	Transmission of electricity
501	40103	Distribution of electricity
502	40104	Supporting services of electricity
503	40201	Collection of gas
504	40202	Distribution of gas
505	40300	Steam and hot water supply
506	41001	Collection, purification and distribution of water
507	41002	Collection and distribution of raw water
508	41003	Supporting services of collection and distribution of water
509	45100	Site preparation
510	45211	Construction of residential building
511	45212	Construction of office building
512	45213	Construction of industrial building
513	45214	Construction of shopping building
514	45215	Construction of healthcare building
515	45216	Construction of educational building
516	45217	Construction of lodgement building
517	45218	Construction of entertainment building
518	45219	Other building constructions
519	45221	Construction of roads, bridges and platforms
520	45222	Construction of railway tracks and bridges
521	45223	Construction of tunnel
522	45224	Construction of watering facilities
523	45225	Construction of processing, distribution and shelter facilities (for water, wastewater and drainage)
524	45226	Construction of processing, distribution and shelter facilities (for oil and gas)
525	45227	Construction of dock
526	45229	Other civil engineering constructions
527	45231	Electric constructions
528	45232	Construction of marine telecommunication navigation facilities, and river signs
529	45233	Construction of air telecommunication navigation
530	45234	Construction of railway signals and telecommunication
531	45235	Construction of central telecommunications
532	45239	Construction of other electric and telecommunications
533	45241	Installation of foundations and pillars
534	45242	Construction of ground water
535	45243	Installation of stagier
536	45244	Installation of roofs/ roof covering
537	45245	Installation of prefab building and framework steel
538	45246	Dredging
539	45249	Other special constructions
540	45311	Installation of water plumbing
541	45312	Installation of electricity
542	45313	Installation of telecommunications
543	45314	Installation of gas
544	45315	Installation of electronics
545	45316	Installation of mechanical
546	45317	Installation of air conditioner
547	45319	Installation of other buildings
548	45321	Installation of civil building electricity
549	45322	Installation of marine and river navigation
550	45323	Installation of meteorology and geophysics
551	45324	Installation of air navigation

552	45325	Installation of railway signals and telecommunications
553	45326	Installation of highway signals and signs
554	45327	Installation of telecommunications
555	45328	Installation of pipelines
556	45329	Installation of other civil buildings
557	45401	Installation of glass and aluminium
558	45402	Installation of floor, wall, sanitary and ceiling equipment
559	45403	Painting
560	45404	Interior decoration
561	45405	Exterior decoration
562	45409	Other building completion
563	45500	Renting of construction or demolition equipment with operator
564	50101	Wholesale of cars
565	50102	Retail sale of cars
566	50201	Wholesale of car parts and accessories
567	50202	Retail sale of car parts and accessories
568	50301	Wholesale of motorcycles, and motorcycle parts and accessories
569	50302	Retail sale of motorcycles, and motorcycle parts and accessories
570	50400	Retail sale of vehicle fuel at gas stations
571	51100	Wholesale of goods on a fee or contract basis
572	51211	Wholesale of agricultural products
573	51212	Wholesale of life animals
574	51213	Wholesale of fishery products
575	51214	Wholesale of forestry and hunting products
576	51220	Wholesale of food, beverages and tobacco
577	51310	Wholesale of textile, apparels and leather
578	51391	Wholesale of house equipment and accessories
579	51392	Wholesale of house chemical and pharmaceutical products
580	51399	Wholesale of other house equipment and accessories
581	51410	Wholesale of gas, liquid, and solid fuel, and similar products
582	51420	Wholesale of metals and metal ores
583	51431	Wholesale of metal products for construction materials
584	51432	Wholesale of glass for construction materials
585	51433	Wholesale of tile, bricks, tiles, and the like made-up clay, lime, cement, or glass
586	51434	Wholesale of cement, lime, sand and stone
587	51435	Wholesale of porcelain construction materials
588	51436	Wholesale of wooden construction materials
589	51437	Wholesale of cat
590	51438	Wholesale of various building materials
591	51439	Wholesale of other construction materials
592	51490	Wholesale of intermediate products, used and scrap
593	51501	Wholesale of machinery, parts and accessories
594	51502	Wholesale of marine transport equipment, parts and accessories
595	51503	Wholesale of land transport equipment (except cars, motorcycles, and the like), parts and accessories
596	51504	Wholesale of air transport equipment, parts and accessories
597	51900	Other wholesale
598	52111	Retail sale in supermarket/ minimarket with food, beverages or tobacco predominating
599	52112	Retail sale in traditional market with food, beverages or tobacco predominating
600	52191	Retail sale in department store with non-food, non-beverages or non-tobacco predominating
601	52192	Retail sale in non-department store with non-food, non-beverages or non-tobacco predominating
602	52211	Retail sale of rice and other grains
603	52212	Retail sale of fruits
604	52213	Retail sale of vegetables
605	52214	Retail sale of livestock products
606	52215	Retail sale of fishery products
607	52219	Retail sale of other agricultural products
608	52221	Retail sale of rice
609	52222	Retail sale of bread, pastry, cake and the like
610	52223	Retail sale of coffee, sugar, brown sugar

611	52224	Retail sale of tofu, tempeh, tauco, and oncom
612	52225	Retail sale of meat and processed water life
613	52226	Retail sale of beverage
614	52227	Retail sale of cigarette and tobacco
615	52228	Retail sale of feed for livestock /poultry/ fish
616	52229	Retail sale of other foods
617	52311	Retail sale of chemicals
618	52312	Retail sale of pharmaceutical goods in pharmacies
619	52313	Retail sale of pharmaceutical goods in other than pharmacies
620	52314	Retail sale of herbs
621	52315	Retail sale of cosmetics
622	52316	Retail sale of fertilizer and pesticides
623	52317	Retail sale of laboratory, pharmacy, and health equipment
624	52318	Retail sale of essential oils
625	52319	Retail sale of other chemical goods n.e.c.
626	52321	Retail sale of textile
627	52322	Retail sale of apparel
628	52323	Retail sale of shoes, sandals, and other footwear
629	52324	Retail sale of clothing accessories and yarn
630	52325	Retail sale of eye glasses
631	52326	Retail sale of jewellery
632	52327	Retail sale of watch
633	52328	Retail sale of bags, wallets, luggage, backpacks and the like
634	52329	Retail sale of other textile, garment, footwear, and personal goods
635	52331	Retail sale of furniture
636	52332	Retail sale of electronics
637	52333	Retail sale of electric equipment and articles
638	52334	Retail sale of kitchen glassware appliances and equipment made-up plastics
639	52335	Retail sale of kitchen glassware appliances and equipment made-up stone or clay
640	52336	Retail sale of kitchen glassware appliances and equipment made-up wood, bamboo, or rattan
641	52337	Retail sale of kitchen glassware appliances and equipment made-up other than plastic, stone, clay, wood, bamboo, or rattan
642	52338	Retail sale of telecommunication equipment
643	52339	Retail sale of other household and kitchen equipment
644	52341	Retail sale of metal products for construction materials
645	52342	Retail sale of glass for construction materials
646	52343	Retail sale of tile, bricks, tiles, and the like made-up clay, lime, cement, or glass
647	52344	Retail sale of cement, lime, sand and stone
648	52345	Retail sale of porcelain construction materials
649	52346	Retail sale of wooden construction materials
650	52347	Retail sale of paint
651	52348	Retail sale of various building materials
652	52349	Retail sale of other construction materials
653	52351	Retail sale of gasoline, premix, and diesel fuel in stores
654	52352	Retail sale of kerosene
655	52353	Retail sale of LPG
656	52354	Retail sale of lubricant
657	52359	Retail sale of other fuels
658	52361	Retail sale of paper, cardboard paper, and paper/ cardboard products
659	52362	Retail sale of writing and drawing equipment
660	52363	Retail sale of printing, publishing and software (software) products
661	52364	Retail sale of sport equipment
662	52365	Retail sale of musical instruments
663	52366	Retail sale of photography equipment and accessories
664	52367	Retail sale of optical equipment and accessories
665	52368	Retail sale of computer and office machinery
666	52371	Retail sale of agricultural machinery and accessories
667	52372	Retail sale of sewing machinery and accessories
668	52373	Retail sale of other machinery and accessories
669	52374	Retail sale of non-motorized land transport equipment and accessories
670	52375	Retail sale of water transport equipment and accessories
671	52381	Retail sale of crafts made-up wood, bamboo, rattan, pandan, grass and the like

672	52382	Retail sale of crafts made-up leather, bone, horn, ivory, fur and animals/ preserved animals
673	52383	Retail sale of crafts made-up metal
674	52384	Retail sale of crafts made-up ceramics
675	52385	Retail sale of kid's toys
676	52386	Retail sale of paintings
677	52389	Retail sale of other crafts, kid's toys, and paintings
678	52391	Retail sale of agricultural equipment
679	52392	Retail sale of carpentry equipment
680	52393	Retail sale of pets
681	52394	Retail sale of florist
682	52395	Retail sale of ornamental plants, fruit seeds and medical plants
683	52399	Retail sale of other commodities (non-food, beverages, or tobacco)
684	52401	Retail sale of second-hand household appliances
685	52402	Retail sale of second-hand apparel, footwear and accessories
686	52403	Retail sale of second-hand personal goods
687	52404	Retail sale of second-hand electric and electronic goods
688	52405	Retail sale of second-hand construction materials and sanitary
689	52406	Retail sale of antiques
690	52409	Retail sale of other second-hand goods
691	52511	Street retail sale of rice and other grains
692	52512	Street retail sale of fruits
693	52513	Street retail sale of vegetables
694	52514	Street retail sale of livestock products
695	52515	Street retail sale of fishery products
696	52516	Street retail sale of ornamental plants and other agricultural products
697	52521	Street retail sale of rice
698	52522	Street retail sale of bread, pastry, cake and the like
699	52523	Street retail sale of coffee, sugar, brown sugar
700	52524	Street retail sale of tofu, tempeh, tauco, and oncom
701	52525	Street retail sale of processed meat and water life
702	52526	Street retail sale of beverage
703	52527	Street retail sale of cigarette and tobacco
704	52528	Street retail sale of feed for livestock /poultry/ fish
705	52529	Street retail sale of other foods
706	52531	Street retail sale of chemicals
707	52532	Street retail sale of pharmaceutical goods
708	52533	Street retail sale of herbs
709	52534	Street retail sale of cosmetics
710	52535	Street retail sale of fertilizer and pesticides
711	52536	Street retail sale of essential oils
712	52539	Street retail sale of other chemical, pharmaceutical, cosmetics, and laboratory equipment n.e.c.
713	52541	Street retail sale of textile
714	52542	Street retail sale of apparel
715	52543	Street retail sale of shoes, sandals, and other footwear
716	52544	Street retail sale of clothing accessories and yarn
717	52545	Street retail sale of eye glasses
718	52546	Street retail sale of jewellery
719	52547	Street retail sale of watch
720	52548	Street retail sale of bags, wallets, luggage, backpacks and the like
721	52549	Street retail sale of other personal goods
722	52551	Street retail sale of electronics
723	52552	Street retail sale of electric equipment and articles
724	52553	Street retail sale of kitchen glassware appliances and equipment made-up plastics
725	52554	Street retail sale of kitchen glassware appliances and equipment made-up stone or clay
726	52555	Street retail sale of kitchen glassware appliances and equipment made-up wood, bamboo, or rattan
727	52556	Street retail sale of kitchen glassware appliances and equipment made-up other than plastic, stone, clay, wood, bamboo, or rattan
728	52557	Street retail sale of sanitary equipment
729	52559	Street retail sale of other household equipment
730	52561	Street retail sale of fuel, gas and lubricants
731	52569	Street retail sale of other fuels

732	52571	Street retail sale of paper, cardboard paper, and paper/ cardboard products
733	52572	Street retail sale of writing and drawing equipment
734	52573	Street retail sale of printing, publishing and software (software) products
735	52574	Street retail sale of sport equipment and musical instruments
736	52575	Street retail sale of photography and optical equipment and accessories
737	52576	Street retail sale of office machinery
738	52577	Street retail sale of other mixed of paper, cardboard, writing, drawing, printing, and publishing products
739	52581	Street retail sale of crafts
740	52582	Street retail sale of kid's toys
741	52583	Street retail sale of paintings
742	52591	Street retail sale of second-hand household appliances
743	52592	Street retail sale of second-hand apparel, footwear and accessories, and personal goods
744	52593	Street retail sale of second-hand electric and electronic goods
745	52594	Street retail sale of antiques
746	52595	Street retail sale of other second-hand goods
747	52600	Other street retail sale
748	52711	Retail sale via media for foods, beverages, tobacco, chemical, cosmetic, and laboratory equipment
749	52712	Retail sale via media for textile, garments, footwear, and personal goods
750	52713	Retail sale via media for household and kitchen appliances
751	52714	Retail sale via media for mixed goods
752	52719	Retail sale via media for other goods
753	52721	Roving retail sale of agricultural products (foods)
754	52722	Roving retail sale of manufacturing products (foods, beverages or tobacco)
755	52723	Roving retail sale of chemical, pharmaceutical, cosmetics, and laboratory equipment
756	52724	Roving retail sale of textile, apparel, footwear, and personal goods
757	52725	Roving retail sale of household and kitchen appliances
758	52726	Roving retail sale of fuel and lubricant
759	52727	Roving retail sale of paper, paper products, stationery, printed goods, sport equipment, musical instruments, photography equipment, and computers
760	52728	Roving retail sale of crafts, kid's toys, and paintings
761	52729	Retail sale of roving other goods
762	53100	Export sale on a fee or contract basis
763	53211	Export sale of agricultural raw material products
764	53212	Export sale of life animals
765	53213	Export sale of fishery products
766	53214	Export sale of forestry and hunting products
767	53220	Export sale of foods, beverages and tobacco
768	53310	Export sale of textile, apparel, and leather
769	53391	Export sale of household appliances and equipment
770	53392	Export sale of household chemical and pharmaceutical goods
771	53399	Export sale of various household appliances and equipment
772	53410	Export sale of gas, liquid, and solid fuel and similar products
773	53420	Export sale of metals and metal ores (mining and quarrying products)
774	53430	Export sale of construction materials (except quarrying products)
775	53491	Export sale of intermediate products
776	53492	Export sale of scrap
777	53500	Export sale of machinery, parts and accessories
778	53900	Other export sale
779	54100	Import sale on a fee or contract basis
780	54211	Import sale of agricultural raw material products
781	54212	Import sale of life animals
782	54213	Import sale of fishery products
783	54214	Import sale of forestry and hunting products
784	54220	Import sale of foods, beverages and tobacco
785	54310	Import sale of textile, apparel, and leather

786	54391	Import sale of household appliances and equipment
787	54392	Import sale of household chemical and pharmaceutical goods
788	54399	Import sale of various household appliances and equipment
789	54410	Import sale of gas, liquid, and solid fuel and similar products
790	54420	Import sale of metals and metal ores
791	54430	Import sale of construction materials
792	54491	Import sale of intermediate products
793	54492	Import sale of scrap
794	54500	Import sale of machinery, parts and accessories
795	54900	Other import sale
796	55111	Five star hotels
797	55112	Four star hotels
798	55113	Three star hotels
799	55114	Two star hotels
800	55115	One star hotels
801	55120	Motels
802	55130	Youth hostel
803	55140	Home stay
804	55150	Campgrounds
805	55160	Caravan stopover
806	55190	Other accommodation service
807	55211	Restaurants (talam kencana)
808	55212	Restaurants (talam selaka)
809	55213	Restaurants (talam gangsa)
810	55214	Restaurants (non talam)
811	55220	Canteens
812	55230	Bar
813	55240	Food and drink shop
814	55250	Food and drink shop (temporary)
815	55260	Catering
816	60110	Rail transport for passengers
817	60120	Rail transport for freight
818	60131	Rail transport for tourism
819	60139	Other rail transports
820	60211	Inter-city inter-province transport
821	60212	Border transport
822	60213	Inter-city within-province transport
823	60214	City transport
824	60215	Rural transport
825	60216	Special transport
826	60217	Cross-border transport
827	60221	Taxi
828	60222	Rent transport
829	60223	Tourism transport
830	60224	Non-motorized transport for passengers
831	60225	Motorcycle taxi
832	60231	Motorized transport for general freight
833	60232	Motorized transport for special freight
834	60233	Non-motorized transport for general freight
835	60300	Transport via pipelines
836	61111	Domestic general marine transport for passengers (scheduled)
837	61112	Domestic general marine transport for passengers (non-scheduled)
838	61113	Domestic general marine transport for freight (scheduled)
839	61114	Domestic general marine transport for freight (non-scheduled)
840	61115	Domestic special marine transport for tourism
841	61116	Domestic special marine transport for freight
842	61117	Domestic remote-area marine transport
843	61118	Domestic traditional marine transport
844	61121	International general marine transport for passengers (scheduled)
845	61122	International general marine transport for passengers (non-scheduled)
846	61123	International general marine transport for freight (scheduled)
847	61124	International general marine transport for freight (non-scheduled)
848	61125	International special marine transport for tourism
849	61126	International special marine transport for freight
850	61127	International traditional marine transport
851	61211	River and lake transport for passengers (fixed and routine route)
852	61212	River and lake transport for passengers (non-fixed and routine route)
853	61213	River and lake transport for tourism (non-fixed and routine route)
854	61214	River and lake transport for general freight and/or animals

855	61215	River and lake transport for special freight
856	61216	River and lake transport for dangerous freight
857	61221	Inter-state transport
858	61222	Inter-province ferry transport (general)
859	61223	Inter-province ferry transport (remote-area)
860	61224	Inter-city ferry transport (general)
861	61225	Inter-city ferry transport (remote-area)
862	61226	Within-city general ferry transport
863	62111	Domestic scheduled air transport (general)
864	62112	Domestic scheduled air transport (remote-area)
865	62120	International scheduled air transport
866	62201	Domestic non-scheduled air transport (general)
867	62202	Domestic non-scheduled air transport (remote-area)
868	62311	Special air transport for spraying and pollination activities
869	62312	Special air transport for photography, surveying and mapping activities
870	62313	Special air transport for sports
871	62314	Special air transport for medical evacuation
872	62320	Special air transport for aircraft crew education
873	62390	Other special air transport
874	63100	Cargo loading services
875	63210	Warehousing
876	63220	Cold storage
877	63230	Bounded warehousing
878	63290	Other warehousing
879	63310	Inland terminal services
880	63321	Sea ports services
881	63322	River and lake port services
882	63323	Harbor and ferry services
883	63330	Airport services
884	63340	Toll road services
885	63351	On street parking services
886	63352	Off street parking services
887	63390	Other supporting transport services
888	63411	Travel agencies services (four chakra)
889	63412	Travel agencies services (three chakra)
890	63413	Travel agencies services (two chakra)
891	63414	Travel agencies services (one chakra)
892	63415	Travel agencies services (non chakra)
893	63420	Travel agencies
894	63430	Tour guide services
895	63440	Convention, exhibition, and incentive travel services
896	63450	Impresario
897	63460	Tourism consultancy services
898	63470	Tourism information services
899	63490	Other travel services
900	63510	Transport handling services
901	63520	Cargo services via railway and land transport
902	63530	Cargo services via ships
903	63540	Cargo services via aircraft
904	63590	Other cargo and packing services
905	63900	Other supporting transport services n.e.c.
906	64110	National post
907	64120	Post service units
908	64130	Private courier service
909	64210	Fixed network
910	64221	Terrestrial mobile network
911	64222	Cellular mobile network
912	64223	Satellite mobile network
913	64311	Premium call services
914	64312	Public radio-call services
915	64313	Radio trunking services
916	64314	Telecommunication stall
917	64319	Other telecommunication services
918	64321	Internet service provider
919	64322	Communication systems services
920	64323	Portal services
921	64324	Voice over internet protocol (VoIP) services
922	64325	Internet stall
923	64329	Other multimedia services
924	64410	Special telecommunications (for personal)
925	64420	Special telecommunications (for defense and security)
926	64430	Special telecommunications (for broadcasting)
927	65110	Central bank
928	65121	Foreign exchange bank
929	65122	Non-foreign exchange bank
930	65123	Sharia bank
931	65191	Rural banks
932	65192	Rural banks (sharia)
933	65199	Other monetary intermediation services

934	65910	Leasing
935	65921	Factoring financing
936	65922	Consumers credit financing
937	65923	Credit card financing
938	65929	Other non-leasing financing
939	65930	Venture capital
940	65940	Pawnshop
941	65950	Credit/saving unions
942	65991	Merger and acquisition services
943	65999	Other financial intermediation services n.e.c.
944	66010	Life insurance
945	66020	Pension funding
946	66030	Non-life insurance
947	67111	Stock exchange
948	67112	Clearing and guarantee
949	67113	Depository and settlement
950	67121	Underwriter
951	67122	Broker dealer
952	67123	Investment manager
953	67131	Trustee
954	67132	Registrar
955	67133	Custodian
956	67134	Stock exchange rating agencies
957	67191	Money changer
958	67199	Other financial supporting services n.e.c.
959	67201	Insurance agent
960	67202	Adjuster
961	67203	Actuarial
962	67204	Insurance broker
963	67209	Other insurance and pension funding supporting services
964	70101	Real estate with own or leased property
965	70102	Boarding house
966	70200	Real estate on a fee or contract basis
967	70310	Tourism area
968	70320	Provision of water tourism facilities
969	71110	Renting of land transport equipment
970	71120	Renting of water transport equipment
971	71130	Renting of air transport equipment
972	71210	Renting of agricultural machinery and equipment
973	71220	Renting of construction and civil engineering machinery and equipment
974	71230	Renting of office machinery and equipment (including computers)
975	71290	Renting of other machinery and equipment n.e.c.
976	71301	Renting of party equipment
977	71302	Renting of personal and household goods
978	71303	Renting of printing and publishing products
979	71304	Renting of recording products
980	71305	Renting of sport equipment and musical instruments
981	71306	Renting of flowers and ornamental plants
982	71309	Renting of other personal and household goods n.e.c.
983	72100	Hardware consultancy
984	72200	Software consultancy
985	72300	Data processing
986	72400	Data base services
987	72500	Maintenance and repair of office, accounting, and computer machinery
988	72900	Other computer-related activities
989	73110	Research and development of natural sciences
990	73120	Research and development of technology and engineering
991	73210	Research and development of social sciences
992	73220	Research and development of humanities
993	74110	Legal services
994	74120	Accounting and tax services
995	74130	Marketing research
996	74140	Business and management consultancy
997	74210	Architectural and engineering activities and related technical consultancy
998	74220	Analysis and testing
999	74300	Advertising
1000	74910	Labour recruitment and provision of personnel
1001	74920	Investigation and security services
1002	74930	Building cleaning services
1003	74940	Photographic services
1004	74950	Packing services
1005	74990	Other business services n.e.c.
1006	75111	House of representative
1007	75112	Administration of the state government and the state secretary
1008	75113	Finance, taxation and customs agencies
1009	75114	Planning agencies
1010	75115	Supreme court

1011	75121	Regulation of education
1012	75122	Regulation of health
1013	75123	Regulation of housing and environment
1014	75124	Regulation of social welfare
1015	75125	Regulation of religious activities
1016	75126	Regulation of communication
1017	75127	Regulation of culture/ arts/ recreation/ sports
1018	75129	Regulation of other social services other than health, education, religion and culture
1019	75131	Government activities on agriculture
1020	75132	Government activities on mining and quarrying
1021	75133	Government activities on manufacture
1022	75134	Government activities on electricity, gas and water
1023	75135	Government activities on construction
1024	75136	Government activities on trade and tourism
1025	75137	Government activities on transport and communication
1026	75138	Government activities on labour and transmigration
1027	75139	Government activities on creating production efficiency and other business activities
1028	75140	Non-line ministries with special tasks
1029	75210	Foreign affairs
1030	75221	Defense institutions and armed forces
1031	75222	Army
1032	75223	Air force
1033	75224	Navy
1034	75231	Police
1035	75232	Civil defense
1036	75233	Judiciary institutions
1037	75300	Compulsory social security
1038	80111	Public pre-school
1039	80112	Public primary school
1040	80113	Public junior high school
1041	80121	Private pre-school
1042	80122	Private primary school
1043	80123	Private junior high school
1044	80211	Public high school
1045	80212	Public vocational high school
1046	80221	Private high school
1047	80222	Private vocational high school
1048	80311	Public higher education (degree program)
1049	80312	Public higher education (non-degree program)
1050	80321	Private higher education (degree program)
1051	80322	Private higher education (non-degree program)
1052	80910	Other public education
1053	80921	Private computer education
1054	80922	Private language education
1055	80923	Private beauty and personality education
1056	80929	Other private skill education
1057	85111	Public hospital
1058	85112	Public polyclinic
1059	85113	Private hospital
1060	85114	Private clinics
1061	85119	Other hospital services
1062	85121	General medical practice
1063	85122	Specialist medical practice
1064	85123	Dental practice
1065	85191	Paramedic health care services
1066	85192	Traditional health care services
1067	85193	Health care supporting services
1068	85200	Veterinary services
1069	85311	Public nursing homes
1070	85312	Private nursing homes
1071	85313	Public orphanage
1072	85314	Private orphanage
1073	85319	Other social homes
1074	85321	Public social activities outside social homes
1075	85322	Private social activities outside social homes
1076	90001	Public health services
1077	90002	Private health services
1078	91110	Activities of business and employers' organisations
1079	91121	Activities of social and society science organisations
1080	91122	Activities of natural science and technology organisation
1081	91200	Activities of labour unions
1082	91910	Activities of religious organisations
1083	91920	Activities of political organisations
1084	91990	Activities of social community organisation
1085	92111	Film production and distribution, and video by government
1086	92112	Film production and distribution, and video by private institutions
1087	92120	Activities of cinemas
1088	92131	Activities of public radio and television
1089	92132	Activities of private radio and television

1090	92141	Activities of drama, music and other entertainment by government
1091	92142	Activities of drama, music and other entertainment by private institutions
1092	92143	Entertainment supporting services
1093	92190	Other entertainment activities
1094	92201	Government news agency
1095	92202	Private news agency
1096	92203	Free lance
1097	92311	Public library and archives
1098	92312	Private library
1099	92321	Public museum
1100	92322	Private museum
1101	92323	Government managed heritage
1102	92324	Private managed heritage
1103	92331	Botanical gardens and zoo
1104	92332	National park
1105	92333	Forest park
1106	92334	Natural tourist park
1107	92335	Protected forest, wildlife, and natural reserves
1108	92336	Hunting parks and gardens
1109	92339	Other than botanical gardens, zoo and wildlife conservation
1110	92411	Billiard
1111	92412	Golf
1112	92413	Bowling
1113	92414	Swimming
1114	92415	Football
1115	92416	Tennis
1116	92417	Fitness/ fitness
1117	92418	Sport centre
1118	92419	Other sports activities
1119	92421	Recreational park
1120	92422	Natural baths
1121	92423	Fishing pond
1122	92424	Sport and game venues
1123	92425	Night club and or disco
1124	92426	Massage
1125	92427	Steam massage
1126	92428	Karaoke
1127	92429	Other recreational services
1128	92431	Agritourism
1129	92432	Water tourism
1130	92433	Natural adventure tourism
1131	92434	Cave tourism
1132	92439	Other special interest tourism
1133	93010	Laundry
1134	93021	Haircut
1135	93022	Beauty salon
1136	93030	Funeral services
1137	93040	Maintenance and repair of car
1138	93050	Maintenance and repair of motorcycle
1139	93061	Repair of personal goods
1140	93062	Repair of household appliances
1141	93069	Repair of others
1142	93091	Tailoring services
1143	93092	Labour distribution services
1144	93093	Fitness centre
1145	93094	Individual services n.e.c.
1146	95000	Individual services for households
1147	99000	International agency and other international extra agencies
1148	99999	Undefined activities

Supplementary Information for Chapter 3

Using Virtual Laboratories for disaster analysis—A case study of Taiwan

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3.1 List of root regions

	Acronyms	Region Name
1.	H.Co	Hsinchu County
2.	Tao	Taoyuan County
3.	Yil	Yilan County
4.	H.Ci	Hsinchu City
5.	Kee	Keelung City
6.	NTa	New Taipei City (Taipei County before 2010)
7.	Taip	Taipei City
8.	Cha	Changhua County
9.	Mia	Miaoli County
10.	Nan	Nantou County
11.	Yun	Yunlin County
12.	Taic	Taichung City
13.	C.Co	Chiayi County
14.	Pen	Penghu County
15.	Pin	Pingtung County
16.	C.Ci	Chiayi City
17.	Kao	Kaohsiung City
18.	Tain	Tainan City
19.	Hua	Hualien County
20.	Tait	Taitung County
21.	Kin	Kinmen County
22.	Lie	Lienchiang County (Matsu)

3.2 List of root sectors

	SICS Code*	Sector Name
1.	111	Growing of Rice
2.	112	Growing of Cereals (Except Rice)
3.	113	Growing of Special
4.	114	Growing of Vegetables
5.	115	Growing of Fruits
6.	116	Growing of Mushrooms
7.	117	Growing of Flowers
8.	119	Growing of Other Crops
9.	121	Raising of Cattle
10.	122	Raising of Swine/Pigs
11.	123	Raising of Chickens
12.	124	Raising of Ducks
13.	129	Other Animal Husbandry
14.	130	Support Activities to Agricultural and Animal Husbandry
15.	210	Afforestation
16.	220	Forest Products Operations
17.	311	Marine Fishing
18.	312	Inland Fishing
19.	321	Marine Aquaculture
20.	322	Inland Aquaculture
21.	50	Extraction of Crude Petroleum and Natural Gas
22.	60	Quarrying of Stone, Sand and Clay
23.	70	Other Mining and Quarrying
24.	81	Processing and Preserving of Meat

25.	82	Processing and Preserving of Fish, Crustaceans, Molluscs and Related Products
26.	83	Processing and Preserving of Fruit and Vegetables
27.	84	Manufacture of Edible Oils and Fats
28.	85	Manufacture of Dairy Products
29.	86	Grain Husking, Manufacture of Grain Mill Products, Starches and Starch Products
30.	87	Manufacture of Prepared Animal Feeds
31.	89	Manufacture of Other Food Products
32.	91	Manufacture of Alcoholic Beverages
33.	92	Manufacture of Non-alcoholic Beverages
34.	100	Manufacture of Tobacco Products
35.	111	Spinning of Yarn
36.	112	Weaving of Textiles
37.	113	Manufacture of Non-woven Fabrics
38.	114	Finishing of Textiles
39.	115	Manufacture of Textile Products
40.	121	Manufacture of Woven Wearing Apparel
41.	122	Manufacture of Knitted and Crocheted Wearing
42.	123	Manufacture of Clothing Accessories
43.	130	Manufacture of Leather, Fur and Related Products
44.	140	Manufacture of Wood and of Products of Wood and
45.	151	Manufacture of Pulp, Paper and Paperboard
46.	152	Manufacture of Containers of Paper and Paperboard
47.	159	Manufacture of Other Paper Products
48.	161	Printing and Service Activities Related to Printing
49.	162	Reproduction of Recorded Media
50.	170	Manufacture of Petroleum and Coal Products
51.	181	Manufacture of Basic Chemical Material
52.	182	Manufacture of Petrochemicals
53.	183	Manufacture of Fertilizers
54.	184	Manufacture of Synthetic Resin, Plastic and Rubber Materials
55.	185	Manufacture of Man-made Fibers
56.	191	Manufacture of Pesticides and Environmental Agents
57.	192	Manufacture of Coatings, Dyes and Pigments
58.	193	Manufacture of Cleaning Preparations
59.	194	Manufacture of Cosmetics
60.	199	Manufacture of Other Chemical Products
61.	200	Manufacture of Pharmaceuticals and Medicinal Chemical Products
62.	210	Manufacture of Rubber Products
63.	220	Manufacture of Plastics Products
64.	231	Manufacture of Glass and Glass Products
65.	232	Manufacture of Refractory Products, Clay Building
66.	233	Manufacture of Cement and Cement Products
67.	234	Cutting, Shaping and Finishing of Stone
68.	239	Manufacture of Other Non-metallic Mineral Products
69.	241	Manufacture of Basic Iron and Steel
70.	242	Manufacture of Aluminum
71.	243	Manufacture of Copper
72.	249	Manufacture of Other Basic Metals
73.	251	Manufacture of Metal Hand tools and Die
74.	252	Manufacture of Metal Structure and Architectural
75.	253	Manufacture of Metal Containers
76.	254	Metalworking Activities
77.	259	Manufacture of Other Fabricated Metal Products
78.	261	Manufacture of Semi-conductors
79.	262	Manufacture of Electronic Passive Devices
80.	263	Manufacture of Bare Printed Circuit Boards
81.	264	Manufacture of Optoelectronic Materials and Components

82.	269	Manufacture of Other Electronic Parts and Components
83.	271	Manufacture of Computers and Peripheral Equipment
84.	272	Manufacture of Communication Equipment
85.	273	Manufacture of Audio and Video Equipment
86.	274	Manufacture of Magnetic and Optical Media
87.	275	Manufacture of Measuring, Navigating, Control Equipment, Watches and Clocks
88.	276	Manufacture of Irradiation and Electromedical Equipment
89.	277	Manufacture of Optical Instruments and Equipment
90.	281	Manufacture of Power Generation, Transmission and Distribution Machinery
91.	282	Manufacture of Batteries
92.	283	Manufacture of Wiring and Wiring Devices
93.	284	Manufacture of Lighting Equipment
94.	285	Manufacture of Domestic Appliances
95.	289	Manufacture of Other Electrical Equipment
96.	291	Manufacture of Metalworking Machinery
97.	292	Manufacture of Other Special-purpose Machinery
98.	293	Manufacture of General-purpose Machinery
99.	301	Manufacture of Motor Vehicles
100.	302	Manufacture of Bodies (Coachwork) for Motor Vehicle
101.	303	Manufacture of Parts for Motor Vehicles
102.	311	Manufacture of Ships, Boats and Parts
103.	312	Manufacture of Motorcycles and Parts
104.	313	Manufacture of Bicycles and Parts
105.	319	Manufacture of Other Transport Equipment and Parts Not Elsewhere Classified
106.	321	Manufacture of Non-metallic Furniture
107.	322	Manufacture of Metallic Furniture
108.	331	Manufacture of Sport and Recreational Goods
109.	332	Manufacture of Medical Instruments and Supplies
110.	339	Manufacturing Not Elsewhere Classified
111.	340	Repair and Installation of Industrial Machinery and Equipment
112.	351	Electricity Supply
113.	352	Gas Supply
114.	353	Steam Supply
115.	360	Water Supply
116.	370	Wastewater (Sewage) Treatment
117.	381	Waste Collection
118.	382	Waste Treatment and Disposal
119.	383	Materials Recovery
120.	390	Remediation Activities and Other Waste Management Services
121.	410	Construction of Buildings
122.	421	Construction of Roads and Railways
123.	422	Construction of Utility Projects
124.	429	Construction of Other Civil Engineering Projects
125.	431	Site Preparation, Foundation and Structure Construction
126.	432	Landscape Construction
127.	433	Electrical, Plumbing and Other Construction Installation Activities
128.	434	Building Completion and Finishing
129.	439	Other Specialized Construction Activities
130.	451	Merchandise Brokers
131.	452	Wholesale of General Merchandise
132.	453	Wholesale of Agricultural Raw Materials and Live
133.	454	Wholesale of Food, Beverages and Tobacco
134.	455	Wholesale of Fabrics and Clothing Accessories
135.	456	Wholesale of Household Appliances and Goods
136.	457	Wholesale of Pharmaceutical and Medical Goods and Cosmetics
137.	458	Wholesale of Cultural and Recreation Goods

138.	461	Wholesale of Construction Materials
139.	462	Wholesale of Chemical Materials and Chemical
140.	463	Wholesale of Fuel and Related Products
141.	464	Wholesale of Machinery and Equipment
142.	465	Wholesale of Motor Vehicles and Motorcycles and Related Parts and Accessories
143.	469	Other Specialized Wholesale
144.	471	Retail Sale in Non-specialized Stores
145.	472	Retail Sale of Food, Beverages and Tobacco in Specialized Stores
146.	473	Retail Sale of Fabrics and Clothing Accessories in Specialized Stores
147.	474	Retail Sale of Household Appliances and Goods in Specialized Stores
148.	475	Retail Sale of Pharmaceutical and Medical Goods and Cosmetics in Specialized Stores
149.	476	Retail Sale of Cultural and Recreation Goods in Specialized Stores
150.	481	Retail Sale of Construction Materials in Specialized
151.	482	Retail Sale of Fuel in Specialized Stores
152.	483	Retail Sale of Information and Communications Equipment in Specialized Stores
153.	484	Retail Sale of Motor Vehicles, Motorcycles and Related Parts and Accessories in Specialized Stores
154.	485	Other Retail Sale in Specialized Stores
155.	486	Retail Sale via Stalls
156.	487	Retail Trade not in Stores or Stalls
157.	491	Transport via Railways
158.	492	Public Rapid Transit
159.	493	Bus Transportation
160.	494	Freight Truck Transport
161.	499	Other Land Transportation
162.	501	Ocean Transportation
163.	502	Inland and Lake Transportation
164.	510	Air Transport
165.	521	Customs Clearance Services
166.	522	Shipping Agency Services
167.	523	Freight Transportation Forwarding Services
168.	524	Service Activities Incidental to Land Transportation
169.	525	Service Activities Incidental to Water Transportation
170.	526	Service Activities Incidental to Air Transportation
171.	529	Other Transportation Support Activities
172.	530	Warehousing and Storage
173.	541	Postal Activities
174.	542	Courier Activities
175.	551	Short Term Accommodation Activities
176.	559	Other Accommodation
177.	561	Restaurants
178.	562	Beverage Service Activities via Shops
179.	563	Food and Beverage Service Activities via Stalls
180.	569	Other Food and Beverage Service Activities
181.	581	Publishing of Books, Periodicals and Other Publishing Activities
182.	582	Software Publishing
183.	591	Motion Picture, Video and Television Programme Activities
184.	592	Sound Recording and Music Publishing Activities
185.	601	Radio Broadcasting
186.	602	Television Broadcasting and Subscription Programming
187.	610	Telecommunications
188.	620	Computer Systems Design Services
189.	631	Web Portals, Data Processing, Hosting and Related Activities
190.	639	Other Information Service Activities
191.	641	Deposit Institutions
192.	642	Financial Holding Companies

193.	643	Trusts, Funds and Other Financial Vehicles
194.	649	Other Financial Intermediation
195.	651	Personal Insurance
196.	652	Property Insurance
197.	653	Reinsurance
198.	654	Pension Funding
199.	655	Activities Auxiliary to Insurance and Pension Funding
200.	661	Securities
201.	662	Futures
202.	663	Activities Auxiliary to Financial Service Activities
203.	664	Fund Management Activities
204.	670	Real Estate Development Activities
205.	681	Real Estate Operation Activities
206.	689	Other Real Estate Activities
207.	691	Legal Activities
208.	692	Accounting, Bookkeeping and Auditing Activities; Tax consultancy
209.	701	Activities of Head Offices
210.	702	Management Consultancy Activities
211.	711	Architecture and Engineering Activities and Related Technical Consultancy
212.	712	Technical Testing and Analysis
213.	721	Research and Experimental Development on Natural Sciences and Engineering
214.	722	Research and Experimental Development on Social Sciences and Humanities
215.	723	Miscellaneous Scientific Research and Development
216.	731	Advertising
217.	732	Market Research and Public Opinion Polling
218.	740	Specialized Design Activities
219.	750	Veterinary Activities
220.	760	Other Professional, Scientific and Technical Activities
221.	771	Renting and Leasing of Machinery and Equipment
222.	772	Renting and Leasing of Transport Equipment
223.	773	Renting and Leasing of Personal and Household Goods
224.	774	Leasing of Intellectual Property and Similar Products, Except copyrighted works
225.	781	Activities of Employment Placement Agencies
226.	782	Human Resources Provision Activities
227.	790	Travel agency, Tour Operator, Reservation Service and Related Activities
228.	800	Security and Investigation Activities
229.	811	Combined Facilities Support Activities
230.	812	Cleaning Activities
231.	813	Landscape Care and Maintenance Service Activities
232.	820	Business and Office Support Activities
233.	831	Public Administration
234.	832	Defence Activities
235.	833	Compulsory Social Security Activities
236.	840	Activities of Extraterritorial Organisations and Bodies
237.	851	Pre-primary Education
238.	852	Primary Education
239.	853	General Secondary Education
240.	854	Technical and Vocational Education
241.	855	Higher Education
242.	856	Special Education
243.	857	Other Education
244.	858	Educational Support Activities
245.	861	Hospital Activities
246.	862	Clinic Activities
247.	869	Other Human Health Activities

248.	870	Residential Care Activities
249.	880	Social Work Activities without Accommodation
250.	901	Artistic Creation
251.	902	Performing Arts
252.	903	Support Activities to Performing Arts
253.	910	Libraries, Archives, Museums and Other Cultural Activities
254.	920	Gambling and Betting Activities
255.	931	Sports Activities
256.	932	Amusement and Recreation Activities
257.	941	Activities of Religious Organisations
258.	942	Activities of Business, Employers, Professional Membership Organisations and Trade Unions
259.	949	Activities of Other Membership Organisations
260.	951	Maintenance and Repair of Motor Vehicles and Motor Vehicle Beauty Shops
261.	952	Repair of Computers, Communication Equipment and Electronic Products
262.	959	Maintenance and Repair of Other Personal and Household Goods
263.	961	Washing and (Dry-) Cleaning of Textile and Fur Products Hairdressing and Other Beauty Treatment
264.	962	Hairdressing
265.	963	Funeral and Related Activities
266.	964	Activities of Households as Employers of Domestic Personnel
267.	969	Other Personal Service Activities Not Elsewhere Classified

Note: *) SICS = Standard Industrial Classification System

3.3 List of mark-up categories

	Acronyms	Mark-up Name
1.	BasP	Basic price
2.	Trans	Transport margin
3.	Trade	Trade margin
4.	VTax	Net taxes on production
5.	ImpD	Net import duties

3.4 List of final demand categories

	Acronyms	Category Name
1.	FCEhousehold	Consumption expenditure by households
2.	FCEgov	Consumption expenditure by the government
3.	GFCF	Gross fixed capital formation
4.	ChInv	Changes in inventories

3.5 List of value-added categories

	Acronyms	Category Name
1.	CoE	Compensation of employees
2.	GOS	Gross operating surplus
3.	CFC	Consumption of fixed capital
4.	ComTax	Net commodity taxes
5.	VAT	Value-added taxes
6.	OtherTax	Other taxes less subsidies
7.	Adjust	Adjustment items

3.6 List of non-survey methods

	Acronyms	Method Name	Source
1.	SLQ	Simple Location Quotient	Lahr 1993
2.	CILQ	Cross-Industry Location Quotient	Smith and Morrison 1974
3.	RLQ	Round's Location Quotient	Round 1978
4.	FLQ	Flegg's Location Quotient	Flegg and Webber 1996
5.	AFLQ	Flegg's Adjusted Location Quotient	Flegg and Webber 2000
6.	RSS	Relative sector sizes	Uribe *et al.* 1966
7.	SCILQ	Symmetric Cross-Industry Location Quotient	Bonfiglio and Chelli 2008
8.	SDP	Supply-Demand Pool	Moore and Petersen 1955
9.	CHARM	Cross-Hauling Adjusted Regionalisation Method	Kronenberg 2009
10.	MCH	Modified Cross-Hauling	Vogt 2011

3.7 Sectoral classifications

	Acronyms	Sector Name	Root Classification
1.	Agr	Agriculture	1-20
2.	Min	Mining and quarrying	21-23
3.	Man	Manufacturing	24-111
4.	Uti	Utilities	112-120
5.	Con	Construction	121-129
6.	Trade	Trade, hotel and restaurant	130-156, 175-180
7.	Trans	Transportation and communication	157-174, 181-190
8.	Fin	Financial services	191-232
9.	Ser	Other services	233-267

3.8 Event matrices

3.8.1 Event matrix Γ for the 2009 Typhoon Morakot

	Agr	Min	Man	Uti	Con	Trade	Trans	Fin	Ser
Hsinchu County	-	-	-	-	-	-	-	-	-
Taoyuan	-	-	-	-	-	-	-	-	-
Yilan	-	-	-	-	-	-	-	-	-
Hsinchu City	-	-	-	-	-	-	-	-	-
Keelung	-	-	-	-	-	-	-	-	-
New Taipei	-	-	-	-	-	-	-	-	-
Taipei	-	-	-	-	-	-	-	-	-
Changhua	-	-	-	-	-	-	-	-	-
Miaoli	-	-	-	-	-	-	-	-	-
Nantou	0.1335	-	0.0006	-	-	0.0012	0.0048	-	0.0012
Yunlin	0.0510	-	0.0005	-	-	0.0017	0.0078	-	-
Taichung	0.0124	-	0.0000	-	-	0.0000	0.0002	-	-
Chiayi County	0.1552	-	0.0070	-	-	0.0212	0.1518	-	0.0067
Penghu	-	-	-	-	-	-	-	-	-
Pingtung	0.2546	-	0.0084	-	-	0.0078	0.0412	-	0.0032
Chiayi City	-	-	-	-	-	-	-	-	-
Kaohsiung	0.1167	-	0.0016	-	-	0.0037	0.0090	-	0.0049
Tainan	0.2286	-	0.0014	-	-	0.0045	0.0199	-	0.0007
Hualien	-	-	-	-	-	-	-	-	-
Taitung	0.2845	-	0.0317	-	-	0.0082	0.0310	-	0.0067
Kinmen	-	-	-	-	-	-	-	-	-
Lienchiang	-	-	-	-	-	-	-	-	-

Sources:

- Typhoon Morakot caused NTD 19 billion losses to agricultural sectors (Council of Agriculture 2010);
- Typhoon Morakot damaged public facilities worth NTD 58.3 billion, manufacturing facilities worth NTD 1.8 billion, and school buildings worth NTD 2.6 billion (Yang *et al.* 2014);
- The Tourism Bureau estimated Typhoon Morakot caused approximately NTD 10.4 billion losses to tourism industry (Shan 2009).

3.8.2 Event matrix Γ for the 2016 Tainan Earthquake

	Agr	Min	Man	Uti	Con	Trade	Trans	Fin	Ser
Hsinchu County	-	-	-	-	-	-	-	-	-
Taoyuan	-	-	-	-	-	-	-	-	-
Yilan	0.0120	-	-	-	-	-	-	-	-
Hsinchu City	-	-	-	-	-	-	-	-	-
Keelung	-	-	-	-	-	-	-	-	-
New Taipei	-	-	-	-	-	-	-	-	-
Taipei	-	-	-	-	-	-	-	-	-
Changhua	-	-	-	-	-	-	-	-	-
Miaoli	-	-	-	-	-	-	-	-	-
Nantou	-	-	-	-	-	-	-	-	-
Yunlin	-	-	-	-	-	-	-	-	-
Taichung	-	-	-	-	-	-	-	-	-
Chiayi County	-	-	-	-	-	-	-	-	-
Penghu	-	-	-	-	-	-	-	-	-
Pingtung	0.0017	-	-	-	-	-	-	-	0.0025
Chiayi City	-	-	-	-	-	-	-	-	-
Kaohsiung	0.0004	-	-	-	-	-	0.0010	-	0.0002
Tainan	0.0037	-	-	-	-	-	-	-	0.0024
Hualien	-	-	-	-	-	-	-	-	-
Taitung	-	-	-	-	-	-	-	-	-
Kinmen	-	-	-	-	-	-	-	-	-
Lienchiang	-	-	-	-	-	-	-	-	-

Sources:

- The 2016 Tainan Earthquake damaged 34 historic monuments which likely required NTD 520 million for repair work;
- The Ministry of Education estimated 481 school buildings were damaged with losses worth NTD 279 million;
- The loss to agricultural and livestock facilities were estimated at NTD 170.7 million (Vervaeck and Daniell 2016).

3.8.3 Event matrix Γ for the 2016 Typhoon Megi

	Agr	Min	Man	Uti	Con	Trade	Trans	Fin	Ser
Hsinchu County	-	-	-	-	-	-	-	-	-
Taoyuan	0.0002	-	-	-	-	-	0.0011	-	0.0001
Yilan	0.0150	-	-	-	-	-	-	-	0.0001
Hsinchu City	-	-	-	-	-	-	-	-	-
Keelung	-	-	-	-	-	-	-	-	-
New Taipei	-	-	-	-	-	-	-	-	-
Taipei	-	-	-	-	-	-	-	-	-
Changhua	-	-	-	-	-	-	-	-	-
Miaoli	0.0066	-	-	-	-	-	-	-	0.0001
Nantou	-	-	-	-	-	-	-	-	-
Yunlin	0.0134	-	-	-	-	-	-	-	0.0001
Taichung	0.0078	-	-	-	-	-	-	-	0.0001
Chiayi County	-	-	-	-	-	-	-	-	-
Penghu	-	-	-	-	-	-	-	-	-
Pingtung	-	-	-	-	-	-	-	-	-
Chiayi City	-	-	-	-	-	-	-	-	-
Kaohsiung	0.0047	-	-	-	-	-	-	-	0.0000
Tainan	0.0034	-	-	-	-	-	-	-	0.0001
Hualien	-	-	-	-	-	-	-	-	-
Taitung	-	-	-	-	-	-	-	-	-
Kinmen	-	-	-	-	-	-	-	-	-
Lienchiang	-	-	-	-	-	-	-	-	-

Sources:

- The Council of Agriculture estimated losses on agriculture sectors were valued at NTD 1.3 billion, and the Ministry of Education estimated damages on 814 school schools around Taiwan were valued at NTD 161 million (Hsu-min *et al.* 2016).
- More than 750 flights departed from Taoyuan International Airport were cancelled (Shan 2016).

3.9 Taiwan's regional output (in NTD billion)

3.9.1 Taiwan's regional output for 1999

	Agr	Min	Man	Uti	Con	Trade	Trans	Fin	Ser
Hsinchu County	17.1	3.4	324.2	5.8	28.3	50.0	21.1	43.8	48.4
Taoyuan	13.8	0.7	1,216.9	15.7	94.5	218.3	122.0	186.2	107.2
Yilan	14.3	2.3	97.9	16.4	30.3	38.2	16.1	23.8	52.3
Hsinchu City	6.5	1.4	375.3	8.5	32.9	59.6	22.9	67.5	54.2
Keelung	1.7	0.9	44.3	37.7	18.3	25.0	37.1	15.8	45.9
New Taipei	9.6	0.5	1,361.9	19.7	222.3	393.4	175.1	317.4	273.9
Taipei	4.9	1.1	653.1	30.4	68.9	627.7	483.9	1,067.3	550.2
Changhua	51.4	0.9	563.3	6.6	28.7	101.3	29.0	62.7	107.7
Miaoli	22.2	10.0	207.1	17.2	26.3	41.9	17.6	32.8	51.6
Nantou	30.6	2.2	113.5	21.2	21.4	39.0	13.2	22.1	54.2
Yunlin	44.1	0.9	184.9	26.0	30.5	48.5	18.8	28.8	60.7
Taichung	44.8	1.3	1,232.4	18.9	147.1	322.8	108.0	271.0	318.8
Chiayi County	33.6	0.5	140.7	6.2	22.4	33.8	11.9	21.1	47.9
Penghu	1.6	0.0	6.3	13.3	4.9	6.6	4.6	3.6	10.6
Pingtung	41.6	3.1	131.2	31.7	32.1	64.1	16.9	33.6	89.1
Chiayi City	3.4	0.6	38.2	17.0	11.4	29.4	9.8	21.5	45.9
Kaohsiung	52.8	0.9	866.4	93.6	185.1	291.8	149.6	267.5	341.5
Tainan	55.6	0.7	877.6	13.2	24.9	179.5	52.2	140.2	194.5
Hualien	10.8	3.9	40.2	27.9	17.7	29.7	14.6	17.3	47.3
Taitung	10.0	2.5	17.6	8.6	9.0	17.0	5.9	8.3	29.0
Kinmen	1.2	0.1	8.9	16.0	5.6	4.7	4.0	2.8	5.8
Lienchiang	0.1	0.0	1.1	2.1	1.5	0.6	1.0	0.5	1.4

3.9.2 Taiwan's regional output for 2009

	Agr	Min	Man	Uti	Con	Trade	Trans	Fin	Ser
Hsinchu County	17.3	2.4	515.6	10.7	30.4	70.6	28.6	57.9	68.7
Taoyuan	14.4	0.8	1,927.7	30.4	101.5	304.3	162.2	235.0	147.5
Yilan	15.0	1.6	158.5	26.2	32.3	54.3	21.2	32.6	74.1
Hsinchu City	6.4	0.9	596.0	15.6	35.4	83.9	31.0	87.6	76.6
Keelung	1.7	0.6	72.4	60.0	19.5	35.7	48.9	22.5	65.5
New Taipei	10.1	0.6	2,160.5	38.3	237.4	546.9	231.4	396.5	373.7
Taipei	5.3	1.2	1,060.9	58.9	72.9	873.7	635.5	1,319.9	746.2
Changhua	51.7	0.6	896.2	13.6	30.9	142.2	39.3	81.5	149.2
Miaoli	22.9	7.3	331.6	27.9	28.5	59.4	23.2	44.0	73.1
Nantou	31.6	1.5	184.2	34.0	23.2	55.5	18.0	30.2	76.5
Yunlin	45.3	0.6	298.2	41.5	33.2	68.9	25.6	38.8	85.4
Taichung	44.9	1.4	1,956.7	36.6	157.6	449.4	143.7	339.5	434.4
Chiayi County	34.5	0.4	227.0	10.0	24.0	48.3	16.2	28.8	68.1
Penghu	1.8	0.0	10.3	21.0	5.6	9.9	6.4	5.9	16.6
Pingtung	42.7	2.2	214.2	50.6	34.4	90.6	23.1	44.9	123.9
Chiayi City	3.6	0.4	62.7	27.0	12.3	41.9	13.3	30.0	65.4
Kaohsiung	52.8	1.0	1,380.9	150.7	197.8	406.7	197.8	335.2	464.8
Tainan	55.5	0.8	1,394.0	25.9	27.0	250.8	70.1	178.0	266.6
Hualien	11.4	2.8	66.5	44.4	19.1	42.4	19.8	24.3	67.4
Taitung	10.6	1.8	29.3	13.6	9.7	24.6	8.1	12.2	42.2
Kinmen	1.3	0.1	14.8	25.4	6.1	7.2	5.5	4.8	9.5
Lienchiang	0.1	0.0	1.7	3.3	1.5	1.0	1.5	0.8	2.3

3.10 Direct losses as a result of reduced consumption possibilities (in NTD mil)

3.10.1 Direct losses of the 1999 Chichi earthquake

	Agr	Min	Man	Uti	Con	Trade	Trans	Fin	Ser
Hsinchu County	-183	-56	-3,396	-54	-225	-1,485	-291	-949	-966
Taoyuan	-68	-4	-13,957	-96	-361	-6,096	-1,874	-4,225	-1,997
Yilan	-153	-41	-732	-161	-309	-1,143	-257	-482	-1,093
Hsinchu City	-29	-22	-4,308	-98	-269	-1,828	-326	-1,651	-1,105
Keelung	-6	-17	-251	-536	-197	-749	-740	-329	-976
New Taipei	-92	-2	-14,613	-174	-2,005	-12,391	-3,079	-7,908	-5,878
Taipei	-5	-10	-3,489	-339	-86	-19,685	-9,452	-28,351	-12,287
Changhua	-601	-11	-5,989	-48	-154	-3,028	-354	-1,139	-2,267
Miaoli	-433	-146	-2,024	-188	-226	-1,229	-340	-659	-1,070
Nantou	-2,299	-37	-799	-260	-204	-1,404	-703	-350	-1,517
Yunlin	-550	-14	-1,430	-311	-318	-1,371	-287	-435	-1,231
Taichung	-1,711	-11	-13,018	-172	-1,255	-10,344	-2,070	-6,686	-7,349
Chiayi County	-376	-7	-1,132	-33	-233	-931	-116	-303	-973
Penghu	-19	0	-8	-193	-66	-172	-88	-60	-196
Pingtung	-465	-52	-704	-301	-346	-1,882	-182	-581	-1,873
Chiayi City	-31	-10	-189	-253	-125	-880	-165	-506	-962
Kaohsiung	-495	-6	-8,120	-819	-1,789	-8,821	-2,581	-6,655	-7,385
Tainan	-546	-3	-9,442	-89	-27	-5,424	-630	-3,102	-4,189
Hualien	-123	-71	-141	-349	-187	-891	-261	-348	-997
Taitung	-126	-47	-22	-82	-100	-492	-85	-122	-584
Kinmen	-14	-2	-38	-246	-64	-134	-77	-47	-94
Lienchiang	0	0	-1	-30	-23	-12	-22	-6	-18

3.10.2 Direct losses of the 2009 Typhoon Morakot

	Agr	Min	Man	Uti	Con	Trade	Trans	Fin	Ser
Hsinchu County	-11	-3	-319	0	-2	-90	-15	-36	-7
Taoyuan	0	0	-1,323	0	-3	-357	-96	-147	-87
Yilan	-7	-1	-60	-4	-2	-48	-10	-12	-5
Hsinchu City	-3	-1	-408	0	-2	-113	-17	-55	-9
Keelung	0	0	-22	-39	-3	-36	-80	-14	-14
New Taipei	0	0	-1,266	0	-18	-610	-138	-212	-37
Taipei	0	0	-289	-1	0	-860	-744	-1,103	-85
Changhua	-31	0	-567	0	-1	-170	-15	-44	-12
Miaoli	-13	-7	-182	-8	-1	-62	-10	-21	-6
Nantou	-1,715	-2	-197	-39	-6	-271	-36	-44	-66
Yunlin	-938	-1	-222	-25	-5	-176	-74	-32	-15
Taichung	-196	0	-1,197	0	-9	-545	-86	-188	-42
Chiayi County	-2,194	-1	-419	-32	-18	-835	-626	-107	-296
Penghu	-1	0	-1	-10	-1	-7	-5	-2	-2
Pingtung	-4,442	-4	-302	-103	-18	-736	-285	-122	-264
Chiayi City	-1	0	-16	-8	-1	-36	-6	-11	-7
Kaohsiung	-2,182	0	-1,179	-164	-43	-1,674	-986	-491	-1,534
Tainan	-4,702	0	-2,018	0	-11	-1,391	-496	-346	-170
Hualien	-6	-2	-12	-20	-1	-35	-10	-8	-6
Taitung	-1,371	-2	-34	-31	-6	-215	-104	-40	-187
Kinmen	0	0	-3	-18	-1	-6	-5	-2	-1
Lienchiang	0	0	0	-2	0	-1	-1	0	0

3.10.3 Direct losses of the 2016 Tainan earthquake

	Agr	Min	Man	Uti	Con	Trade	Trans	Fin	Ser
Hsinchu County	0	0	-6	0	0	-2	0	-1	0
Taoyuan	0	0	-25	0	0	-7	-2	-3	-2
Yilan	-76	0	-7	-1	0	-11	-1	-2	-1
Hsinchu City	0	0	-8	0	0	-2	0	-1	0
Keelung	0	0	0	-2	0	-1	-1	0	0
New Taipei	0	0	-24	0	0	-12	-3	-4	-1
Taipei	0	0	-6	0	0	-15	-11	-20	-2
Changhua	-1	0	-11	0	0	-3	0	-1	0
Miaoli	0	0	-3	0	0	-1	0	0	0
Nantou	0	0	-1	0	0	-1	0	0	0
Yunlin	0	0	-2	0	0	-1	0	0	0
Taichung	0	0	-22	0	0	-10	-1	-3	-1
Chiayi County	0	0	-2	0	0	-1	0	0	0
Penghu	0	0	0	-1	0	0	0	0	0
Pingtung	-31	0	-4	-5	-1	-13	-2	-6	-202
Chiayi City	0	0	0	0	0	-1	0	0	0
Kaohsiung	-9	0	-24	-4	-2	-21	-97	-15	-63
Tainan	-81	0	-48	0	0	-35	-4	-18	-414
Hualien	0	0	0	-1	0	-1	0	0	0
Taitung	0	0	0	0	0	0	0	0	0
Kinmen	0	0	0	-1	0	0	0	0	0
Lienchiang	0	0	0	0	0	0	0	0	0

3.10.4 Direct losses of the 2016 typhoon Megi

	Agr	Min	Man	Uti	Con	Trade	Trans	Fin	Ser
Hsinchu County	0	0	-10	0	0	-3	0	-1	0
Taoyuan	-1	0	-54	0	0	-19	-82	-12	-18
Yilan	-95	0	-10	-2	0	-14	-1	-3	-8
Hsinchu City	0	0	-13	0	0	-4	-1	-2	0
Keelung	0	0	-1	-1	0	-1	-1	0	0
New Taipei	0	0	-41	0	-1	-20	-5	-7	-1
Taipei	0	0	-9	0	0	-26	-14	-26	-3
Changhua	-1	0	-18	0	0	-6	0	-1	0
Miaoli	-63	0	-16	-1	0	-9	-1	-3	-6
Nantou	-2	0	-2	0	0	-2	0	0	0
Yunlin	-259	0	-28	-5	-1	-29	-2	-5	-4
Taichung	-119	0	-63	0	-1	-40	-4	-12	-17
Chiayi County	-2	0	-3	0	0	-2	0	0	0
Penghu	0	0	0	0	0	0	0	0	0
Pingtung	-2	0	-2	0	0	-3	0	0	0
Chiayi City	0	0	-1	0	0	-1	0	0	0
Kaohsiung	-94	0	-35	-4	-1	-28	-5	-9	-16
Tainan	-76	0	-44	0	0	-20	-2	-6	-10
Hualien	0	0	0	-1	0	-1	0	0	0
Taitung	-1	0	0	0	0	-1	0	0	0
Kinmen	0	0	0	-1	0	0	0	0	0
Lienchiang	0	0	0	0	0	0	0	0	0

3.11 Indirect losses (in NTD million)

3.11.1 Indirect losses of the 1999 Chichi earthquake

	Agr	Min	Man	Uti	Con	Trade	Trans	Fin	Ser
Hsinchu County	-114	-42	-3,056	0	-28	-956	-184	-465	-84
Taoyuan	-1	0	-12,620	-2	-50	-3,725	-1,142	-2,009	-1,858
Yilan	-62	-31	-651	-92	-28	-569	-142	-222	-79
Hsinchu City	-25	-13	-3,915	-1	-39	-1,195	-222	-793	-118
Keelung	-2	-12	-225	-480	-27	-386	-437	-181	-105
New Taipei	0	0	-13,238	-3	-317	-6,973	-1,919	-3,807	-692
Taipei	0	0	-3,086	-5	-1	-8,841	-6,102	-13,337	-1,548
Changhua	-322	-6	-5,383	0	-21	-1,783	-189	-569	-159
Miaoli	-141	-127	-1,840	-147	-25	-711	-141	-307	-80
Nantou	-393	-27	-786	-174	-25	-740	-123	-188	-98
Yunlin	-238	-10	-1,272	-172	-24	-690	-126	-188	-73
Taichung	-320	0	-11,923	-3	-197	-5,919	-1,080	-3,171	-697
Chiayi County	-163	-5	-1,000	-29	-16	-475	-63	-123	-52
Penghu	-3	0	-6	-135	-7	-72	-47	-29	-16
Pingtung	-200	-39	-615	-191	-27	-839	-106	-241	-108
Chiayi City	-7	-8	-167	-159	-18	-402	-92	-237	-82
Kaohsiung	-283	0	-7,284	-804	-268	-4,694	-1,602	-3,006	-727
Tainan	-352	0	-8,466	-2	-25	-3,133	-378	-1,431	-348
Hualien	-37	-57	-123	-275	-18	-401	-149	-159	-72
Taitung	-32	-34	-18	-48	-9	-203	-35	-51	-33
Kinmen	-1	-2	-33	-213	-5	-60	-40	-21	-8
Lienchiang	0	0	-1	-17	-1	-4	-8	-3	-2

3.11.2 Indirect losses of the 2009 Typhoon Morakot

	Agr	Min	Man	Uti	Con	Trade	Trans	Fin	Ser
Hsinchu County	-10	-1	-308	0	-1	-87	-14	-34	-5
Taoyuan	0	0	-1,280	0	-3	-343	-92	-140	-83
Yilan	-6	0	-59	-3	-1	-46	-9	-10	-3
Hsinchu City	-2	0	-395	0	-2	-108	-16	-52	-7
Keelung	0	0	-21	-37	-2	-34	-79	-12	-12
New Taipei	0	0	-1,226	0	-18	-589	-133	-203	-35
Taipei	0	0	-281	0	0	-838	-732	-1,084	-83
Changhua	-30	0	-550	0	-1	-163	-14	-42	-10
Miaoli	-12	-5	-176	-7	-1	-60	-10	-19	-4
Nantou	-310	-1	-195	-38	-5	-269	-18	-43	-21
Yunlin	-186	0	-219	-24	-4	-174	-18	-31	-13
Taichung	-36	0	-1,160	0	-9	-528	-74	-180	-40
Chiayi County	-380	-1	-401	-32	-17	-360	-49	-106	-58
Penghu	0	0	-1	-9	0	-6	-3	0	-1
Pingtung	-781	-2	-300	-102	-18	-734	-46	-121	-67
Chiayi City	0	0	-16	-7	0	-34	-5	-9	-5
Kaohsiung	-281	0	-1,126	-162	-43	-965	-295	-485	-142
Tainan	-646	0	-1,989	0	-11	-1,110	-91	-342	-106
Hualien	-4	-1	-11	-19	0	-34	-9	-6	-4
Taitung	-215	-1	-14	-30	-6	-214	-23	-38	-22
Kinmen	0	0	-3	-17	0	-5	-3	-1	0
Lienchiang	0	0	0	-1	0	0	-1	0	0

3.11.3 Indirect losses of the 2016 Tainan earthquake

	Agr	Min	Man	Uti	Con	Trade	Trans	Fin	Ser
Hsinchu County	0	0	-6	0	0	-2	0	-1	0
Taoyuan	0	0	-24	0	0	-6	-2	-3	-2
Yilan	-10	0	-7	-1	0	-11	-1	-2	-1
Hsinchu City	0	0	-7	0	0	-2	0	-1	0
Keelung	0	0	0	-2	0	-1	-1	0	0
New Taipei	0	0	-23	0	0	-11	-3	-4	-1
Taipei	0	0	-5	0	0	-15	-11	-20	-1
Changhua	-1	0	-10	0	0	-3	0	-1	0
Miaoli	0	0	-3	0	0	-1	0	0	0
Nantou	0	0	-1	0	0	-1	0	0	0
Yunlin	0	0	-2	0	0	-1	0	0	0
Taichung	0	0	-21	0	0	-9	-1	-3	-1
Chiayi County	0	0	-2	0	0	-1	0	0	0
Penghu	0	0	0	-1	0	0	0	0	0
Pingtung	-5	0	-4	-5	-1	-13	-2	-6	-3
Chiayi City	0	0	0	0	0	-1	0	0	0
Kaohsiung	-2	0	-23	-4	-2	-20	-14	-15	-6
Tainan	-11	0	-47	0	0	-35	-4	-18	-7
Hualien	0	0	0	-1	0	-1	0	0	0
Taitung	0	0	0	0	0	0	0	0	0
Kinmen	0	0	0	-1	0	0	0	0	0
Lienchiang	0	0	0	0	0	0	0	0	0

3.11.4 Indirect losses of the 2016 typhoon Megi

	Agr	Min	Man	Uti	Con	Trade	Trans	Fin	Ser
Hsinchu County	0	0	-10	0	0	-3	0	-1	0
Taoyuan	0	0	-52	0	0	-18	-11	-12	-18
Yilan	-13	0	-10	-2	0	-14	-1	-3	-1
Hsinchu City	0	0	-12	0	0	-3	-1	-2	0
Keelung	0	0	-1	-1	0	-1	-1	0	0
New Taipei	0	0	-39	0	-1	-19	-4	-7	-1
Taipei	0	0	-9	0	0	-25	-14	-26	-2
Changhua	-1	0	-18	0	0	-5	0	-1	0
Miaoli	-9	0	-16	-1	0	-9	-1	-2	-1
Nantou	-2	0	-2	0	0	-2	0	0	0
Yunlin	-42	0	-28	-5	-1	-29	-2	-4	-2
Taichung	-11	0	-62	0	-1	-39	-4	-12	-3
Chiayi County	-2	0	-3	0	0	-1	0	0	0
Penghu	0	0	0	0	0	0	0	0	0
Pingtung	-2	0	-2	0	0	-3	0	0	0
Chiayi City	0	0	-1	0	0	-1	0	0	0
Kaohsiung	-10	0	-34	-4	-1	-28	-5	-9	-3
Tainan	-10	0	-43	0	0	-20	-2	-6	-2
Hualien	0	0	0	-1	0	-1	0	0	0
Taitung	-1	0	0	0	0	-1	0	0	0
Kinmen	0	0	0	-1	0	0	0	0	0
Lienchiang	0	0	0	0	0	0	0	0	0

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Supplementary Information for Chapter 4

Demand-driven GHG emissions of Swedish regions: 2008–2016

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4.1 List of root regions

	Code	Region Name
1	114	Upplands-Väsby
2	115	Vallentuna
3	117	Österåker
4	120	Värmdö
5	123	Järfälla
6	125	Ekerö
7	126	Huddinge
8	127	Botkyrka
9	128	Salem
10	136	Haninge
11	138	Tyresö
12	139	Upplands-Bro
13	140	Nykvarn
14	160	Täby
15	162	Danderyd
16	163	Sollentuna
17	180	Stockholm
18	181	Södertälje
19	182	Nacka
20	183	Sundbyberg
21	184	Solna
22	186	Lidingö
23	187	Vaxholm
24	188	Norrtälje
25	191	Sigtuna
26	192	Nynäshamn
27	305	Håbo
28	319	Älvkarleby
29	330	Knivsta
30	331	Heby
31	360	Tierp
32	380	Uppsala
33	381	Enköping
34	382	Östhammar
35	428	Vingåker
36	461	Gnesta
37	480	Nyköping
38	481	Oxelösund
39	482	Flen
40	483	Katrineholm
41	484	Eskilstuna
42	486	Strängnäs
43	488	Trosa
44	509	Ödeshög
45	512	Ydre
46	513	Kinda
47	560	Boxholm
48	561	Åtvidaberg
49	562	Finspång
50	563	Valdemarsvik
51	580	Linköping
52	581	Norrköping
53	582	Söderköping
54	583	Motala
55	584	Vadstena
56	586	Mjölby
57	604	Aneby
58	617	Gnosjö
59	642	Mullsjö
60	643	Habo
61	662	Gislaved
62	665	Vaggeryd
63	680	Jönköping
64	682	Nässjö
65	683	Värnamo
66	684	Sävsjö
67	685	Vetlanda
68	686	Eksjö
69	687	Tranås
70	760	Uppvidinge
71	761	Lessebo
72	763	Tingsryd
73	764	Alvesta
74	765	Älmhult
75	767	Markaryd
76	780	Växjö
77	781	Ljungby
78	821	Högsby
79	834	Torsås
80	840	Mörbylånga
81	860	Hultsfred
82	861	Mönsterås
83	862	Emmaboda
84	880	Kalmar
85	881	Nybro
86	882	Oskarshamn
87	883	Västervik
88	884	Vimmerby
89	885	Borgholm
90	980	Gotland
91	1060	Olofström
92	1080	Karlskrona
93	1081	Ronneby
94	1082	Karlshamn
95	1083	Sölvesborg
96	1214	Svalöv
97	1230	Staffanstorp
98	1231	Burlöv
99	1233	Vellinge
100	1256	Östra Göinge
101	1257	Örkelljunga
102	1260	Bjuv
103	1261	Kävlinge
104	1262	Lomma
105	1263	Svedala

106	1264	Skurup	160	1466	Herrljunga
107	1265	Sjöbo	161	1470	Vara
108	1266	Hörby	162	1471	Götene
109	1267	Höör	163	1472	Tibro
110	1270	Tomelilla	164	1473	Töreboda
111	1272	Bromölla	165	1480	Göteborg
112	1273	Osby	166	1481	Mölndal
113	1275	Perstorp	167	1482	Kungälv
114	1276	Klippan	168	1484	Lysekil
115	1277	Åstorp	169	1485	Uddevalla
116	1278	Båstad	170	1486	Strömstad
117	1280	Malmö	171	1487	Vänersborg
118	1281	Lund	172	1488	Trollhättan
119	1282	Landskrona	173	1489	Alingsås
120	1283	Helsingborg	174	1490	Borås
121	1284	Höganäs	175	1491	Ulricehamn
122	1285	Eslöv	176	1492	Åmål
123	1286	Ystad	177	1493	Mariestad
124	1287	Trelleborg	178	1494	Lidköping
125	1290	Kristianstad	179	1495	Skara
126	1291	Simrishamn	180	1496	Skövde
127	1292	Ängelholm	181	1497	Hjo
128	1293	Hässleholm	182	1498	Tidaholm
129	1315	Hylte	183	1499	Falköping
130	1380	Halmstad	184	1715	Kil
131	1381	Laholm	185	1730	Eda
132	1382	Falkenberg	186	1737	Torsby
133	1383	Varberg	187	1760	Storfors
134	1384	Kungsbacka	188	1761	Hammarö
135	1401	Härryda	189	1762	Munkfors
136	1402	Partille	190	1763	Forshaga
137	1407	Öckerö	191	1764	Grums
138	1415	Stenungsund	192	1765	Årjäng
139	1419	Tjörn	193	1766	Sunne
140	1421	Orust	194	1780	Karlstad
141	1427	Sotenäs	195	1781	Kristinehamn
142	1430	Munkedal	196	1782	Filipstad
143	1435	Tanum	197	1783	Hagfors
144	1438	Dals-Ed	198	1784	Arvika
145	1439	Färgelanda	199	1785	Säffle
146	1440	Ale	200	1814	Lekeberg
147	1441	Lerum	201	1860	Laxå
148	1442	Vårgårda	202	1861	Hallsberg
149	1443	Bollebygd	203	1862	Degerfors
150	1444	Grästorp	204	1863	Hällefors
151	1445	Essunga	205	1864	Ljusnarsberg
152	1446	Karlsborg	206	1880	Örebro
153	1447	Gullspång	207	1881	Kumla
154	1452	Tranemo	208	1882	Askersund
155	1460	Bengtsfors	209	1883	Karlskoga
156	1461	Mellerud	210	1884	Nora
157	1462	Lilla Edet	211	1885	Lindesberg
158	1463	Mark	212	1904	Skinnskatteberg
159	1465	Svenljunga	213	1907	Surahammar

214	1917	Heby
215	1960	Kungsör
216	1961	Hallstahammar
217	1962	Norberg
218	1980	Västerås
219	1981	Sala
220	1982	Fagersta
221	1983	Köping
222	1984	Arboga
223	2021	Vansbro
224	2023	Malung
225	2026	Gagnef
226	2029	Leksand
227	2031	Rättvik
228	2034	Orsa
229	2039	Älvdalen
230	2061	Smedjebacken
231	2062	Mora
232	2080	Falun
233	2081	Borlänge
234	2082	Säter
235	2083	Hedemora
236	2084	Avesta
237	2085	Ludvika
238	2101	Ockelbo
239	2104	Hofors
240	2121	Ovanåker
241	2132	Nordanstig
242	2161	Ljusdal
243	2180	Gävle
244	2181	Sandviken
245	2182	Söderhamn
246	2183	Bollnäs
247	2184	Hudiksvall
248	2260	Ånge
249	2262	Timrå
250	2280	Härnösand
251	2281	Sundsvall
252	2282	Kramfors
253	2283	Sollefteå
254	2284	Örnsköldsvik
255	2303	Ragunda
256	2305	Bräcke
257	2309	Krokom
258	2313	Strömsund
259	2321	Åre
260	2326	Berg
261	2361	Härjedalen
262	2380	Östersund
263	2401	Nordmaling
264	2403	Bjurholm
265	2404	Vindeln
266	2409	Robertsfors
267	2417	Norsjö
268	2418	Malå
269	2421	Storuman
270	2422	Sorsele
271	2425	Dorotea
272	2460	Vännäs
273	2462	Vilhelmina
274	2463	Åsele
275	2480	Umeå
276	2481	Lycksele
277	2482	Skellefteå
278	2505	Arvidsjaur
279	2506	Arjeplog
280	2510	Jokkmokk
281	2513	Överkalix
282	2514	Kalix
283	2518	Övertorneå
284	2521	Pajala
285	2523	Gällivare
286	2560	Älvsbyn
287	2580	Luleå
288	2581	Piteå
289	2582	Boden
290	2583	Haparanda
291	2584	Kiruna

4.2 List of root sectors

	SNI code	Sector name
1	1110	Growing of cereals (except rice), leguminous crops and oil seeds
2	1120	Growing of rice
3	1131	Growing of potatoes
4	1132	Growing of sugar beet
5	1133	Growing of vegetables in the open
6	1134	Growing of vegetables in greenhouses
7	1135	Growing of mushrooms etc.
8	1140	Growing of sugar cane
9	1150	Growing of tobacco
10	1160	Growing of fibre crops
11	1191	Growing of flowers and ornamental plants in greenhouses
12	1199	Growing of other non-perennial crops n.e.c.
13	1210	Growing of grapes
14	1220	Growing of tropical and subtropical fruits
15	1230	Growing of citrus fruits
16	1240	Growing of pome fruits and stone fruits
17	1250	Growing of other tree and bush fruits and nuts
18	1260	Growing of oleaginous fruits
19	1270	Growing of beverage crops
20	1280	Growing of spices, aromatic, drug and pharmaceutical crops
21	1290	Growing of other perennial crops
22	1301	Plant propagation in greenhouses
23	1302	Plant propagation in the open
24	1410	Milk production and raising of dairy cattle
25	1420	Raising of other cattle and buffaloes
26	1430	Raising of horses and other equines
27	1440	Raising of camels and camelids
28	1450	Raising of sheep and goats
29	1461	Raising of piglets
30	1462	Raising of swine for slaughter
31	1471	Egg production
32	1472	Raising of poultry
33	1491	Reindeer husbandry
34	1492	Breeding of pet animals
35	1499	Raising of other animals n.e.c.
36	1500	Mixed farming
37	1610	Support activities for crop production
38	1620	Support activities for animal production
39	1630	Post-harvest crop activities
40	1640	Seed processing for propagation
41	1700	Hunting, trapping and related service activities
42	2101	Forest management
43	2102	Silviculture
44	2109	Other forestry activities
45	2200	Logging
46	2300	Gathering of wild growing non-wood products
47	2401	Wood measurement
48	2409	Other support services to forestry
49	3111	Marine trawling
50	3119	Other marine fishing
51	3120	Freshwater fishing
52	3210	Marine aquaculture
53	3220	Freshwater aquaculture
54	5100	Mining of hard coal
55	5200	Mining of lignite
56	6100	Extraction of crude petroleum
57	6200	Extraction of natural gas
58	7100	Mining of iron ores
59	7210	Mining of uranium and thorium ores
60	7290	Mining of other non-ferrous metal ores
61	8110	Quarrying of ornamental and building stone, limestone, gypsum, chalk and slate
62	8120	Operation of gravel and sand pits; mining of clays and kaolin
63	8910	Mining of chemical and fertiliser minerals
64	8920	Extraction of peat
65	8930	Extraction of salt
66	8990	Other mining and quarrying n.e.c.
67	9100	Support activities for petroleum and natural gas extraction
68	9900	Support activities for other mining and quarrying
69	10111	Livestock slaughtering
70	10112	Processing and preserving of meat in cuts
71	10120	Processing and preserving of poultry meat
72	10130	Production of meat and poultry meat products
73	10200	Processing and preserving of fish, crustaceans and molluscs
74	10310	Processing and preserving of potatoes

75	10320	Manufacture of fruit and vegetable juice
76	10390	Other processing and preserving of fruit and vegetables
77	10410	Manufacture of oils and fats
78	10420	Manufacture of margarine and similar edible fats
79	10511	Cheese production
80	10519	Other dairy production
81	10520	Manufacture of ice cream
82	10611	Production of flour
83	10612	Manufacture of breakfast cereals, blended flour mixes and other prepared grain mill products
84	10620	Manufacture of starches and starch products
85	10710	Manufacture of bread; manufacture of fresh pastry goods and cakes
86	10721	Manufacture of crispbread
87	10722	Manufacture of rusks, biscuits and preserved pastry goods and cakes
88	10730	Manufacture of macaroni, noodles, couscous and similar farinaceous products
89	10810	Manufacture of sugar
90	10821	Manufacture of sugar confectionery
91	10822	Manufacture of cocoa and chocolate confectionery
92	10830	Processing of tea and coffee
93	10840	Manufacture of condiments and seasonings
94	10850	Manufacture of prepared meals and dishes
95	10860	Manufacture of homogenised food preparations and dietetic food
96	10890	Manufacture of other food products n.e.c.
97	10910	Manufacture of prepared feeds for farm animals
98	10920	Manufacture of prepared pet foods
99	11010	Distilling, rectifying and blending of spirits
100	11020	Manufacture of wine from grape
101	11030	Manufacture of cider and other fruit wines
102	11040	Manufacture of other non-distilled fermented beverages
103	11050	Manufacture of beer
104	11060	Manufacture of malt
105	11070	Manufacture of soft drinks; production of mineral waters and other bottled waters
106	12000	Manufacture of tobacco products
107	13100	Preparation and spinning of textile fibres
108	13200	Weaving of textiles
109	13300	Finishing of textiles
110	13910	Manufacture of knitted and crocheted fabrics
111	13921	Manufacture of curtains, bed linen and other linen goods
112	13922	Manufacture of tarpaulins, tents, sails etc.
113	13930	Manufacture of carpets and rugs
114	13940	Manufacture of cordage, rope, twine and netting
115	13950	Manufacture of non-wovens and articles made from non-wovens, except apparel
116	13960	Manufacture of other technical and industrial textiles
117	13990	Manufacture of other textiles n.e.c.
118	14110	Manufacture of leather clothes
119	14120	Manufacture of workwear
120	14130	Manufacture of other outerwear
121	14140	Manufacture of underwear
122	14190	Manufacture of other wearing apparel and accessories
123	14200	Manufacture of articles of fur
124	14310	Manufacture of knitted and crocheted hosiery
125	14390	Manufacture of other knitted and crocheted apparel
126	15110	Tanning and dressing of leather; dressing and dyeing of fur
127	15120	Manufacture of luggage, handbags and the like, saddlery and harness
128	15200	Manufacture of footwear
129	16101	Sawmilling
130	16102	Planing of wood
131	16103	Impregnation of wood
132	16210	Manufacture of veneer sheets and wood-based panels
133	16220	Manufacture of assembled parquet floors
134	16231	Manufacture of prefabricated wooden buildings
135	16232	Manufacture of wooden doors
136	16233	Manufacture of wooden windows

137	16239	Manufacture of other builders carpentry and joinery n.e.c.
138	16240	Manufacture of wooden containers
139	16291	Manufacture of wood fuels
140	16292	Manufacture of other products of wood
141	16293	Manufacture of articles of cork, straw and plaiting materials
142	17111	Manufacture of mechanical or semi-chemical pulp
143	17112	Manufacture of sulphate pulp
144	17113	Manufacture of sulphite pulp
145	17121	Manufacture of newsprint
146	17122	Manufacture of other printing paper
147	17123	Manufacture of kraft paper and paperboard
148	17129	Manufacture of other paper and paperboard
149	17211	Manufacture of corrugated paper and paperboard and corrugated board containers
150	17219	Manufacture of other containers of paper and paperboard
151	17220	Manufacture of household and sanitary goods and of toilet requisites
152	17230	Manufacture of paper stationery
153	17240	Manufacture of wallpaper
154	17290	Manufacture of other articles of paper and paperboard
155	18110	Printing of newspapers
156	18121	Printing of periodicals
157	18122	Book printing and other printing
158	18130	Pre-press and pre-media services
159	18140	Binding and related services
160	18200	Reproduction of recorded media
161	19100	Manufacture of coke oven products
162	19200	Manufacture of refined petroleum products
163	20110	Manufacture of industrial gases
164	20120	Manufacture of dyes and pigments
165	20130	Manufacture of other inorganic basic chemicals
166	20140	Manufacture of other organic basic chemicals
167	20150	Manufacture of fertilisers and nitrogen compounds
168	20160	Manufacture of plastics in primary forms
169	20170	Manufacture of synthetic rubber in primary forms
170	20200	Manufacture of pesticides and other agrochemical products
171	20300	Manufacture of paints, varnishes and similar coatings, printing ink and mastics
172	20410	Manufacture of soap and detergents, cleaning and polishing preparations
173	20420	Manufacture of perfumes and toilet preparations
174	20510	Manufacture of explosives
175	20520	Manufacture of glues
176	20530	Manufacture of essential oils
177	20590	Manufacture of other chemical products n.e.c.
178	20600	Manufacture of man-made fibres
179	21100	Manufacture of basic pharmaceutical products
180	21200	Manufacture of pharmaceutical preparations
181	22110	Manufacture of rubber tyres and tubes; retreading and rebuilding of rubber tyres
182	22190	Manufacture of other rubber products
183	22210	Manufacture of plastic plates, sheets, tubes and profiles
184	22220	Manufacture of plastic packing goods
185	22230	Manufacture of builders' ware of plastic
186	22290	Manufacture of other plastic products
187	23110	Manufacture of flat glass
188	23120	Shaping and processing of flat glass
189	23130	Manufacture of hollow glass
190	23140	Manufacture of glass fibres
191	23190	Manufacture and processing of other glass, including technical glassware
192	23200	Manufacture of refractory products
193	23310	Manufacture of ceramic tiles and flags
194	23320	Manufacture of bricks, tiles and construction products, in baked clay
195	23410	Manufacture of ceramic household and ornamental articles
196	23420	Manufacture of ceramic sanitary fixtures
197	23430	Manufacture of ceramic insulators and insulating fittings

198	23440	Manufacture of other technical ceramic products
199	23490	Manufacture of other ceramic products
200	23510	Manufacture of cement
201	23520	Manufacture of lime and plaster
202	23610	Manufacture of concrete products for construction purposes
203	23620	Manufacture of plaster products for construction purposes
204	23630	Manufacture of ready-mixed concrete
205	23640	Manufacture of mortars
206	23650	Manufacture of fibre cement
207	23690	Manufacture of other articles of concrete, plaster and cement
208	23701	Cutting, shaping and finishing of building stone
209	23709	Cutting, shaping and finishing of ornamental stone
210	23910	Production of abrasive products
211	23991	Manufacture of stone and mineral wool products
212	23999	Manufacture of various other non-metallic mineral products n.e.c.
213	24100	Manufacture of basic iron and steel and of ferro-alloys
214	24200	Manufacture of tubes, pipes, hollow profiles and related fittings, of steel
215	24310	Cold drawing of bars
216	24320	Cold rolling of narrow strip
217	24330	Cold forming or folding
218	24340	Cold drawing of wire
219	24410	Precious metals production
220	24420	Aluminium production
221	24430	Lead, zinc and tin production
222	24440	Copper production
223	24450	Other non-ferrous metal production
224	24460	Processing of nuclear fuel
225	24510	Casting of iron
226	24520	Casting of steel
227	24530	Casting of light metals
228	24540	Casting of other non-ferrous metals
229	25110	Manufacture of metal structures and parts of structures
230	25120	Manufacture of doors and windows of metal
231	25210	Manufacture of central heating radiators and boilers
232	25290	Manufacture of other tanks, reservoirs and containers of metal
233	25300	Manufacture of steam generators, except central heating hot water boilers
234	25400	Manufacture of weapons and ammunition
235	25500	Forging, pressing, stamping and roll-forming of metal; powder metallurgy
236	25610	Treatment and coating of metals
237	25620	Machining
238	25710	Manufacture of cutlery
239	25720	Manufacture of locks and hinges
240	25730	Manufacture of tools
241	25910	Manufacture of steel drums and similar containers
242	25920	Manufacture of light metal packaging
243	25930	Manufacture of wire products, chain and springs
244	25940	Manufacture of fasteners and screw machine products
245	25991	Manufacture of sinks, sanitary ware etc. of metal for construction purposes
246	25999	Manufacture of various other fabricated metal products n.e.c.
247	26110	Manufacture of electronic components
248	26120	Manufacture of loaded electronic boards
249	26200	Manufacture of computers and peripheral equipment
250	26300	Manufacture of communication equipment
251	26400	Manufacture of consumer electronics
252	26510	Manufacture of instruments and appliances for measuring, testing and navigation
253	26520	Manufacture of watches and clocks
254	26600	Manufacture of irradiation, electromedical and electrotherapeutic equipment
255	26700	Manufacture of optical instruments and photographic equipment
256	26800	Manufacture of magnetic and optical media
257	27110	Manufacture of electric motors, generators and transformers
258	27120	Manufacture of electricity distribution and control apparatus

259	27200	Manufacture of batteries and accumulators
260	27310	Manufacture of fibre optic cables
261	27320	Manufacture of other electronic and electric wires and cables
262	27330	Manufacture of wiring devices
263	27400	Manufacture of electric lighting equipment
264	27510	Manufacture of electric domestic appliances
265	27520	Manufacture of non-electric domestic appliances
266	27900	Manufacture of other electrical equipment
267	28110	Manufacture of engines and turbines, except aircraft, vehicle and cycle engines
268	28120	Manufacture of fluid power equipment
269	28130	Manufacture of other pumps and compressors
270	28140	Manufacture of other taps and valves
271	28150	Manufacture of bearings, gears, gearing and driving elements
272	28210	Manufacture of ovens, furnaces and furnace burners
273	28220	Manufacture of lifting and handling equipment
274	28230	Manufacture of office machinery and equipment (except computers and peripheral equipment)
275	28240	Manufacture of power-driven hand tools
276	28250	Manufacture of non-domestic cooling and ventilation equipment
277	28290	Manufacture of other general-purpose machinery n.e.c.
278	28300	Manufacture of agricultural and forestry machinery
279	28410	Manufacture of metal forming machinery
280	28490	Manufacture of other machine tools
281	28910	Manufacture of machinery for metallurgy
282	28920	Manufacture of machinery for mining, quarrying and construction
283	28930	Manufacture of machinery for food, beverage and tobacco processing
284	28940	Manufacture of machinery for textile, apparel and leather production
285	28950	Manufacture of machinery for paper and paperboard production
286	28960	Manufacture of plastics and rubber machinery
287	28990	Manufacture of other special-purpose machinery n.e.c.
288	29101	Manufacture of passenger cars and other light motor vehicles
289	29102	Manufacture of trucks and other heavy motor vehicles
290	29200	Manufacture of bodies (coachwork) for motor vehicles; manufacture of trailers and semi-trailers
291	29310	Manufacture of electrical and electronic equipment for motor vehicles
292	29320	Manufacture of other parts and accessories for motor vehicles
293	30110	Building of ships and floating structures
294	30120	Building of pleasure and sporting boats
295	30200	Manufacture of railway locomotives and rolling stock
296	30300	Manufacture of air and spacecraft and related machinery
297	30400	Manufacture of military fighting vehicles
298	30910	Manufacture of motorcycles
299	30920	Manufacture of bicycles and invalid carriages
300	30990	Manufacture of other transport equipment n.e.c.
301	31011	Manufacture of office and shop furniture
302	31012	Manufacture of office and shop fittings
303	31021	Manufacture of kitchen furniture
304	31022	Manufacture of kitchen fittings
305	31030	Manufacture of mattresses
306	31090	Manufacture of other furniture
307	32110	Striking of coins
308	32120	Manufacture of jewellery and related articles
309	32130	Manufacture of imitation jewellery and related articles
310	32200	Manufacture of musical instruments
311	32300	Manufacture of sports goods
312	32400	Manufacture of games and toys
313	32501	Manufacture of medical and dental instruments and supplies

314	32502	Manufacture of artificial teeth, dentures, dental plates etc.
315	32910	Manufacture of brooms and brushes
316	32990	Other manufacturing n.e.c.
317	33110	Repair of fabricated metal products
318	33120	Repair of machinery
319	33130	Repair of electronic and optical equipment
320	33140	Repair of electrical equipment
321	33150	Repair and maintenance of ships and boats
322	33160	Repair and maintenance of aircraft and spacecraft
323	33170	Repair and maintenance of other transport equipment
324	33190	Repair of other equipment
325	33200	Installation of industrial machinery and equipment
326	35110	Production of electricity
327	35120	Transmission of electricity
328	35130	Distribution of electricity
329	35140	Trade of electricity
330	35210	Manufacture of gas
331	35220	Distribution of gaseous fuels through mains
332	35230	Trade of gas through mains
333	35300	Steam and air conditioning supply
334	36001	Collection, treatment and supply of groundwater
335	36002	Collection, treatment and supply of surface water
336	37000	Sewerage
337	38110	Collection of non-hazardous waste
338	38120	Collection of hazardous waste
339	38210	Treatment and disposal of non-hazardous waste
340	38220	Treatment and disposal of hazardous waste
341	38311	Dismantling of car wrecks
342	38312	Dismantling of electric and electronic equipment
343	38319	Dismantling of other wrecks
344	38320	Recovery of sorted materials
345	39000	Remediation activities and other waste management services
346	41100	Development of building projects
347	41200	Construction of residential and non-residential buildings
348	42110	Construction of roads and motorways
349	42120	Construction of railways and underground railways
350	42130	Construction of bridges and tunnels
351	42210	Construction of utility projects for fluids
352	42220	Construction of utility projects for electricity and telecommunications
353	42910	Construction of water projects
354	42990	Construction of other civil engineering projects n.e.c.
355	43110	Demolition
356	43120	Site preparation
357	43130	Test drilling and boring
358	43210	Electrical installation
359	43221	Installation of heating and sanitary equipment
360	43222	Installation of ventilation equipment
361	43223	Installation of refrigeration and freezing equipment
362	43229	Other plumbing
363	43290	Other construction installation
364	43310	Plastering
365	43320	Joinery installation
366	43330	Floor and wall covering
367	43341	Painting
368	43342	Glazing
369	43390	Other building completion and finishing
370	43911	Erection of sheet-metal roof covering
371	43912	Erection of other roof covering and frames
372	43991	Renting of construction or demolition equipment with operator
373	43999	Various other specialised construction activities n.e.c.
374	45110	Sale of cars and light motor vehicles
375	45191	Sale of lorries, buses and specialised motor vehicles
376	45192	Sale of caravans, motor homes, trailers and semi-trailers
377	45201	Non-specialised maintenance and repair of motor vehicles
378	45202	Bodywork repair and painting of motor vehicles
379	45203	Installation and repair and painting of electrical and electronic motor vehicle equipment
380	45204	Tyre service
381	45310	Wholesale trade of motor vehicle parts and accessories
382	45320	Retail trade of motor vehicle parts and accessories

383	45400	Sale, maintenance and repair of motorcycles and related parts and accessories
384	46110	Agents involved in the sale of agricultural raw materials, live animals, textile raw materials and semi-finished goods
385	46120	Agents involved in the sale of fuels, ores, metals and industrial chemicals
386	46130	Agents involved in the sale of timber and building materials
387	46141	Agents involved in the sale of machinery, industrial equipment, ships and aircraft except office machinery and computer equipment
388	46142	Agents involved in the sale of office machinery and computer equipment
389	46150	Agents involved in the sale of furniture, household goods, hardware and ironmongery
390	46160	Agents involved in the sale of textiles, clothing, fur, footwear and leather goods
391	46170	Agents involved in the sale of food, beverages and tobacco
392	46180	Agents specialised in the sale of other particular products
393	46190	Agents involved in the sale of a variety of goods
394	46210	Wholesale of grain, unmanufactured tobacco, seeds and animal feeds
395	46220	Wholesale of flowers and plants
396	46230	Wholesale of live animals
397	46240	Wholesale of hides, skins and leather
398	46310	Wholesale of fruit and vegetables
399	46320	Wholesale of meat and meat products
400	46330	Wholesale of dairy products, eggs and edible oils and fats
401	46340	Wholesale of beverages
402	46350	Wholesale of tobacco products
403	46360	Wholesale of sugar and chocolate and sugar confectionery
404	46370	Wholesale of coffee, tea, cocoa and spices
405	46380	Wholesale of other food, including fish, crustaceans and molluscs
406	46390	Non-specialised wholesale of food, beverages and tobacco
407	46410	Wholesale of textiles
408	46420	Wholesale of clothing and footwear
409	46431	Wholesale of electrical household appliances
410	46432	Wholesale of radio, television and video equipment
411	46433	Wholesale of recorded audio and video tapes, CDs and DVDs
412	46434	Wholesale of electrical equipment
413	46435	Wholesale of photographic and optical goods
414	46440	Wholesale of china and glassware and cleaning materials
415	46450	Wholesale of perfume and cosmetics
416	46460	Wholesale of pharmaceutical goods
417	46470	Wholesale of furniture, carpets and lighting equipment
418	46480	Wholesale of watches and jewellery
419	46491	Wholesale of sporting equipment
420	46492	Wholesale of stationary and other office goods
421	46499	Wholesale of other household goods n.e.c.
422	46510	Wholesale of computers, computer peripheral equipment and software
423	46521	Wholesale of electronic components
424	46522	Wholesale of telecommunications equipment and parts
425	46610	Wholesale of agricultural machinery, equipment and supplies
426	46620	Wholesale of machine tools
427	46630	Wholesale of mining, construction and civil engineering machinery
428	46640	Wholesale of machinery for the textile industry and of sewing and knitting machines
429	46650	Wholesale of office furniture
430	46660	Wholesale of other office machinery and equipment
431	46691	Wholesale of measuring and precision instruments
432	46692	Wholesale of computerized materials handling equipment
433	46699	Wholesale of other machinery and equipment n.e.c.
434	46710	Wholesale of solid, liquid and gaseous fuels and related products

435	46720	Wholesale of metals and metal ores
436	46731	Wholesale of wood and other construction materials
437	46732	Wholesale of sanitary equipment
438	46741	Wholesale of hardware
439	46742	Wholesale of plumbing and heating equipment
440	46750	Wholesale of chemical products
441	46761	Wholesale of industry supplies
442	46762	Wholesale of packaging materials
443	46769	Wholesale of other intermediate products n.e.c.
444	46771	Wholesale in car wrecks
445	46772	Wholesale of metal waste and scrap
446	46773	Wholesale of non-metal waste and scrap
447	46900	Non-specialised wholesale trade
448	47111	Retail sale in department stores and the like with food, beverages or tobacco predominating
449	47112	Retail sale in other non-specialised stores with food, beverages or tobacco predominating
450	47191	Other retail sale in department stores and the like
451	47199	Other retail sale in non-specialised stores n.e.c.
452	47210	Retail sale of fruit and vegetables in specialised stores
453	47220	Retail sale of meat and meat products in specialised stores
454	47230	Retail sale of fish, crustaceans and molluscs in specialised stores
455	47241	Retail sale of bread, cakes and flour confectionery in specialised stores
456	47242	Retail sale of sugar confectionery in specialised stores
457	47250	Retail sale of beverages in specialised stores
458	47260	Retail sale of tobacco products in specialised stores
459	47291	Retail sale of health foods in specialised stores
460	47299	Other retail sale of food in specialised stores n.e.c.
461	47300	Retail sale of automotive fuel in specialised stores
462	47410	Retail sale of computers, peripheral units and software in specialised stores
463	47420	Retail sale of telecommunications equipment in specialised stores
464	47430	Retail sale of audio and video equipment in specialised stores
465	47510	Retail sale of textiles in specialised stores
466	47521	Retail sale of wood and other building materials in specialised stores
467	47522	Retail sale of plumbing and heating equipment in specialised stores
468	47523	Retail sale of paints in specialised stores
469	47531	Retail sale of carpets, rugs, wall and floor coverings in specialised stores
470	47532	Retail sale of home furnishing textiles in specialised stores
471	47540	Retail sale of electrical household appliances in specialised stores
472	47591	Retail sale of home furniture in specialised stores
473	47592	Retail sale of office furniture in specialised stores
474	47593	Retail sale of glassware, china and kitchenware in specialised stores
475	47594	Retail sale of electrical fittings in specialised stores
476	47595	Retail sale of musical instruments and music scores in specialised stores
477	47610	Retail sale of books in specialised stores
478	47621	Retail sale of newspapers in specialised stores
479	47622	Retail sale of stationery in specialised stores
480	47630	Retail sale of music and video recordings in specialised stores
481	47641	Retail sale of sporting equipment except bicycles in specialised stores
482	47642	Retail sale of bicycles in specialised stores
483	47643	Retail sale of boats and boating accessories in specialised stores
484	47650	Retail sale of games and toys in specialised stores
485	47711	Retail sale of mens, womens and childrens clothing in specialised stores

486	47712	Retail sale of mens clothing in specialised stores
487	47713	Retail sale of womens clothing in specialised stores
488	47714	Retail sale of childrens clothing in specialised stores
489	47715	Retail sale of furs in specialised stores
490	47721	Retail sale of footwear in specialised stores
491	47722	Retail sale of leather goods in specialised stores
492	47730	Dispensing chemist
493	47740	Retail sale of medical and orthopaedic goods in specialised stores
494	47750	Retail sale of cosmetic and toilet articles in specialised stores
495	47761	Retail sale of flowers, plants, seedsand fertilisers in specialised stores
496	47762	Retail sale of pet animals and pet food in specialised stores
497	47771	Retail sale of watches and clocks in specialised stores
498	47772	Retail sale of jewellery in specialised stores
499	47781	Retail sale of spectacles and other optical goods except photographic equipment in specialised stores
500	47782	Retail sale of photographic equipment in specialised stores
501	47783	Retail sale of art in specialised stores; art gallery activities
502	47784	Retail sale of coins and stamps in specialised stores
503	47789	Other retail sale in specialised stores n.e.c.
504	47791	Retail sale of antiques and second-hand books in stores
505	47792	Retail sale of other second-hand goods in stores
506	47793	Activities of auctioning houses
507	47810	Retail sale via stalls and markets of food, beverages and tobacco products
508	47820	Retail sale via stalls and markets of textiles, clothing and footwear
509	47890	Retail sale via stalls and markets of other goods
510	47911	Non-specialised retail sale via mail order houses or via Internet
511	47912	Retail sale of clothing via mail order houses or via Internet
512	47913	Retail sale of books and other media goods via mail order houses or via Internet
513	47914	Retail sale of computers and other electronic equipment via mail order houses or via Internet
514	47915	Retail sale of sports and leisure goods via mail order houses or via Internet
515	47916	Retail sale of household goods via mail order houses or via Internet
516	47917	Internet retail auctions
517	47919	Other retail sale via mail order houses or via Internet
518	47991	Retail sale on commission
519	47992	Ambulatory and occasional retail sale of food
520	47993	Ambulatory and occasional retail sale of other goods
521	47994	Auctions not in stores or Internet
522	47999	Retail sale not in stores, stalls or markets n.e.c.
523	49100	Passenger rail transport, interurban
524	49200	Freight rail transport
525	49311	Urban and suburban road passenger transport
526	49319	Other urban and suburban passenger land transport
527	49320	Taxi operation
528	49390	Other passenger land transport n.e.c.
529	49410	Freight transport by road
530	49420	Removal services
531	49500	Transport via pipeline
532	50101	Scheduled sea and coastal passenger water transport
533	50102	Non-scheduled sea and coastal passenger water transport
534	50201	Scheduled sea and coastal freight water transport
535	50202	Non-scheduled sea and coastal freight water transport
536	50301	Scheduled inland passenger water transport
537	50302	Non-scheduled inland passenger water transport
538	50401	Scheduled inland freight water transport
539	50402	Non-scheduled inland freight water transport
540	51101	Scheduled passenger air transport
541	51102	Non-scheduled passenger air transport

542	51211	Scheduled freight air transport
543	51212	Non-scheduled freight air transport
544	51220	Space transport
545	52100	Warehousing and storage
546	52211	Towing incidental to land transportation
547	52219	Other service activities incidental to land transportation
548	52220	Service activities incidental to water transportation
549	52230	Service activities incidental to air transportation
550	52241	Harbour cargo handling
551	52249	Other cargo handling
552	52290	Other transportation support activities
553	53100	Postal activities under universal service obligation
554	53201	Other postal activities
555	53202	Courier activities
556	53203	Newspaper distribution
557	55101	Hotels with restaurant except conference centres
558	55102	Lodging activities of conference centres
559	55103	Hotels without restaurant
560	55201	Youth hostels
561	55202	Other short-stay accommodation
562	55300	Camping grounds, recreational vehicle parks and trailer parks
563	55900	Other accommodation
564	56100	Restaurants and mobile food service activities
565	56210	Event catering activities
566	56291	Canteens
567	56292	Catering for hospitals
568	56293	Catering for schools, welfare and other institutions
569	56294	Catering for the transport sector
570	56299	Other catering
571	56300	Beverage serving activities
572	58110	Book publishing
573	58120	Publishing of directories and mailing lists
574	58131	Publishing of daily newspapers
575	58132	Publishing of advertising newspapers
576	58140	Publishing of journals and periodicals
577	58190	Other publishing activities
578	58210	Publishing of computer games
579	58290	Other software publishing
580	59110	Motion picture, video and television programme production activities
581	59120	Motion picture, video and television programme post-production activities
582	59130	Motion picture, video and television programme distribution activities
583	59140	Motion picture projection activities
584	59200	Sound recording and music publishing activities
585	60100	Radio broadcasting
586	60200	Television programming and broadcasting activities
587	61100	Wired telecommunications activities
588	61200	Wireless telecommunications activities
589	61300	Satellite telecommunications activities
590	61900	Other telecommunications activities
591	62010	Computer programming activities
592	62020	Computer consultancy activities
593	62030	Computer facilities management activities
594	62090	Other information technology and computer service activities
595	63110	Data processing, hosting and related activities
596	63120	Web portals
597	63910	News agency activities
598	63990	Other information service activities n.e.c.
599	64110	Central banking
600	64190	Other monetary intermediation
601	64201	Activities of financial holding companies
602	64202	Activities of non-financial holding companies
603	64301	Investment funds
604	64309	Other trusts, funds and similar financial entities
605	64910	Financial leasing
606	64920	Other credit granting
607	64991	Activities of investment companies and venture capital companies
608	64992	Trading in securities on own account
609	64993	Trading in securities for a limited and closed group of owners

610	64999	Various other financial service activities, except insurance and pension funding n.e.c.
611	65111	Unit link insurance
612	65119	Other life insurance
613	65120	Non-life insurance
614	65200	Reinsurance
615	65300	Pension funding
616	66110	Administration of financial markets
617	66120	Security and commodity contracts brokerage
618	66190	Other activities auxiliary to financial services, except insurance and pension funding
619	66210	Risk and damage evaluation
620	66220	Activities of insurance agents and brokers
621	66290	Other activities auxiliary to insurance and pension funding
622	66301	Investment fund management activities
623	66309	Other fund management activities
624	68100	Buying and selling of own real estate
625	68201	Renting and operating of own or leased dwelllings
626	68202	Renting and operating of own or leased industrial premises
627	68203	Renting and operating of own or leased other premises
628	68204	Property management of tenant-owners associations
629	68209	Other renting and operating of own or leased real estate
630	68310	Real estate agencies
631	68320	Management of real estate on a fee or contract basis
632	69101	Legal advisory and representation activities of solicitors firms
633	69102	Other legal advisory activities
634	69103	Advisory activities concerning patents and copyrights
635	69201	Accounting and bookkeeping activities
636	69202	Auditing activities
637	69203	Tax consultancy
638	70100	Activities of head offices
639	70210	Public relations and communication activities
640	70220	Business and other management consultancy activities
641	71110	Architectural activities
642	71121	Construction and civil engineering activities and related technical consultancy
643	71122	Industrial engineering activities and related technical consultancy
644	71123	Electric engineering activities and related technical consultancy
645	71124	Engineering activities and related technical consultancy in energy, environment, plumbing, heat and air-conditioning
646	71129	Other engineering activities and related technical consultancy
647	71200	Technical testing and analysis
648	72110	Research and experimental development on biotechnology
649	72190	Other research and experimental development on natural sciences and engineering
650	72200	Research and experimental development on social sciences and humanities
651	73111	Advertising agency activities
652	73112	Delivery of advertising material
653	73119	Other advertising activities
654	73120	Media representation
655	73200	Market research and public opinion polling
656	74101	Industrial and fashion design
657	74102	Graphic design
658	74103	Activities of interior decorators
659	74201	Portrait photography
660	74202	Advertising photography
661	74203	Press and other photography
662	74204	Photographic laboratory activities
663	74300	Translation and interpretation activities
664	74900	Other professional, scientific and technical activities n.e.c.
665	75000	Veterinary activities
666	77110	Renting and leasing of cars and light motor vehicles
667	77120	Renting and leasing of trucks
668	77210	Renting and leasing of recreational and sports goods
669	77220	Renting of video tapes and disks
670	77290	Renting and leasing of other personal and household goods

671	77310	Renting and leasing of agricultural machinery and equipment
672	77320	Renting and leasing of construction and civil engineering machinery and equipment
673	77330	Renting and leasing of office machinery and equipment (including computers)
674	77340	Renting and leasing of water transport equipment
675	77350	Renting and leasing of air transport equipment
676	77390	Renting and leasing of other machinery, equipment and tangible goods n.e.c.
677	77400	Leasing of intellectual property and similar products, except copyrighted works
678	78100	Activities of employment placement agencies
679	78200	Temporary employment agency activities
680	78300	Other human resources provision
681	79110	Travel agency activities
682	79120	Tour operator activities
683	79900	Other reservation service and related activities
684	80100	Private security activities
685	80200	Security systems service activities
686	80300	Investigation activities
687	81100	Combined facilities support activities
688	81210	General cleaning of buildings
689	81221	Other building cleaning activities
690	81222	Chimney cleaning
691	81290	Other cleaning activities
692	81300	Landscape service activities
693	82110	Combined office administrative service activities
694	82190	Photocopying, document preparation and other specialised office support activities
695	82200	Activities of call centres
696	82300	Organisation of conventions and trade shows
697	82910	Activities of collection agencies and credit bureaus
698	82920	Packaging activities
699	82990	Other business support service activities n.e.c.
700	84111	Executive and legislative administration of central and local government
701	84112	Inspection, control, permit and licensing activities of central and local government
702	84113	Fiscal activities
703	84114	Public dissemination of information
704	84115	Supporting service activities for the government as a whole
705	84121	Administration of primary and secondary education
706	84122	Administration of higher education and research
707	84123	Administration of health care
708	84124	Administration of social welfare
709	84125	Administration of culture, environment, housing etc. programmes
710	84131	Administration of infrastructure programmes
711	84132	Administration of programmes relating to agriculture, forestry and fishing
712	84133	Administration of labour market programmes
713	84139	Administration of other business, industry and trade programmes
714	84210	Foreign affairs
715	84221	Military defence activities
716	84222	Defence support activities
717	84223	Civil defence activities
718	84231	Public prosecutor activities
719	84232	Law court activities
720	84233	Detention and rehabilitation of criminals
721	84240	Public order and safety activities
722	84250	Fire service activities
723	84300	Compulsory social security activities
724	85100	Pre-primary education
725	85201	Compulsory comprehensive school education and pre-school class
726	85202	Special school primary education
727	85311	General secondary education
728	85312	Municipal adult education
729	85321	Technical and vocational secondary education
730	85322	Special school secondary education
731	85323	Other secondary education

732	85324	School activities for occupational drivers
733	85410	Post-secondary non-tertiary education
734	85420	Tertiary education
735	85510	Sports and recreation education
736	85521	Activities of municipal culture schools
737	85522	Other cultural education
738	85530	Driving school activities
739	85591	Labour market training
740	85592	Folk high school education
741	85593	Activities of adult education associations
742	85594	Staff training
743	85599	Various other education n.e.c.
744	85600	Educational support activities
745	86101	Hospital primary health activities
746	86102	Specialised hospital somatic activities
747	86103	Specialised hospital psychiatric activities
748	86211	General primary medical practice activities
749	86212	Other general medical practice activities
750	86221	Specialist medical practice activities, at hospitals
751	86222	Specialist medical practice activities, not at hospitals
752	86230	Dental practice activities
753	86901	Activities of medical laboratories etc.
754	86902	Ambulance transports and ambulance health care activities
755	86903	Primary health activities, not physicians
756	86904	Activities of dental hygienists
757	86905	Activities of physiotherapists etc.
758	86909	Other human health activities n.e.c.
759	87100	Residential nursing care activities
760	87201	Care in special forms of accommodation for persons with mental retardation and mental disability
761	87202	Care in special forms of accommodation for children and young people with substance abuse problems
762	87203	Care in special forms of accommodation for adults with substance abuse problems
763	87301	Care in special forms of accommodation for the elderly
764	87302	Care in special forms of accommodation for disabled persons
765	87901	Twenty-four hours care with accommodation for children and young people with social problems
766	87902	Care with accommodation for adults n.e.c.
767	88101	Social work activities without accommodation for the elderly
768	88102	Social work activities without accommodation for disabled persons
769	88910	Child day-care activities
770	88991	Social work activities for children and young people with social problems
771	88992	Day-care activities for adults with substance abuse problems
772	88993	Social work activities without accommodation for adults n.e.c.
773	88994	Humanitarian relief activities
774	88995	Operation of refugee camps
775	90010	Performing arts
776	90020	Support activities to performing arts
777	90030	Artistic creation
778	90040	Operation of arts facilities
779	91011	Library activities
780	91012	Archives activities
781	91020	Museums activities
782	91030	Operation of historical sites and buildings and similar visitor attractions
783	91040	Botanical and zoological gardens and nature reserves activities
784	92000	Gambling and betting activities
785	93111	Operation of ski facilities
786	93112	Operation of golf courses
787	93113	Operation of motor racing tracks
788	93114	Operation of horse race tracks
789	93119	Operation of arenas, stadiums and other sports facilities
790	93120	Activities of sport clubs
791	93130	Fitness facilities
792	93191	Horse racing activities
793	93199	Other sports activities n.e.c.
794	93210	Activities of amusement parks and theme parks
795	93290	Other amusement and recreation activities
796	94111	Activities of business membership organisations

797	94112	Activities of employers' membership organisations
798	94120	Activities of professional membership organisations
799	94200	Activities of trade unions
800	94910	Activities of religious organisations
801	94920	Activities of political organisations
802	94990	Activities of other membership organisations n.e.c.
803	95110	Repair of computers and peripheral equipment
804	95120	Repair of communication equipment
805	95210	Repair of consumer electronics
806	95220	Repair of household appliances and home and garden equipment
807	95230	Repair of footwear and leather goods
808	95240	Repair of furniture and home furnishings
809	95250	Repair of watches, clocks and jewellery
810	95290	Repair of other personal and household goods
811	96011	Washing and (dry-)cleaning for businesses and institutions
812	96012	Washing and (dry-)cleaning for households
813	96021	Hairdressing
814	96022	Beauty treatment
815	96030	Funeral and related activities
816	96040	Physical well-being activities
817	96090	Other personal service activities n.e.c.
818	97000	Activities of households as employers of domestic personnel
819	98100	Undifferentiated goods-producing activities of private households for own use
820	98200	Undifferentiated service-producing activities of private households for own use
821	99000	Activities of extraterritorial organisations and bodies

Supplementary Information for Chapter 5

Responsibility for food loss from a regional supply-chain perspective

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5.1 Sectoral classification

The classifications of the 19 sectors are '14 types of vegetables', 'other agricultural', three major food business stakeholders ('food manufacturing', 'food-related business and the social service industry', and 'restaurant and food service industry'), and 'other'. The 'Other agricultural' sector includes livestock because potatoes are used as food in industries such as dairy cattle farming and hogs. The aggregation of the three stakeholders in food-related businesses is listed in *SI* 5.2 below. The remining sectors listed in Japan's I-O table 2011 are aggregated into the 'other' sector.

5.2 List of aggregated food business sectors

Aggregated sector for analysis	**Japan National I-O classification**
Food manufacture	Meat
	Beef
	Pork
	Chicken meat
	Miscellaneous meat
	By-products of slaughtering and meat processing
	Processed meat products
	Bottled or canned meat products
	Dairy farm products
	Drinking milk
	Dairy products
	Frozen fish and shellfish
	Salted, dried or smoked seafood
	Bottled or canned seafood
	Fish paste
	Miscellaneous processed seafood
	Grain milling
	Milled rice
	Miscellaneous grain milling
	Flour and miscellaneous grain milled products
	Wheat flour
	Miscellaneous grain milled products
	Noodles
	Bread
	Confectionery
	Bottled or canned vegetables and fruits
	Preserved agricultural foodstuffs (except bottled or canned)

	Sugar Refined sugar Miscellaneous sugar and by-products of sugar manufacturing Starch Dextrose, syrup and isomerized sugar Animal oil and fats, vegetable oil and meal Vegetable oil Animal oils and fats Cooking oil Vegetable meal Condiments and seasonings Prepared frozen foods Retort foods Dishes, sushi and lunch boxes School lunch (public) School lunch (private) Miscellaneous foods Refined sake Malt liquors Whiskey and brandy Miscellaneous liquors Soft drinks
Restaurant and food service industry	Eating and drinking services
Food related business and social services	Hotels Sport facility service, public gardens and amusement parks Ceremonial occasions Medical service (hospitalisation) Medical service (dentistry) Medical service (miscellaneous medical service) Social welfare (public) Social welfare (private, non-profit) Social welfare (profit-making) Nursing care (facility services) Nursing care (except facility services) Services relating to air transport Private non-profit institutions serving households, n.e.c.

Supplementary Information for Chapter 6

The carbon footprint of global tourism

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6.1 Methods

Carbon footprint analyses have recently been carried out using a hybrid method (Bullard et al. 1978a; Suh and Nakamura 2007), combining detailed bottom-up process information about the system under study with comprehensive top-down I-O data on the background economy (Minx et al. 2009; Wiedmann 2009). This choice of method holds a number of benefits. Most importantly, it circumvents the problem of systematic truncation errors due to setting of finite system boundaries (Suh et al. 2004) whilst at the same time guaranteeing complete coverage of upstream supply chain contributions (Moskowitz and Rowe 1985). Here, "complete coverage" means that all upstream supply chain contributions such as emissions embodied in anything that a "tourist" as per UNWTO definition (*SI* 2.1) consumes – food, accommodation, transport, fuel, and shopping – are included in the footprint measure. Second, I-O-assisted carbon footprinting is supported by a long history of numerous applications (see for example Hoekstra 2010). Third, international standards on integrated physical and monetary accounting by the United Nations (UN 1999; UNSD 2014) mean that I-O-based footprint analyses can be undertaken with consistent scope on a number of complementary indicators, such as energy (Lan et al. 2016), biodiversity (Lenzen et al. 2012b), air pollution (Kanemoto et al. 2014b), water (Feng et al. 2011), land (Moran et al. 2013), nitrogen (Oita et al. 2016) and material flow (Wiedmann et al. 2015). Finally, a number of very detailed large-scale global MRIO databases have recently become available (Tukker and Dietzenbacher 2013). As a result, carbon footprint analyses incorporating the global international trade network are now almost routinely carried out (Hertwich and Peters 2009). Auxiliary analyses and tools have been developed, touching on issues related to causal driver identification (Arto and Dietzenbacher 2014; Xu and Dietzenbacher 2014; Malik et al. 2016), aggregation bias (Su and Ang 2010; Su et al. 2010; Zhou et al. 2013; Steen-Olsen et al. 2014), sensitivity (Wilting 2012) and uncertainty (Lenzen et al. 2010), database comparisons (Arto et al. 2014; Inomata and Owen 2014; Moran and Wood 2014; Owen et al. 2014), and corporate reporting (Huang et al. 2009). Global carbon footprints have featured prominently in policy and the media (BBC News 2008; Peters and Hertwich 2008b; BBC News 2009; Lenzen et al. 2010; Atkinson et al. 2011; Barrett et al. 2013; Wiedmann and Barrett 2013).

One interesting aspect in carbon footprints not only of tourism is what can be described as *additionality*, or *systemic* or *rebound effects*, meaning for example that the carbon footprint of a wind turbine could include a credit for displaced coal or gas, and an addition for the increased need of grid balancing and back-up (Pehnt 2006); or the carbon footprint of a recommended diet could include the carbon footprint of those commodities that are purchased with the money saved (since the recommended diet is generally cheaper) (Lenzen and Dey 2002); or the carbon footprint of defense spending could be offset against the carbon footprint of the portfolio that the government funds would alternatively be spent on (Heyes and Liston-Heyes 1993). In the context of the tourism carbon footprint: if visitors had not embarked on their journey, they would have eaten and travelled at home, giving rise to the question of whether the carbon footprint of tourism should be net of carbon emissions associated with such alternative activities, or in other words, should only comprise *additional* emissions (in the sense of the Clean Development Mechanism, Shrestha and Timilsina 2002). In this work, we do not attempt to quantify additionality, systemics and rebounds, because of a number of reasons. First, footprint or consequential LCA studies that include such rebounds or systemic changes are rare at the national level (Heyes and Liston-Heyes 1993; Lenzen and Dey 2002; Pehnt 2006), and virtually absent at the global level, because of the inherent difficulty in specifying and estimating the often complex, alternative scenarios that would have occurred in the absence of the activities under investigation. Offsetting food consumption, shopping and travel behavior of tourists against their practices at home, for all individual countries and five years, requires information that is clearly not available. The majority of footprint and LCA studies generally view the so-called functional unit as a clear-cut, distinct entity, including every activity that fell within the scope of the study (Minx et al. 2009), and without the requirement of capturing wider systemic effects (Wiedmann and Minx 2008). In the context of tourism this means accepting as a fact that tourists do not eat at home but at their destination, and that the food consumed must be considered as one necessary component for realising – in LCA parlance – the functional unit "visit". Second, past practices aside, we must not simply omit, for example, the food eaten at the tourist destination from the footprint calculation, because the consumption patterns of tourists are found to be different from their lifestyle at home. Visitors tend to use more private transportation than public transportation (Le-Klähn and Hall 2014), consume more water (Gössling et al. 2012), and eat more processed food (especially alcoholic drinks and meat products – see also Fig. *SI* 6.6) (Collins et al. 2007). Third, in our case, including food consumption is important in the case of international tourism, because these purchases by visitors increase the carbon footprint of destinations, as opposed to the carbon footprints of the visitors' home country. This matters for international embodied carbon transfers (Peters et al. 2011).

See separate online-only methods section for details on the methodology used in this article.

6.2 TSAs, data processing and uncertainty

6.2.1 The TSA concept

The TSA concept was proposed by the United Nations and other multi-lateral organisations in 1993 to provide a comprehensive and consistent evaluation framework for documenting the economic contribution of tourism consumption to a national economy (United Nations 1993). This framework first provides a definition and measurement regarding visitor and their consumption, ensuring a consistent base for individual regions to gauge the scale of tourism activities. Based on the United Nations (UN) and the World Tourism Organisation (WTO; hereafter UNWTO), a tourist is defined as "*he/she is taking a trip or a visit to a place outside his/her usual environment for less than a year and for a purpose other than being employed by a resident entity there*" while tourist expenditure as "*the amount paid for the acquisition of consumption goods and services as well as valuables, for own use or to give away, for and during tourism trips*" (UNSD-EUROSTAT-OECD-WTO 2008). In the following we will use the terms "tourist" and "visitor" synonymously.

The compilation of a TSA proceeds by first estimating total visitor expenditure by major items, and then bridge the type of visitor expenditures with the supply of tourism products to indicate the proportion of supply by industries that is contributed by visitors. A ratio between tourism consumption and total value of output of an industry (accommodation, air transportation or entertainment services) is calibrated to portray the significance of tourism to the sales of this specific sector. The sum across tourism sales from sectors that are directly serving visitors then provides an economic estimate that is consistent under the Systems of National Account (SNA). Besides visitor consumption, a broader TSA also measures the contribution to investment in fixed capital by businesses, and quantifies the value provided by certain non-profit organisations and governments to serve visitors (Frechtling 1999). Due to the cost- and labour-intensiveness of data collection, most countries currently focus only on the main core of a TSA, presenting the economic activities associated with direct tourist monetary consumption, without explicitly addressing other components of services associated with vacation accommodation on own account, tourism social transfers in kind, and other imputed consumption types (Libreros et al. 2006). The coverage of our analysis is therefore limited to carbon emissions associated with annual tourist consumption in cash.

The UNWTO recommends that tourism expenditure is measured and reported by products based on the Central Product Classification (CPC) 5-digit system. While each country is allowed to adjust the CPC based on country-specific context, the most commonly adopted categories are package travel, accommodation, food and beverage, local transport, international transport, transport equipment rental, recreation, shopping and others. Transport sectors can be further segmented by railway, road, water and air depending on data availability.

6.2.2 Compiling a set of TSAs

To compile a global visitor expenditure database, our search for the individual TSA reports starts with a list from the UNWTO, identifying around 60 countries that in 2010 had produced or were currently developing a TSA exercise (World Tourism Organisation 2010). Electronic resources from the UNWTO, OECD, EU, governmental reports, or journal articles were searched in order to locate national TSA consumption data. Finally, we identified 55 full TSA reports from major tourism countries, covering around 88% (2009 – 87.2%, 2010 – 88.3%, 2011 – 88.3%, 2012 – 88.1%, 2013 – 88.1%) of the global tourism consumption.

The TSA reports collected from individual countries are expressed at a different level of resolution, with various degrees of disaggregation across tourist groups and consumption items. This creates a problem in the process of calibrating the national tourism carbon emissions. We dealt with these data inconsistency problems as follows:

6.2.2.1 Dealing with a lack of disaggregated information

The first data challenge is the lack of a detailed disaggregation of consumption by visitor types. The UNWTO recommends trip expenditure to be reported by two visitor categories (exemplified for the TSA of country s):

i. Domestic tourism expenditure ($\tilde{y}_{j1}^{ss}$): this includes two sub-categories:
   1) tourism expenditure by resident visitors within the economy of reference for their domestic travel, and
   2) tourism expenditure by residents within the national boundary for their outbound travel. This includes purchases directly associated with the outbound trip (such as suitcases or camera), local transportation to/from the airport, and

international airfares paid to national airlines registered in the economy of reference.

ii. Inbound tourism expenditure (an export of country s to residents of countries t; $\tilde{y}_{j1}^{st}$ where $t \neq s$): Tourism expenditure by foreign visitors within the economy of reference. This includes all spending at destination, and international airfares paid to national airlines registered in the economy of reference.

Separating visitor consumption by visitor categories provides advantages for quantifying economic contributions and carbon responsibilities. While domestic tourism expenditure can be seen as a process of income-redistribution, inbound tourism expenditure functions as an export, earning foreign payments and leading to a net increase of GDP. Estimating tourism carbon footprints based on such separated data allows a direct assessment on the trade-off between economic impacts and environmental externalities for developing domestic versus inbound tourism. In addition, differentiating journeys made by residents versus visitor groups from foreign residences is a major prerequisite for assigning carbon responsibility: The RBA principle and the DBA principle both require linking residence information with consumer and producer establishments, respectively. This separation allows tourism carbon emissions to be discussed from the perspectives of origin countries, destination countries, or the rest of world (RoW).

One third of our collected TSA reports document expenditure of categories j from different visitor groups, whilst the remainder just reports one aggregated total. To break down aggregated expenditure into parts for domestic and inbound tourism, we use parameters reported by the WTTC (WTTC 2010-2014) in their annual economic impact analysis report for more than 100 countries. In these country reports, domestic and foreign tourist expenditure are estimated separately, providing a direct ratio for disaggregation from the TSAs into domestic and international spending, $\tilde{y}_{j1}^{ss}$ and $\tilde{y}_{j1}^{s.}$.

6.2.2.2 Temporal inconsistencies

The second data challenge is the inconsistency in time: Some countries only possess full TSA data for the early 1990s, while other countries have up-to-date information (to 2015 at the time of writing). To provide a compatible and consistent study basis, we updated the TSA reports of 55 countries into the same study period, 2009~2013. This required country-specific demand indicators to proxy the changes of domestic and inbound tourist consumption over time. Either visitor consumption data or arrival data, from the national tourism offices and WTO, were utilized to update TSA results from the base year to the projected period.

For those 139 countries without a TSA, data on total inbound visitor expenditure were first retrieved from the (UNWTO 2009-2013). Supplementing these with parameters that specify percentages of domestic vs. inbound tourism spending (WTTC 2010-2014), we are able to estimate 2009~2013 total visitor expenditure for any given country.

6.2.3 Estimate inbound visitor consumption by country of departure

After compiling a global longitudinal visitor expenditure database, the next step is to establish the origin-destination (O-D) pattern for inbound travel. Inbound tourism expenditure reported by the standard TSA only report one aggregate number without identifying point of origin (departure country) of foreigners or their associated spending. To estimate inbound spending to destination *s* from individual countries t, we use origin- and destination-specific data from the World Tourism Organisation (UNWTO 2009-2013) containing "*arrivals of non-resident visitors at national borders by country of residence*", as a proxy to allow us to estimate normalized weights w^{st} for allocating the inbound tourism expenditure $\tilde{y}_{j1}^{st} = w^{st}\left(\tilde{y}_{j1}^{s\cdot}\right)$ across countries of residence t of inbound visitors. While UNWTO data are complete for about 80% total visitor movements (2009 – 79.8%, 2010 – 94.5%, 2011 – 95.6%, 2012 – 95.8%, 2013 – 95.6%), additional steps are taken to estimate the bilateral travel flows. First, official inbound/outbound data published by individual tourism authority are manually searched online for important destinations countries across five continents. Secondly, for the remaining missing component, the bilateral travel flow is estimated based on the gravity model assumption (Chasapopoulos et al. 2014; Morley et al. 2014), which allocates the undistributed inbound visits to the remaining departure countries in a direct proportion to the gross national GDP of the visitor's country (approximating purchasing power for tourism activities), and in inverse proportion to the distance between two countries (approximating cost of journey).

6.2.4 Dealing with international transport

As stipulated by the Kyoto Protocol, emissions from international aviation and shipping (aircraft and shipping bunkers) are excluded from reporting to the United Nations Framework Convention on Climate Change (UNFCCC), because of methodological incompleteness and inconsistencies (Rypdal 2001), in particular the difficulty of allocating emissions to either the country of journey origin, destination, or airline / shipping ownership. It was agreed instead to work on reducing emissions from aircraft through the International Civil Aviation Organisation and International Maritime Organisation, respectively.

Assigning international transport emissions in the context of tourism is an important but a complex issue. Cross-board aviation accounts for as much as 40% of direct tourism carbon emission and, in some instances, is projected to increase to more than 85% of total emissions for certain countries by 2050 (Dubois and Ceron 2006). Although the importance of international flights is greatly recognized, aviation emissions are handled differently by accounting principles, and by empirical applications. The territorial or Kyoto Protocol perspective would completely ignore emissions associated with international bunkers to be in line with the IPCC suggestions. The DBA approach takes a different perspective by including all the emissions produced by national carriers for its inbound, outbound and stop-over services. The RBA approach, on the other hand, traces the emissions of residents' round-trip flight to a specific country. The RBA output comprises air pollution emitted from domestic and foreign-registered airlines by a share contributed by its own residents. In terms of empirical applications, some may only take into account energy use by national carriers, while others may look into all flights by inbound visitors to the country (Dwyer et al. 2010). No consensus has been reached for dealing with the tourism aviation in the tourism context. Even so, it is stressed that this critical component should be included in the national accounting framework so that adequate tourism carbon efficiency can be established and compared across industries (Becken and Patterson 2006; Dwyer et al. 2010; de Bruijn et al. 2014; Sun 2014).

The scope of the national tourism carbon footprint calibrated in this study is based on visitor expenditure reported in the TSA, which documents all tourism economic activities within the national boundary, including national registered carriers (both aviation and marine transportation). In this approach, emissions are only attributable to the tourism sector of a country when the transaction creates an economic significance at the geographic territory. National carriers are included as their sales are documented in the Systems of National Account, and their energy use is allocated for the proportion contributed by inbound and outbound visitors arriving to and departing from the country. Internationally-registered carriers are assumed to leave no economic contribution and their emissions are excluded. The underlying logic for such a treatment is that the economic benefits of those transactions accrue to the destinations so that the host nation bears the responsibility to mitigate and control the national carriers' emissions (Peters and Hertwich 2008a; Sun 2014; 2016).

The United Nation's System of Environmental-Economic Accounting (SEEA, UNSD 2014) differs somewhat from UNFCCC guidelines. The German Federal Statistical Office (Statistisches Bundesamt 2011) writes: "*The Environmental-Economic Accounting concept is more comprehensive than the IPCC concept: In addition to the emissions according to the IPCC it includes the emissions arising from [...] international aviation and shipping. [...] The delimitations made in the Environmental-Economic Accounting are geared to the definitions and delimitations of the economic performance parameters used in the national accounts. According to the international system of national accounts (SNA 2008), the measurement of activities refers to the economic units (residents) in an economic area. This means that the calculation of energy consumption and CO2 emissions in Environmental-Economic Accounting is also based on the residence concept.*" This perspective implies that for the purposes of a carbon footprint, emissions from international travel are always allocated to the country of residence of the entity carrying out the economic activity, ie the visitor. As with any other commodity, such emissions are calculated based on

- expenditure of households on international transport $\tilde{y}^{st}_{\text{air transport,1}}$ as recorded in the final demand matrix, based on national I-O tables for expenditures on resident transport establishments, and based on statistics on trade in services (UN 2009; OECD 2010) for expenditures on non-resident transport establishments; and
- on the emissions intensities of the air transport sectors $q^{s}_{\text{air transport}}$ in the resident and non-resident economies, based on various data sources (see Section 2 in Kanemoto et al. 2014a).

For example, the direct CO_2 emissions associated with a German citizen flying on a UAE-based airline from Cyprus to Malta are part of Germany's carbon footprint, and are calculated as $q^{\text{UAE}}_{\text{air transport}} \times \tilde{y}^{\text{UAE,Germany}}_{\text{air transport,1}}$. Here the producer, emitter and final seller is r = s = UAE, and the consumer t = Germany. The direct CO_2 emissions associated with an

Australian citizen flying on an Australian airline from Fiji to Kiribati are part of Australia's carbon footprint, and are calculated as $q^{\text{Australia}}_{\text{air transport}} \times \tilde{y}^{\text{Australia,Australia}}_{\text{air transport,1}}$.[1]

These examples show that the TSA and I-O accounting principles care only about the residence of the producing establishment, and that CO_2 emissions are allocated irrespective of country of origin and destination. Having said this, and given that most airlines operate flights to and from their resident country, in most cases at least one of origin or destination country is likely to coincide with the residence of the transport establishment.

6.2.5 Integrating TSA and MRIO data

A TSA captures economic transactions within the national boundary for visitors taking trips within, towards or from the country of reference. It does not reflect economic activities at foreign destinations from outbound travel nor airfares paid to foreign-based airlines. TSAs have been used before as the basis for consumption-based accounting (CBA) and for establishing I-O-based tourism carbon footprints, for example for Wales, UK (Munday et al. 2013), Taiwan (Sun 2014), Australia (Dwyer et al. 2010), Spain (Cadarso et al. 2015), and Switzerland (Perch-Nielsen et al. 2010). Integrating a TSA into the final-demand block of an MRIO database offers several advantages. First, the TSA conceptual framework and data compliance are comprehensive and consistent across nations, allowing inter-country comparisons on tourism economic significance, GHG emissions, and tourism eco-efficiency. Second, both the TSA and MRIO databases comply with the System of National Accounts, allowing individual destinations to benchmark their tourism development against other sectors in the economy in terms of both economic and environmental performance. Third, adopting the TSA concept offers a straightforward treatment of the international aviation issue. Aviation emissions are only attributable to the tourism sector of a country when the transaction of the air transportation creates an economic significance at the geographic territory.

[1] The I-O calculus also covers indirect emissions arising from air travel. To stick with one of the examples: the total CO_2 emissions associated with a German citizen flying on a UAE-based airline from Cyprus to Malta are part of Germany's carbon footprint, and are calculated as $\sum_{r,i} q^r_i L^{r,\text{UAE}}_{i,\text{air transport}} \times \tilde{y}^{\text{UAE,Germany}}_{\text{air transport,1}}$. This footprint component originates in a multitude of countries r and sectors i, depending on the supply chain network underlying the UAE air transport sector. This footprint may include contributions such as the 3rd-order supply chain $q^{\text{Canada}}_{\text{non-ferrous metal}} A^{\text{Canada,USA}}_{\text{non-ferrous metal,aircraft}} A^{\text{USA,UAE}}_{\text{aircraft,air transport}} \times \tilde{y}^{\text{UAE,Germany}}_{\text{air transport,1}}$ describing emissions by Canadian manufacturers of non-ferrous metal exported to the USA for making aircraft, which in turn are exported to the UAE for providing air transport to the German passenger.

Technically, TSA data enter Leontief's model as final demand[2] $\tilde{\mathbf{y}}$, where the 39 classifications of the original TSAs (Tab. *SI* 6.1) and the MRIO database are bridged using concordance matrices. A concordance matrix **C** shows an entry C_{ij} = 1 where TSA class *i* corresponds to MRIO class *j*, and 0 elsewhere.

Final demand in turn drives economic output $\tilde{\mathbf{x}} = (\mathbf{I} - \mathbf{T}\hat{\mathbf{x}}^{-1})^{-1}\tilde{\mathbf{y}}\mathbf{1}^{\mathbf{y}}$, which then causes the carbon footprint of tourism, $\tilde{Q} = \mathbf{q}\tilde{\mathbf{x}}$, as explained in *SI* 6.1.2.1.[3] Here, **T** is an $N\times N$ MRIO matrix listing international trade transactions (so-called intermediate demand) between countries, and **y** is an $N\times M$ matrix of final demand by M global agents (households, governments, the capital sector, stocks) of N products. Both matrices are expressed in units of money. The sum of intermediate and final demand equals total economic output $\mathbf{x} = \mathbf{T}\mathbf{1}^{\mathbf{T}} + \mathbf{y}\mathbf{1}^{\mathbf{y}}$, with $\mathbf{1}^{\mathbf{T}} = \underbrace{\{1,1,\dots,1\}'}_{N \text{ elements}}$ and $\mathbf{1}^{\mathbf{y}} = \underbrace{\{1,1,\dots,1\}'}_{M \text{ elements}}$ being suitable summation operators, and with the $'$ symbol denoting vector transposition. This accounting identity can be transformed into the fundamental I-O equation $\mathbf{x} = (\mathbf{I} - \mathbf{T}\hat{\mathbf{x}}^{-1})^{-1}\mathbf{y}\mathbf{1}^{\mathbf{y}}$, where **I** is an $N\times N$ identity matrix. This equation represents Leontief's demand-pull model of the economy (Leontief 1966), where the provision of final demand **y** requires – directly and indirectly via international trade routes throughout a global supply chain network – total output **x** to be produced (Dixon 1996). The matrix $(\mathbf{I} - \mathbf{T}\hat{\mathbf{x}}^{-1})^{-1}$ is Leontief's inverse.

Writing out the tensor products in this aggregate relationship for the scalar $\tilde{Q}$ allows unraveling carbon footprints into supplying and demanding regions, commodities and agents (Kanemoto et al. 2012). The most general breakdown of the carbon footprint in an MRIO setting is achieved by an element-wise product $\mathbf{q}\#\mathbf{L}\#\tilde{\mathbf{y}}$, or $\tilde{Q}^{rst}_{ijk} = q^r_i L^{rs}_{ij} \tilde{y}^{st}_{jk}$, where $\mathbf{L} = (\mathbf{I} - \mathbf{T}\hat{\mathbf{x}}^{-1})^{-1}$ is the Leontief inverse, and where r counts regions of production and therefore emissions, s regions of final sale (eg of airfares and food services, often the tourist destinations), t the regions of final demand (the residence of the visitors), i the commodities produced during emission, j the commodities consumed (airfares, hotels etc), and k the consuming agents (practically only households, k=1).

For further technical details, see *SI* 6.1.2.1.

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[2] According to the UNWTO, travel for business purposes is to be included in the official TSAs. The treatment of business trip expenses for I-O analysis is different across studies. Some authors argue that it should be treated as an intermediate input, not as final demand – see Libreros et al. 2006 However, in our global study this approach is impossible to implement, since there exists no information on the sectoral identity of the businesses in questions, let alone of which downstream sectors their business-travel carbon emissions would have to be passed on to under consumption-based accounting (CBA). Data availability aside, allocating business travel to final demand is unlikely to introduce a significant error, since a) private travel constitutes the clear majority of travel activities, and b) there is no double-counting problem since we do not compare the carbon footprint of tourism with the carbon footprint of commodities purchased from business-travelling establishments. Finally, from a conceptual perspective, including business travel into intermediate demand is undesirable since it would lead to significantly underestimating the global carbon footprint of tourism as defined by the UNWTO, since then the carbon emissions from business travel would become embodied in consumer goods and services that are unrelated to tourism activities, and hence missed.

[3] The $\sim$ symbol denotes a particular final demand stressor $\tilde{\mathbf{y}}$ for the Leontief model. This stressor does not normally satisfy the national accounting identity.

Tab. *SI* 6.1: 39-product group classification in the TSAs

A	Accommodation, food and beverage serving services
Aa	Accommodation services
Aa1	Hotels and similar (include motel)
Aa2	Imputed and actual rent on vacation homes
Aa3	Meals from accommodation
Ab	Food and beverage serving services
B	Transportation services
Ba	Passenger transport services
Ba1	Road transportation
Ba11	Railways passenger transport
Ba12	On-road passenger transport
Ba2	Air transportation
Ba3	Water transportation
Bb	Fuel and Other Automotive Products
Bb1	Fuel (petrol, diesel)
Bb2	Other Automotive Products
Bc	Transport equipment rental services
Bd	Repair and maintenance
Be	Passenger transport supporting services
C	Travel agency and tour operator services
D	Recreational, cultural and sporting services
E	Other tourism goods and services
Ea	Miscellaneous tourism services
Ea1	Education services
Ea2	Convention fees
Ea3	Medical services
Ea4	Financial and insurance services
Ea5	Postal and Communication Services
Ea6	Others
Eb	Other goods (shopping)
Eb1	Cosmetics & Skin Care / Perfume
Eb2	Electrical / Photographic Goods
Eb3	Foodstuff, Alcohol and Tobacco
Eb4	Garments / Fabric and Leather / Synthetic Goods
Eb5	Jewellery and Watch
Eb6	Medicine / Chines Herbs
Eb7	Souvenirs / Handicrafts and Gifts
Eb8	Other Items
TT	TOTAL

6.2.6 Uncertainty

Data quality and detail in the TSAs varies between countries, which is reflected in the different levels of the classification descriptors in Tab. *SI* 6.1 Some countries specify detailed types of tourist expenditures, but others just report sub-totals and/or totals. Lack of detail will have a particular influence on the carbon footprint of TSA classes E (Other tourism goods and services), Ea (Miscellaneous tourism services), Eb (Other goods – shopping), and TT (Total), because these classes are very broad and could potentially include a wide and varying mix of products with different emissions characteristics. We deal with this circumstance by including in our TSA-to-MRIO bridging concordance **C**, all possible goods and services that tourists could buy (most manufactured goods and commercial services, but no mining products, basic chemicals and metals, construction services, pipeline transport, and so on). We determine the mix of products bought at any particular tourist destination by distributing the sub-total or total expenditure on TSA classes E, Ea, Eb and TT across MRIO classes according to total sales of the destination country. For example, if sales of electronic goods are generally high in Japan, we assume that they are equally high in tourist's consumption basket. Obviously, if electronic goods were hardly sold in, say Gambia, then the expenditure of tourists to Gambia would not include them. Of course, this assumption carries a degree of uncertainty, since there may not be a proportionality between national sales and tourist consumption. Further sources of stochastic uncertainty exist within the measurement of primary data such as **Q** and **T** (Bullard and Sebald 1977).

In order to assess the influence of allocation and parametrical uncertainty on our carbon footprint results, we carry out a detailed uncertainty analysis, using error propagation (Lloyd and Ries 2007; Imbeault-Tétreault et al. 2013). The calculation of carbon footprints based on I-O analysis involves a matrix inversion ($\mathbf{L} = (\mathbf{I} - \mathbf{T}\hat{\mathbf{x}}^{-1})^{-1}$), and as a consequence analytical error propagation is not possible (Lenzen 2011). I-O researchers have gotten around this difficulty by resorting to Monte-Carlo approaches (Bullard and Sebald 1977; 1988; Nansai et al. 2001; Yoshida et al. 2002). Here, uncertainty is propagated using standard deviations (Lenzen et al. 2010) $\sigma_{\mathbf{Q}}, \sigma_{\mathbf{T}}$ and $\sigma_{\mathbf{y}}$ [sourced from the same MRIO database, Eora (Lenzen et al. 2012a; Lenzen et al. 2013), as constructed in the Global MRIO Virtual Laboratory (Lenzen et al. 2017)]. for perturbing the basic data items $\mathbf{Q}$, $\mathbf{T}$ and $\mathbf{y}$, then calculating perturbed carbon footprints, and then gathering these for a large number of perturbation runs. Standard deviations of derived carbon footprint measures are then taken from the statistical distribution of the perturbations. More specifically, we generate normally distributed random numbers $\nu \in \mathcal{N}(0|1)$ and use these perturb the basic footprint equation $\tilde{Q} = \mathbf{Q}\hat{\mathbf{x}}^{-1}(\mathbf{I} - \mathbf{T}\hat{\mathbf{x}}^{-1})\tilde{\mathbf{y}}$ to (Heijungs and Lenzen 2014)

$$\tilde{Q}^{\mathrm{p}} = \mathbf{Q}^{\mathrm{p}}\widehat{\mathbf{x}^{\mathrm{p}}}^{-1}\left(\mathbf{I} - \mathbf{T}^{\mathrm{p}}\widehat{\mathbf{x}^{\mathrm{p}}}^{-1}\right)\tilde{\mathbf{y}}^{\mathrm{p}}\,, \qquad (SI\ 2.1)$$

where $\mathbf{x}^{\mathrm{p}} = \mathbf{T}^{\mathrm{p}}\mathbf{1}^{N} + \mathbf{y}^{\mathrm{p}}$, and where the logarithmic perturbations

$$\mathbf{Q}^{\mathrm{p}} = 10^{\log_{10}\mathbf{Q} + \nu\sigma_{\log_{10}\mathbf{Q}}} \text{ and } \mathbf{T}^{\mathrm{p}} = 10^{\log_{10}\mathbf{T} + \nu\sigma_{\log_{10}\mathbf{T}}} \qquad (SI\ 2.2)$$

ensure that neither $\mathbf{Q}^{\mathrm{p}}$ nor $\mathbf{T}^{\mathrm{p}}$ will ever become negative (Heijungs and Lenzen 2014). Here, the standard deviation of logarithms can be approximated by Lenzen et al. 2010.

$$\sigma_{\log_{10}x} \approx \log_{10}(x + \sigma_x) - \log_{10}(x) = \log_{10}\left(\frac{x+\sigma_x}{x}\right). \qquad (SI\ 2.3)$$

The perturbation of the tourist demand stressor $\tilde{\mathbf{y}}$ to $\tilde{\mathbf{y}}^{\mathrm{p}}$ proceeds in a slightly different way. As discussed above, the uncertainty in $\tilde{\mathbf{y}}$ is more on of allocation, not of measurement. As such, we perturb the bridging procedure $\tilde{\mathbf{y}} = \mathbf{C} \times \mathbf{TSA}$ that translates from the 39 categories in the TSAs (Tab. *SI* 6.1) into the MRIO classification. More specifically, for MRIO region r we have $\tilde{y}_i^r = \sum_j C_{ij}^r \times TSA_j$, with the concordance bridge matrix $\mathbf{C}$ being normalized as $\sum_i C_{ij}^r = 1 \forall r, j$. Our approach to determining allocation uncertainty is to perturb the concordance matrix as $C^{\mathrm{p}}{}_{ij}^{r} = C_{ij}^r \zeta_{ij}^r / \sum_i C_{ij}^r \zeta_{ij}^r$, where the $\zeta_{ij}^r \in \mathcal{U}(1 - \bar{\zeta}|1 + \bar{\zeta})$ are uniformly distributed between $1 - \bar{\zeta}$ and $1 + \bar{\zeta}$. In our work, we use $\bar{\zeta} = 0.9$, which we think is a rather extreme way of simulating mis-allocation. To give a simple example, this procedure could mean that the initial allocation of, say 10% of TSA class shopping (Eb in Tab. *SI* 6.1) to MRIO class electronics and 10% to MRIO class clothing, can be perturbed to 1% electronics and 19% clothing. The perturbed tourist demand stressor is then $\tilde{\mathbf{y}}^{\mathrm{p}} = \mathbf{C}^{\mathrm{p}} \times \mathbf{TSA}$.

Finally, in our Monte-Carlo analysis, perturbations as in equation *SI* 2.1 are repeated P times, and outcomes $\tilde{Q}^{(p=1,\ldots,P)}$ collected. Finally, a normal distribution is fitted to a frequency plot of the $\tilde{Q}^{(p)}$, and the standard deviation $\sigma_{\tilde{Q}}$ derived from the fit. In order to obtain an accurate estimate of $\sigma_{\tilde{Q}}$, P needs to be large enough for the frequency plot of the $\tilde{Q}^{(p)}$ to be smooth. In this work, $P = 10^4$.

6.3 Additional data

6.3.1 Countries in our analysis and UN ISO-3 acronyms[4] used

Tab. *SI* 6.2: Country names and ISO-3 codes.

Country name	ISO-3 acronym
Afghanistan	Afg
Albania	Alb
Algeria	Dza
Angola	Ago
Argentina	Arg
Armenia	Arm
Australia	Aus
Austria	Aut
Azerbaijan	Aze
Bahrain	Bhr
Bangladesh	Bgd
Barbados	Brb
Belgium	Bel
Belize	Blz
Benin	Ben
Bolivia	Bol
Bosnia and Herzegovina	Bih
Botswana	Bwa
Brazil	Bra
Brunei Darussalam	Brn
Bulgaria	Bgr
Burkina Faso	Bfa
Burundi	Bdi
Cambodia	Khm
Cameroon	Cmr
Canada	Can
Cabo Verde	Cpv
Central African Republic	Caf
Chile	Chl
China	Chn
Colombia	Col
Congo	Cog
Costa Rica	Cri
Croatia	Hrv
Cuba	Cub
Cyprus	Cyp
Czech Republic	Cze
Côte d'Ivoire	Civ
D.R. of the Congo	Cod
Denmark	Dnk
Dominican Republic	Dom
Ecuador	Ecu
Egypt	Egy
El Salvador	Slv
Eritrea	Eri
Ethiopia	Eth
Fiji	Fji
Finland	Fin
France	Fra
French Polynesia	Pyf
Gambia	Gmb
Georgia	Geo
Germany	Deu
Ghana	Gha
Greece	Grc
Guatemala	Gtm
Guinea	Gin
Haiti	Hti
Honduras	Hnd
Hungary	Hun
India	Ind
Indonesia	Idn
Iran	Irn
Iraq	Irq
Ireland	Irl
Israel	Isr
Italy	Ita
Jamaica	Jam
Japan	Jpn
Jordan	Jor
Kazakhstan	Kaz
Kenya	Ken
Kuwait	Kwt
Kyrgyzstan	Kgz
Lao PDR	Lao
Latvia	Lva
Lebanon	Lbn
Liberia	Lbr
Libya	Lby
Lithuania	Ltu
Madagascar	Mdg
Malawi	Mwi
Malaysia	Mys
Maldives	Mdv
Mali	Mli
Malta	Mlt
Mauritius	Mus
Mexico	Mex
Mongolia	Mng
Morocco	Mar
Mozambique	Moz
Myanmar	Mmr
Namibia	Nam
Nepal	Npl
Netherlands	Nld
New Caledonia	Ncl
New Zealand	Nzl
Nicaragua	Nic
Niger	Ner
Nigeria	Nga
Norway	Nor
Oman	Omn
Pakistan	Pak
Panama	Pan
Papua New Guinea	Png
Paraguay	Pry
Peru	Per
Philippines	Phl
Poland	Pol
Portugal	Prt
Qatar	Qat
Republic of Korea	Kor
Romania	Rou
Russian Federation	Rus
Rwanda	Rwa
Samoa	Wsm
Saudi Arabia	Sau
Senegal	Sen
Serbia	Srb
Seychelles	Syc
Sierra Leone	Sle
Singapore	Sgp
Slovakia	Svk
Slovenia	Svn
South Africa	Zaf
Spain	Esp
Sri Lanka	Lka
Suriname	Sur
Sweden	Swe
Switzerland	Che
Syrian Arab Republic	Syr
Taiwan	Twn
Tajikistan	Tjk
Thailand	Tha
Macedonia	Mkd
Togo	Tgo
Trinidad and Tobago	Tto
Tunisia	Tun
Turkey	Tur
Uganda	Uga
Ukraine	Ukr
United Arab Emirates	Are
United Kingdom	Gbr
Tanzania	Tza
United States of America	Usa
Uruguay	Ury
Uzbekistan	Uzb
Vanuatu	Vut
Venezuela	Ven
Viet Nam	Vnm
Yemen	Yem
Zambia	Zmb
Zimbabwe	Zwe

6.3.1.1 List of member countries in the five annual per-capita GDP groups

[4] https://unstats.un.org/unsd/tradekb/Knowledgebase/50347/Country-Code.

Tab. *SI* 6.3a: Countries in the five annual per-capita GDP groups (supporting Figs. *SI* 6.2-6.4).

Class	Low	Low-middle	Middle	Middle-high	High
Income bracket (US$/cap)	<$1k	$1k-$4k	$4k-$8k	$8k-$25k	>$25k
Population (mill)	788.7	2523	1853	916.9	942.1
Countries	Afghanistan	Armenia	Albania	Argentina	Australia
	Bangladesh	Bolivia	Algeria	Bahrain	Austria
	Benin	Cambodia	Angola	Barbados	Belgium
	Burkina Faso	Cameroon	Azerbaijan	Botswana	Brunei
	Burundi	Congo	Belize	Brazil	Canada
	Central African Republic	Côte d'Ivoire	Bosnia and Herzegovina	Chile	Cyprus
	DR Congo	Egypt	Bulgaria	Costa Rica	Denmark
	Eritrea	Ghana	Cabo Verde	Croatia	Finland
	Ethiopia	Guatemala	China	Czech Republic	France
	Gambia	Honduras	Colombia	Hungary	French Polynesia
	Guinea	India	Cuba	Kazakhstan	Germany
	Haiti	Indonesia	Dominican Republic	Latvia	Greece
	Kenya	Kyrgyzstan	Ecuador	Lebanon	Ireland
	Liberia	Lao PDR	El Salvador	Lithuania	Israel
	Madagascar	Mongolia	Fiji	Malaysia	Italy
	Malawi	Morocco	Georgia	Maldives	Japan
	Mali	Nicaragua	Iran	Malta	Kuwait
	Mozambique	Nigeria	Iraq	Mauritius	Netherlands
	Myanmar	Pakistan	Jamaica	Mexico	New Caledonia
	Nepal	Papua NG	Jordan	Oman	New Zealand
	Niger	Philippines	Libya	Panama	Norway
	Rwanda	Senegal	Namibia	Poland	Qatar
	Sierra Leone	Sri Lanka	Paraguay	Portugal	Singapore
	Tajikistan	Syria	Peru	South Korea	Slovenia
	Togo	Ukraine	Samoa	Romania	Spain
	Uganda	Uzbekistan	Serbia	Russia	Sweden
	Tanzania	Viet Nam	South Africa	Saudi Arabia	Switzerland
	Zimbabwe	Yemen	Thailand	Seychelles	UAE
		Zambia	Macedonia	Slovakia	UK
			Tunisia	Suriname	USA
			Vanuatu	Taiwan	
				Trinidad & Tobago	
				Turkey	
				Uruguay	
				Venezuela	

Tab. *SI* 6.3b: Travelers in the three annual per-capita GDP groups.

Class	Low	Low	Middle	Middle	High	High
Bracket (US$/cap)	<2.9k	<2.9k	$ 2.9k -10.9k	$ 2.9k -10.9k	$1000k	$1000k
Population (mill)	2829	2829	2785	2785	1405	1405
Travelers	Afghanistan	Malawi	Albania	Jordan	Australia	New Caledonia
	Bangladesh	Mali	Algeria	Kazakhstan	Austria	New Zealand
	Benin	Mozambique	Angola	Lebanon	Bahrain	Norway
	Bolivia	Myanmar	Argentina	Libya	Barbados	Oman
	Burkina Faso	Nepal	Armenia	Malaysia	Belgium	Poland
	Burundi	Nicaragua	Azerbaijan	Maldives	Brunei Darussalam	Portugal
	Cambodia	Niger	Belize	Mexico	Canada	Qatar
	Cameroon	Nigeria	Bosnia and Herzegovina	Mongolia	Chile	Republic of Korea
	Central African Republic	Pakistan	Botswana	Morocco	Croatia	Russian Federation
	Congo	Papua New Guinea	Brazil	Namibia	Cyprus	Saudi Arabia
	Côte dIvoire	Philippines	Bulgaria	Panama	Czech Republic	Seychelles
	D.R. of the Congo	Rwanda	Cabo Verde	Paraguay	Denmark	Singapore
	Eritrea	Senegal	China	Peru	Finland	Slovakia
	Ethiopia	Sierra Leone	Colombia	Romania	France	Slovenia
	Gambia	Tajikistan	Costa Rica	Samoa	French Polynesia	Spain
	Ghana	Togo	Cuba	Serbia	Germany	Sweden
	Guinea	Uganda	Dominican Republic	South Africa	Greece	Switzerland
	Haiti	United Republic of Tanzania: Mainland	Ecuador	Sri Lanka	Hungary	Taiwan
	Honduras	Uzbekistan	Egypt	Suriname	Ireland	Trinidad and Tobago
	India	Viet Nam	El Salvador	Syrian Arab Republic	Israel	Turkey
	Kenya	Yemen	Fiji	Thailand	Italy	United Arab Emirates
	Kyrgyzstan	Zambia	Georgia	The former Yugoslav Republic of Macedonia	Japan	United Kingdom
	Lao Peoples Democratic Republic	Zimbabwe	Guatemala	Tunisia	Kuwait	United States
	Liberia		Indonesia	Ukraine	Latvia	Uruguay
	Madagascar		Iran (Islamic Republic of)	Vanuatu	Lithuania	Venezuela (Bolivarian Republic of)
			Iraq		Malta	
			Jamaica		Mauritius	
					Netherlands	

6.3.1.2 List of countries for which detailed national TSAs were sourced

Australia	Estonia	Korea	Portugal
Austria	Finland	Latvia	Romania
Brazil	France	Lithuania	Singapore
Bulgaria	Germany	Macao	Slovak
Canada	Honduras	Malaysia	Slovenia
Chile	Hong Kong	Mexico	South Africa
China	Hungary	Morocco	Spain
Colombia	Iceland	Netherlands	Sri Lanka
Croatia	India	New Zealand	Sweden
Cyprus	Indonesia	Norway	Switzerland
Czech Republic	Ireland	Oman	Taiwan
Denmark	Israel	Peru	United Kingdom
Ecuador	Italy	Philippines	United States
Egypt	Japan	Poland	

6.3.2 Greenhouse gases included, and their Global Warming Potentials

The Global Warming Potentials (GWP) allow for a comparison of the global warming impacts of different gases. Carbon dioxide is used as a reference point for the calculation of GWP of different gases. By definition, carbon dioxide has a GWP of 1. The GWPs are calculated for a specific time period, typically 100 years (IPCC 2017). Gases with a large GWP have a high warming potential, i.e. for a given amount of mass nitrous oxide traps more energy than methane. Hydrofluorocarbons, chloroflurocarbons, sulfur hexafluoride and nitrogen trifluoride are considered high GWP gases because they trap considerably more heat than carbon dioxide.

Tab. *SI* 6.4: Greenhouse gases and their Global Warming Potentials.

Species	**Chemical formula**	**Global Warming Potential**
Carbon dioxide	CO_2	1
Methane	CH_4	25
Nitrous oxide	N_2O	298
Hydrofluorocarbons	HFC	3772
Chlorofluorocarbon	CFC	8925
Sulfur hexafluoride	SF_6	22800
Nitrogen trifluoride	NF_3	17200

Sub-sonic aviation is responsible for the emission of a range of short-lived greenhouse gases that are not listed in Tab. *SI* 6.4. These include (Lee et al. 2010) NO_x responsible for the formation of tropospheric O_3 with a positive radiative forcing (RF; warming) and for the destruction of ambient CH_4 with a negative RF (cooling); sulphate particles from sulphur in the fuel (negative RF); soot particles (positive RF); contrails in the wake of an aircraft (positive RF); cloud formation (positive RF). Except for CO_2 emissions from the combustion of aircraft fuel, all other effects on global temperature increases are very poorly understood, highly uncertain, and lacking globally comprehensive databases across individual countries and multiple years. In addition, possibly except for aircraft-induced cloudiness and contrails, the effects of these short-lived greenhouse gases, in terms of a number of specifically developed emission metrics (Fuglestvedt et al. 2010), are likely to be smaller than those of fuel-borne CO_2. This is particularly true when applying a 50-year time horizon that matches contemporary policy targets.

6.3.3 Commodity acronyms used in *SI* 6.4.2 and 6.4.5.

Tab. *SI* 6.5: Commodity acronyms and full sector names.

Sector acronyms	Sector names	Notes
Ag	Agriculture	
Min	Mining	- The general classes 'Hospitality' and 'Transport' are due to data that do not allow distinguishing hotels and restaurants, and transport modes, respectively.
Food	Food	- 'Transport' is mostly road transport based on modal data by the WTO.
Good	Goods	- 'Goods' and 'Services' are goods and services other than those covered by the other categories, restricted to those items that visitors typically buy (that is excluding construction materials, livestock, electricity etc).
Utils	Utilities	- "Agriculture" includes hunting and fishing, and "Utilities" include electricity, gas and water.
Constr	Construction	
Trade	Trade	
Hosp	Hospitality	
Acc	Accommodation	
Rest	Restaurants	
Trans	Transport	
Road	Road Transport	
Rail	Rail Transport	
Air	Air Transport	
Water	Water Transport	
Serv	Services	

6.4 Detailed results

In the following, we will use the term "carbon footprint" to mean the footprint of global tourism in units of CO_2 equivalents (CO_2-e), even though this measure includes greenhouse gases such as N_2O that do not contain carbon. Greenhouse gases included in our analysis are listed in *SI* 6.3.2.

6.4.1 Global tourism carbon footprint estimates for 2009-2013

On the back of a growth in tourist expenditure from 2.5 $tr in 2009 to 4.7 $tr in 2013, the global carbon footprint increased rapidly from 3.9 Gt CO_2-e to 4.4 Gt CO_2-e during the same period. More than half of this carbon footprint was caused in high-income country destinations (DBA perspective; left column in Fig. *SI* 6.2), and by visitors from high-income countries (RBA perspective; right column in Fig. *SI* 6.2).

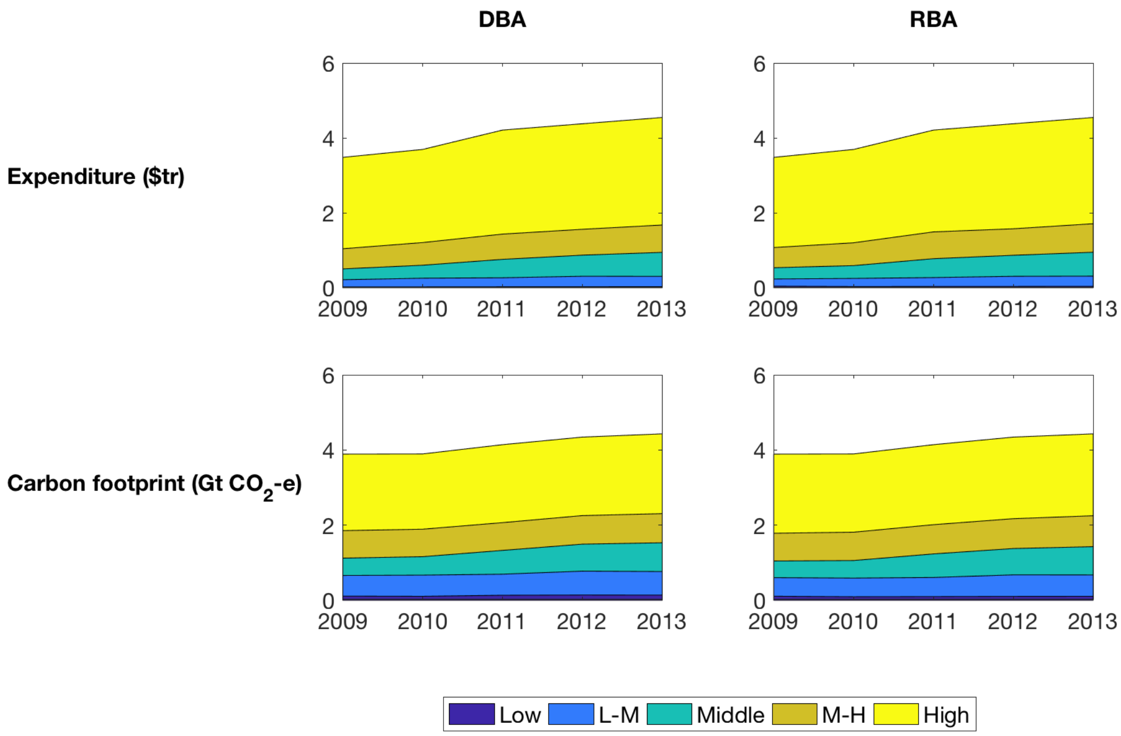

Fig. *SI* 6.2: Evolution of the expenditure and carbon footprint of global tourism between 2009 and 2013, clockwise from top right: $\tilde{y}^{.t}_{.1}$, $\tilde{Q}^{..t}_{..1}$, $\tilde{Q}^{.s.}_{..1}$, $\tilde{y}^{s.}_{.1}$. Coloured bands represent five income groups containing approximately 35 countries each (see membership in *SI* 6.3.1.1), starting from low-income (L; purple) to high-income (H; yellow).

Note: The five annual per-capita GDP brackets are L <$1k, L-M $1k-$4k, M $4k-$8k, M-H $8k-$25k, H >$25k. Average annual growth rates in the income bands are 2.4% (L), 9.3% (L-M), 23.9% (M), 7.1% (M-H) and 3.4% (H).

We present per-capita results in addition to totals, in order to show a) who – as a host – suffers a large burden from tourism, and b) who exerts the pressure that leads to these burdens. In this context we use the terms "net travelers" and "net hosts".

A per-capita-based view of the global carbon footprint of tourism (Fig. *SI* 6.3) confirms the trends in totals. Driven by increasing levels of expenditure, high-income-country per-capita carbon footprints surpass 2 tonnes, more than 10 times higher than those for low-income countries. Again, there is no clear distinction between the DBA and RBA accounting perspectives: per-capita carbon footprints are high in high-income destinations (bottom left) as well as for high-income visitors (bottom right).

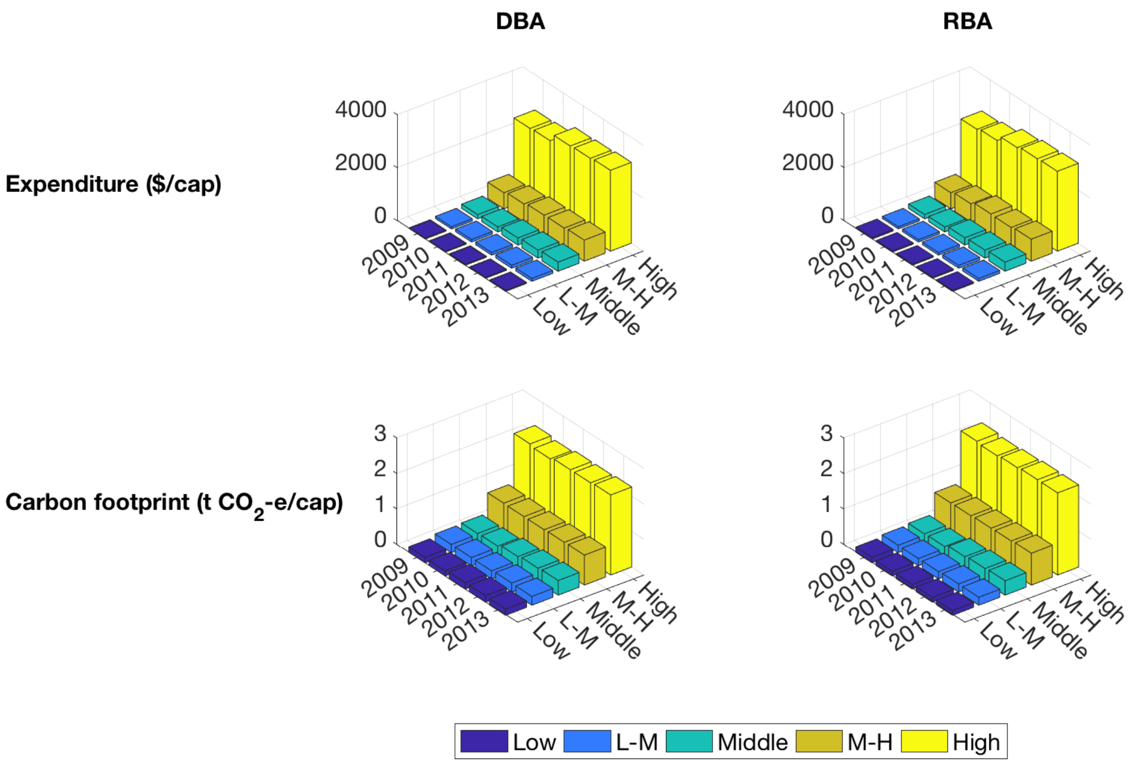

Fig. *SI* 6.3: Evolution of the per-capita expenditure and carbon footprint of global tourism between 2009 and 2013, clockwise from top right: $\tilde{y}^{\cdot t}_{\cdot 1}$, $\tilde{Q}^{\cdot\cdot t}_{\cdot\cdot 1}$, $\tilde{Q}^{\cdot s \cdot}_{\cdot\cdot 1}$, $\tilde{y}^{s \cdot}_{\cdot 1}$. Coloured bands represent five income groups containing approximately 35 countries each (see membership in *SI* 6.3.1.1), starting from low-income (L; purple) to high-income (H; yellow).

Note: The five annual per-capita GDP brackets are L <$1k, L-M $1k-$4k, M $4k-$8k, M-H $8k-$25k, H >$25k. Average annual growth rates in the income bands are 0.4% (L), 7.6% (L-M), 22.6% (M), 6.2% (M-H) and 2.9% (H). These growth rates are lower than those of the totals in Fig. *SI* 6.2, because they are net of population growth.

The overall difference between DBA and RBA accounting perspectives is small because – simply speaking – tourism is high-income business. By far the largest volume of visitor movements (almost 40% of total) occurs amongst high-income countries (Fig. *SI* 6.4), meaning that both destinations (DBA) as well as visitors (RBA) feature similar footprint characteristics.

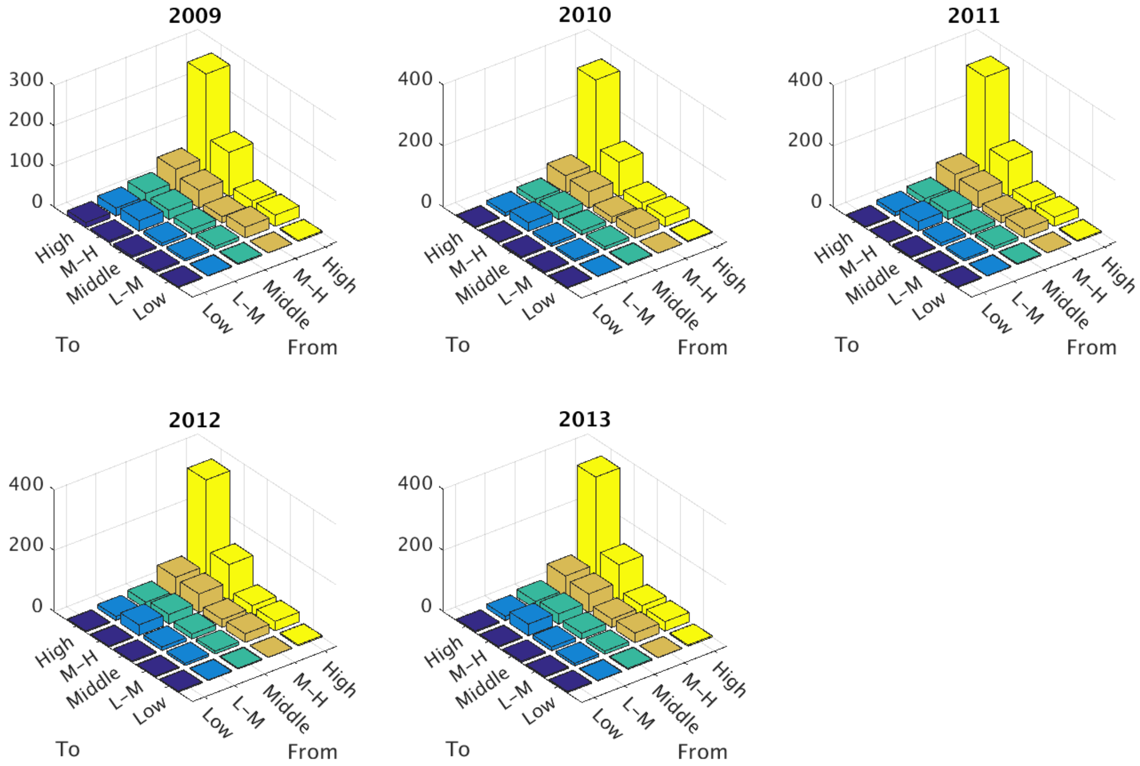

Fig. *SI* 6.4: International visitor movements (in millions) within and between five income groups containing approximately 35 countries each (see membership in *SI* 6.3.1.1), starting from low-income (purple) to high-income (yellow).
Note: The five annual per-capita GDP brackets are L <$1k, L-M $1k-$4k, M $4k-$8k, M-H $8k-$25k, H >$25k.

Whilst at the global level, DBA and RBA yield almost identical results, this is not the case for each country (Fig. *SI* 6.5). For example, under DBA the USA has a tourism carbon footprint of about 900 Mt CO_2-e, whilst under RBA, US visitors are responsible for 770 Mt CO_2-e, characterising the US as a "net tourist destination". The same holds for popular tourist destinations such as Thailand, Vietnam, Egypt, Greece, Spain, Morocco, Croatia and Mauritius. On the other hand, Canada, the UK, China, Japan, Germany, the Netherlands and Switzerland have a higher carbon footprint under RBA than under DBA, characterising them as "net traveller origins".

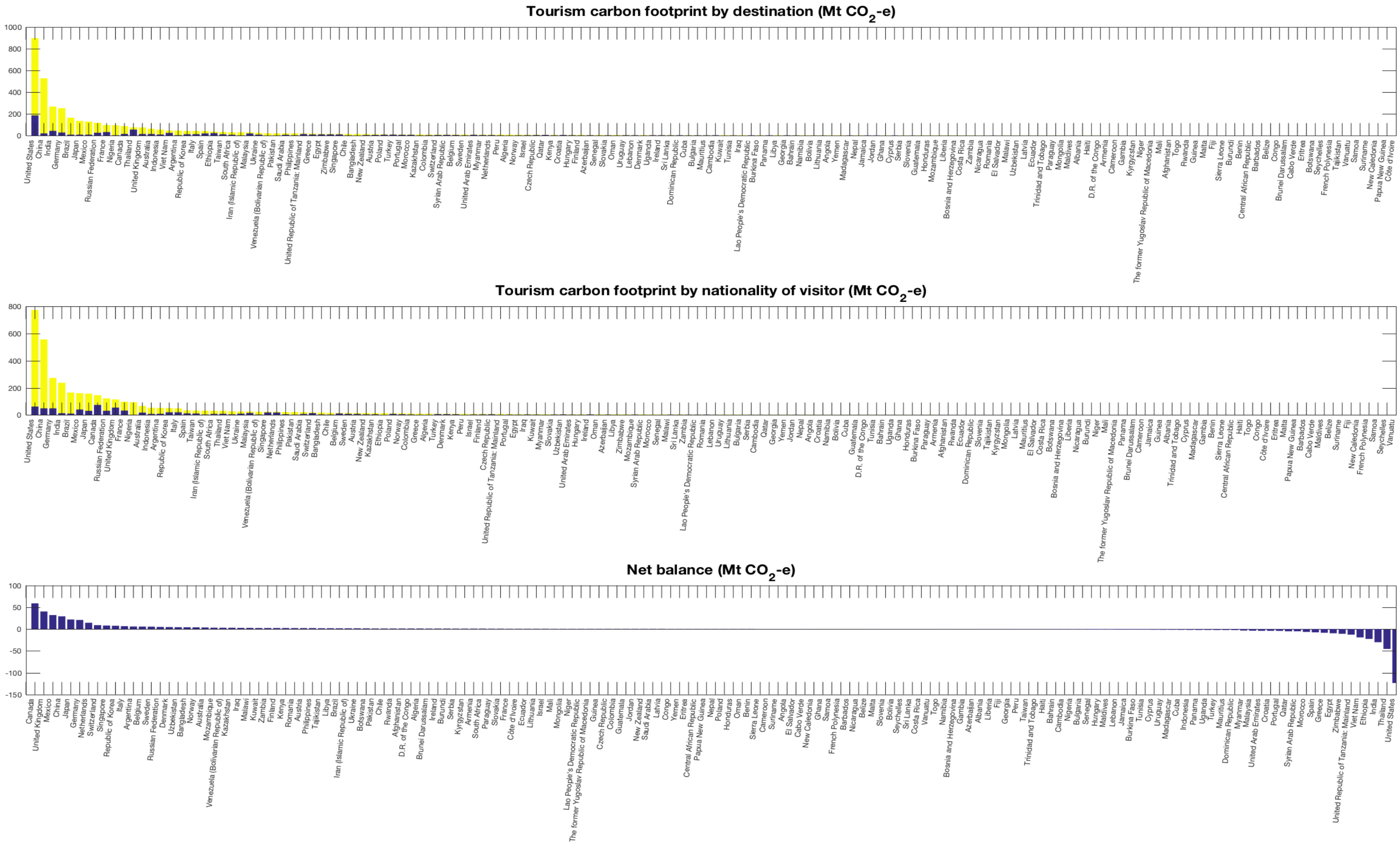

Fig. *SI* 6.5: Global tourism carbon footprint by destination (DBA, $\tilde{Q}^{\cdot s \cdot}_{\cdot\cdot 1}$) and visitor nationality (RBA, $\tilde{Q}^{\cdot\cdot t}_{\cdot\cdot 1}$), and the net trade balance $\tilde{Q}^{\cdot\cdot r}_{\cdot\cdot 1} - \tilde{Q}^{\cdot r \cdot}_{\cdot\cdot 1}$. Each bar distinguishes domestic travel (yellow) and international travel (blue).

6.4.2 Important commodities in the global tourism carbon footprint

Whether visitors are from high-income or low-income countries determines their spending pattern and therefore their carbon footprint (left column in Fig. *SI* 6.6): Whilst high-income visitors spend relatively more money on air travel and shop more for goods, low-income visitors buy more unprocessed food (shown under "Ag") and spend less money on hospitality.

Whether tourism occurs in high-income or low-income destinations determines visitors' spending pattern and therefore their carbon footprint as well (centre column in Fig. *SI* 6.6): Whilst high-income destinations are often reached by air travel and include high-end accommodation, restaurants and goods shopping in the visitor's experience, low-income destinations rely more on road transport, and feature food provision through retail rather than restaurants.

High-, middle- and low-income country all include industries that are situated at the origins of supply chains, where greenhouse gas emissions take place (right column in Fig. *SI* 6.6): Whilst tourism supply chains ending in high-income countries are often associated with airlines and other transport establishments combusting petroleum-based fuels, tourism supply chains ending in low-income countries often involve agriculture emitting through animals' enteric fermentation and land use changes. All producer locations include utilities with emissions mainly from coal- and gas-fired power plants, and mining operations emitting through fuel combustion as well as venting and flaring.

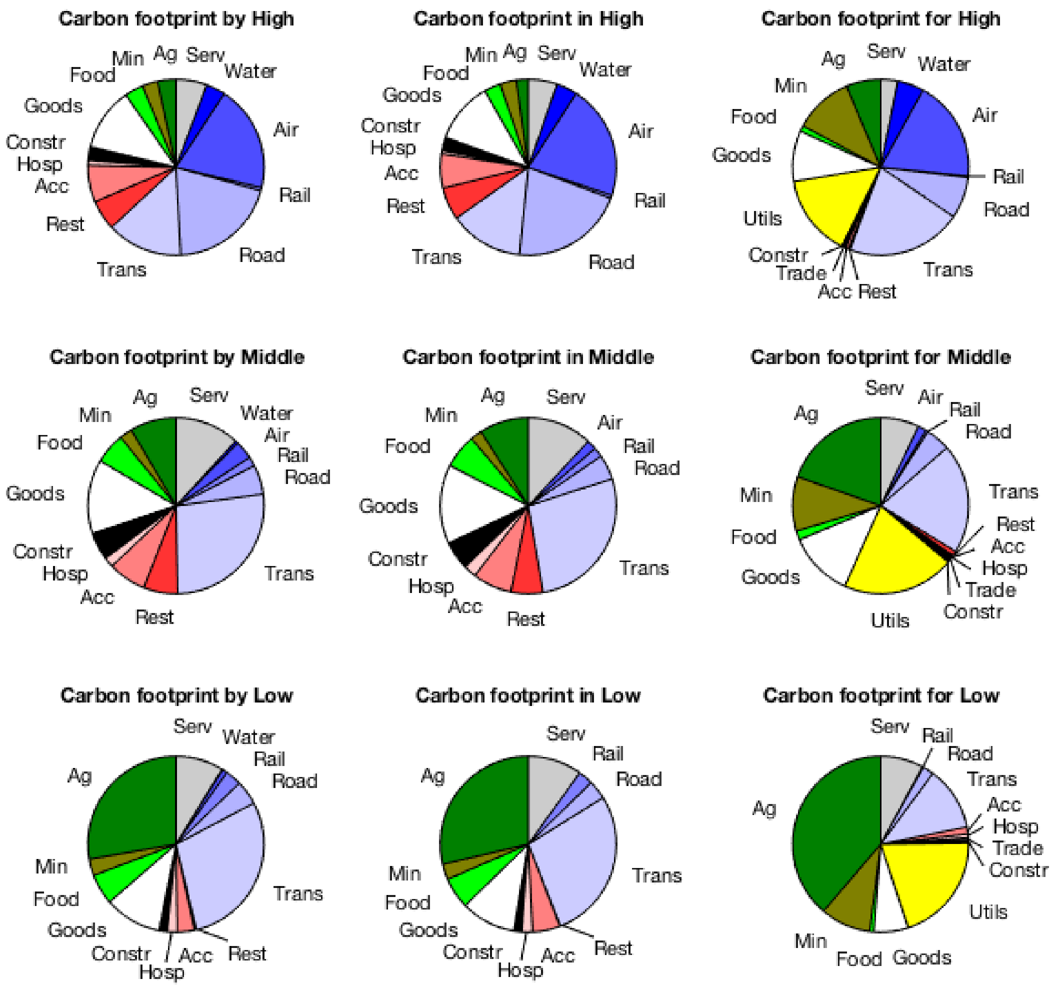

Fig. *SI* 6.6: Commodity content of carbon footprints of tourism, for high-, middle- and low-income countries (rows), and for visitors (left column, $\tilde{Q}^{\cdot\cdot t}_{\cdot j1}$), destinations (centre column, $\tilde{Q}^{\cdot s\cdot}_{\cdot j1}$) and emitters (right column, $\tilde{Q}^{r\cdot\cdot}_{i\cdot 1}$). For explanations of commodity acronyms see SI 6.6.3.3). Note: The three annual per-capita GDP brackets are L <\$3k, M \$3k-\$10k, H >\$10k.

Tab. *SI* 6.6: Expenditure, carbon footprint and carbon multiplier of various commodities for years 2009-2013.

Tab. *SI* 6.6a Expenditure

Expenditure on various commodities ($bn)

Commodities	2009	2010	2011	2012	2013
Agriculture	81.9 (2.35%)	93.4 (2.53%)	106 (2.53%)	115 (2.62%)	122 (2.68%)
Mining	54.8 (1.57%)	61.8 (1.67%)	75.5 (1.79%)	83 (1.9%)	85.4 (1.88%)
Food	121 (3.47%)	134 (3.63%)	149 (3.53%)	158 (3.61%)	166 (3.66%)
Goods	552 (15.8%)	572 (15.5%)	654 (15.5%)	676 (15.4%)	699 (15.4%)
Utilities	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
Construction	151 (4.34%)	161 (4.36%)	181 (4.3%)	192 (4.38%)	203 (4.47%)
Trade	0.927 (0.0266%)	0.921 (0.0249%)	0.992 (0.0236%)	0.874 (0.02%)	0.916 (0.0202%)
Hospitality unspecified	87.1 (2.5%)	98.3 (2.66%)	99.7 (2.37%)	110 (2.5%)	112 (2.45%)
Accommodation	546 (15.7%)	558 (15.1%)	629 (14.9%)	630 (14.4%)	640 (14.1%)
Food & beverage serving	394 (11.3%)	419 (11.4%)	470 (11.2%)	492 (11.2%)	517 (11.4%)
Transport unspecified	368 (10.6%)	400 (10.8%)	473 (11.2%)	493 (11.3%)	512 (11.3%)
Road transport	118 (3.39%)	128 (3.46%)	161 (3.82%)	168 (3.83%)	170 (3.73%)
Rail transport	51.8 (1.49%)	55.8 (1.51%)	65.6 (1.56%)	70.4 (1.61%)	69.8 (1.54%)
Air transport	317 (9.11%)	346 (9.36%)	386 (9.17%)	398 (9.08%)	403 (8.86%)
Water transport	24.9 (0.717%)	26.5 (0.718%)	28.1 (0.666%)	29.2 (0.668%)	30.4 (0.67%)
Services	613 (17.6%)	638 (17.3%)	730 (17.3%)	763 (17.4%)	816 (18%)

Tab. *SI* 6.6b Carbon footprint

Carbon footprint by purchased commodity (Mt CO_2-e)

Commodities	2009	2010	2011	2012	2013
Agriculture	315 (8.1%)	302 (7.75%)	318 (7.68%)	342 (7.88%)	353 (7.96%)
Mining	115 (2.95%)	112 (2.87%)	116 (2.81%)	122 (2.82%)	121 (2.73%)
Food	173 (4.44%)	173 (4.44%)	175 (4.23%)	187 (4.32%)	194 (4.38%)
Goods	482 (12.4%)	481 (12.3%)	501 (12.1%)	525 (12.1%)	534 (12%)
Utilities	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
Construction	113 (2.9%)	114 (2.93%)	123 (2.97%)	133 (3.05%)	139 (3.13%)
Trade	0.206 (0.0053%)	0.201 (0.00515%)	0.194 (0.00469%)	0.172 (0.00396%)	0.166 (0.00374%)
Hospitality unspecified	60.1 (1.54%)	59.8 (1.54%)	54.5 (1.32%)	60.9 (1.4%)	58.1 (1.31%)
Accommodation	282 (7.24%)	268 (6.88%)	273 (6.59%)	277 (6.39%)	282 (6.37%)
Food & beverage serving	187 (4.81%)	193 (4.95%)	208 (5.02%)	218 (5.02%)	227 (5.11%)
Transport unspecified	763 (19.6%)	766 (19.7%)	814 (19.7%)	862 (19.8%)	871 (19.7%)
Road transport	459 (11.8%)	471 (12.1%)	565 (13.7%)	593 (13.7%)	602 (13.6%)
Rail transport	37.5 (0.963%)	40.1 (1.03%)	46.4 (1.12%)	51.8 (1.19%)	54.6 (1.23%)
Air transport	523 (13.5%)	531 (13.6%)	534 (12.9%)	536 (12.4%)	547 (12.4%)
Water transport	104 (2.68%)	102 (2.62%)	94.5 (2.28%)	95.5 (2.2%)	97.9 (2.21%)
Services	276 (7.1%)	282 (7.25%)	318 (7.68%)	339 (7.81%)	350 (7.91%)

Tab. *SI* 6.6c Carbon multiplier (derived from the Eora MRIO database, see *SI* 6.1.2)

Carbon multiplier by purchased commodity (kg CO_2-e/$ final demand)

Commodities	2009	2010	2011	2012	2013
Agriculture	3.85	3.23	2.99	2.98	2.89
Mining	2.09	1.81	1.54	1.47	1.42
Food	1.43	1.29	1.18	1.19	1.17
Goods	0.874	0.84	0.765	0.776	0.764
Utilities	n.a.	n.a.	n.a.	n.a.	n.a.
Construction	0.745	0.709	0.679	0.692	0.683
Trade	0.222	0.218	0.196	0.197	0.181
Hospitality unspecified	0.69	0.608	0.547	0.556	0.521
Accommodation	0.516	0.481	0.434	0.44	0.441
Food & beverage serving	0.475	0.46	0.442	0.443	0.438
Transport unspecified	2.08	1.92	1.72	1.75	1.7
Road transport	3.89	3.69	3.51	3.53	3.55
Rail transport	0.723	0.719	0.707	0.736	0.782
Air transport	1.65	1.53	1.38	1.35	1.36
Water transport	4.19	3.85	3.37	3.27	3.21
Services	0.451	0.443	0.436	0.444	0.429
Total tourism	1.12	1.05	0.984	0.992	0.975
Global average	0.801	0.772	0.721	0.716	0.715

Tab. *SI* 6.6c lists only an aggregation of carbon multipliers from the Eora MRIO database (Lenzen et al. 2012a; Lenzen et al. 2013). This database distinguished multipliers of almost 15,000 country-sector pairs. Tab. *SI* 6.6c compares the tourism industry against other industries. The comparison is between entire sectors, ie tourism is compared against construction in general, not just tourism-related construction.

6.4.3 Uncertainty

The results from 42,000 Monte-Carlo runs yield that global tourism's carbon footprint in 2013 lies

- between 4.2 and 4.8 Gt CO_2-e at the 95.5%-level of confidence, and
- between 4.1 and 4.9 Gt CO_2-e at the 99.7%-level of confidence.

These estimates include parametrical uncertainty of the entire MRIO database, and allocation uncertainty caused during the bridging between unknown TSA consumption categories and MRIO sectors (see *SI* 6.6.2.6).

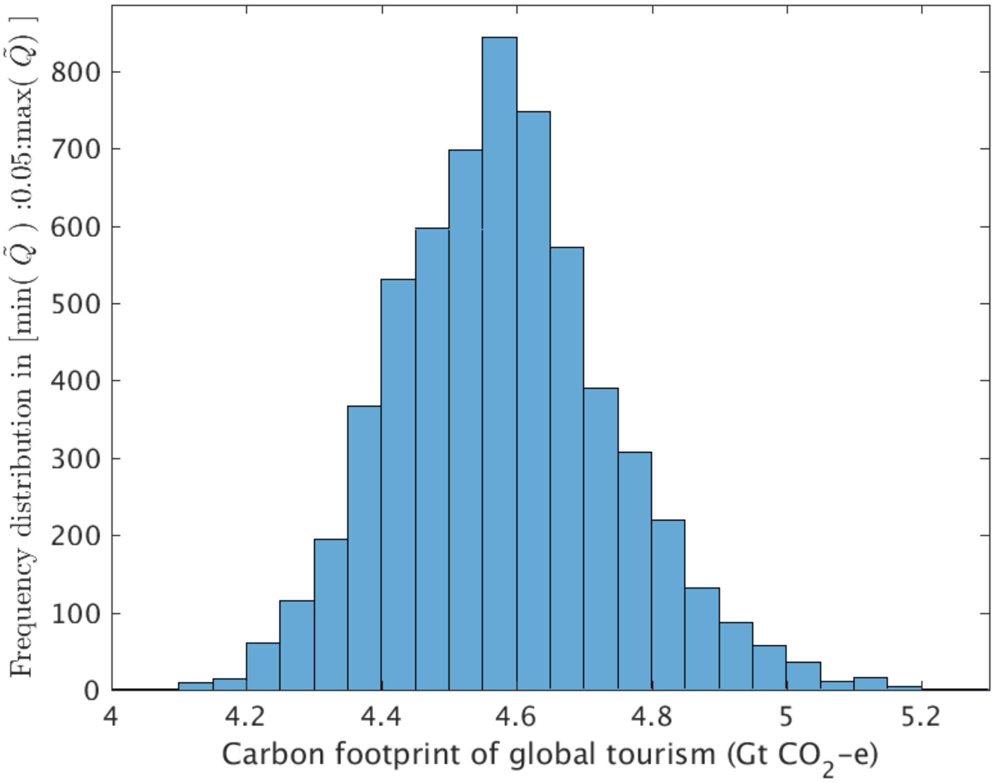

Fig. *SI* 6.7: Frequency distribution of the carbon footprint of global tourism.

We find that the contributions of commodity groups as distinguished in *SI* 6.6.4.2 are certain (95.5% level of confidence, or the 2□□band) to within ±10% to ±30%, but that the total carbon footprint is certain (95.5% level of confidence) to within about ±7.1% (Tab. *SI* 6.7).

These results can be understood as follows. The contributions of the shopping and food categories vary within about ±10% from their unperturbed value even though the TSA-to-MRIO allocation is perturbed by up to ±90%. This is because the perturbation is stochastic, and an increase in a particular tourist spending category for one country may cancel out by a decrease in the same tourist spending category for another country. This is a typical feature of error propagation (Heijungs and Lenzen 2014), where the relative standard deviations of aggregate measures stay relatively low because the standard deviations of their components (factors, summands) partially cancel out. The same holds for the total carbon footprint, where the relative standard deviation is lower than that of any consumption category. Once again, the stochastic errors of contributing components partially cancel out.

Tab. *SI* 6.7: As in Tab *SI* 6b, carbon footprint by purchased commodity (Mt CO_2-e), but including 2σ standard deviation estimates.

Consumption category	Carbon footprint (Mt CO_2-e)	2σ Standard (Mt CO_2-e)	deviation (%)
Agriculture	353	109	30.4
Mining	121	33.8	27.4
Food	194	27.2	13.3
Goods	534	44.5	8.0
Construction	139	27.9	17.1
Hospitality unspecified	58	6.8	11.3
Accommodation	282	27.2	9.5
Food & beverage serving	227	28.2	11.6
Transport unspecified	871	128	14.2
Road transport	602	49.1	8.1
Rail transport	55	11.9	20.4
Air transport	547	178	32.3
Water transport	98	48.6	49.5
Services	351	43.7	11.7
Total	4,430	324	7.1

6.4.4 Comparison with prior work

We are able to compare our results to prior work that covers either the world or an entire country (UNWTO et al. 2008; WTO-UNEP 2008; Dwyer et al. 2010; Peeters and Dubois 2010; Cadarso et al. 2015; Gössling and Peeters 2015). Considering the differences in base years, scope, data sources, and methods employed, the results are in reasonable agreement even at the sectoral level of detail. We choose 2010 as the basis for the comparison because the TSA data coverage is slightly better than for 2009.

Note that the way relative contributions (percentages within totals[16], or contributions to GDP, WTTC 2016) are calculated varies from report to report. Notably, two reference points are important: 1) whether direct, indirect and induced effects are included, and 2) whether only CO_2 or also non-CO_2 greenhouse gases (CO_2-equivalents) are included. i) In the UNWTO-UNEP_WMO's report[16] only direct CO_2 emissions are addressed, without including indirect, upstream (footprint) supply chain contributions, and without considering other types of GHG gases. For example, when translating percentages to refer to the same CO_2-e emission definition, the UNWTO's result only corresponds to 2.8% of the global base, half of the originally quoted value (Tab. *SI* 6.8). ii) The WTTC study (WTTC 2016) arrives at the 10% tourism contribution (year 2016) to GDP by including direct, indirect and induced economic effects. The latter include the effects of households' earning-spending-earning cycles, and multipliers obtained from such so-called type-II calculations are usually much higher than those of the more common (type-I) calculations (Katz 1980; Miller 1980) that include direct and indirect contributions. iii) Our study is of type I (including direct and indirect effects). We did not opt for a type-II approach, because such calculations usually require information on value-added and final demand to be distinguished by income class, to ensure that the earning-spending cycles are appropriately represented (Lenzen and Schaeffer 2004b; a). Comprehensive income-class detail on value-added and final demand is not available at the global level.

The different approaches mean that percentage estimates as originally quoted are not directly comparable between the UNWTO-UNEP-WMO, the WTTC, and our study.

Tab. *SI* 6.8: Comparison of direct emissions in our study against other estimates of global tourism CO_2 emissions.

No	**Sources**	**Scope 1**	**Scope 2**	**Scope 3**	**Base year**	**Direct emissions**	**% of direct air emissions**	**Contribution to global CO_2 emissions**	**Contribution to global CO_2-e emissions**
1	Our estimates	Direct + indirect emissions	Transport, food, shopping, lodging, activities and others	CO_2, CH_4, N_2O, HFCs, CFCs, SF_6 and NF_3	2013	2.92 Gt CO_2e	> 459 Mt CO_2-e (16%)*	8.1%	5.3%
2	WTO-UNEP 2008	Direct emissions	accommodation, transport, activities	CO_2	2005	1.30 Gt CO_2	520 Mt CO_2 (40%)	4.9%	2.8%
3	Gössling and Peeters 2015	Direct emissions	accommodation, transport, activities	CO_2	2010	1.12 Gt CO_2	NA	NA	NA
4	Peeters and Dubois 2010	Direct emissions	accommodation, transport, activities	CO_2	2005	1.17 Gt CO_2	503 Mt CO_2 (43%)	4.4%	2.5%

* Estimates differ because of two reasons: 1) some air transport emissions are included in the unspecified 'Transport' category, this is because despite the TSAs distinguishing transport modes, some countries' I-O databases do not; and 2) we include methane and nitrous oxide emissions that make food footprints more important. Nevertheless, our total air transport emissions estimate (> 459 Mt CO_2-e) is close to that from previous studies (500-520 Mt CO_2-e).

Tab. *SI* 6.9: Comparison of the global carbon footprint $\tilde{Q}^{\cdot s}_{\cdot j1}$ by selling sector, between this work and UNWTO, UNEP & WMO (UNWTO et al. 2008). UNWTO, UNEP & WMO (UNWTO et al. 2008) includes direct and some lower-order emissions only.

	Carbon emissions (Mt CO_2)	
Commodity	UNWTO et al. 2008	this work 2010
Agriculture		211
Mining		77
Food		137
Goods		687
Utilities		
Construction		117
Trade		
Hospitality unspecified		50
Accommodation	274	281
Food & beverage serving		223
Transport unspecified	465	830
Road transport		12
Rail transport		54
Air transport	515	545
Water transport		96
Services	48	264
TOTAL	1303	3593

Tab. *SI* 6.10: Comparison of Spain's tourism carbon footprints $\tilde{Q}^{r}_{i.1}$ by emitting sector, between this work and Cadarso et al. 2015. Cadarso *et al*'s assessment is for 2007 and excludes goods.

Commodity	Carbon emissions (Mt CO_2) Cadarso et al. 2015 2007	 this work 2010
Agriculture	4.10	5.83
Mining	2.52	8.52
Food	1.04	0.80
Goods		7.32
Utilities	9.86	8.54
Construction		
Trade		
Hospitality unspecified	0.22	0.75
Accommodation		
Food & beverage serving		
Transport unspecified	10.47	10.53
Road transport		
Rail transport		
Air transport		
Water transport	0.69	0.66
Services	1.13	1.20
TOTAL	30.03	44.16

Tab. *SI* 6.11: Comparison of Australia's tourism carbon footprints $\tilde{Q}^{r}_{i.1}$ by emitting sector, between this work and Dwyer et al. 2010. Dwyer *et al*'s assessment is for 2004.

Commodity	Carbon emissions (Mt CO_2) Dwyer et al. 2010 2004	 this work 2010
Agriculture	5.76	13.34
Mining	0.76	0.63
Food	0.30	0.79
Goods	4.11	5.96
Utilities	7.57	11.10
Construction		0.26
Trade	0.28	0.11
Hospitality unspecified		0.01
Accommodation	0.97	0.17
Food & beverage serving		0.01
Transport unspecified	7.08	13.92
Road transport	0.27	0.86
Rail transport		0.03
Air transport		
Water transport		0.32
Services	0.35	0.60
TOTAL	27.45	48.09

6.4.5 Production Layer Decomposition

A production layer decomposition (PLD) unravels the contributions to footprints from different upstream layers of the supply chain system. Visitor expenditures have an economic footprint in that visitor demand requires various upstream producers to provide inputs that are ultimately need to supply the commodities that visitors purchase.

Global visitor expenditure on tourism activities was about 4.8 $tr in 2013 (layer 0, left panel in Fig. *SI* 6.8), with goods, hospitality, transport and services being the main commodities purchased. Further upstream, these commodities required inputs from agriculture, mining, wholesale and retail trade, construction and utilities (water, gas and electricity). Total economic output ultimately needed to satisfy 4.7 $tr of tourism demand was about 14 $tr (layer 15, left panel in Fig. *SI* 6.8).

Similarly, we estimate that the 2013 carbon footprint of tourism operators directly supplying tourists amounted to about 2.9 Gt CO_2-e (counting production layers 0 and layer 1 as an upper limit, right panel in Fig. *SI* 6.8), which exceeds prior estimates by the WTO (UNWTO et al. 2008) (see Tab. *SI* 6.9) and by Gössling and Peeters 2015. Including all upstream supply chain contributions, the total carbon footprint was 4.5 Gt CO_2-e (layer 15, right panel in Fig. *SI* 6.8). Road and air transport and utilities, in particular electricity, feature prominently upstream, because of their high carbon intensity. In contrast, general services and hospitality are less important because of their relatively low carbon intensities.

These results prove how important it is to include I-O analysis into the methods applied for enumerating the carbon footprint of tourism. Without using I-O analysis, it is impossible to capture higher-order supply chain contributions, simply because there are too many supply chains to be followed up manually (Bullard et al. 1978b; Moskowitz and Rowe 1985). In an I-O system where each producer requires inputs from, say, 100 suppliers, the 1st production layer includes 100 supply chains, the 2nd layer 100^2 = 10,000, the 3rd layer 100^3 = 1 million, and the 4th layer 100^4 = 100 million supply chains. Such extensive networks are impossible to evaluate using conventional bottom-up process-type Life-Cycle Assessment methods (Suh et al. 2004).

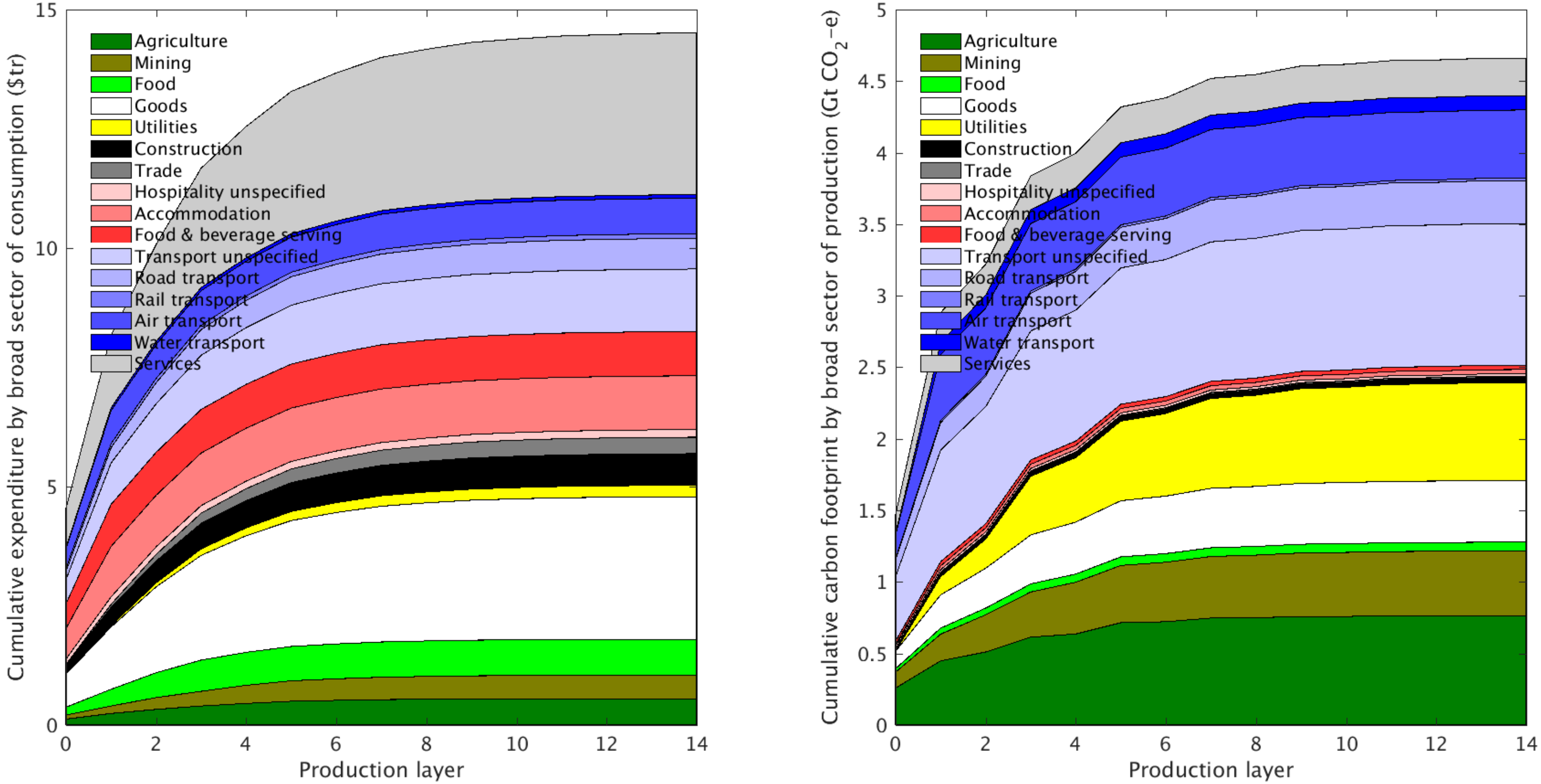

Fig. *SI* 6.8: Cumulative Production Layer Decompositions. Left panel: PLD of the economic output required to satisfy tourist demand $\tilde{\mathbf{x}} = (\mathbf{I} + \mathbf{A} + \mathbf{A}^2 + \cdots)\tilde{\mathbf{y}}\mathbf{1}^{\mathbf{y}}$. Right panel: PLD of the of the global tourism carbon footprint $\tilde{Q} = \mathbf{q}(\mathbf{I} + \mathbf{A} + \mathbf{A}^2 + \cdots)\tilde{\mathbf{y}}\mathbf{1}^{\mathbf{y}}$. For more details on the PLD method see *SI* 6.1.2.2 and for explanations of commodities see *SI* 6.6.3.3).

6.4.6 The global tourism greenhouse gas footprint

Industry sectors differ with respect to their emissions profile across various greenhouse gases. CO_2 is associated mainly with fuel combustion and land use changes, and therefore important for transport and energy conversion. CH_4 is emitted from animals (enteric fermentation and manure) and during oil and gas extraction (venting and flaring), and is therefore important for agriculture and mining. Emissions of N_2O and other greenhouse gases (see *SI* 6.3.2) occur in agriculture as well during industrial processes; in terms of equivalent CO_2 emissions they are less important. Whilst we needed to exclude short-lived greenhouse gases from aviation, aviation-induced clouding and contrails could however play a significant role (*SI* 3.2).

The total global tourism carbon footprint of 4.1 Gt CO_2-e consists mainly of 3.2 Gt CO_2-e in from of CO_2 emissions for moving planes and road vehicles, electricity for running hotels and restaurants, and from the combustion of various fuels required to manufacture consumer goods purchased by tourists (Fig. *SI* 6.9). 0.7 Gt CO_2-e in from of CH_4 are emitted mainly from farms in the supply chain network of food processing and retail, from oil and gas rigs extracting feedstock that is transformed into refined fuels used in just about any sector of the economy, and directly from various manufacturing sectors producing consumer goods.

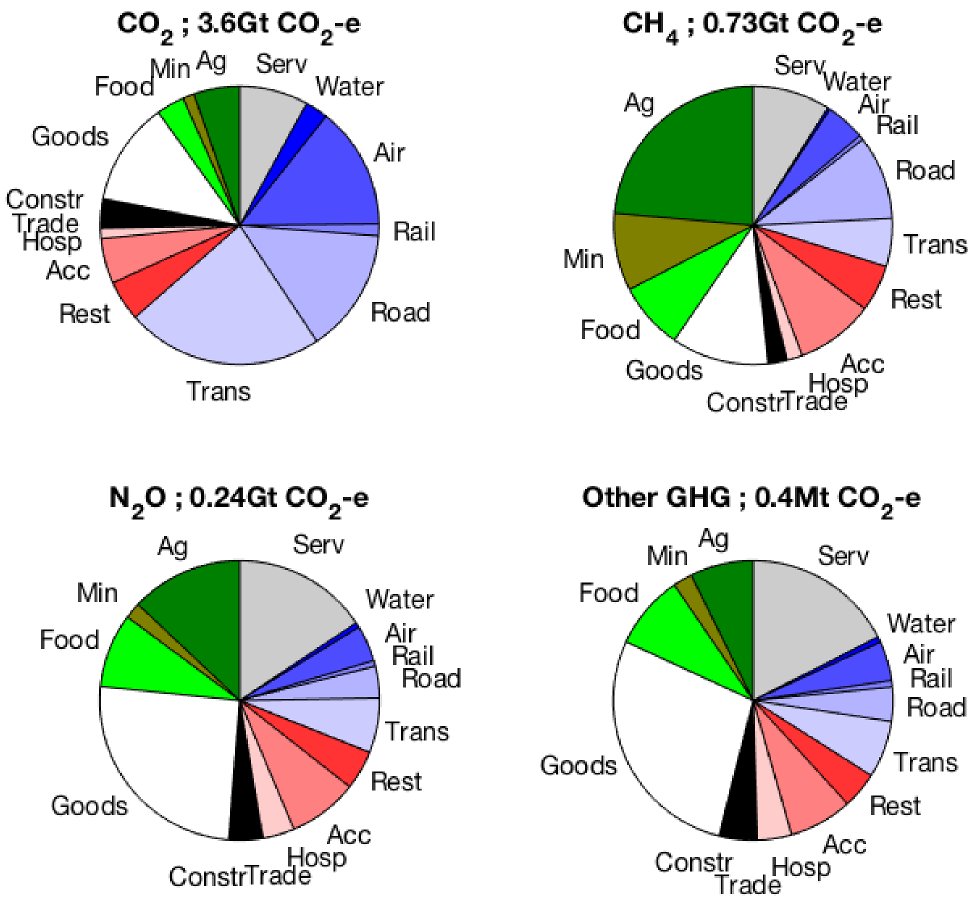

Fig. *SI* 6.9: Global tourism carbon footprint for CO_2, CH_4, N_2O and other greenhouse gases (GHG, see *SI* 6.3.2), for the year 2013.

6.4.7 Growth in the global tourism carbon footprint

Half of the total 2009-2013 carbon footprint growth of 1.1 Gt CO_2-e occurred in high-income countries and due to high-income visitors, with the remainder recorded for middle-income countries (Fig. *SI* 6.10), notably China (see *SI* 6.6.3.1.1). Middle-income countries recorded the highest growth rate of the tourism carbon footprint (22.6% p.a.).

RBA allows examining changes in visitors' carbon footprint. Chinese visitors alone contributed to an average annual increase in the global tourism carbon footprint of 75 Mt CO_2-e, followed by the United States (25 Mt CO_2-e), India (19 Mt CO_2-e) and Canada (12 Mt CO_2-e).

DBA enables monitoring changes in the carbon footprint of destinations. Small-island destinations with low populations are especially vulnerable to high and increasing tourist load (McElroy 2006; Lenzen 2008), and this is reflected in the Maldives, the Seychelles, Mauritius, Trinidad and Tobago, Malta, Vanuatu, Fiji, Samoa, French Polynesia and Cabo Verde occupying top-ranking positions in terms of the per-capita increase in the tourism carbon footprint within their territory. For every inhabitant of Maldives, tourism has brought significant income, but also an annual carbon footprint increase of nearly 300 kg.

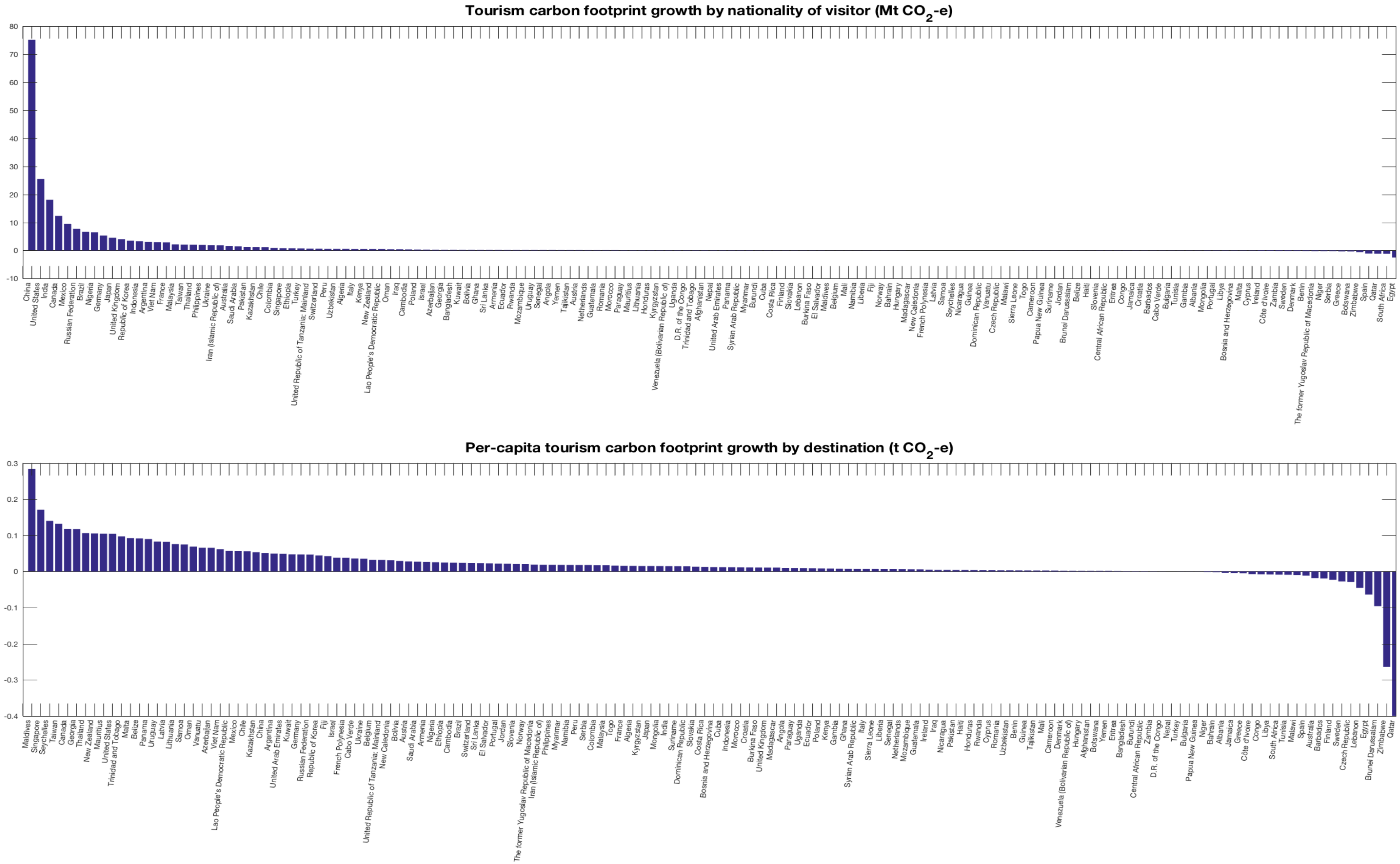

Fig. *SI* 6.10: Growth in the tourism carbon footprint by visitor nationality (RBA, $\tilde{Q}^{\cdot\cdot t}_{\cdot\cdot 1}$), and destination (DBA, $\tilde{Q}^{\cdot s \cdot}_{\cdot\cdot 1}$).

6.4.8 Using multiple regression to investigate possible drivers of tourism carbon footprints

Multiple regression can be used to reveal drivers of the carbon footprint F. In our work, we follow Wier et al. 2001 and Lenzen et al. 2006 and formulate a multiplicative relationship for per-capita carbon footprints as $F = k\, x^{\eta_{x,0}+\theta x}\, e^{\varrho_q q}\, e^{\varrho_t t}$.

6.4.8.1 Regression coefficients

Before carrying out our regression analysis, we test all variables for multicollinearity (Tab. *SI* 6.12). None of the explanatory variables are highly correlated, so we did not exclude any of them in our regression.

Tab. *SI* 6.12: Pairwise linear correlation coefficients between all variables.
CF = carbon footprint, GDP = Gross Domestic Product.

	DBA Per-capita CF	Per-capita GDP	Carbon intensity	Time
DBA Per-capita CF		0.63	-0.17	-1.11×10^{-4}
Per-capita GDP	0.63		-0.29	0.04
Carbon intensity	-0.17	-0.29		-0.006
Time	-1.11×10^{-4}	0.04	-0.006	

Our multiple regression of tourism carbon footprints across 162 countries and 5 years yields the following results (Tabs. *SI* 6.13 and *SI* 6.14):

Tab. *SI* 6.13: Regression results for the destination-based accounting (DBA) perspective (goodness of fit R^2 = 0.74).
*** = statistically significant at the 99%-level of confidence, ** = @ 95% level, * = @ 90%-level.

	Regression parameter	Standard deviation (%)	t statistics	Significance
Hosts' pc GDP x	$\eta_{x,0} = 0.78$	0.098	10.2	***
	$\theta = 6.17\times10^{-8}$	6.61	0.15	
Carbon intensity q	$\varrho_q = 0.30$	0.16	6.1	***
Time t	$\varrho_t = -6.5\times10^{-3}$	6.03	0.17	
Constant k	$k = 4.06\times10^{-4}$	0.08	11.82	***

Tab. *SI* 6.14: Regression results for the residence-based accounting (RBA) perspective (goodness of fit R^2 = 0.80).
*** = statistically significant at the 99%-level of confidence, ** = @ 95%-level, * = @ 90%-level.

	Regression parameter	Standard deviation (%)	t statistics	Significance
Travelers' pc GDP x	$\eta_{x,0} = 0.69$	0.095	10.48	***
	$\theta = 6.09\times10^{-7}$	0.58	1.73	*
Carbon intensity q	$\varrho_q = 0.21$	0.21	4.84	***
Time t	$\varrho_t = -8.3\times10^{-3}$	4.07	0.25	
Constant k	$k = 9.23\times10^{-4}$	0.08	12.24	***

6.4.8.2 Range of per-capita tourism carbon footprints under DBA and RBA

The range of per-capita tourism carbon footprints is different under DBA (≈0 to 4 t CO_2-e/cap) and RBA (≈0 to 5 t CO_2-e/cap) accounting. How can we understand this difference? Imagine a 2-billion-people world with one part being wealthy frequent travelers from uninteresting countries, and the other being poor and populous but popular tourist destination. Per-capita footprints under DBA will be low for the wealthy group (because not many tourist go there) and low for the poor group (because of their high population). Per-capita footprints under RBA will be high for the wealthy group (because they travel a lot) but again low for the poor group (because they do not travel a lot).

6.4.8.3 Per-capita GDP elasticities of the tourism carbon footprint

The GDP-elasticity of the carbon footprint is in both accounting perspectives highly significant and positive. These results agree well with prior work on nations (Wier et al. 2001,Lenzen et al. 2006) and cities (Lenzen et al. 2004), where expenditure elasticities between 0.5 and 0.9 were reported for many nations.

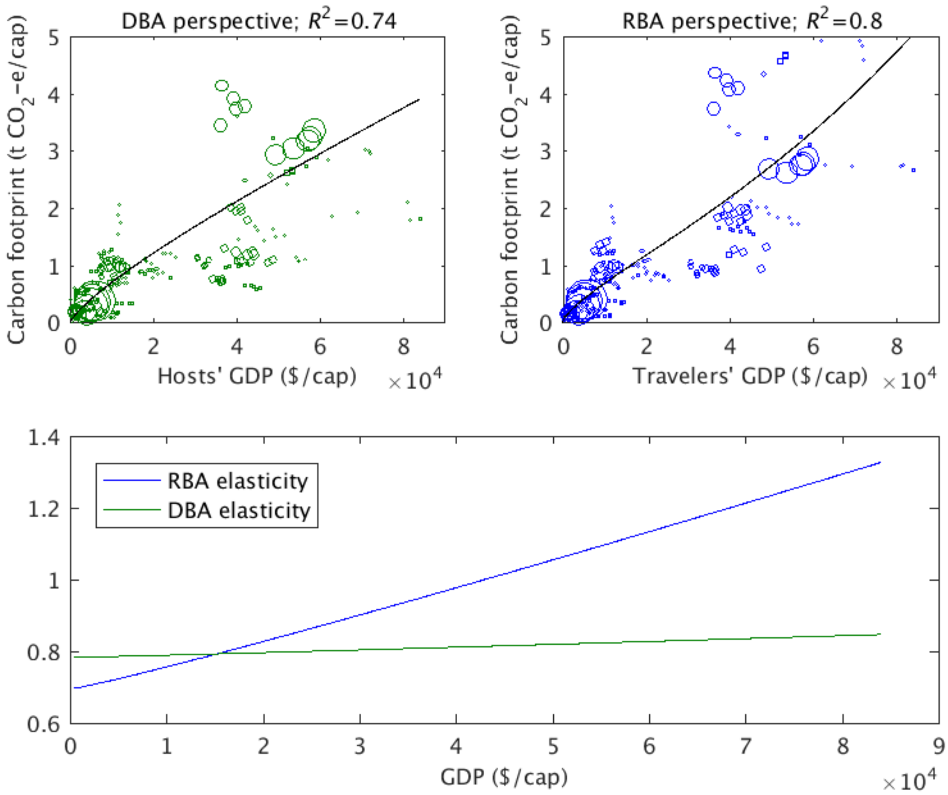

Fig. *SI* 6.11: Regressions and elasticity functions for the multiple regression of tourism carbon footprints according to the DBA perspective (green) and RBA perspective (blue). Circle size in upper panels represents population.

For RBA, the variation *θ* of the elasticity with affluence (measured as per-capita GDP) is also significant and positive, meaning that the GDP-elasticity of the carbon footprint increases with increasing affluence (from 0.7 to 1.3). Along with the higher goodness of fit of the RBA-based regression (R^2 = 0.80 instead of DBA's R^2 = 0.72), this shows that per-capita GDP is a stronger driver in the RBA perspective than in the TSA perspective (Tabs. *SI* 6.13 and *SI* 6.14, and Fig. *SI* 6.11). This is to be expected, because per-capita GDP at the tourist destination does not necessarily translate into tourism carbon footprints, simply because luxury resorts may exist in poor countries. In contrast, per-capita GDP at the visitor home does translate into tourism carbon footprints, as wealth determines the ability to travel.

The fact that in the RBA perspective, the GDP-elasticity increases with affluence is a noteworthy result, since for the higher per-capita ranges (> $40,000 per annum) this elasticity becomes larger than 1, meaning that, for example, if per-capita GDP increased by 10%, the per-capita tourism carbon footprint would increase by more than 10%. This effect is due to tourism being a luxury good the consumption of which a) is largely restricted to the wealthy segment of the global population, and b) does not appear to satiate towards higher incomes. Above-unity elasticities are documented in prior work on Brazilian households by Cohen et al. 2005, who found that their propensity to consume fuel for mobility increased more than proportionally with income as Brazil went through a rapid development phase.

6.4.8.4 Remaining regression coefficients

A sea-change decrease in the carbon intensity of production by 100 g CO_2-e/$ causes carbon footprints to decrease by 3.0% (DBA) and 2.1% (RBA) respectively, reflecting that more carbon-efficient technology has a beneficial effect. Carbon intensity has a stronger influence on carbon footprints under the DBA perspective, because it relates to the destinations where visitors consume, as opposed to their home country (MRIO perspective).

The reason for the carbon intensity effect on tourism carbon footprint being relatively weak is the dominance of the affluence effect (*SI* 6.4.8.3). As countries become wealthier, their carbon intensity decreases (Fig. *SI* 6.12). However, affluence growth outpaces technology improvements in driving up emissions, leading the carbon footprint to increase whilst their technology becomes more carbon efficient. This becomes evident when carrying out a single regression with the carbon intensity term, that is $F = k\ e^{\varrho_q q}$. This form yields a negative coefficient for the elasticity ϱ_q, suggesting that the footprint increases with decreases carbon intensity (compare also with the negative correlation coefficient in Tab. *SI* 6.12). Of course, this counterintuitive behaviour comes about because of the missing affluence term $x^{\eta_{x,0}+\theta x}$; once this is included the role of the carbon intensity in the regression diminishes. These counteracting effects are well demonstrated and explained in Structural Decomposition Analyses (SDAs) of global greenhouse gas emissions (Arto and Dietzenbacher 2014; Malik et al. 2016).

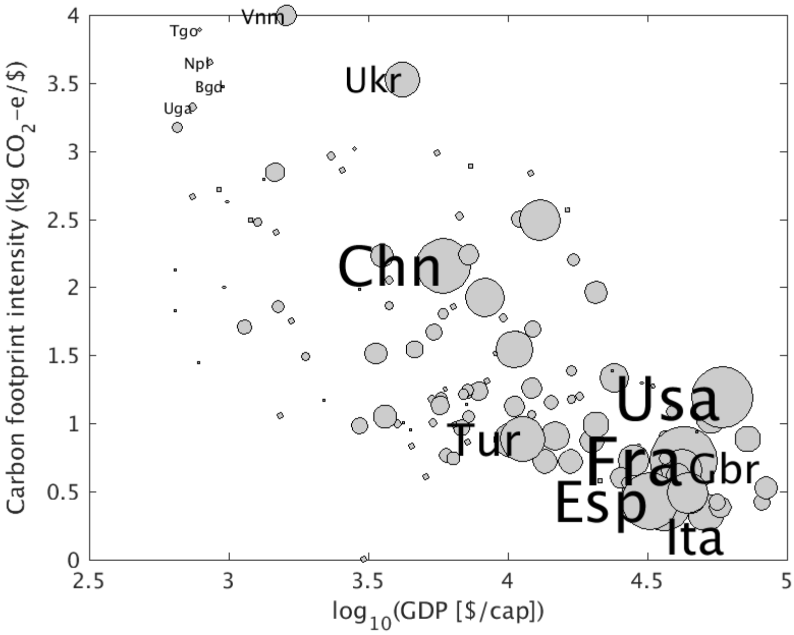

Fig. *SI* 6.12: Carbon footprint intensity ($\tilde{Q}^{s}_{..1}/\tilde{y}^{s}_{.1}$, in units of kg CO_2-e/$) as a function of per-capita GDP. Circle size represents number of incoming visitors. As countries become wealthier the carbon intensity of their tourism operations decreases.

Time as such does not have a significant influence, showing that the increase in the global tourism carbon footprint is not primarily a matter of changing circumstances (beyond affluence and technology, for example social norms).

6.4.8.5 Visualisation of regression results

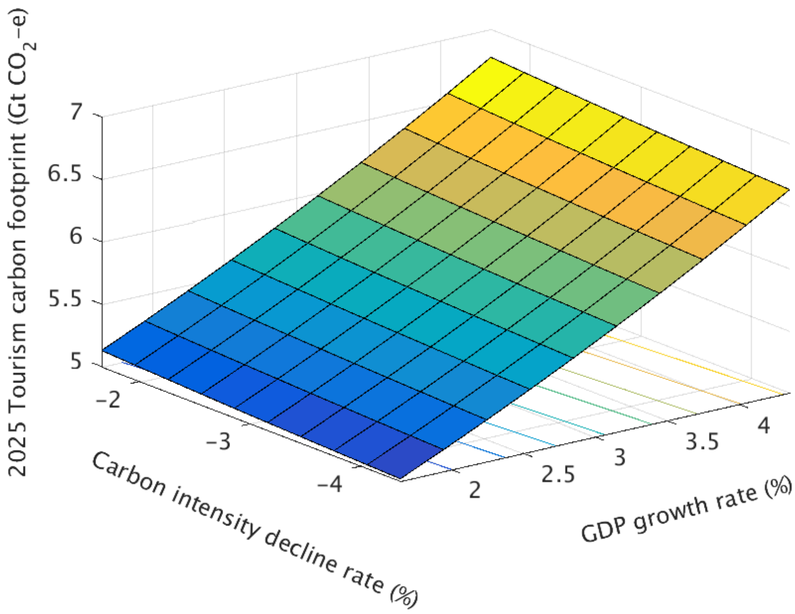

Fig. *SI* 6.13: Projections of the 2025 global tourism carbon footprint (based on DBA and RBA multiple regressions).

6.5 Future research outlook

The principle of "common but differentiated responsibility" is embraced by Paris Agreement, acknowledging the individual responsibility and capacity of carbon mitigation in the light of national circumstances (United Nations 2015). This study provides the first compressive economic and tourism emissions distribution pattern globally and future research can leverage this result to discuss the design/impact/implications of abatement policies by complying with this principle. Related issues include the attribution of carbon responsibility between major departure countries versus small island destination countries; the impact of mitigation on "net destinations" and "net origins" from economic and environmental perspectives; or the discussion of climate justice: "who can travel, for how long, using which transport mode, why, and how comfortably (p.1041)" (Dubois et al. 2011).

Human decision-making is a cognitive process resulting in the selection of a belief or a course of action among several alternatives. Results of this study pinpoint the carbon intensive nature of tourism, and this serve as a foundation for possible changes of current mindset among consumers, firms and policymakers. A future research on the relationship between information dissemination and behavior changes toward a more sustainable travel behaviors and production technology would confirm whether footprint information will effectively change our courses of actions, at least on travel.

Our research also serves as a starting point to further theoretical developments. Due to the lacking of empirical data in the past, the environmental and economic trade-off of tourism services remain an untouched filed. By filling this information gap, our results enable further discussion on tourism Environmental Kuznets Curve or the tourism Pollution Heaven Theory, which advance our understanding on 1) whether tourism development can improve/deteriorate national emissions efficiency over time, 2) the comparative advantages of individual countries on developing tourism against other potential alternatives, and 3) the net-effect of tourism emissions transfer with respect to different abatement regulation.

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