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RESEARCH ARTICLE

Tourism carbon footprint inventories: A review of the environmentally extended input-output approach

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ABSTRACT

Environmentally extended input-output models have emerged as a new macro level approach to compile tourism carbon footprint inventories. Set against the traditional bottom-up method, this paper explains how environmentally extended input-output models can assist to address multiple aspects of tourism carbon management, and to review current applications for the system boundary issue, identifying variations due to carbon footprint definition, data, and the economic model itself. Recommendations are made on improving consistency of application through the tourism satellite account framework and the treatment of embedded emissions of imports. Last, we propose an agenda to integrate its procedure into national systems linking the sectoral carbon emissions of tourism with international climate commitments and progressing implementation of the Sustainable Development Goals.

Introduction

Bidirectional interconnection among tourism, the environment and sustainable development exists. Tourism contributes to, and at the same time is affected by, national climate commitments under the Paris Agreement, and the societal transitions to achieve the United Nations Sustainable Development Goals (Boluk, Cavaliere, & Higgins-Desbiolles, 2019; Scott, Hall, & Gössling, 2016). The relevance of tourism to the Paris Agreement is evidenced as 40% of the measures in the Nationally Determined Contributions acknowledge tourism either as a country priority, as part of their mitigation and adaptation strategies, or as a sector vulnerable to climate change (UNWTO & UNDP, 2017). Similarly, the critical role of tourism to enhance progress of the Sustainable Development Goals was clearly identified, especially: goal 8 *decent work and economic growth*, goal 12 *responsible consumption and protection*, and goal 14 *the sustainable use of oceans and marine resources* (UNWTO, 2015).

Better management of tourism to contribute to Paris Agreement and Sustainable Development Goals is currently hampered by a significant data gap. The UN World Tourism Organization specifically indicated that "the lack of a sectoral (carbon emission) perspective does not allow creating links between the contribution of tourism industries to the nationally determined contributions and the efforts being undertaken by tourism stakeholders operating internationally" (UNWTO & UNDP, 2017). The lack of comprehensive, reliable and credible national tourism emission inventories presents challenges for many countries to develop their climate-centred tourism policy (Gössling, 2013; OECD-UNEP, 2011; Scott, Gössling, Hall, & Peeters, 2016). In addition, our understanding toward the deep and diverse linkage effects of the "tourism development—carbon emissions—destination sustainability nexus"

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remains mostly qualitative[1] (Northrop, Biru, Lima, Bouye, & Song, 2016)(Northrop, Biru, Lima, Bouye, & Ranping, 2016)

A comprehensive and credible tourism sector level carbon emission inventory is the foundation for developing cohesive climate policy and sustainable development policy with respect to tourism. Two distinct approaches of calculating tourism carbon emissions have been developed in the literature: the bottom-up and the top-down method (Becken & Patterson, 2006). The bottom-up method includes the basic engineering approach while the top-down method encompasses the environmentally extended input-output (EEIO, referred as input-output) model and the more dynamic Computable General Equilibrium model. Traditionally, the bottom-up method that sums up emissions through all elements of travel consumption was preferred, including the prominent case of the first global tourism carbon assessment by WTO-UNEP-WMO (2008) (see Appendix 1 for cases which adopted the bottom-up approach). However, in recent years, the input-output model, where all emissions occurring along the chains of production and distribution are traced through the economic-environmental accounts, is seen as providing several distinct benefits in tourism carbon management.

The most appealing feature of the input-output approach is its ability to present a complete scope of the tourism carbon footprint, defined as the direct and indirect greenhouse gas emissions (Wiedmann & Minx, 2008). The approach covers direct emissions produced by tourism industries, and all rounds of the indirect effect throughout the supply chain within and outside the destination country (Berners-Lee, Howard, Moss, Kaivanto, & Scott, 2011). In addition, input-output is the only appraisal tool that enables a national tourism carbon inventory to be comprehensive and compatible with the System of National Accounts (Sun, Lenzen, & Liu, 2019). This critical evidence helps in assessing the contribution of tourism to the global and national emission inventories and judging whether tourism has become an important polluting sector (Lenzen et al., 2018).

Besides the carbon emission assessment, this method is recognized to effectively address multi-faceted information on sustainability, quantifying the linkages between tourism's contribution in the economy and its impact on emissions. Indicators, such as gross domestic product, employment, water consumption, and waste generation, can be displayed side by side with the tourism carbon footprint (Lundie, Dwyer, & Forsyth, 2007; Sun & Pratt, 2014). This synergizes the trade-offs that can arise between tourism and many Sustainable Development Goals.

A valid implementation of an input-output analysis however requires a detailed discussion on its system boundary that delineates what components should be included and evaluated in the tourism carbon footprint. Due to the composite nature of tourism, great variation in what was being covered and assessed for the emissions was observed among existing tourism applications. Gössling (2013) reviewed tourism carbon reports across 22 countries and territories and concluded that variations were substantial due to subjective system boundaries, especially with the treatment of international bunker fuel used for international aviation and maritime transport. A similar observation was also made by Sun (2014) who contrasted four national and eight regional tourism carbon emission studies for components that were analysed. While many studies attempt to measure the scale of climate impact of tourism, the issue of consistency has a profound impact on the final result as the magnitude (tourism carbon footprint) and intensity (tourism carbon emission per GDP) are strongly influenced by the system boundary which may lead to conflicting and confusing results across studies.

Understanding how individual components have affected the input-output assessment becomes critical because the system boundary is the key to identifying the quantity of carbon emissions associated with tourism development and which stakeholders (producers, consumers and territories) are responsible for mitigation. The purposes of this paper are first to review existing input-output applications in tourism carbon footprint inventories by comparing global, country, and regional case studies. Specific attention focuses on the possible variations that may arise due to the allocation principle, data, input-output models and their inherent constraints. Second, we provide recommendations on how to consistently deliver an input-output study for tourism, working with various system boundary parameters. Last, the paper proposes systemic and institutional prioritisation to adopt the input-output method as an effective tool to link the sectoral carbon emissions of tourism with international climate commitments and to progress implementation of the Sustainable Development Goals.

The environmentally extended input-output model

Environmentally extended input-output models have become a valuable approach for the analysis of environmental impacts of economic activities and for supporting related economic and environmental policies (Hoekstra, 2010). The foundation of the model rests on the input-output table and coefficients of natural resource or pressures (such as greenhouse gasses or pollutants, land or water use) (Leontief & Ford, 1972). The first parameter, the input-output table, describes the structure of the economy as an interlinked network where industries provide intermediate products to other industries and final products to the final demand sectors (household, government, private investment and net export) and generate value added (such as profits, wages and tax). The second parameter, coefficients of natural resources or pressures, on the other hand, capture how sectors use natural resource inputs and produce various types of pollution when delivering one dollar of output.

[1] To measure the contribution of tourism industries to the Sustainable Development Goals, the World Tourism Organization and United Nations Statistics Division are currently developing the "Measuring the Sustainability of Tourism" system to quantify impacts of tourism in the economy, environment and host communities, which focus primarily on the direct economic and environmental effect on tourism industries (UNWTO, 2017b & 2018a). The indirect effects of tourism on other sectors and international trade throughout the supply chain are recommended to be "analysed separately" (UNWTO, 2018b).

The basic input-output model

The fundamental component of the input-output analysis is to use a matrix (input-output table) to fully capture the inter-industry linkages and the production technology of sectors of an economy. The input-output table expresses the industry output ($\boldsymbol{X}$) as the sum of the interindustry flows ($\mathbf{AX}$, transaction between sectors to sectors) and sales to final demand ($\boldsymbol{Y}$, transaction from sectors to final consumer). The production of wool, for example, can be sold to the textile industry as an intermediate input, or to the household for their final use (without reselling). Output used by other sectors is determined by the local production technology, represented by proxy through the technical coefficients ($\mathbf{A}$) that shows the direct input requirements by unit of output for each sector. The total output of an economy, $\boldsymbol{X}$, then, can be expressed as the sum of intermediate consumption, $\boldsymbol{AX}$, and final demand, $\boldsymbol{Y}$, as follows (Miller & Blair, 2009):

$$\boldsymbol{X} = \boldsymbol{AX} + \boldsymbol{Y} \tag{1}$$

By rearranging Eq. (1), we have the fundamental equation of input-output analysis:

$$\boldsymbol{X} = (\boldsymbol{I} - \boldsymbol{A})^{-1}\boldsymbol{Y} \tag{2}$$

where $(\boldsymbol{I} - \boldsymbol{A})^{-1}$ is the Leontief Inverse that provides the direct and indirect requirements to satisfy one additional dollar of final demand. If including consumption from income generated, the induced effect can be estimated. The environmental extension of input-output analysis is to incorporate a vector of emissions coefficients, $\boldsymbol{e}$, that shows the direct emissions by unit of output, which is calculated by dividing total emissions $\boldsymbol{E}$ by the total output ($\boldsymbol{e} = \boldsymbol{E}\widehat{\boldsymbol{x}}^{-1}$). The formula to calculate the total emissions associated with a given level of final demand ($\boldsymbol{y}$), such as total tourism consumption for a given country, is expressed in Eq. (3), in which $\boldsymbol{e}(\boldsymbol{I} - \boldsymbol{A})^{-1}$ is the emissions multiplier that provides total carbon emissions associated with one dollar spending in final demand.

$$\boldsymbol{E} = \boldsymbol{e}(\boldsymbol{I} - \boldsymbol{A})^{-1}\boldsymbol{y} \tag{3}$$

Assumptions and limitations in operation

To operationalize the input-output model, several assumptions are employed, such as linearity or proportionality, constant price and no capacity constraints (Miller & Blair, 2009). Becken and Patterson (2006) summarized two major limitations for tourism input-output applications—homogeneity and proportionality. Homogeneity refers to the assumption that all business firms produce using the standard production technology of the sector, profiled in the input-output table. This is the case where a $100 spent at five-star hotel would be assumed to produce the same amount of carbon impact as $100 spent at a basic motel, because most input-output tables cannot reflect the heterogeneity of production for the numerous small and medium tourism enterprises. In practice, the homogeneity assumption underestimates environmental burdens from below-average firms and fails to reward environmentally friendly producers. Proportionality, on the other hand, refers to constant returns to scale, implying the environmental impact will be doubled if consumption of one service (such as accommodation) is doubled. This assumption does not permit the consideration of price fluctuations or capacity utilization ratios; two factors which will influence the stability of input-output coefficients (Sun & Wong, 2014).

Variations of input-output models

One distinct advantage of the input-output method over the bottom up approach is its ability to address linkages between the defined territory with the 'rest of world' through international trade (Wiedmann, Wilting, Lenzen, Lutter, & Palm, 2011). This allows the model to quantify the resource and pollution content for imports that are utilized to support the production or consumption of a territory. Two distinct input-output models are developed to model the international trade—the multiregional model and the single region model.

Multiregional input-output models (MRIO)

Multiregional input-output models first appeared in the 1950s, but their use has been fueled by the recent developments of several multiregional input-output databases (Inomata & Owen, 2014; Peters, Davis, & Andrew, 2012), becoming the norm in footprint calculation at the global level. The standard multiregional model includes a comprehensive dataset that presents regions and countries with their own technology and trade. The environmental extension provides detailed accounts of production processes and pollution intensities per sector in each country (Davis & Caldeira, 2010; Peters, 2008). The multiregional input-output model has been recognized as the best framework to deliver critical information for directing sustainable consumption and production policies because of its effectiveness in differentiating the embedded environmental effects through international supply chains, including feedback loops and identifying environmental responsibility by the consumer or producer respectively (Wiedmann et al., 2011).

Single region input-output models (SRIO)

As the name indicates, the single region input-output model on the other hand is constructed based on one country's individual input-output table and the connection with other regions or countries is not profiled, therefore the model fails to include the feedbacks and interrelationships between them. Consequently, the environmental impacts of imports and indirect multiregional trades are ignored, leading to an underestimated result. The common way of avoiding this limitation is to include imports from the "rest of the world" using information from national input-output tables and applying the domestic technology assumption to approximate the environmental impacts of imports (Munksgaard & Pedersen, 2001; Peters & Hertwich, 2008; Sánchez-Chóliz & Duarte, 2004). It is assumed that the production technology and the emission intensities are the same for the country and the "rest of the

Table 1
Comparison of tourism EEIO studies.

Paper	Coverage	Visitor segments[a]	Type of consumption[b]	International aviation included[c]	Environmental variables	Imports included	SRIO or MRIO	Separate tourism sector
Global studies								
Lenzen et al. (2018)	160 countries 2009–2013	TSA	TSA	Destination approach: TSA. Residence approach: residents share of domestic and foreign-based carriers	CO2e	Yes	MRIO	No
National studies								
Dwyer, Forsyth, Spurr, & Hoque, 2010	Australia 2003–04	TSA	TSA	Production approach = TSA Expenditure approach = TSA + non-Australian-based	CO2e	Yes (DTA)	SRIO	No
Meng, Xu, Hu, Zhou, & Wang, 2016	China 2002–05–07–10	TSA	TSA	TSA	CO2e, energy intensity	Not specified	SRIO	Yes
Zhong et al., 2015	China 2007	Domestic tourism	TSA	Not specified	CO_2e	Not specified	SRIO	Yes
Cadarso, Gómez, López, Tobarra, & Zafrilla, 2015	Spain 1995–2007	TSA and public administration expenses	TSA	TSA	CO2e	Yes (DTA)	SRIO	No
Cadarso, Gómez, López, & Tobarra, 2016	Spain 1995–2007	TSA, public administration, and gross capital formation of tourism activities	TSA + private tourism investment	TSA	CO2e	Yes (DTA)	SRIO	No
Sun, 2014	Taiwan 2006	TSA	TSA	TSA	CO2e, energy	Yes. (DTA)	SRIO	No
Sun, 2016	Taiwan 2001–2011	TSA	TSA	TSA	CO2	Yes	MRIO	No
Becken & Patterson, 2006[d]	New Zealand, 1997–98	TSA	TSA	TSA	CO2, Energy	Not specified	SRIO	Yes
Sharp, Grundius, & Heinonen, 2016	Iceland 2013	Inbound tourism	Local transport, accommodation and restaurants, retail goods and leisure services	National and international carriers included	CO2e	Yes (DTA)	Hybrid approach (SRIO-LCA)	No
Regional studies								
Tang & Ge 2018	Shanghai, China	D + I	No TSA Transport, accommodation, catering, shopping, tourism attractions, entertainment, telecommunications, others	Not specified	CO2e	Not specified	SRIO	No
Munday, Turner & Jones 2013	Wales, UK	D + I	No TSA Personal transport (cars), non-private transport, hotels and restaurants, retail, recreation services	No	CO2e	Yes	SRIO	No
Cai, 2016	South Tyrol, Italy	Overnight tourists	TSA Excludes private vehicles	Not specified	CO2e	Yes	MRIO	Yes
Tsukui, Ichikawa & Kagatsume 2017	Tokyo and Kyoto, Japan	Domestic overnight tourists	No TSA Travel, lodging, souvenir, dining, other	No	CO2e, waste generation, waste	Yes	MRIO	No

(*continued on next page*)

Table 1 (*continued*)

Paper	Coverage	Visitor segments[a]	Type of consumption[b]	International aviation included[c]	Environmental variables	Imports included	SRIO or MRIO	Separate tourism sector
					transportation, landfilling			
Whittlesea & Owen, 2012	South West England	Day and overnight visitors	No TSA Accommodation, food, travel, shopping, attractions, activities, events, services	Not specified	CO2e Radiative forcing included (increasing air travel by 1.9)	Yes	SRIO	No
Visitor segments								
Sun & Pratt, 2014	Taiwan	Inbound tourism (4 groups)	No TSA Tourism spending on 15 categories of tourism products	Yes	CO2e, water footprint	No	Single region CGE	No
Lundie et al., 2007	Australia	Inbound tourism (12 groups)	No TSA Tourism spending on 13 categories of tourism products	Yes	CO2e, primary energy use, water use, ecological footprint (ha)	Not specified	Hybrid approach (SRIO + onsite editing)	No

Note

[a] "TSA": visitor segments including domestic tourism, inbound tourism, and domestic outbound expenditure in country/region.

"D + I": visitor segments including domestic tourism and inbound tourism.

[b] "TSA": visitor expenditure including package travel, accommodation, food and beverage, local transport, international transport, transport equipment rental, recreation, shopping and other.

[c] "TSA": international aviation emissions are those produced by national carriers based on the proportion contributed by inbound and outbound tourists.

[d] A separate technical report provided detailed tourism carbon emission results for New Zealand (Patterson & McDonald, 2004). This is believed to be the first literature to analyze tourism carbon emissions using the input-output approach.

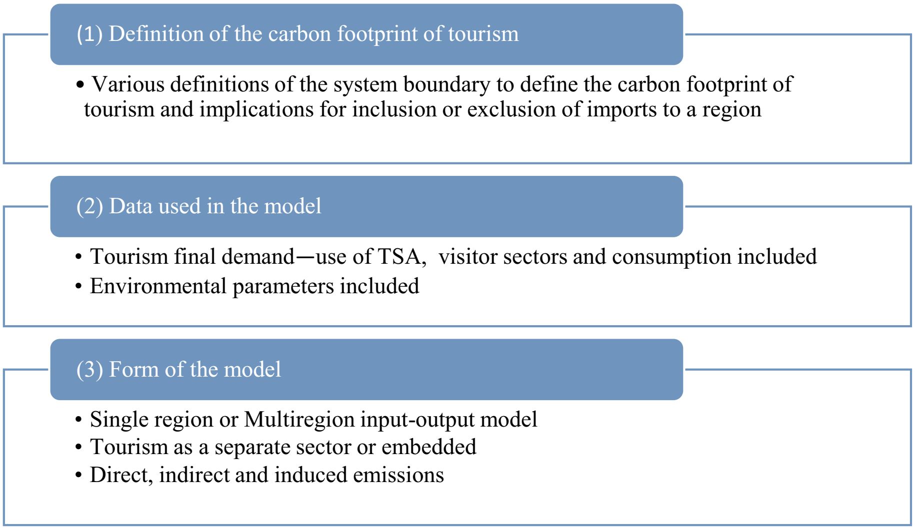

Fig. 1. Sources of variation in EEIO approaches.

world", no matter whether the inputs are domestically produced or imported. This assumption is common in the literature, however, this is a restrictive assumption, since production technology and emission intensities are different among countries and, as a result, it biases the estimations. In addition, the smaller the country or region of analysis, the more open the economy and the higher the relevance of imports, the more the domestic technology assumption will inevitably lead to a large under-estimation error. Please see Appendix 2 for a numerical example, showing the magnitude of differences regarding the model choice.

Review of tourism EEIO applications in carbon emissions

This section turns to examining the empirical studies undertaken using input-output to estimate the environmental impact of tourism. In reviewing the literature for this chapter, we identified one study at the global level (Lenzen et al., 2018) and 16 studies at the country and regional levels (please see Table 1 for the list of papers reviewed and their main characteristics).

It seems that there is no single standard approach yet developed to define the boundaries and scope in the tourism context. Researchers faced some constraints arising from the availability of data in appropriate forms and the availability of economic models that they could employ to study carbon impacts of tourism. Innovations made to overcome these constraints have led to progress in development of the various input-output approaches, however the different approaches make comparisons difficult. For this reason, we have focussed on methods rather than on results in this review, and classified variations arising from (1) definition of the carbon footprint of tourism; (2) the data used in the study, and (3) the type of the input-output models used (Fig. 1).

Variations in the system boundary used to define the carbon footprint

The input-output model is a well-established method to calculate carbon footprints for economic activity at the different spatial levels of global, country, region, and city (Davis & Caldeira, 2010; Wiedmann, Chen, & Barrett, 2016) and for different consumption patterns or types of consumers (Behrens et al., 2017; Duarte et al., 2016; Lenzen & Peters, 2010). However, tourism is an economic activity that involves residents and foreigners travelling inside or outside the country/region borders, with expenditures for that travel at home and at the destination. It is therefore difficult to set the boundaries for footprint calculations and define which components should be incorporated as part of the "tourism carbon footprint" for a given destination. We find in the literature several definitions, displayed in Table 2. We can find three main criteria to define tourism carbon inventories: (1) production, (2) consumption, and (3) destination. The first two principles follow the two most common carbon accounting measures at the country level: production-based inventories and consumption-based inventories (Munksgaard & Pedersen, 2001; Peters & Hertwich, 2008) and the third arises specifically in the tourism framework. We found that authors adopt various allocation principles to define tourism carbon footprint, and this is the primary reason for the variation across literature.

The *production-based approach* (PBA), *tourism producer responsibility* (TPR) and *production accounting principle* (PAP) are measures that aim to calibrate the carbon footprint from the producers' perspective. The differences are that the *production accounting principle* and *tourism producer responsibility* do not include imports (only emissions from domestic production) while the *production-based approach* does; furthermore, the *production accounting principle* also includes emissions from intermediate inputs exported and used to satisfy other country foreign tourist demand. Consequently, the *production accounting principle* is consist with the internationally recognized "production-based inventories" (Sun et al., 2019).

Residence-based accounting (RBA) is the same concept as the *consumption accounting principle* (CAP) and both focus on the country where the tourist resides, and both are the closest versions to the internationally accepted "consumption-based accounting". In fact, the consumption

Table 2
Tourism carbon inventories definitions.

Principle	Name	Definition	Source
1. Production related principles	Production-based approach (PBA)	Includes emissions directly produced by tourism industries, emissions from country-based airlines (inbound and outbound services), emissions from imports used as inputs in producing goods and services for sale to the country's tourism industry (but not imports directly purchased by tourists)	Dwyer et al. (2010)
	Tourism producer responsibility (TPR)	Accounts for the total emissions generated in a country that are linked to the supply of tourist-demanded goods and services (it is a domestic carbon footprint and the demand comes from either resident or inbound tourists).	Cadarso et al. (2015)
	Production Accounting Principle (PAP)	Emissions from the production of tourism services that are registered in the country of reference, disregarding where this good is consumed or by whom. Accounts for territorial emissions.	Sun et al. (2019)
2. Consumption related principles	Residence-based accounting (RBA)	Allocates emissions to the country of residence of tourists and matches the scope and definition of the conventional carbon footprint definition	Lenzen et al. (2018)
	Consumption Accounting Principle (CAP)	Total emissions embodied in resident tourists travelling at home and outbound.	Sun et al. (2019)
3. Destination related principles	Expenditures-based approach (EBA)	Emissions from expenditures by non-resident-based and domestic tourists on tourism in the country (including emissions from national and international aviation, from imports directly purchased and expenditures at home by outbound resident tourists, but excluding outbound airfares)	Dwyer et al. (2010)
	Tourism carbon footprint (TCF)	Adds emissions from intermediate and final imports to TPR.	Cadarso et al. (2015)
	Destination-based accounting (DBA)	Allocates emissions to the country of tourist destination.	Lenzen et al. (2018)
	Tourism Satellite Account Principle (TSAP)	Consists of the domestic and foreign emissions that are produced to support all travel activities within the geographic territory of an economy	Sun et al. (2019)

accounting principle can be seen as the missing element in most tourism carbon footprint calculations. Very few have attempted to have a full accounting of the total emissions to satisfy a country's population for their domestic and international tourism demand.

Finally, *destination-based accounting* (DBA), the *expenditures-based approach* (EBA), the *tourism carbon footprint* (TCF) and the *tourism satellite account principle* (TSAP) have the same philosophy of focusing on the territory where the tourism activities occur (Sun et al., 2019). A tourism satellite account (TSA) specifies the total expenditure which occurs to a destination, and then the domestic and international emissions produced to satisfy all tourism consumption in a destination are included. The majority of tourism carbon footprint analysis adopts the *tourism satellite account principle*, which traces the domestic and international emissions for all tourism expenditure reported within the defined territory.

In summary, "production" attributes tourism carbon inventories based on the territory where the firms are located, "consumption" allocates emissions to country where tourists reside, and "destination" aggregates emissions domestically and internationally as a result of tourism consumption within the region. For example, a Japanese visitor consumes France-made bottled water in China. The emissions of this bottled water is assigned to France based on the "production" accounting, to Japan for the "consumption" framework, and to China for the "destination" scope, respectively.

The decision to adopt which type of tourism carbon footprint definition also influences the treatment of imports. Logically, inclusion of imports will lead to higher impacts attributed to tourism at the subject destination. At a country level, imports contributed about 17% of the Australian tourism carbon footprint (Dwyer et al., 2010) and more than 50% in the Spanish case (Cadarso et al., 2015). In subnational studies, since regions are usually more open economies, the relevance of emissions embodied in imports is expected to be higher. Most of the regional level models reviewed did include imports in their emissions calculations.

Variations in the data used

This group of variations includes the tourism final demand changes considered (specific visitor segments, consumption items included) and the environmental parameters included in the models as impacts from tourism activities. At times, the approach taken in analysis was due to data availability or constraints, but for other studies, a deliberate approach was taken to address the policy issues that were the focus of the study.

Tourism final demand changes

Both the selection of visitor segments included, and consumption items considered vary among studies. Where researchers have access to a tourism satellite account, this will define the standard data boundary for the analysis, and have the following inclusions in the 'tourism sector':

(i) Consumption by sectors: hotel, transport, food, shopping, recreational activities, and other sectors with a threshold amount of spending by tourists.

(ii) Visitors covered: domestic, inbound and a proportion of outbound (for their domestic spending).
(iii) Industry covered: only services directly provided by national providers will be considered. This includes international aviation by domestic carriers but excludes international aviation service by foreign carriers. Notably, only international aviation emissions by national carriers will be accounted for.
(iv) A broader tourism satellite account also measures the contribution to investment in fixed capital by businesses, and quantifies the value provided by certain non-profit organizations and governments to serve visitors. These two factors are considered by the World Travel and Tourism Council (WTTC) when they compute the economic impacts of tourism.

Of the studies reviewed, 8 national studies and the global study had access to tourism satellite accounts. At country level, the most common procedure was to include all domestic tourism expenditure, inbound tourism expenditures and domestic expenditures for outbound travel (Cadarso et al., 2015; Cadarso et al., 2016; Dwyer et al., 2010; Meng et al., 2016; Sun, 2014, 2016) and the same type of visitor expenditures were accounted for in the global study (Lenzen et al., 2018). The availability of additional data allowed the analysis to go beyond visitor expenditure—addressing the tourism expenditure by public administration in the Spanish cases and the assessment of the carbon footprint linked to the tourism investments (Cadarso et al., 2016).

Cases are also available to contrast to the relative contribution of environmental impact by a particular segment. This includes those that considered domestic overnight tourists only (e.g. (Tsukui, Ichikawa, & Kagatsume, 2017)), international tourists only (e.g. Sharp et al., 2016), international tourists by country of origin (Lundie et al., 2007; Sun & Pratt, 2014) or tourists who were rural residents versus urban residents (Zhong et al., 2015).

Another visitor segment rarely treated separately in the literature is business tourism. This kind of tourism is an intermediate consumption made up of expenditures from business trips and represents expenditures required (as other intermediate inputs) to obtain other products. As a result, there are two different procedures: treat business tourism expenditures as a visitor segment in final demand or to include them within the purchasers' intermediate consumption and modify accordingly the technical coefficients of production of each sector with business travel expenditures. Only Cadarso et al. (2015) and Cadarso et al. (2016) use the second approach, following the recommendation of the Spanish Statistical Institute.

Categories of tourism consumption items included in input-output studies also varied among studies. Where researchers had access to a tourism satellite account that records tourism consumption across several sectors of the economy, usually both tourism-characteristic and tourism-related sectors, the inclusion of consumption items was more complete. Again, this was the case of most country and global level studies. Differences here arose from different sector classification and disaggregation in tourism satellite accounts, such as the availability of separate information about shopping and different types of transport. In the studies reviewed, the number of categories ranged from 7 standard, highly aggregated 'tourism' characteristic expenditure sectors (Cai, 2016) to 30 tourism products (Tang & Ge, 2018).

Arguably the most significant choice in the models is the treatment of emissions intensive international aviation. Of the studies reviewed, 2 national studies did include international aviation emissions from both national and international carriers (Dwyer et al., 2010; Sharp et al., 2016). Another 6 studies considered only the emissions of international aviation from national carriers, as they follow the "*destination-based accounting*".

Environmental parameters included in the model

Most studies presented CO_2 equivalents (CO_2e) figures including carbon dioxide and the other five recognized greenhouse gasses. Only one study went a step further to consider radiative forcing of contrail cirrus by aviation; Whittlesea and Owen (2012) multiplied the aviation CO_2e measure by 1.9. A number of these environmentally extended studies also included results on energy intensity (Becken & Patterson, 2006; Meng et al., 2016; Sun, 2014), waste generation (Tsukui, Ichikawa & Kagatsume 2017), water use (Sun & Pratt, 2014) and ecological footprint (Lundie et al., 2007). This illustrates the versatility of the EEIO model in including a range of environmental parameters.

Variations arising from the form of the input-output model

Single vs multiregional models

As mentioned above, single region models that focus on one individual country, and multiregional models that consider countries' interconnections through global value chains can be used for tourism carbon accounting. In the tourism framework, the assessment of carbon emissions using multiregional models are not yet the most common approach. At country level, only one study uses multiregional modelling (Sun, 2016), and it is also the model used in the tourism carbon emissions analysis at global level (Lenzen et al., 2018). In those cases where imports are included in the analysis of emissions, the single region models adopt the domestic technology assumption, so imports are assumed to have the same technology of production and the same emission intensity as the domestic products they substitute (Cadarso et al., 2015; Cadarso et al., 2016; Dwyer et al., 2010; Sharp et al., 2016; Sun, 2014). An example of multiregional approach focussed at a regional level was provided by Cai (2016), who modelled tourism in the South Tyrol region in Italy, with three external regions. Significantly, about four fifths of emissions of travellers to South Tyrol occurred from activities situated outside the South Tyrol borders.

Tourism as part of the economy or a separate sector

Tourism is composed of different goods and services of different sectors to satisfy tourists' demand, so the tourism industry participates in several sectors of the economy. The transversal character of the tourism industry allows for two different ways of isolating the part of the economy linked to the tourism activities. The first one and the most common in the literature reviewed consists of identifying the production of a sector linked to tourism by the final demand that tourists exert on the sector (Cadarso et al., 2015; Lenzen et al., 2018). The second approach calculates tourism impacts by adding an additional tourism sector to the economy

(Becken & Patterson, 2006; Cai, 2016; Meng et al., 2016; Zhong et al., 2015). The first approach has an advantage because both the structure of inputs and emissions intensities, come from tourist demand on the sector. That is, the emissions or energy intensity of the tourism sector is the result of each sector of the economy directly or indirectly involved to provide the tourists' needs. An additional advantage of the final demand approach is that it allows for accounting for different specific consumption patterns by type of tourist—domestic or inbound, as in most of the cases reviewed, or by country of origin (Lenzen et al., 2018).

Direct, indirect and induced emissions

All the studies reviewed calculated both direct and indirect emissions, as would be expected using the input-output methodology. One study (Tang & Gee, 2018) took the approach that there are no direct emissions from tourism, all are indirect. Notably, none of the studies reviewed reported induced emissions that arise from the economic activity of people who earn money as part of direct and indirect production and then spend it in the economy. Most tourism economic impact analysis, such as the World Travel & Tourism Council tourism economic assessments, does include induced effects in total gross domestic product estimates. Aligning environmental and economic assessments is an issue to explore for future input-output approaches.

Recommendations

Implementation of the environmental extended input-output analysis

The system boundary selected for an input-output analysis substantially influences the resulting magnitude of the tourism carbon footprint. Here we present some recommendations on how to carry out an input-output carbon study with respect to the selection of the carbon footprint definition, data and the economic model itself.

The tourism carbon accounting definition depicts what components should be incorporated into the analysis, and the choice depends on what type of questions the analysis aims to address (Sun et al., 2019). First, if the goal is to document the full-scale sectoral level tourism carbon footprint, it would be desirable to follow the boundaries of tourism satellite account and calculate carbon footprint measures through the principle of the *destination-based accounting*. Its advantages are: it is the most common measure at the national level, it is comprehensive (accounts for all domestic and international emissions driven by the tourism inside the country borders) and it provides full comparability because it is based on the common principles of a tourism satellite account that is compiled within the National Accounts. We believe these are the required characteristics of a standard approach and offer several distinct benefits in carbon management (Lenzen et al., 2018). First, inter-country comparisons of tourism economic significance, carbon emissions and tourism eco-efficiency are made possible because the tourism satellite account conceptual framework and data compliance are consistent across nations. Second, the tourism satellite account data complies with National Accounts, allowing tourism to be benchmarked against other sectors in the economy in terms of its economic and environmental performance. Third, a straightforward treatment of the international aviation issue is provided. Aviation emissions are allocated to a country based on the economic transactions that are reported in the tourism satellite account by the national carriers.

However, we also agree if the goal is to assess changes in the tourism carbon footprint due to policies and measures, different definitions and their related system boundaries become optional. For example, the *production-based accounting* measure is best suited for monitoring territorial emissions and forms a base to apply abatement policies toward domestic producers. The *consumption-based accounting* measure on the other hand is good for defining the climate impact of residents travelling domestically and abroad.

Similar consideration is applied to the treatment of the radiative forcing factor of contrail cirrus through aviation (Burkhardt & Kärcher, 2011). For the sectoral tourism carbon inventory to be consistent with national accounts, the radiative forcing factor needs to be temporally ignored because the National Greenhouse Gas Inventory does not consider this effect as specified by the Intergovernmental Panel on Climate Change guidelines (IPCC, 2006). For other policies or measure-related assessments for the aviation sector, this becomes optional.

Continuing with the model form, including tourism activities as a cross-sectoral activity, instead of as an additional sector, is a more straightforward procedure and provides more flexibility for applications, such as splitting tourism demand by tourist characteristics (residence, income). Where the researchers are attempting a comprehensive understanding of the environmental impact of tourism, it is argued that the domestic tourism, inbound tourism, and outbound tourism for its domestic spending should be included, although inclusion would depend on the data availability. Regardless of the detail included, providing separate carbon footprints for each tourism segment and major consumption categories would improve comparability.

Tourism interconnects domestic and foreign sectors through global value chains, and generates value and environmental impacts at destination and beyond the borders (Sun, 2019). Consequently, the best practices in input-output carbon accounting of tourism would require the inclusion of imports. However, we note that the treatment of imports should be carefully considered. Embedded emissions through imports must be excluded if the study aims to rank tourism contribution to the national emissions inventory or to identify the influence of tourism in Nationally Determined Contributions within the Paris Agreement. On the other hand, a standard modelling of tourism carbon emissions that considers imports would help to map out how a given tourism consumption can contribute to emissions globally through linkage effects, avoiding a false impression that tourism is clean, green and non-consumptive within their own territory. In this regard, multi-regional and single region input-output models with the domestic production technology assumption are both recommended, depending on the data availability and quality.

Policy relevant recommendations

The feasibility of an input-output evaluation of tourism emissions has been greatly enhanced in recent years due to the wider availability of tourism satellite account and economic-environmental input-output tables at the regional and global level. The World

Tourism Organization (2010) identified that around 60 countries in 2010 had produced or were currently developing a TSA exercise, covering more than 80% of total global tourism consumption. At the same time, several global input-output databases, such as EORA, EXIOBASE, the Global Trade Analysis Project MRIO table (GTAP-MRIOT), and the World Input-Output Database (WIOD), are now available, providing long-term country-specific economic and environmental parameters (Inomata & Owen, 2014). These multiregional input-output databases provide a convenient platform from which to calibrate and compare cross-country tourism carbon emissions.

We see input-output models as providing a time- and cost-efficient pathway to establish international compatible tourism carbon accounts—linking strongly to how tourism can contribute to the Paris Agreement and Sustainable Development Goals. Specifically, three areas of development are called for to enhance this method in addressing tourism carbon management.

Prioritise tourism carbon estimation through supranational collaboration

The current applications of estimating tourism carbon emissions mostly rely on case studies without a systematic, cohesive effort to track and identify long term tourism climate impacts. The development of harmonized tourism carbon indicators requires supranational collaboration, especially of the following two agencies: the World Tourism Organization and the World Travel and Tourism Council. The latter is the custodian of tourism economic data for 185 countries and 25 regions of the world, with most countries covered for the past 25 years based on the country-level tourism satellite account (World Travel and Tourism Council, 2018b). This data infrastructure has great potential to be integrated with the carbon footprint calculation through the above-mentioned multiregional input-output models. This will create a tourism economic and carbon emission database that is updated annually at global, regional, and individual country levels, making indicators comparable across countries and among sectors inside the country. In addition, the World Travel and Tourism Council database can be easily expanded from a single country perspective to greater geo-political regions which may have collective policies in place that influence tourism's carbon performance. Prominent cases include the emissions trading scheme in the EU (European Commission, 2019), the Open Skies agreements between ASEAN 10 countries (ASEAN, 2016), or the One Belt One Road policy that promotes the social-culture and mobility connection between Asia, Europe and Africa by the Chinese government (Huang, 2016).

We recognize that the World Travel and Tourism Council economic impact model employs several strong assumptions. Especially, criticisms are raised regarding unreliable tourism consumption patterns for countries that do not have tourism satellite accounts, and inconsistent visitor statistics due to lack of thorough or consistent measurement by various governments and international organizations (Pratt & Tolkach, 2018; WTTC, 2018). We also agree that these factors may cause an estimation error for both economic and environmental appraisals. However, this system is the best starting point to establish a global and inter-governmental tourism carbon database without enormous investment and years of data compilation. Significantly, with the extensive media channels that have been established by the World Travel and Tourism Council and World Tourism Organization, linking existing economic data with environmental accounts provides a great opportunity to disseminate information regarding the trade-off between GDP and emissions that are relevant to tourism.

At the national level, developing tourism carbon emission inventories are advocated as a priority for the top 20 tourism carbon emitters because global tourism emissions are predominately contributed by a selected few countries. If comparing national tourism emissions based on the *tourism satellite account principle*, USA, China and Germany were the biggest emitters in 2013, contributing about 24%, 14% and 7% of the global tourism carbon footprint, respectively. In fact, the top 20 countries were responsible for around 80% of global tourism emissions (Appendix 3). This implies that just a 5% reduction of their aggregate emissions would create a 4% global reduction effect in tourism's carbon footprint, sufficient to stabilize its upward trend. Therefore, priority should be directed to those 20 countries to build up their national carbon accounting procedures and to integrate tourism into their System of National Accounts. This will especially highlight how tourism can assist or deter the progress of their national effort in carbon mitigation.

Promote triple-bottom line assessments in national carbon management

Sustainable tourism is managed through the triple-bottom-line concept in which tourism takes full account of its current and future economic, social and environmental impacts. The same principle should apply to carbon management, because a cohesive strategy simultaneously addressing economic, environmental and social dimensions would create a better opportunity for a country to successfully transit to a low carbon society. While a great effort has been made on economic and environmental appraisals, assessments of social impacts associated with climate change and its mitigation actions are still in a preliminary stage.

With the recent development of the social life cycle assessment, the input-output model is further expanded from an economic and environmental tool to appraise changes in social dimensions (Kühnen & Hahn, 2017; Sala, Vasta, Mancini, Dewulf, & Rosenbaum, 2015). Depending on the social inventory data that is established, social life cycle analysis based on the input-output model is capable of addressing important social issues such as: labour equality with respect to female employment, working time, wage distribution, human rights on child labour, community infrastructure or fair trade (Papong, Itsubo, Malakul, & Shukuya, 2015; Sala et al., 2015).

OECD-UNEP (2011) states that any large scale, long-term carbon mitigation policies would inevitably lead to constraints in current travel styles and remodification of economic structures and that governments should actively address resulting social changes in order to garner support from the grassroots. Especially, the climate-tourism—-income—society dilemma will be significant for destinations that lack of the capacity to navigate unemployment and consumption reduction when tourism demand is reduced by carbon measures (Nurse, Edwards, & Dookie, 2018; Read, 2010). The input-output model has a great capacity to assist a seamless integration of the three pillars of sustainability into a macro-level policy framework whose hallmark is to disseminate balanced information on tourism, carbon emissions and social welfare to policy makers and the public at large.

Embrace emerging opportunities for input-output modelling of tourism carbon emissions

Advancements in computational power and input-output modelling have substantially evolved economy-wide carbon footprint calculation in the past decade (Malik, McBain, Wiedmann, Lenzen, & Murray, 2018). Leveraging these advancements for tourism, there is a great potential to further develop input-output applications in the tourism carbon footprint domain. The first direction is the ability to incorporate subnational or city level analysis with high-resolution regional-detailed data structures. Especially, footprint analysis at the city level is increasingly available to provide insights into the relationships between urban consumption, life styles, and environmental impacts: for example, for Aveiro, Portugal (Dias, Lemos, Gabarrell, & Arroja, 2014), Chinese megacities (Feng, Hubacek, Sun, & Liu, 2014), and 1894 municipalities in Japan (Wakiyama, Lenzen, Geschke, Bamba, & Nansai, 2020). In the tourism context, metropoles are catalysts of global travel as they currently account for nearly half of overall international travel, and 72 major tourism cities contributed 24% of global tourism GDP (World Travel and Tourism Council, 2018a). Emission analysis at the city level will map out hotspots of goods, services, energy and the related environmental pollution as a result of tourism, providing opportunities for mitigation at the municipal level. This regional analysis however needs to carefully consider the homogeneity assumption to avoid adopting the national carbon efficiency for regional tourism firms.

The second opportunity is to develop hybrid models for tourism. Hybrid models improve the accuracy of footprint calculation by replacing monetary data with physical data to solve the problem of price heterogeneity (Malik et al., 2018). Relaxing the assumption of constant price is important for tourism as this industry is characterised by its discriminatory pricing strategies. A doubling of price during high seasons is less likely to lead to a doubling of use of energy among firms, but the linearity assumption of the input-output model will inevitably lead to overestimation. The adoption of hybrid input-output models for tourism, especially with respect to the treatment of aviation and accommodation by modelling flight-miles and room nights instead of monetary units, will reduce estimation errors (Becken & Shuker, 2019; Gössling et al., 2005). In addition, hybrid models provide a bridging platform to the bottom-up approach in carbon measurement, allowing tourists' behaviour (distance travelled, nights stayed) to be better modelled within the input-output framework.

Conclusions

The environmentally extended input-output model has distinct advantages to enable macro-level tourism carbon management. Specifically, this approach assists in gauging the full scale of the environmental externality of tourism consumption, monitoring the trade-offs between the economic and environmental components, and locating the mitigation options from various approaches. This is an evaluation tool well suited to measure the sectoral-level carbon emissions of tourism within the Paris Agreement while at the same time linking the carbon account with the progress of Sustainable Development Goals, documenting the intertwining relationships between the sustainable development and climate agendas.

Input-output carbon accounting of tourism provides relevance, completeness, transparency and comparability in the sense of including all relevant emissions in a consistent way. Results of input-output estimates are however critically influenced by the system boundary used. All relevant literature thus needs to disclose significant assumptions, data restrictions and boundary definitions in a more transparent way. This aspect is required to assess accuracy, to reduce uncertainties with data improvement and to enable users to make informed choices.

Tourism industries need to identify the risks but also the opportunities that the fight against climate change poses to them. Risks include the regulatory measures than can affect the company or its suppliers, environmental impact related lawsuits, increases in supply chain costs or decrease in demand for products with relatively high environmental costs. Opportunities on the other hand include savings in costs by increasing efficiency, new incentives for innovation, improved reputation, consumer loyalty, responsibility and company differentiation (CDP, 2017, 2019; Kareiva, McNally, McCormick, Miller, & Ruckelshaus, 2015; Lister, 2018). Input-output carbon accounting will help to identify those risks and opportunities along the global value chain and provide benchmarking for the present situation and future achievements.

Overall, great potential exists to effectively promote the input-output method in the tourism contexts and enhance its link with practice and policy. The successful implementation of an input-output analysis requires interdisciplinary collaboration among academics, practitioners, and policy makers to understand its assumptions and operation and to recognize its applicability to address the information complexity in climate action.

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Appendix A. Supplementary data

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