Developing and applying input-output analysis tools for assessing sustainability and informing global frameworks

Vivienne Rebecca-Ann Wellisch Reiner

A thesis submitted in fulfilment of the requirements for the degree of Doctor of Philosophy

School of Physics

Faculty of Science

The University of Sydney

4 March 2026

Originality

I certify that this thesis is my own work, that I developed the intellectual content and that any assistance relied on in producing this thesis has been acknowledged. This thesis has not been submitted for publication or any other purposes.

AI has not been relied upon for research or to produce content for this thesis. Editorial services by Gillian Begg were commissioned for checking typographical aspects such as section numbering.

Vivienne Rebecca-Ann Wellisch Reiner

Signed 04/03/2026

Acknowledgements

I commenced my PhD not long after the unprecedented 2019-20 mega-fires in Australia and the resumption of business-as-usual post-COVID-19. I wanted to gain science skills to add to my sustainability communications and engagement experience but this journey has also changed the course of my life. This thesis is dedicated to my children, who will inherit the planet, in large part, as my generation leaves it.

I am indebted to my amazing supervisors, Professors Arunima Malik and Manfred Lenzen: their generosity, guidance and insights have been truly invaluable.

Half this thesis has focused on directing input-output analysis to calculate the University of Sydney's scope-3 emissions up- and downstream; many people played crucial roles in this project, from promoting the concept to championing its final publication in the climate-related disclosures. Special mention goes to the University's Sustainability and Finance teams and in particular, Armando Aragon who supported this at every step and whose technical understanding as well as commitment helped translate this from an academic exercise into an example of university leadership in sustainability reporting.

Thanks is also due to numerous colleagues in the Integrated Sustainability Analysis (ISA) group, as well as to Sebastian Juraszek and his team for managing the School of Physics' advanced computational requirements, and others in the School and elsewhere at the University of Sydney who offered advice and shared their knowledge. I am also grateful to this thesis's examiners and to the editors and the anonymous reviewers who have improved the published papers that follow. Finally, a great deal of thanks is owed to my friends and family, who have lived through the PhD with me; to those of you who read proofs, offered ideas and helped keep me focused on the important things, this is also your achievement.

It has been an honour undertaking this PhD with ISA; I can only hope that the benefit extends well beyond the pleasure I experienced being involved in this critical quantitative sustainability analysis.

Vivienne Rebecca-Ann Wellisch Reiner

Signed 13/11/2025

This research was supported by an Australian Government Research Training Program (RTP) Scholarship. In addition to the RTP fee offset scholarship for all domestic students, this thesis was supported by an RTP stipend scholarship.

Attribution / Publications

- Chapter 2 of this thesis is published as:

  Reiner, V., Pathirana, N. L., Sun, Y.-Y., Lenzen, M., & Malik, A. (2024). Wish You Were Here? The Economic Impact of the Tourism Shutdown from Australia's 2019-20 'Black Summer' Bushfires. *Economics of Disasters and Climate Change*, *8*(1), 107-127. https://doi.org/10.1007/s41885-024-00142-8

  I conceptualised the study, conducted research and scenario analysis and drafted the manuscript, which was initially edited by Arunima Malik and Manfred Lenzen. Navoda Liyana Pathirana wrote most of the coding, Ya-Yen Sun provided advice on tourism data and analysis, Arunima Malik advised on methodological design and wrote the test coding, and Manfred Lenzen provided critical oversight.

- Chapter 3 of this thesis is published as:

  Reiner, V., Malik, A., & Murray, J. (2025). Can global modern slavery be footprinted for corporate due diligence? A data analysis and review. *Journal of Industrial Ecology, 29*(4), 1077-1089. https://doi.org/10.1111/jiec.70037

  I undertook the data analysis, extended the research into qualitative analysis, conducted interviews and drafted the main text; Joy Murray conceived the initial study idea, which I then developed; Arunima Malik contributed to the literature review and reviewed the methods. All authors contributed to the editing.

- Chapter 4 of this thesis is under review:

  Reiner, V (*under review*). Income-based responsibility for organisations: A framework and demonstration of corporate sales-chain analysis.

  I designed the key aspects of this novel framework and wrote the paper as sole author. Manfred Lenzen and Arunima Malik are acknowledged for providing advice and supervisory support.

- Chapter 5 of this thesis is submitted as:

  Reiner, V., & Malik, A. (*under review*). Scope-3 emissions and Sustainability impact throughout the value chain: An approach to mandatory environmental due diligence.

I designed the study, undertook the analysis and drafted the paper. Arunima Malik advised on methodology and reviewed the paper. Both authors contributed to the editing.

Other academic outputs resulting from this PhD but not included in this thesis:

International-conference presentation

Reiner, V. (2024, 27 June). *Integrated Scope 3 and Nature Footprint Across the Supply Chain* [Concurrent session], 2024 ISCN Conference, Lausanne, Switzerland. https://coda.io/d/2024-ISCN-Conference-Website_dWeKRnU7np9/Program-and-Sessions_suFkdL9J#Conference-Program_tua01912/r50&view=full

Book chapters

Reiner, V., & Malik, A. (2026). Climate Change Threats to Supply Chains in Australia's Food Bowl. In P. Pradhan & L. P. Pant (Eds.), *The Elgar Companion on Food System Transformation for Sustainable Development* (Chapter 19). Edward Elgar Publishing Ltd. https://www.elgaronline.com/edcollbook/book/9781035332854/9781035332854.xml

Hu, Y., **Reiner, V.**, Li, M., & Malik, A. (2026). Responsible Food Production and Consumption. In P. Pradhan & L. P. Pant (Eds.), *The Elgar Companion on Food System Transformation for Sustainable Development* (Chapter 15). Edward Elgar Publishing Ltd. https://www.elgaronline.com/edcollbook/book/9781035332854/9781035332854.xml

I confirm the above attribution statements are correct.
Vivienne Rebecca-Ann Wellisch Reiner

Signed 13/11/2025

As the supervisors for the candidature upon which this thesis is based, we confirm that the authorship attribution statements above are correct.

Arunima Malik — Signed 14/11/2025

Manfred Lenzen — Signed 13/11/2025

Acronyms and synonyms

For details about input-output (IO) calculus, see Chapter 5 *Supplementary Information*.

$\mathbf{A}$ matrix: Technical coefficients matrix. Also referred to as the "direct requirements" matrix.

$\bar{\mathbf{A}}$ matrix, also referred to as the $\mathbf{B}$ matrix: Allocation or sales-coefficients matrix.

Bushfires: Australian English. Also called wildfires.

CBA: Consumption-based accounting**.** An EEIO approach to emissions accounting (see EEIO below).

Consumption-based impact: Based on upstream IO analysis that uses expenditure as the stressor.

Corporate reporting: Used synonymously for organisational due diligence.

Direct intensity: The intensity per unit of total output, usually denoted as $\mathbf{q}$ and sometimes $\mathbf{f}$.

Downstream IO analysis: Based on the Ghosh model; income-based IO analysis is downstream.

EEIO: Environmentally extended input-output analysis. This term is used generally where physical accounts are attached to the economic-based IO calculus, including social indicators.

EF: Emission factor or emissions factor. Also referred to as emission intensity. If incorporating the upstream inter-industry supply chain, the emission factor is the *total*-emission intensity ($\mathbf{m}$).

Footprint: May be used to refer to impact including the indirect value chain, using IO analysis.

Final demand: Also called "final consumption", as opposed to inter-industry transactions.

Forced labour: Non-consensual labour; may be used interchangeably with human trafficking.

Ghosh inverse: May be denoted by $\mathbf{G}$, or $\bar{\mathbf{L}}$ as the supply-side alternative of the Leontief inverse.

Ghosh model: Downstream IO analysis; based on the Ghosh inverse.

Human trafficking: Also referred to as trafficking in persons. May involve forced-labour travel.

Income-based emission factor: EF derived from downstream IO analysis (Ghosh model).

Income-based IO impact: Based on downstream IO analysis that uses income as the stressor.

Input-output (IO) analysis: Also denoted by IOA.

IOA: Input-output analysis.

IOT: Input-output tables.

Inter-industry: Also written as "interindustry". This is business-to-business transactions, also referred to in IOA as *intermediate* supply and use, as opposed to *final* demand or *primary* inputs.

Leontief inverse. Denoted by the letter $\mathbf{L}$. Incorporates the entire inter-industry supply chain.

Leontief model: Upstream IO analysis; based on the Leontief inverse.

Megafire: Also mega-fire; has been used to describe fires of extreme size, behaviour or impact.

mHRDD: Mandatory human rights due diligence. See UN Human Rights https://www.ohchr.org/

mHREDD: Mandatory human rights and environmental due diligence; see European Union.

MRIO: Multi-region input-output analysis. Also referred to as multi-regional IO analysis. Based on MRIO tables (MRIOT).

GMRIO: Global MRIO i.e., worldwide, not just two or more regions.

Modern slavery: Not defined in international law; may include a range of exploitative-labour practices such as forced labour, human trafficking, debt bondage and forced marriage.

Order of production: The level of the production layer of tier in a value-chain "tree" or PLD.

PBA: Production-based accounting**.** Also referred to as territorial-based accounting.

PLD: Production layer decomposition. Disentangles the value chain by orders of production.

Production-based impact: Has been used to describe upstream IO analysis that uses emitting industries as the stressor. However, the "production" could also refer to producer-countries (territories) or supply-side (downstream) calculus.[2]

Production layer: Tiers or orders of production, e.g., production-layer 1 upstream (downstream) comprises Tier-1 suppliers (customers). An IO analytical technique is PLD.

Spend-based emission factor: EF derived from upstream IO analysis (Leontief model).

Territorial-based accounting: A country's emissions, produced in its territory. See also PBA.

Tier-1 suppliers (customers): The first order of production in a PLD.

TIP: Trafficking in persons**;** also referred to as human trafficking. May involve forced-labour travel.

$\mathbf{T}$ **matrix**: Matrix of inter-industry transactions, or intermediate demand. Also denoted by $\mathbf{Z}$.

Total intensity: Denoted as $\mathbf{m}$ regarding upstream impact. Also referred to as a total backward multiplier or linkage for upstream or an emission factor (EF) for greenhouse gasses.

Wildfires: Also called bushfires.

Upstream IO analysis: Based on the Leontief model. Spend-based IOA is upstream.

$\mathbf{Z}$ **matrix**: Also denoted by $\mathbf{T}$**.** Matrix of inter-industry transactions; also referred to as intermediate demand.

---

[1] European Commission. (2022). *Making Mandatory Human Rights and Environmental Due Diligence Work for All: Guidance on designing effective and inclusive accompanying support to due diligence legislation*. European Union. https://international-partnerships.ec.europa.eu/system/files/2022-07/making-mandatory-human-rights-and-environmental-due-diligence-work-for-all_en.pdf

[2] For clarity regarding the latter, in addition to upstream IO accounting "consumption based" (CBA), two other distinct approaches have been termed "production based" (PBA) for territorial accounting and "income-based" for downstream IO analysis.

Contents

ABSTRACT OF THIS THESIS

This thesis takes a double-materiality approach, first by considering global warming, in quantifying the cost of a climate catastrophe generally and on sectors and regions, using robust, holistic and standardised input-output (IO) analysis. Acting locally at the enterprise level, IO analysis is used with process-based data where possible for comprehensive Climate-and-Nature reporting, from financial and broader impact perspectives. Global frameworks for mandatory human rights and environmental due diligence (mHREDD) are expanding their reach and interoperability, so the question of whether IO analysis is applicable to modern slavery reporting is also analysed. IO analysis is an ideal vehicle for interrogating indicators of additive quantum along the entire inter-industry value chain, so if global modern-day slavery could be reliably estimated then it could be used to trace supply-chain risk. However, no global data could be recommended for the calculation of modern-slavery multipliers but this research recommends tailored risk analysis in areas supported by rich data. To apply IO analysis across the value chain for established indicators, a hybrid-[lifecycle assessment] LCA-IO analysis framework is developed to extend downstream IO analysis to the enterprise level using estimated income per sector for the reporting entity. Next, a model is built that includes income and expenses; IO analysis is then applied to reporting in line with the International Sustainability Standards Board generally, as well as across scope-3 Greenhouse Gas Protocol categories and biodiversity-related indicators for the Taskforce on Nature-related Financial Disclosures. Having demonstrated the applicability of IO analysis to Climate- and Nature due diligence, mandating its use becomes paramount; such a mandatory scope-3 method for the calculation of indirect impact enables all organisations to make comprehensive disclosures on a level playing field to address the sustainability crisis.

1. OVERVIEW

1.1. Purpose and significance

It has been said that two of the defining challenges of our time are poverty/inequality and the climate emergency (see e.g., (Stern, 2015)) and that these may be viewed as interrelated, framed in a broader context of sustainability of people and planet (World Commission on Environment and Development, 1987). Taking a sustainability systems approach, the overarching aim of this thesis is to tackle this complex problem from the perspective of increasingly interoperable frameworks for mandatory human rights and environmental due diligence (mHREDD), by assessing, applying and developing the comprehensive and standardised methodology input-output (IO) analysis for climate- and general-sustainability disclosures.

1.2. Background

Australia is known for being a land of climate extremes but in 2019 experienced what was then its hottest year on record in addition to a record drought (Norman et al., 2021), favourable conditions for what became known as "Black summer". The catastrophic 2019-20 bushfires, which burned in every State and Territory and reached their peak in the Christmas/New Year period, overall covered more than one-fifth of Australia's continental forest biome, an area that was globally unprecedented (Boer et al., 2020) and affected almost three billion animals (van Eeden et al., 2020). At least 33 people were killed (Binskin et al., 2020b) from the bushfires (also called wildfires) and in addition, the Gospers Mountain megafire in New South Wales bushland to Sydney's north reportedly spread to within a day's reach of the built-up fringe suburb of Hornsby (McDonald, 2020); at risk were 20,000 homes within 100 metres of bush (Hannam, 2016). In the most-impacted State of NSW, modelling had not anticipated the fire extent for any time in the future (Sanderson & Fisher, 2020). However, worse fires are expected from global warming, since these fires occurred in the absence of El Niño, which in Australia is associated with hotter and drier conditions (Mullins, 2021). The bushfire season ended in March 2020, the same month that Australia's borders closed for the first time because of the coronavirus pandemic. The switch from one disaster to the next hampered data-collection of the bushfires damages and quantification of the total economic impact. The interim observations of the Royal Commission into National Natural Disaster Arrangements highlighted key areas of economic

damage being tourism, in addition to agriculture and forestry (Binskin et al., 2020a), while the final report of what is referred to as the Bushfires Royal Commission made a conservative estimate of money *spent directly on recovery* as being more than AU$8 billion (Binskin et al., 2020b, p. 458); of course, such a non-IO estimate *does not include any indirect impacts* along supply chains.

Globally there is no agreed approach for quantifying disaster costs and this is also the case for Australia, where challenges include a lack of timely, benchmarkable data (Handmer et al., 2018; Handmer et al., 2017). This may partly explain a reactive approach that leads to budgetary issues; at the time of writing, the Australian government had been re-evaluating its approach, whereby the three-year forward estimates for "natural-disaster relief" are based on past disasters, which is consistent with the funding mechanism for payments to States/Territories that is contingent on eligible trigger events (Satherley & May, 2022). Methods for quantifying disasters include assessing insured losses, although the scope by definition is limited, computable general equilibrium (CGE), which is based in part on IO tables but allows modellers substantial flexibility and therefore is characterised by a lack of standardisation (Zhou & Chen, 2021), extending IO to a social accounting matrix (SAM) (Okuyama & Santos, 2014) which, through focusing on more social data therefore tends to have a higher level of sector aggregation (Okuyama & Sahin, 2009); and conventional IO analysis, which underpins this thesis. Conventional IO analysis has the advantage of standardisation while incorporating the entire supply chain using calculus based on static, empirical data of the inter-relationships between sectors' purchases and sales. The linearity can be a limitation in terms of substitutability and price changes in the short-term (Rose, 2004). However, limitations may be addressed through hybrid approaches within an IO framework as discussed generally by Galbusera & Giannopoulos (2018) and demonstrated in the Californian wildfires study by Wang et al. (2018).

Quantifying the cost of climate change can assist with cost-benefit analysis, and IO analysis can also highlight hotspots along supply chains for rebuilding and mitigation efforts. This method is particularly useful for providing a robust macroeconomic perspective and identifying vulnerable regional industries. With mandatory human rights and environmental due diligence, organisations are increasingly being required not only to quantify material environmental *financial* risks to the business but in response must also measure and report on the organisation's material *impact* as part of the sustainability crisis, what is referred to as "double materiality" (European Commission, 2022). Human-rights frameworks now include a focus on slavery-like activities, for example "trafficking in people" legislation or "Modern Slavery Acts",

while more broadly sustainability due diligence involves reporting for "climate" and separately for general "sustainability" impacts. Recent global and regional regulations and Standards include the International Sustainability Standards Board (ISSB) and the CS3D *Corporate Sustainability Due Diligence Directive* (2024). In common with these frameworks is a requirement to consider the organisations' impact in the extended value chain.

In terms of human rights, the first *Modern Slavery Act* was only introduced a decade ago (2015). The focus of national modern-slavery reporting requirements at the time of writing was on eligible organisations producing a modern-slavery statement because of low levels of maturity (McGaughey et al., 2022). However, this could change, with reviews of the Australian and UK Acts recommending expanding from transparency to requiring organisational due diligence on supply chains (McMillan, 2023; Select Committee on the Modern Slavery Act 2015, 2024). Even countries that do not have their own legislation are increasingly likely to have their exports scrutinised from substantial importing blocs that now have regulations, such as the European Union and the United States, the latter of which includes legislation such as the updated TVPA (*Trafficking Victims Protection Act of 2017*, 2018). As well, although the ISSB's first two Standards do not include modern-slavery specifically, the ISSB has been considering "human capital" in its 2024-2026 workplan (IFRS, n.d.).

A challenge in identifying risk is that the activity is illicit and difficult to measure. However, there exist several well-known modern-slavery databases that update regularly as well as estimates. These include the United Nations' Global Trafficking in Persons report (GLOTIP), the United States' List of Goods Produced by Child Labor or Forced Labor, and the Walk Free foundation's Global Slavery Index (GSI). The GSI is the most disaggregated estimates of modern slavery at the national level (Lavelle-Hill et al., 2021) and perhaps because of this, it is also highly cited. It is based on the regional Global Estimates of Modern Slavery, which is an extension of the previous iterations of the ILO Global Estimate of *Forced Labour* (my emphasis) (International Labour Organization, 2012), however in addition to being co-authored by the International Organization for Migration, the Global Estimates of Modern Slavery is co-authored by philanthropic organisation Walk Free (International Labour Organization (ILO) et al., 2022), which was founded by mining magnate Andrew Forrest and his partner Nicola Forrest. In this expanded Global Estimates, forced marriage plus forced labour is defined as modern slavery in reaching the total of almost 50 million people. Moving along a continuum of modern-slavery definitions from forced labour to forced marriage (for example, is child labour forced, is prostitution consensual, is an arranged marriage forced etc) can involve increasingly qualitative judgements. This highlights the importance of considering anthropological approaches to managing human rights

(Merry, 2016). There is no *international* definition for or regulation of "modern slavery", although there is for trafficking in persons (United Nations, 2000). Even for such human trafficking, it can be a challenge to identify cases for official reporting, and the cited numbers vary greatly (Feingold, 2010). Regardless of measurement challenges, trafficking data is valuable for activities such as trend analysis, while estimates of modern slavery are also useful for advocacy.

Organisations required to report on risk beyond their tier-one suppliers may be more likely to *rely on global modern-slavery data or estimates as actual representations of global modern-slavery populations* as underlying data for the powerful tool of IO analysis to footprint risk along the supply chain. From a more localised perspective, IO analysis has also been used for tailored analysis of risk in particular sectors or regions, enabled by labour-intensive data-collection. An unintended consequence of mandatory modern-slavery reporting is that organisations may take a "tick box" approach, as noted in the UK government's consultation on transparency in supply chains (Home Office, 2020). This has underscored the need for interrogation of available modern-slavery data and estimates upon which such universal, global analysis and reparative action may be based.

As with human rights, so too has climate due diligence until recently reflected a relatively low level of maturity, focussing on a reporting organisation's direct emissions (scope 1) along with emissions from purchased or acquired electricity, steam, heat or cooling (scope 2). The Greenhouse Gas Protocol was established in the late 1990s because of the need for an international standard for corporate greenhouse gas accounting and reporting; it recommended that scope-3 emissions be optionally considered as an innovative approach in areas that may be useful (World Business Council for Sustainable Development & World Resources Institute, 2004, p. 29). Under scope-3 reporting mandated in the ISSB's IFRS S2, the method to follow is the GHG Protocol (World Resources Institute & World Business Council for Sustainable Development, 2011); all 15 categories are to be considered and the reporting entity must disclose any cases where it is considered impracticable to estimate scope-3 emissions, after "making every reasonable effort to do so" (International Sustainability Standards Board, 2023, p. 36). The GHG Protocol has noted that additional measures would be required to enable comparisons between companies, such as consistency in the scope-3 method and data relied upon (World Resources Institute & World Business Council for Sustainable Development, 2011, p. 06). Two decades after its first Standard was published, the GHG Protocol announced a review of several of its Standards including the scope-3 Standard, which was planned to be finalised in 2027 (Greenhouse Gas Protocol, 2025).

In addition to the GHG Protocol covering downstream scope-3 categories including inter-industry ("processing") stages, the new EU regulations extend downstream; for example, the *Corporate Sustainability Reporting Directive* includes scope 3 "where relevant" (2023), which is defined by the related [ESRS] *European Sustainability Reporting Standards* as material impact aligned with the GHG Protocol categories (2023). However at the time that the GHG Protocol's scope-3 Standard and guidance were released (World Resources Institute & World Business Council for Sustainable Development, 2011, 2013), income-based downstream IO analysis was in its infancy (Marques et al., 2013; Marques et al., 2012). Using upstream IO analysis, what are referred to as "spend-based", industry-average emission factors are calculated; it is this spend-based data that is referred to by the GHG Protocol (World Resources Institute & World Business Council for Sustainable Development, 2013) as well as by the ESRS (European Commission, 2023a, p. 29); however not referenced is the income-based downstream equivalent: in the past decade, *income-based* emission factors been demonstrated in high-impact journals e.g., (Chen et al., 2017; Starr et al., 2023; Xu et al., 2019).

The emerging environment of mandatory sustainability reporting means there is now a handful of global and regional largely interoperable frameworks as a modern response to the challenge of sustainable development; the global architecture has been summarised visually by the TNFD (2023, p. 20). The field of integrated reporting has grown substantially in the past decade (Songini et al., 2023) and IO analysis is well-placed to underpin new global requirements in a way that is standardised and comprehensive, to a high degree of resolution.

This thesis does not focus on the fact that although an output of economic activity is pollution and associated ill-health, some activities and actors are largely focused on positive impact, for example, the role that knowledge institutions play in health and sustainability research. This somewhat limit in scope not to extend to so-called scope-4 "avoided emissions" is in line with the GHG Protocol, which requires companies to disclose their gross emissions. In fact, GHG Protocol co-founder the World Resources Institute released a paper on avoided emissions but the GHG Protocol has not progressed the concept (Russell, 2018). While emissions avoidance has a role to play, addressing actual greenhouse gasses emitted is a priority in terms of a sustainable climate.

1.3. Methods summary

1.3.1. IO analysis

As summarised in the introductory sections of the papers (**Chapters 2-5**) in this thesis, IO analysis is governed by UN standards (1999) and has proven to be flexible, both in terms of being tailored to a range of research questions, as well incorporating engineering data. IO analysis is one of the most widely applied methods in economics (Baumol, 2000; Miller & Blair, 2009, p. 1) and is based on IO tables in the almost universal System of National Accounts (European Communities et al., 2009) from countries' statistical agencies, as well as international trade data from organisations such as UN Comtrade and Eurostat. IO analysis was developed from the 1930s by Wassily Leontief, first for the United States economy (Leontief, 1936) and rose to popularity during the oil shocks in the 1970s, winning Leontief a Nobel Prize in 1973. Leontief created IO analysis to show the inter-dependencies throughout the economic system. The underlying assumption is equilibrium whereby total output ($\mathbf{x}$) equals total input ($\mathbf{x}'$) i.e., it encompasses all sales and all purchases, including capital outlays and investments; such a complete picture therefore enables empirical and holistic analysis (Leontief, 1936). The Leontief equation is therefore able to capture elegantly the complexity in the economy: $\mathbf{x} = \mathbf{L}\mathbf{y}$ (Rose & Miernyk, 1989) where $\mathbf{y}$ is final demand in monetary units and the $\mathbf{L}$ multiplier is the famous Leontief inverse that incorporates the entire supply chain.

From the early days, Leontief had envisioned sustainability applications (Leontief, 1970). Environmentally extended IO analysis (EEIO) links physical quantities, from so-called satellite accounts ($\mathbf{Q}$) for example of pollution or employment, to the economy's IO tables. The indicators are tracked as coefficients alongside the supply and use of sector inputs and outputs as part of the cycle of consumption and production. In this way, embodied impact can be calculated along the inter-industry value chain. IO analysis avoids the truncation errors of traditional lifecycle assessment (LCA), which by its nature must create a system boundary within which to direct its process-based analysis. It has been found that LCA truncation errors can render the results as unreliable (Lenzen, 2000), and the GHG Protocol recognises that for complex organisations, a process-based approach may be expensive and time-consuming, rendering such bottom-up approaches impractical (World Resources Institute & World Business Council for Sustainable Development, 2013, p. 17). On the other hand, the disadvantages of EEIO to which the GHG Protocol referred in terms of specificity and accuracy have in the decade since been addressed in large part through the development of

supercomputing infrastructure that enables the interrogation of billions of supply chains,[3] supported by collaborative research platforms (see Section 1.3.1.2) that facilitate timely data collection as well as efficient IO analysis for Australia (Lenzen et al., 2017b) and globally (Lenzen et al., 2017a; Moran & Wood, 2014; Stadler et al., 2018), through multi-region IO analysis (MRIO) . With LCA data having the advantage of locally significant information over the industry-averages of IO, hybrid IO-LCA approaches can include process-based data where possible, while covering the higher-order value-chains using IO analysis.

IO analysis disaggregates the economy into sectors. The matrix of intermediate transactions ($\mathbf{T}$), can be analysed from the perspective of each sector's (intermediate) *demand* (columns in $\mathbf{T}$), which in addition to the column vector of final demand ($\mathbf{y}$) adds up to total output ($\mathbf{x}$). Conversely, $\mathbf{T}$ can be analysed from the perspective of intermediate *supply* enabling each sector (rows in $\mathbf{T}$), which in addition to the row vector of primary inputs/value-added ($\mathbf{v}$) adds up to total input ($\mathbf{x}'$).

The *Supplementary Information* in **Chapter 5** details key IO calculus upstream and downstream. Some highlights are below.

Developed initially from a consumption-based accounting (CBA) perspective, the total output ($\mathbf{x}$) can also be written in a more descriptive calculus whereby:

$$\mathbf{x} = (\mathbf{I} - \mathbf{T}\hat{\mathbf{x}}^{-1})^{-1}\mathbf{y}$$

where $(\mathbf{I} - \mathbf{T}\hat{\mathbf{x}}^{-1})^{-1}$ is the Leontief inverse, $\mathbf{I}$ is an identity matrix and $\hat{\mathbf{x}}$ is total output as a diagonal matrix. The technical coefficients matrix ($\mathbf{T}\hat{\mathbf{x}}^{-1}$), also denoted by $\mathbf{A}$, comprises fixed input coefficients, or a "production recipe", per monetary unit of total output ($\mathbf{x}$). In EEIO, the embodied upstream impact, also referred to as a footprint (F) can be described as:

$$F = \mathbf{q}\mathbf{L}\mathbf{y}$$

where $\mathbf{q}$ is a row vector of *direct* intensities of the chosen satellite ($\mathbf{Q}$) per monetary unit of sectoral output in $\mathbf{x}$. The standard IO notation is followed here in terms of italics denoting scalars, lower-case letters denoting vectors and upper-case letters generally denoting matrices.

[3] For example, GLORIA Release 059 IO tables are comprised of 120 sectors and 164 regions = 120*164 = 19,680 regional sectors; **production-layer 2** (tier 2) is the first layer of the *indirect* supply chain (tier-1 suppliers to our direct suppliers), which involves the technical-coefficients matrix ($\mathbf{A}$) of size 19,680 regional sectors; **production-layer 3** is represented by a matrix of size $19{,}680^2$ = 3.873e+08 supply-chain calculations and at **production-layer 4**, this increases to $19{,}680^3$ = 7.622e+12 = 7622 billion; my analysis in Chapters 4-5 included 10 production layers = calculations of $19{,}680^9$.

The footprint can be disaggregated by sector and simply re-written as:

$$\mathbf{F} = \mathbf{m}' \circ \mathbf{y}$$

where $\mathbf{m}$ is a row vector of *total* intensities, the prime symbol ($'$) represents transposition and the Hadamard ($\circ$) represents element-wise multiplication. This is the approach that carbon accountants take to calculate company emissions when using spend-based industry-average emission factors per relevant sector (in $\mathbf{m}$) multiplied by the expenditure on the relevant sector (in $\mathbf{y}$).

An extension to the IO approach was proposed by Ghosh, for situations where final demand could not be the driver of economic activity (Ghosh, 1958). Ghosh described an alternate IO calculus that could be applied to describe the economy under circumstances such as monopoly or a centralised economy. Developed to show the *enabling impact from a supply perspective*, the total input ($\mathbf{x}'$) is also described as a function of primary inputs and the sales-chain multiplier whereby:

$$\mathbf{x}' = \mathbf{v}(\mathbf{I} - \hat{\mathbf{x}}^{-1}\mathbf{T})^{-1}$$

where $(\mathbf{I} - \hat{\mathbf{x}}^{-1}\mathbf{T})^{-1}$ is the Ghosh inverse ($\bar{\mathbf{L}}$), which encapsulates the entire sales chain. In the Ghosh inverse, $\hat{\mathbf{x}}^{-1}$ is total *input* as a diagonal matrix, with the pre-multiplication of ($\mathbf{T}$) resulting in the allocation matrix ($\hat{\mathbf{x}}^{-1}\mathbf{T}$), or $\bar{\mathbf{A}}$, comprising fixed output coefficients per monetary unit of total input ($\mathbf{x}'$).

In EEIO, enabled downstream impact ($\bar{F}$) can be described as:

$$\bar{F} = \mathbf{v}\bar{\mathbf{L}}\mathbf{q}'$$

where $\mathbf{q}$ is the vector of direct intensity per unit sectoral output.

Put simply, the footprint can be re-written as:

$$\bar{\mathbf{F}} = \mathbf{v}' \circ \bar{\mathbf{m}}'$$

Similar to its upstream equivalent, the equation above therefore has been used to calculate emissions when using income-based industry-average emission factors (in $\bar{\mathbf{m}}$) multiplied by income earned from the relevant sector (in $\mathbf{v}$).

In both upstream and downstream approaches, $\mathbf{q}$ is derived from the vector of total impact ($\mathbf{Q}$) and is calculated as $\mathbf{Q}\hat{\mathbf{x}}^{-1}$, where $\mathbf{x}$ is total output. Therefore it can be seen that the total impact ($\mathbf{Q}$), for example global greenhouse gas emissions, can be apportioned according to the perspectives of fulfilling the requirements for consumption (upstream) or production

(downstream). In hybrid assessments, process-based data may be introduced into the analysis. For corporate reporting, the organisation's expenditure is used as a proxy for final demand ($\mathbf{y}$) to calculate its upstream inter-industry impact, and the organisation's income is used as a proxy for primary inputs ($\mathbf{v}$) to calculate its downstream inter-industry impact. These total-lifecycle approaches from upstream and downstream perspectives variously for an organisation may not result in double-counting, if emissions are not identified upstream and downstream from the same pool of sectoral emissions. In any case, the GHG Protocol allows for additional calculations to be made to remove double-counting (e.g., between upstream and downstream categories) (World Resources Institute & World Business Council for Sustainable Development, 2013, p. 111). The Protocol does not specify how this should be done, only to say that it should be highlighted where the emissions remain reported, using cross-references if required (2011, p. 57). The Protocol acknowledges that by companies assuming responsibility for indirect emissions, from a national accounting perspective, there will be double-counting along the value chain (p. 108). However, mutually exclusive "shared responsibility" approaches for consumers and producers have been suggested, which may be seen as being more equitable and robust, while avoiding double-counting (Wang et al., 2024). Potential shared-responsibility approaches are discussed in **Chapter 4** and a practical example in line with the current GHG Protocol is suggested in **Chapter 5**.

1.3.1.1. Disaster IO analysis

In IO disaster analysis (the subject of **Chapter 2**), the total economic shock over the short term is quantified as the difference between the pre- and post-disaster economy. Our starting point is the "basic equation" $\tilde{\mathbf{x}} = (\mathbf{I} - \hat{\boldsymbol{\gamma}})\mathbf{x}$ (Steenge & Bočkarjova, 2007). Here, a diagonal "event" matrix ($\hat{\boldsymbol{\gamma}}$) comprising relative losses in total output are the stressor for the supply-chain calculus in reaching the new equilibrium, albeit as a weaker economy, recalling that $\mathbf{x} = \mathbf{L}\mathbf{y}$ and $\mathbf{y} = (\mathbf{I} - \mathbf{A})\mathbf{x}$. This sub-stream of IO analysis has been the basis of numerous disaster assessments, as discussed in the Chapter 2 Methods. Developments of the IO disaster model have focused on improving accuracy in reflecting real-world events. A limitation of the initial Steenge-Bočkarjova method was that this unbound approach meant there could be negative post-disaster final demand, but subsequent models have imposed reparative constraints. An adjustment was made by Schulte in den Bäumen et al. (2014), who relaxed the assumption of a constant production recipe by allowing for substitution, such that marginal inputs in the $\mathbf{A}$ matrix were reduced to zero. However, this determination to eliminate a particular range of small coefficients as supposedly immaterial, in order to achieve non-negative final demand, is uniformly and therefore arbitrarily imposed, since marginal inputs may not ultimately be

immaterial. More recently a solution to this random adjustment in $\mathbf{A}$ has been demonstrated by Faturay et al. (2020), who achieved non-negative values in net outputs for final demand ($\tilde{\mathbf{y}}$) through an optimisation function, while requiring that production adhere in the short-term to the pre-disaster production recipe $\mathbf{A}$. Under this approach, the post-disaster total output is determined by *maximising* the economy-wide total output max($\sum \tilde{x}_i$), while being subject to the two constraints of $\tilde{\mathbf{x}} \leq (\mathbf{I} - \hat{\boldsymbol{\gamma}})\mathbf{x}_0$ and $\tilde{\mathbf{y}} \geq 0$. However, this latest model relies on some degree of regional-sector stability regarding the *proportionate* losses ($\boldsymbol{\gamma}$) as the driver of post-disaster production. This is because the calculated losses could spike unexpectedly throughout sectors and regions in finding a solution to $\tilde{\mathbf{y}} = (\mathbf{I} - \mathbf{A})\tilde{\mathbf{x}}$ within the constraints including non-negative final demand ($\tilde{\mathbf{y}}$), for example in the case of a *catastrophic* proportionate loss in the event "gamma" matrix $\boldsymbol{\gamma}$. This model, which was initially applied to a Taiwan case study, has been used in recent studies such as to assess Australian food- and nutritional security under various climate projections (Malik et al., 2022) and to undertake a world-first study of the socio-economic losses and environmental gains of COVID-19 (Lenzen et al., 2020). This model (Faturay et al., 2020) is also the basis of the economic disaster assessment in Chapter 2 of this thesis.

1.3.1.2. The Industrial Ecology Virtual Laboratory (IELab)

The IO analysis described in this thesis is undertaken in the Industrial Ecology Virtual Laboratory (https://ielab.info/), a cloud-based IO platform in high-performance computing environment, built by the Integrated Sustainability Analysis (ISA) group at the University of Sydney. The IELab first pioneered collaborative virtual IO research infrastructure for Australia, enabling academic and corporate members to undertake analysis without having to compile IO databases from scratch, at detailed sub-national levels (Lenzen et al., 2014). The IELab concept extended to several other countries and then to the Global MRIO Lab (Lenzen et al., 2017a) and now GLORIA: the Global Resource Input-Output Assessment database; GLORIA was initially built for the UN International Resource Panel (Lenzen et al., 2022) and also underpins the UN-supported Sustainable Consumption and Production Hotspot Analysis Tool (https://scp-hat.org/). Many of GLORIA's economic, social and environmental indicators can be viewed via the open-access SCP-HAT portal online. The bushfires research in **Chapter 2** used the Australian IELab infrastructure, including codes such as rebalancing the IO tables, in order to perform the analysis. The global sustainability analyses in **Chapters 4-5** used GLORIA Release 059 IO tables that were subject to pre-processing techniques such as mirroring as described in the release notes (Lenzen & Li, 2024); **Chapter 3** was also focused on GLORIA in its assessment of global modern-slavery data for a potential satellite account for IO analysis.

1.3.2. Mixed methods

For the analysis of modern-slavery data, estimates and potential proxies, which is the focus of **Chapter 3**, both quantitative and qualitative research was performed. This analysis was organised as the precursor to potential inclusion of a modern-slavery indicator/satellite in $\mathbf{Q}$ (Section 1.3.1, para. 2) in the GLORIA MRIO (Lenzen et al., 2022; Schandl et al., 2024) as noted below.

1.3.2.1 Quantitative database analysis

Undertaken as part of the Open Analysis to Address Slavery in Supply chains (OAASIS) project (The University of Sydney, n.d.), the key aim of the research was to determine whether a modern-slavery indicator could be compiled and used for IO analysis. Therefore, only data that met the following criteria to align with IO analysis was considered:

- Additive: Was in additive format or could easily be transformed into data that can be summed.
- Highly disaggregated: Was highly disaggregated in sectors and/or regions or could easily be transformed into such data. If data only covered a small number of regions, this was only acceptable if it reflected a lack of modern slavery in non-represented regions, rather than substantial data-collection issues.

1.3.2.2. Qualitative analysis

The research benefitted from guidance from former UN experts in human trafficking and other collaborators of OAASIS (The University of Sydney, n.d.), , both formal and informal, and their contacts. To make use of their collective knowledge, interviews and follow-up correspondence were carried out where possible, including with experts who consented to being acknowledged in the paper and those who required anonymity. An in-depth literature review expanded on the information gained from the expert guidance via OAASIS, and was later extended in response to subject-matter expert feedback from the peer-review process. The literature review covered not only the indicators in question but also qualitative approaches to measuring human-rights, as well investigating the small number of tailored hybrid IO analysis of "slavery-like" indicators in sectors and regions that made use of robust localised data.

1.3.3. Framework development

Key aspects of mHREDD are considered within an IO framework. As part of this, the potential for modern slavery to be quantified is analysed regarding Human Rights Due Diligence/general-sustainability disclosures (Section 1.3.2). In terms of Environmental reporting, climate as well as biodiversity-related due diligence is addressed. For climate-related disclosures, the

applicability of IO analysis is demonstrated in terms of costing physical risks in the disaster analysis (Section 1.3.1.1), and as part of calculating scope-3 emissions, a novel framework was required in particular to measure downstream emissions in order to apply IO analysis across the GHG Protocol categories; the downstream method that is developed can be applied to any sustainability indicators in an IO satellite account ($\mathbf{Q}$) but this framework is focused on GHG emissions because of the increasingly mandatory scope-3-emissions reporting requirements. An extension of downstream income-based IO analysis is therefore undertaken, to complement upstream spend-based IO analysis, since globally there has not been any paper published that describes income-based IO analysis at the enterprise level, i.e., by using an organisation's income as a proxy for primary inputs/value added ($\mathbf{v}$), as described in Section 1.3.1; this comprises **Chapter 4**; the downstream enterprise approach is then incorporated into the whole-of-value-chain case study (**Chapter 5**), which describes *upstream* and *downstream* hybrid IO-LCA applied to *Climate* and general-*Sustainability* frameworks using the same underlying global MRIO database. The novel, downstream framework developed for hybrid income-based IO-LCA analysis at the enterprise level includes a focus on demonstrating how an organisation's income can be harmonised with economic sectors in order to perform the IO calculus downstream.

1.4. Research gaps

Three key research gaps related to sustainability reporting are addressed, in the areas of (economic) disaster analysis, modern-slavery due diligence and environmental impact.

i. Disasters and IO analysis: A research gap was identified for the 2019-20 bushfires in that, unlike Australia's disastrous floods two years later (Clun, 2023), there was no *comprehensive assessment* of the economic cost (for example, focussing on all the Natural-Catastrophe-declared areas and/or all key economic areas as identified by the Bushfires Royal Commission (Binskin et al., 2020b). As well, no assessment of any aspect of the fires had been undertaken using IO analysis. **Disaster analysis of this kind can be used in climate-related disclosures**.

   Nationally post-fire *estimates* commonly ranged from more than $10 billion (Binskin et al., 2020b) to $100 billion (Deloitte Access Economics, 2021). One study using computable general equilibrium (CGE) assessed the impact on the State of Victoria overall as being $2.1 billion (Victoria State Government, 2021), while another study

using CGE estimated the national impact as $10 billion by focussing on input data of direct damages from eastern Australia (Wittwer & Waschik, 2021); however, such a focus therefore failed to take into account the extent of devastation in South Australia, which was one of the most-impacted States that in addition to the eastern Australian States of Queensland, NSW and Victoria, was declared a "Natural Catastrophe" (Insurance Council of Australia, 2021). As well, CGE is likely to underestimate losses because of the underlying assumption of perfect market knowledge and decision-makers optimising all of the time; the latter is not an issue when the external economic shock is small and the timeframe is more than one year, however the opposite tends to be the case with natural hazards (Rose, 2004, p. 26).

From an industry perspective, a costing was carried out regarding food systems but did not focus on the forestry aspect of agriculture, perhaps because forestry damages took time to assess during "salvage" attempts at selling lower-grade, damaged timber rather than lose entire plantations. Another key bushfire impact was from the contraction of tourism, which the Bushfires Royal Commission referred to as "indirect" because its fire damages may not be as obvious in the way that agriculture endured physical destruction. However, tourism is a critical part of Australia's economy, with the visitor economy by definition including business- and education-related travel, the latter of which, when combined with personal travel has been responsible for more export income than natural gas. The tourism industry publishes quarterly expenditure data and also conducted a survey to assess the impact of the bushfires (as opposed to COVID-19 for example) on the tourism losses. With readily available data from an industry whose peak season coincided with "Black summer", tourism was identified as a suitable candidate for IO analysis regarding the chain-reaction effect from the direct economic damages resulting from the catastrophe.

ii. Modern-slavery data and estimates:

   a. Although overall there has been much analysis of the limitations of various data and estimates, these tended to focus on a particular area, such as trafficking/forced labour generally or the highly critiqued Global Slavery Index (GSI). Regarding the latter, some methodology was updated in the 2023 GSI but papers had only analysed early iterations (Gallagher, 2017; Weitzer, 2014).
   a. Additionally, key databases such as the GSI and the United Nations' Global report on Trafficking in Persons (GLOTIP) had not been publicly analysed in terms of the technical requirements for IO satellite development and compatibility with

the assumption of homogeneity underpinning the industry-averages of IO sector groupings. It is specifically because IO analysis is such a powerful tool for identifying supply-chain hotspots calculated from the satellite (indicator) data that assessing the robustness of any potential modern-slavery satellite for inclusion in an MRIO database is paramount.

These areas are directly relevant to modern-slavery due diligence. In the future, modern slavery may also be expressly included in general sustainability-related disclosures.

iii. The final two chapters, before the Conclusion, are focused on **Climate- and general Sustainability disclosures.**

a. Downstream IO analysis: Although income-based IO analysis is frequently used, for example for measuring indicators at global, regional or sub-national levels, no paper has described its use at the level of an enterprise. Furthermore, organisations tend to treat "downstream" impact in a limited way, for example as relating to a product's *use* and *end-of-life,* rather than *enabled impact* throughout the inter-industry sales chain (Lenzen & Murray, 2010). The GHG Protocol has recognised the difficulty that organisations may have in identifying *indirect*-use phases of a product and reasoned that in those cases exclusions regarding such downstream categories can be justified (World Resources Institute & World Business Council for Sustainable Development, 2011, p. 60). In this vein, universities have excluded some downstream Protocol categories from their analysis (Stridsland et al., 2024, p. 5), despite being knowledge-creating institutions that play a crucial role in the business ecosystem. Such a dearth of corporate reporting of emissions downstream is significant, since globally, frameworks and Standards are increasingly requiring organisations not only to consider the impact from upstream (suppliers) but also from downstream (customers). The lack of publicly available knowledge systems and infrastructure has to date resulted in a missed opportunity, regarding downstream corporate sales-chain analysis to uncover the enabled impact linked to our income as a result of the sectors to whom we sell.

b. Climate-and-Sustainability disclosures: The new environment of increasingly global interoperable frameworks for climate- and general-sustainability due diligence provides a unique opportunity to apply IO analysis to contribute to integrated reporting. Currently, global frameworks such as the ISSB and the

TNFD lack a unifying methodology, which means that action on the ISSB's IFRS S2 climate-related disclosures could have unintended consequences in terms of simultaneously addressing the IFRS S1 general-sustainability disclosures and/or the TNFD. Given the converging climate- and biodiversity-related crises and the need to take a systems approach to global sustainability, holistic and robust due diligence may be critical.

1.5. Aim and objectives

The aim of this thesis is to assess and develop tools for climate- and general sustainability-related disclosures within the new mHREDD environment. To this end, separate research questions are addressed: question (ii) below addresses (human rights) modern-slavery due diligence, while the other research questions together cover environmental due diligence, with (i) relevant to climate-change financial risks, while questions (iii-iv) are relevant not only for *financial* reporting but also extend to non-financial sustainability *impact*. The research questions under investigation are below.

i. *Disaster risk to business*: IO analysis of Australia's mega-fires – What are some potential economic impacts from a climate-fuelled catastrophe and how can we quantify the cost of the unprecedented 2019-20 Australian bushfires on tourism supply chains? (See **Chapter 2** of this thesis.)
ii. *Modern slavery supply-chain analysis* – Can a manifestation of extreme inequality, being illicit, modern-day slavery, be quantified globally and what role could IO analysis play in identifying hotspots for corporate reporting? (See **Chapter 3**.)
iii. *Novel downstream framework for organisations* – How can IO analysis be applied to organisational income? A framework is developed in this regard and alternate scenarios are tested using a University case study. (See **Chapter 4**).
iv. *Comprehensive and holistic Climate- and Sustainability due diligence* – How can a range of sustainability impacts of an organisation be quantified in line with global frameworks, using IO analysis to include the entire inter-industry value chain? (See **Chapter 5**.)

1.6. Structure and contribution of this thesis

In addition to the **Overview** and **Conclusions Chapters 1** & **6**, this thesis comprises papers that have been published (**Chapters 2-3**) and have been submitted to journals and are under review (**Chapters 4-5**), each of which answer specific research questions. Regarding the contribution of the various chapters, the remainder of this thesis is structured as follows:

Chapter 2 analyses the economic impact of the globally unprecedented Australian 2019-20 bushfires from the tourism shutdown. Drawing on survey data on direct damages, the supply-chain analysis analyses the cost of the bushfires separately from that of the coronavirus pandemic that followed directly afterwards. Based on industry averages, the IO disaster analysis takes a macroeconomic perspective regarding supply-chain financial impact and vulnerable industries. From a materiality perspective, this IO disaster analysis can offer regional economy-level insights into the material financial cost to tourism-related Australian businesses and thereby highlight the sectors that may have most to gain through planning, adaptation and mitigation regarding the increasing threat of bushfire catastrophes from global warming.

After interrogating IO analysis regarding an extreme manifestation of climate change, being the unprecedented mega-fires, another extreme is interrogated regarding poverty/inequality, since modern slavery is difficult to measure directly, and challenges neoliberal capitalist notions of the social licence of an unfettered market. Therefore, moving from focusing solely on *financial* materiality, the remainder of the thesis focuses on potential solutions (from a double-materiality perspective i.e., financial and impact materiality) in terms of comprehensive, robust and disaggregated measurement and reporting in order to take reparative action.

Chapter 3 reports on a comprehensive, critical data analysis regarding global modern slavery. The resultant paper is the first study to assesses the applicability of IO analysis to quantify embodied modern slavery along supply chains, taking into account the robustness of available data. It also investigates the role of hybrid analysis for human-rights due diligence in particular sectors and regions.

Chapter 4 extends well-established downstream IO analysis by developing a framework to apply income-based IO analysis at the *enterprise* level. This is believed to be the first time that such a method has ever been used, in terms of directing IO analysis at the *sector-level* income of an organisation rather than relying on *industry averages* to apportion the total income from downstream customers, in order to calculate the downstream impact. Although novel, the new framework demonstrates an approach to IO analysis downstream that is similar to upstream IO

analysis but draws on the recommendation in the System of National Accounts to *exclude public-sector activity* as non-market (European Communities et al., 2009), but only for grant income, and draws on the recommendation of ISIC to treat public-sector as any other sector, according to the type of activity (United Nations Statistics Division, 2008), but only for non-grant income.

Chapter 5 then shows how IO analysis can be applied across the inter-industry value chain, to global Climate and Nature Standards and regulations. Importantly, it uses the framework developed in this thesis to compare greenhouse gas emissions in GHG Protocol categories downstream in addition to upstream and uses the same underlying input data for assessment of other indicators. This chapter's **Supplementary Information** lists key IO equations up- and downstream, which, while not novel, brings together in a straightforward manner the calculus for whole-of-value-chain analysis, for the carbon accountant or auditor.

Chapter 6 presents the key findings in demonstrating to what extent IO analysis generally and the novel framework specifically can be directed across the new mHREDD frameworks. Future research directions, as well as policy priorities that follow from this thesis, are also discussed.

1.7. References

Baumol, W. J. (2000). Leontief's Great Leap Forward: Beyond Quesnay, Marx and von Bortkiewicz. *Economic Systems Research*, *12*(2), 141-152. https://doi.org/10.1080/09535310050005662

Binskin, M., Bennett, A., & Macintosh, A. (2020a). *Royal Commission into National Natural Disaster Arrangements: Interim observations*. Commonwealth of Australia. https://www.royalcommission.gov.au/system/files/2021-08/interim-observations-rcnda.pdf

Binskin, M., Bennett, A., & Macintosh, A. (2020b). *Royal Commission into National Natural Disaster Arrangements: Report*. Commonwealth of Australia. https://oia.pmc.gov.au/sites/default/files/posts/2022/11/Royal%20Commission%20into%20National%20Natural%20Disaster%20Arrangements%20-%20Report%20%20%5Baccessible%5D.pdf

Boer, M. M., Resco De Dios, V., & Bradstock, R. A. (2020). Unprecedented burn area of Australian mega forest fires. *Nature Climate Change*, *10*(3), 171-172. https://doi.org/10.1038/s41558-020-0716-1

Chen, G., Hadjikakou, M., & Wiedmann, T. (2017). Urban carbon transformations: unravelling spatial and inter-sectoral linkages for key city industries based on multi-region input–output analysis. *Journal of Cleaner Production*, *163*, 224-240. https://doi.org/10.1016/j.jclepro.2016.04.046

Clun, R. (2023, January 12). Floods cost economy $5 billion last year. *Sydney Morning Herald*. https://www.smh.com.au/politics/federal/floods-cost-economy-5-billion-last-year-20230112-p5cc1t.html

Commission of the European Communities - Eurostat, International Monetary Fund, Organization for Economic Co-operation and Development, United Nations, & World Bank. (1993). System of National Accounts. unstats.un.org/unsd/nationalaccount/docs/1993sna.pdf

Corporate Sustainability Reporting Directive 2023 (EU). Directive 2022/2464. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32022L2464

Corporate Sustainability Due Diligence Directive 2024 (EU) Directive 2024/1760. https://eur-lex.europa.eu/eli/dir/2024/1760/oj

Deloitte Access Economics. (2021). *Special report: Update to the economic costs of natural disasters in Australia* - Australian Business Roundtable for Disaster Resilience & Safer Communities. https://www2.deloitte.com/content/dam/Deloitte/au/Documents/Economics/deloitte-au-economics-abr-natural-disasters-061021.pdf

European Commission. (2022). *Making Mandatory Human Rights and Environmental Due Diligence Work for All: Guidance on designing effective and inclusive accompanying support to due diligence legislation*. European Union. https://international-partnerships.ec.europa.eu/system/files/2022-07/making-mandatory-human-rights-and-environmental-due-diligence-work-for-all_en.pdf

European Sustainability Reporting Standards 2023 (EU) Commission Delegated Regulation 2023/2772. https://eur-lex.europa.eu/legal-content/en/TXT/?uri=CELEX:32023R2772

European Communities, International Monetary Fund, Organisation for Economic Co-operation and Development, United Nations, & World Bank. (2009). System of National Accounts 2008. https://unstats.un.org/unsd/nationalaccount/docs/sna2008.pdf

Faturay, F., Sun, Y.-Y., Dietzenbacher, E., Malik, A., Geschke, A., & Lenzen, M. (2020). Using virtual laboratories for disaster analysis: A case study of Taiwan. *Economic Systems Research*, *32*(1), 58-83. https://doi.org/10.1080/09535314.2019.1617677

Feingold, D. A. (2010). Trafficking in numbers: The social construction of human trafficking data. In P. Andreas & K. M. Greenhill (Eds.), *Sex, Drugs and Body Counts: The Politics of Numbers in Global Crime and Conflict* (pp. 46-74). Cornell University Press. https://www.researchgate.net/publication/284800222_Trafficking_in_numbers_The_social_construction_of_human_trafficking_data

Galbusera, L., & Giannopoulos, G. (2018). On input-output economic models in disaster impact assessment. *International Journal of Disaster Risk Reduction*, *30*, 186-198. https://doi.org/10.1016/j.ijdrr.2018.04.030

Gallagher, A. T. (2017). What's wrong with the Global Slavery Index? *Anti-Trafficking Review*(8), 90-112. https://doi.org/10.14197/atr.20121786

Ghosh, A. (1958). Input-Output Approach in an Allocation System. *Economica*, *25*(97), 58-64. https://doi.org/10.2307/2550694

Greenhouse Gas Protocol. (2025, January 16). *2024 Reflections and Looking Ahead: Letter from GHG Protocol Steering Committee Chair and Vice Chair* [Announcement]. https://ghgprotocol.org/blog/2024-reflections-and-looking-ahead-letter-ghg-protocol-steering-committee-chair-and-vice-chair

Handmer, J., Ladds, M. A., & Magee, L. (2017). Pragmatic disaster loss assessment. *Nature Climate Change*, *7*(8), 536-536. https://doi.org/10.1038/nclimate3349

Handmer, J., Ladds, M., & Magee, L. (2018). Updating the costs of disasters in Australia. *Australian Journal of Emergency Management*, *33*(2), 41-46. http://classic.austlii.edu.au/au/journals/AUJlEmMgmt/2018/36.html

Hannam, P. (2016, November 8). The 10 Sydney regions most exposed to bushfire risk. *The Sydney Morning Herald*. https://www.smh.com.au/environment/the-10-sydney-regions-most-exposed-to-bushfire-risk-20161107-gsk08y.html

Home Office. (2020). *Transparency in supply chains consultation: Government response*. Modern Slavery Unit. https://assets.publishing.service.gov.uk/media/5f69c90ed3bf7f723e21c152/Government_response_to_transparency_in_supply_chains_consultation_21_09_20.pdf

IFRS. (n.d.). *Human Capital*. Retrieved June 23, 2025, from https://www.ifrs.org/projects/work-plan/human-capital/

Insurance Council of Australia. (2021). *Insurance Catastrophe Resilience Report: 2020-21*. https://insurancecouncil.com.au/wp-content/uploads/2021/09/ICA008_CatastropheReport_6.5_FA1_online.pdf

International Labour Organization. (2012). *ILO Global Estimate of Forced Labour: Results and Methodology* [technical report]. https://www.ilo.org/publications/ilo-global-estimate-forced-labour-2012-results-and-methodology

International Labour Organization (ILO), Walk Free, & International Organization for Migration (IOM). (2022). *Global Estimates of Modern Slavery: Forced Labor and Forced Marriage*. https://www.ilo.org/wcmsp5/groups/public/---ed_norm/---ipec/documents/publication/wcms_854733.pdf

International Sustainability Standards Board. (2023). *IFRS Sustainability Disclosure Standard: Climate-related Disclosures* (ISSB Standard No. IFRS S2). https://www.ifrs.org/issued-standards/ifrs-sustainability-standards-navigator/ifrs-s2-climate-related-disclosures.html/content/dam/ifrs/publications/html-standards-issb/english/2023/issued/issbs2/

Lavelle-Hill, R., Smith, G., Mazumder, A., Landman, T., & Goulding, J. (2021). Machine learning methods for “wicked” problems: Exploring the complex drivers of modern slavery. *Humanities and Social Sciences Communications*, *8*(1), 274. https://doi.org/10.1057/s41599-021-00938-z

Lenzen, M. (2000). Errors in Conventional and Input-Output—based Life—Cycle Inventories. *Journal of Industrial Ecology*, *4*(4), 127-148. https://doi.org/10.1162/10881980052541981

Lenzen, M. (2008). Double-Counting in Life Cycle Calculations. *Journal of Industrial Ecology*, *12*(4), 583-599. https://doi.org/10.1111/j.1530-9290.2008.00067.x

Lenzen, M., Geschke, A., Wiedmann, T., Lane, J., Anderson, N., Baynes, T., Boland, J., Daniels, P., Dey, C., Fry, J., Hadjikakou, M., Kenway, S., Malik, A., Moran, D., Murray, J., Nettleton, S., Poruschi, L., Reynolds, C., Rowley, H., . . . West, J. (2014). Compiling and using input–output frameworks through collaborative virtual laboratories. *Science of The Total Environment*, *485-486*, 241-251. https://doi.org/10.1016/j.scitotenv.2014.03.062

Lenzen, M., Geschke, A., Abd Rahman, M. D., Xiao, Y., Fry, J., Reyes, R., Dietzenbacher, E., Inomata, S., Kanemoto, K., Los, B., Moran, D., Schulte In Den Bäumen, H., Tukker, A., Walmsley, T., Wiedmann, T., Wood, R., & Yamano, N. (2017a). The Global MRIO Lab – charting the world economy. *Economic Systems Research*, *29*(2), 158-186. https://doi.org/10.1080/09535314.2017.1301887

Lenzen, M., Geschke, A., Malik, A., Fry, J., Lane, J., Wiedmann, T., Kenway, S., Hoang, K., & Cadogan-Cowper, A. (2017b). New multi-regional input–output databases for Australia: Enabling timely and flexible regional analysis. *Economic Systems Research*, *29*(2), 275-295. https://doi.org/10.1080/09535314.2017.1315331

Lenzen, M., Li, M., Malik, A., Pomponi, F., Sun, Y.-Y., Wiedmann, T., Faturay, F., Fry, J., Gallego, B., Geschke, A., Gómez-Paredes, J., Kanemoto, K., Kenway, S., Nansai, K., Prokopenko, M., Wakiyama, T., Wang, Y., & Yousefzadeh, M. (2020). Global socio-economic losses and environmental gains from the Coronavirus pandemic. *PLOS ONE*, *15*(7), e0235654. https://doi.org/10.1371/journal.pone.0235654

Lenzen, M., Geschke, A., West, J., Fry, J., Malik, A., Giljum, S., Milà I Canals, L., Piñero, P., Lutter, S., Wiedmann, T., Li, M., Sevenster, M., Potočnik, J., Teixeira, I., Van Voore, M., Nansai, K., & Schandl, H. (2022). Implementing the material footprint to measure progress towards Sustainable Development Goals 8 and 12. *Nature Sustainability*, *5*(2), 157-166. https://doi.org/10.1038/s41893-021-00811-6

Lenzen, M., & Li, M. (2024). *GLORIA MRIO database Release 059* [Release notes]. Industrial Ecology Virtual Laboratory.

Lenzen, M., & Murray, J. (2010). Conceptualising environmental responsibility. *Ecological Economics*, *70*(2), 261-270. https://doi.org/10.1016/j.ecolecon.2010.04.005

Leontief, W. (1936). Quantitative input and output relations in the economic systems of the United States. *The Review of Economics and Statistics*, *18*(3), 105-125. https://doi.org/10.2307/1927837

Leontief, W. (1970). Environmental Repercussions and the Economic Structure: An Input-Output Approach. *The Review of Economics and Statistics*, *52*(3), 262-271. https://doi.org/10.2307/1926294

Malik, A., Li, M., Lenzen, M., Fry, J., Liyanapathirana, N., Beyer, K., Boylan, S., Lee, A., Raubenheimer, D., Geschke, A., & Prokopenko, M. (2022). Impacts of climate change and extreme weather on food supply chains cascade across sectors and regions in Australia. *Nature Food*, *3*(8), 631-643. https://doi.org/10.1038/s43016-022-00570-3

Marques, A., Rodrigues, J., Lenzen, M., & Domingos, T. (2012). Income-based environmental responsibility. *Ecological Economics*, *84*, 57-65. https://doi.org/10.1016/j.ecolecon.2012.09.010

Marques, A., Rodrigues, J., & Domingos, T. (2013). International trade and the geographical separation between income and enabled carbon emissions. *Ecological Economics*, *89*, 162-169. https://doi.org/10.1016/j.ecolecon.2013.02.020

McDonald, P. (2020, July 26). *Anatomy of a mega-fire: Black Summer* [Special report]. ABC. https://www.youtube.com/watch?v=SlGmatigAy4

McGaughey, F., Voss, H., Cullen, H., & Davis, M. C. (2022). Corporate Responses to Tackling Modern Slavery: A Comparative Analysis of Australia, France and the United Kingdom. *Business and Human Rights Journal*, *7*(2), 249-270. https://doi.org/10.1017/bhj.2021.47

McMillan, J. (2023). *Report of the statutory review of the Modern Slavery Act 2018 (Cth): The first three years* [Report]. Commonwealth of Australia. https://www.ag.gov.au/sites/default/files/2023-05/Report%20-%20Statutory%20Review%20of%20the%20Modern%20Slavery%20Act%202018.PDF

Merry, S. E. (2016). *The seductions of quantification: Measuring human rights, gender violence, and sex trafficking*. The University of Chicago Press. https://doi.org/10.7208/chicago/9780226261317.001.0001

Miller, R. E., & Blair, P. D. (2009). *Input-Output Analysis: Foundations and Extensions* (2nd ed.). Cambridge University Press. https://doi.org/10.1017/CBO9780511626982

Modern Slavery Act 2015 (UK) c. 30. https://www.legislation.gov.uk/ukpga/2015/30/contents

Modern Slavery Act 2015 Committee. (2024). *The Modern Slavery Act 2015: becoming world-leading again* - Report of Session 2024–25 (HL Paper 8). House of Lords. https://publications.parliament.uk/pa/ld5901/ldselect/ldmodslav/8/8.pdf

Moran, D., & Wood, R. (2014). CONVERGENCE BETWEEN THE EORA, WIOD, EXIOBASE, AND OPENEU'S CONSUMPTION-BASED CARBON ACCOUNTS. *Economic Systems Research*, *26*(3), 245-261. https://doi.org/10.1080/09535314.2014.935298

Mullins, G. (2021). *Firestorm: Battling super-charged natural disasters*. Viking, Penguin Random House Australia.

Norman, B., Newman, P., & Steffen, W. (2021). Apocalypse now: Australian bushfires and the future of urban settlements. *npj Urban Sustainability*, *1*(2). https://doi.org/10.1038/s42949-020-00013-7

Okuyama, Y., & Sahin, S. (2009). *Impact estimation of disasters: a global aggregate for 1960 to 2007 (English)*. (Policy Research working paper 4963, Issue. http://documents.worldbank.org/curated/en/787121468340170531

Okuyama, Y., & Santos, J. R. (2014). Disaster impact and input-output analysis *Economic Systems Research*, *26*(1), 1-12. https://doi.org/10.1080/09535314.2013.871505

Protocol to Prevent, Suppress and Punish Trafficking in Persons Especially Women and Children, supplementing the United Nations Convention against Transnational Organized Crime, Nov. 15, 2000, General Assembly resolution 55/25. https://www.ohchr.org/en/instruments-mechanisms/instruments/protocol-prevent-suppress-and-punish-trafficking-persons

Rose, A. (2004). Economic Principles, Issues, and Research Priorities in Hazard Loss Estimation. In (pp. 13-36). Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-540-24787-6_2

Rose, A., & Miernyk, W. (1989). Input–Output Analysis: The First Fifty Years. *Economic Systems Research*, *1*(2), 229-272. https://doi.org/10.1080/09535318900000016

Russell, S. (2018). *Estimating and Reporting the Comparative Emissions Impacts of Products* [Working Paper, World Resources Institute]. https://ghgprotocol.org/sites/default/files/2023-03/18_WP_Comparative-Emissions_final.pdf

Sanderson, B. M., & Fisher, R. A. (2020). A fiery wake-up call for climate science. *Nature Climate Change*, *10*(3), 175-177. https://doi.org/10.1038/s41558-020-0707-2

Satherley, T., & May, D. (2022). Natural disasters and climate risk. In: Department of Parliamentary Services (Ed.), *BRIEFING BOOK: KEY ISSUES FOR THE 47TH PARLIAMENT* (pp. 22-29). Parliamentary Library, Department of Parliamentary Services. https://www.aph.gov.au/About_Parliament/Parliamentary_departments/Parliamentary_Library/Research/Briefing_Book/47th_Parliament/NaturalDisastersClimateRisk

Schandl, H., Marcos-Martinez, R., West, J., Miatto, A., Lutter, S., Lieber, M., Giljum, S., Lenzen, M., Li, M., Wang, H., Tanikawa, H., Krausmann, F., Eisenmenger, N., & Fischer-Kowalski, M. (2024). Global material flows and resource productivity: The 2024 update. *Journal of Industrial Ecology*, *28*(6), 2012-2031. https://doi.org/10.1111/jiec.13593

Schulte in den Bäumen, H., Moran, D., Lenzen, M., Cairns, I., & Steenge, A. (2014). How severe space weather can disrupt global supply chains. *Natural Hazards and Earth System Sciences*, *14*(10), 2749-2759. https://doi.org/10.5194/nhess-14-2749-2014

Songini, L., Pistoni, A., Comerio, N., & Tettamanzi, P. (2023). A decade of integrated reporting studies: state of the art and future research implications. *Accounting, Auditing & Accountability Journal*, *36*(9), 226-252. https://doi.org/10.1108/AAAJ-10-2021-5490

Stadler, K., Wood, R., Bulavskaya, T., Södersten, C.-J., Simas, M., Schmidt, S., Usubiaga, A., Acosta-Fernández, J., Kuenen, J., Bruckner, M., Giljum, S., Lutter, S., Merciai, S., Schmidt, J. H., Theurl, M. C., Plutzar, C., Kastner, T., Eisenmenger, N., Erb, K.-H., … Tukker, A. (2018). EXIOBASE 3: Developing a Time Series of Detailed Environmentally Extended Multi-Regional Input-Output Tables. *Journal of Industrial Ecology*, *22*(3), 502-515. https://doi.org/10.1111/jiec.12715

Starr, J., Nicolson, C., Ash, M., Markowitz, E. M., & Moran, D. (2023). Income-based U.S. household carbon footprints (1990–2019) offer new insights on emissions inequality and climate finance. *PLOS Climate*, *2*(8), e0000190. https://doi.org/10.1371/journal.pclm.0000190

Steenge, A. E., & Bočkarjova, M. (2007). Thinking about Imbalances in Post-catastrophe Economies: An Input–Output based Proposition. *Economic Systems Research*, *19*(2), 205-223. https://doi.org/10.1080/09535310701330308

Stern, N. (2015). Economic development, climate and values: making policy. *Proceedings of the Royal Society B 282*(1812). https://doi.org/10.1098/rspb.2015.0820

Stridsland, T., Boeve, T. M., Løkke, S., & Sanderson, H. (2024). Collaborative approaches to greenhouse gas inventory in higher education: Insights from the Universities Denmark Group. *Heliyon*, *10*(10), e30370. https://doi.org/10.1016/j.heliyon.2024.e30370

Task team on ISIC. (2024). *Introduction of the Standard Industrial Classification of All Economic Activities, Revision 5 (ISIC Rev.5): (Part of forthcoming UN publication)*. https://unstats.un.org/unsd/classifications/Econ/Download/In%20Text/ISIC5_Intro_11Mar2024.pdf

The University of Sydney. (n.d.). *The OAASIS Project: Open analysis to address slavery in supply chains*. Retrieved September 3, 2025, from https://www.sydney.edu.au/science/our-research/research-areas/physics/big-data-combatting-modern-slavery.html

[TNFD] Taskforce on Nature-related Financial Disclosures. (2023). *Recommendations of the Taskforce on Nature-related Financial Disclosures* [Final recommendations of TNFD]. https://tnfd.global/publication/recommendations-of-the-taskforce-on-nature-related-financial-disclosures/#publication-content

Trafficking Victims Protection Act of 2017 (2018). 34 USC 10101 note. https://www.congress.gov/115/plaws/publ393/PLAW-115publ393.pdf

United Nations Statistics Division. (1999). *Handbook of input-output table compilation and analysis*. https://digitallibrary.un.org/record/370160?ln=en

United Nations Statistics Division. (2008). *International Standard Industrial Classification of All Economic Activities (ISIC) Rev.4*. https://unstats.un.org/unsd/classifications/Econ/Download/In%20Text/ISIC_Rev_4_publication_English.pdf

United Nations Statistics Division. (2015). Central Product Classification (CPC): Version 2.1. https://unstats.un.org/unsd/classifications/unsdclassifications/cpcv21.pdf

van Eeden, L., Nimmo, D., Mahony, M., Herman, K., Ehmke, G., Driessen, J., O'Connor, J., Bino, G., Taylor, M., & Dickman, C. (2020). *Impacts of the unprecedented 2019-20 bushfires*

on Australian animals [Report prepared for WWF-Australia]. https://www.wwf.nl/globalassets/pdf/wwf-impacts-of-the-unprecedented-2019-2020-bushfires-on-australian-animals.pdf

Wang, D., Guan, D., Zhu, S., Kinnon, M. M., Geng, G., Zhang, Q., Zheng, H., Lei, T., Shao, S., Gong, P., & Davis, S. J. (2021). Economic footprint of California wildfires in 2018. *Nature Sustainability*, *4*(3), 252-260. https://doi.org/10.1038/s41893-020-00646-7

Wang, J., Ji, C.-J., Liu, Y., Shan, Y., Hubacek, K., Wei, Y.-M., & Wang, K. (2024). Re-investigating the shared responsibility for trade-embodied carbon emissions. *Ecological Economics*, *220*, 108162. https://doi.org/10.1016/j.ecolecon.2024.108162

Weitzer, R. (2014). New Directions in Research on Human Trafficking. *The ANNALS of the American Academy of Political and Social Science*, *653*(1), 6-24. https://doi.org/10.1177/0002716214521562

Wittwer, G., Li, K., & Yang, S. (2021). *The economic impacts of the 2019-20 bushfires on Victoria*. In: Department of Treasury and Finance (Ed.), Victoria's Economic Bulletin (Vol. 5) (pp. 33-54). Victoria State Government. https://www.dtf.vic.gov.au/sites/default/files/2024-10/Victoria%27s-Economic-Bulletin-Volume-5.pdf

Wittwer, G., & Waschik, R. (2021). Estimating the economic impacts of the 2017–2019 drought and 2019–2020 bushfires on regional NSW and the rest of Australia. *Australian Journal of Agricultural and Resource Economics*, *65*(4), 918-936. https://doi.org/10.1111/1467-8489.12441

World Commission on Environment and Development. (1987). *Report of the World Commission on Environment and Development: "Our common future"* [Brundtland report]. https://digitallibrary.un.org/record/139811?ln=en&v=pdf#files

World Business Council for Sustainable Development & World Resources Institute. (2004). *The Greenhouse Gas Protocol: A Corporate Accounting and Reporting Standard - REVISED EDITION*. https://ghgprotocol.org/sites/default/files/standards/ghg-protocol-revised.pdf

World Resources Institute & World Business Council for Sustainable Development. (2011). *Corporate Value Chain (Scope 3) Accounting and Reporting Standard: Supplement to the GHG Protocol Corporate Accounting and Reporting Standard*. https://ghgprotocol.org/sites/default/files/standards/Corporate-Value-Chain-Accounting-Reporing-Standard_041613_2.pdf

World Resources Institute & World Business Council for Sustainable Development. (2013). *Technical guidance for calculating scope 3 emissions: Supplement to the Corporate Value Chain (Scope 3) Accounting & Reporting Standard*. https://ghgprotocol.org/sites/default/files/standards/Scope3_Calculation_Guidance_0.pdf

Xu, L., Chen, G., Wiedmann, T., Wang, Y., Geschke, A., & Shi, L. (2019). Supply-side carbon accounting and mitigation analysis for Beijing-Tianjin-Hebei urban agglomeration in China. *Journal of Environmental Management*, *248*, 109243. https://doi.org/10.1016/j.jenvman.2019.07.014

Zhou, L., & Chen, Z. (2021). Are CGE models reliable for disaster impact analyses? *Economic Systems Research*, *33*(1), 20-46. https://doi.org/10.1080/09535314.2020.1780566

2. DISASTER RISK TO BUSINESS – IO ANALYSIS OF AUSTRALIA'S MEGA-FIRES

Reiner, V., Pathirana, N. L., Sun, Y.-Y., Lenzen, M., & Malik, A. (2024). Wish You Were Here? The Economic Impact of the Tourism Shutdown from Australia's 2019-20 'Black Summer' Bushfires, *Economics of Disasters and Climate Change*, *8*(1), 107-127. https://doi.org/10.1007/s41885-024-00142-8

Paper: Wish you were here? The economic impact of the tourism shutdown from Australia's 2019-20 "Black summer" bushfires

Abstract

Tourism, including education-related travel, is one of Australia's top exports and generates substantial economic stimulus from Australians travelling in their own country, attracting visitors to diverse areas including World Heritage rainforests, picturesque beachside villages, winery townships and endemic wildlife. The globally unprecedented 2019-20 bushfires burned worst in some of these pristine tourist areas. The fires resulted in tourism shutting down in many parts of the country over the peak tourist season leading up to Christmas and into the New Year, and tourism dropped in many areas not physically affected by the fires. Our research quantified the cost of the short-term shock from tourism losses across the entire supply chain using input-output (IO) analysis, which is the most common method for disaster analysis; to this end, we also developed a framework for disaggregating the direct fire damages in different tourism sectors from which to quantify the impacts, because after the fires, the economy was affected by COVID-19. We calculated losses of AU$2.8 billion in total output, $1.56 billion in final demand, $810 million in income and 7300 jobs. Our estimates suggest aviation shouldered the most losses in both consumption and wages/salaries, but that accommodation suffered the most employment losses. The comprehensive analysis highlighted impacts throughout the nation, which could be used for budgeting and rebuilding in community-and-industry hotspots that may be far from the burn scar.

2.1. Introduction

Australia's 2019-20 bushfires were unprecedented globally, burning through more than one-fifth of its temperate broadleaf and mixed-forest biome (Boer et al., 2020) over several months, and including every State and Territory. Starting in what was then Australia's hottest and driest year on record (Norman et al., 2021), in a nation used to increasing extremes (Gergis, 2018), the fires killed or displaced an estimated three billion animals (van Eeden et al., 2020) in addition to at least 33 people (Royal Commission into National Natural Disaster Arrangements, 2020). At its peak, Australia's worst fire, the Gospers Mountain mega-fire that formed from the convergence of six fires, was one day away from spreading from bushland to the built-up Sydney suburb of Hornsby (McDonald, 2020), where 20,000 homes lie within 100 metres of the bush (Hannam, 2016). The ferocity of the fires has also raised questions about cumulative or irreversible damage, for example to rainforest dating back to the Jurassic Period, including cultural heritage (Australian Government Department of Agriculture, Water and Environment, 2020); animals (Murphy & van Leeuwen, 2021) such as the koala becoming endangered in New South Wales (NSW), Queensland (QLD) and the Australian Capital Territory (ACT) (Dalton, 2022); and potentially climate targets as a result of greenhouse gases emitted from the fires (van der Velde

et al., 2021). The fires resulted in about 830 million tonnes of carbon dioxide-equivalent emissions (Australian Government Department of Industry, 2020), which is one-and-a-half times Australia's annual emissions for the previous year to March 2019, of 538.9 Mt $C0_2$-e (Australian Government Department of the Environment and Energy, 2019). The Australian government (2020) noted that bushfires tend to result in a carbon sink in future years as a result of regrowth, however, concerns have been raised regarding the extent of Australia's 2019-2020 fires in terms of post-fire recovery (Boer et al., 2020).

The bushfires (also called wildfires) started in mid-2019; in the nation's north, what became known as the Queensland bushfires between September to December 2020, marked the start of a catastrophic season. The QLD fires affected a number of tourism areas, including the World Heritage Lamington National Park, where the historic Binna Burra Lodge was destroyed, along with Parks and road infrastructure (Binna Burra, 2022; Queensland Government, 2020). A State of Emergency had been declared briefly in November. In December the fires intensified in NSW, VIC and South Australia (SA) in the lead-up to Christmas and in the early New Year period, disrupting the peak tourist season, with many tourists stranded, evacuated or cancelling trips. A "Tourist leave zone" was set up in NSW, extending 500 km from Batemans Bay along the coast to the VIC border in the first week of January. The Rural Fire Service warned of upcoming weekend fires "the same or worse" than the devastating New Year's Eve fires and encouraged holiday-makers to get out of harm's way and allow emergency workers to focus on protecting the local communities (BBC, 2020). Tourism Australia paused its advertisement *Matesong,* which focused on celebrity Kylie Minogue (Bourke, 2020) and an image of the spots of bushfires over a month on a map of Australia was Tweeted by singer Rihanna and went viral, giving the impression that the whole of the country was on fire simultaneously (Rannard, 2020). In Australia's 4th-most visited island, SA's Kangaroo Island, catastrophic conditions resulted in evacuations and the death of two people before the fires were brought under control in late January (Kangaroo Island Council, 2020). With conditions improving in some areas such as the NSW Blue Mountains, Australia's capital, the ACT became the worst-hit region in February (Tourism Research Australia, 2020a, 2020b), experiencing the most hazardous air quality in the world (Norman et al., 2021). Melbourne was also affected by hazardous air-quality levels and smog from the fires made its way across the globe (Rodriguez, 2020), before the bushfire season ended in March 2020.

In some regions directly affected by fires, business takings were reduced by more than 70% in the important summer holiday period; in addition to losses from tourism, residents also spent less because of safety- and supply-chain disruptions (Indigo Shire Council, 2020; McIlwain,

2020). Research showed that at its peak, awareness about the fires was close to 100% across all markets (Tourism Australia, 2020), and the government's export arm noted that tourism and education was its most-impacted industry (Austrade, 2020, p. 2).

The federal government provided an AU$76 million Rebuilding Australian Tourism package and among other initiatives, Tourism Australia executed a successful "Holiday here this year" campaign after some of the worst of the fires, in January, encouraging Australians to return to bushfire-affected areas and support local communities across the country. In February an international campaign was launched, called "There's still nothing like Australia", building on a pre-fire campaign, "There's nothing like Australia"; however, all marketing was stopped because of increasing coronavirus travel restrictions, and Australia comprehensively closed its international borders on 20 March 2020.

What has been referred to as Australia's "Black summer" could be a sign of things to come (Canadell et al., 2021; Handmer et al., 2018; Norman et al., 2021; Van Oldenborgh et al., 2021) in a continent already subject to heatwaves and drought, which is being exacerbated by climate change (Gergis, 2018). In particular, bushfires have been increasing their share compared to other natural hazards; this trend has been noted in Australia as well as globally (Handmer et al., 2018; Swiss Re, 2021)

This is, to our knowledge, the first supply-chain analysis of the cost of the 2019-20 bushfire tourism damages on the Australian economy and is based on the popular technique input-output (IO) analysis. Drawing on surveys by Tourism Research Australia about the direct impact of the bushfires, we calculate losses across the entire supply chain, uncovering hotspots in particular sectors and regions.

This paper is set out as follows: Brief overviews of IO analysis, as well as the IO disaster analysis stream and its application to this study are detailed in the Methods section. Key findings are set out in the Results, risks to long-term tourism as well as future research recommendations are outlined in the Discussion, and we then conclude.

2.2. Methods

2.2.1. Overview of input-output analysis

This study draws on input-output (IO) analysis, a methodology that is globally standardised and enables impact analysis along the entire supply chain. In comparison to production-based

accounting, where impacts are relegated to the producer or territory responsible, IO underpins consumption-based accounting because it traces the impact of intermediate industry demand in addition to the impact of final demand from the consumption of a good or service (Afionis et al., 2017). In this way, IO analysis facilitates comprehensive impact analysis such as carbon footprints that include all scope-3 emissions. Furthermore, IO analysis facilitates researcher and policy expert insights, through the ability to provide highly disaggregated information at the sectoral and regional levels and across a wide range of indicators (Wiedmann, 2009); outputs range from headline figures on gross domestic product (GDP) and environmental impacts to a breakdown of employment impacts in specific regions or sectors.

IO analysis was developed by economist Wassily Leontief during the 1930s and 1940s to enable practitioners to quantify the relationship between inputs into, and outputs of economic activity, including pollution (Leontief, 1936). With the methodology demonstrating the relationships between consumption and production and enabling the identification of supply-chain hotspots (Leontief, 1966), IO analysis increased in popularity during the 1970s oil shocks, winning Leontief a Nobel Prize (The Nobel Prize, 1973).

Because it is based on the economic structure of nations, Leontief's prize-winning formula overcomes barriers such as data collection from indirect suppliers faced in traditional life-cycle assessment (LCA). Traditional LCA tends to be limited to direct (on-site) impacts or else typically does not extend beyond direct suppliers or suppliers of direct suppliers. However, hybrid IO-LCA studies can make use of LCA's bottom-up data while benefitting from the calculation of higher orders of production via IO's top-down approach. The structure of IO analysis additionally lends itself to numerous applications related to economic activity (Wiedmann, 2009), extending to environmental and social indicators and answering complex and novel research questions (for a recent example, see Malik et al. (2022)).

Multi-region input-output (MRIO) models were expanded globally by research collaborations (Lenzen et al., 2017a; Lenzen et al., 2017b; Lenzen et al., 2013; Malik et al., 2019; Tukker & Dietzenbacher, 2013). These developments were supported by increased data availability and improvements in high-performance computing that enables the analysis of billions of supply chains.

Global, multi-regional analysis, also referred to as GMRIO draws on data issued regularly by more than 100 statistical agencies around the world and is routinely employed by organisations such as the OECD, the European Commission and the World Bank. Recently, IO analysis was used to build an open-access database on behalf of the UN for the measurement of countries'

economic, social and environmental indicators against the Sustainable Development Goals (SDGs), for standardised reporting and hotspot analysis (Lenzen et al., 2022).

IO analysis draws on input-output tables (IOTs) from countries' statistical agencies as part of the almost universal System of National Accounts 2008 framework (European Commission et al., 2009). IO analysis also draws from international data providers such as Eurostat and sources such as UN Comtrade, the data from which can be used to build inter-country supply-and-use-tables that form the basis of IOTs. Just as the System of National Accounts has facilitated international comparisons across significant economic activities, so too has IO and its extended environmental, social and disaster analysis facilitated comparisons of impacts across companies, industries and regions; IO analysis is governed by standards set by the United Nations (United Nations Statistics Division, 1999).

In this study, negative entries in the final-demand and value-added blocks of the pre-disaster MRIO tables were removed by mirroring, as described in Section 4 of Lenzen et al. (2014b).

2.2.2. Disaster analysis sub-stream of IO

Research focusing on quantifying the impacts of disasters was not common until a string of disasters in the decade from the 1990s, including the Kobe earthquake in 1995, the Indian Ocean earthquake and tsunami in 2004 and Hurricane Katrina in 2005 (Okuyama, 2007). The need for routine, effective and efficient quantification of economic impacts, in order to adapt and mitigate against catastrophic disasters, is now considered urgent (Okuyama & Santos, 2014). An increasing focus on quantifying disasters, assisted by increased data availability has led to the development and advancement of empirical research methodologies including econometric models, social accounting matrix (SAM), computable general equilibrium (CGE) and IO disaster analysis as well as hybrid models (for example, as proposed by Oosterhaven (2017). The relative strengths and applicability of various approaches have been well-discussed in the disaster analysis literature; CGE and IO models are commonly used (Galbusera & Giannopoulos, 2018; Steenge & Bočkarjova, 2007; Zhou & Chen, 2021), with IO analysis increasingly popular in recent years (Bočkarjova et al., 2004; Li et al., 2013; Schulte in den Bäumen et al., 2015) to become the most commonly employed method for disaster impact analysis (Okuyama & Santos, 2014). For example, IO analysis has been used recently to quantify the impacts of cyclone Debbie in Australia (Lenzen et al., 2019), earthquakes in Taiwan (Faturay et al., 2020a), COVID-19 (Lenzen et al., 2020) and the Venezuelan energy crisis (Li et al., 2022).

With IO models previously established as the major tool of impact analysis that assesses more than one region (Richardson, 1985), this methodology plays a crucial role in tracing the indirect, flow-on effects from large-scale disasters in an increasingly globalised world (Steenge & Bočkarjova, 2007). IO post-disaster analysis calculates impacts from direct damages data rather than relying on expected future trends as inputs to the model. In addition to its universality, IO disaster assessment because of its relatively straightforward structure, has also enabled integrative approaches where IO is incorporated with other models to enable them to assess higher-order (indirect) effects, such as for CGE (Koks et al., 2016; Rose, 1995) and transportation networks (Okuyama, 2007). In comparison, CGE's approach in simulating future states is more flexible, which can be a weakness. In a meta-analysis of CGE studies, Zhou and Chen (2021) concluded that variability in results because of practitioner assumptions inherent in the modelling remain a challenge. An assumption that the market produces optimal outcomes and the economy re-adjusts towards equilibrium over the longer term can provide an underestimation of losses, particularly where a large disruption occurs in a short timeframe (less than a year), which typifies natural hazards (Rose, 2004). Oosterhaven (2022) details a new approach, which has been referred to as IO/SU non-linear programming and allows for substitutability, as well as price rises, which minimise business disruption; however, it may be less suitable for quantifying the impacts of complex disasters where shortages are common, along with business shutdowns. Recognising the imbalance that exists in the aftermath of a disaster and the new situation the economy faces as a result of spillover impacts along supply chains, Steenge and Bočkarjova (2007) built on the concept of a basic equation, using IO analysis, to describe the pre- and post-disaster economies, with the idea that governments can use the model to determine market interventions and analyse alternate pathways to the desired post-catastrophe equilibrium.

We follow the approach by Steenge and Bočkarjova to determine the short-term post-disaster loss for the economy, which has been built on in recent studies to improve the disaster model. Limitations of IO disaster analysis have included the fact that the rigid structure requires constant prices and does not take account of real-world behaviour such as substitution of goods and services; however, advances have gone some way to addressing several limitations. Steenge and Bočkarjova described a "basic equation" that can be represented as $\tilde{\mathbf{x}} = (\mathbf{I} - \hat{\boldsymbol{\gamma}})\mathbf{x}$ – where the potential maximum production of each sector of the impacted economy $\tilde{\mathbf{x}}$ takes into account the event matrix of losses placed on the diagonal, gamma hat ($\hat{\boldsymbol{\gamma}}$), of proportionate production losses that shinks the pre-disaster economy $\mathbf{x}$, so that losses in total output are the difference between this new output level and the initial output (Bočkarjova et al., 2004; Steenge

& Bočkarjova, 2007). Total output is determined according to standard IO anaysis: $\mathbf{x} = (\mathbf{I} - \mathbf{A})^{-1}\mathbf{y}$, where $\mathbf{I}$ is an identity matrix of 1's on the diagonal and 0's elsewhere; the $\mathbf{I}$ matrix is the same dimensions as the direct requirements matrix $\mathbf{A}$ to which it relates, which is a "production recipe" of the selected sector groupings comprising the economy, with the inputs into each sector are a fraction adding up to $1 (or other monetary unit as relevant) worth of production; $(\mathbf{I} - \mathbf{A})^{-1}$ being the famous Leontief inverse $\mathbf{L}$ that includes the entire supply chain, and demand from end-consumers $\mathbf{y}$ (also referred to as final demand or consumption) being equal to $(\mathbf{I} - \mathbf{A})\mathbf{x}$. A relaxation of Steenge's approach is described by Schulte in den Bäumen et al. (2014). Developed to be used in instances when the "unbound" constant production recipe approach results in negative final demand ($\mathbf{y}$) values, this method assumes that very small, marginal inputs to production, in the $\mathbf{A}$ matrix, are substitutable, meaning intermediate demand can shoulder some of the shock to ensure no negative final demand in order to reflect better the real world. To achieve this, marginal inputs in $\mathbf{A}$ are reduced to zero to ensure the post-event final demand sectors in $\mathbf{y}$ are either zero or positive.

An alternative to removing marginal inputs in $\mathbf{A}$ was developed by Faturay et al. (2020a) because small values may nonetheless be important in complex supply-chain interactions; this approach uses optimisation coding in MATLAB to determine the maximum total output. Given the disaster "basic equation" $\tilde{\mathbf{x}} = (\mathbf{I} - \hat{\boldsymbol{\gamma}})\mathbf{x}$, with $\mathbf{x} = (\mathbf{I} - \mathbf{A})^{-1}\mathbf{y}$, the optimisation approach determines the post-disaster economy within the constraints of non-negative values in $\mathbf{y}$ and short-term output being limited by maximum production. This model was used in a comprehensive footprint of the first COVID-19 lockdown (Lenzen et al., 2020) and more recently in projections of climate impacts on the Australian food system (Malik et al., 2022). A new "minimum-disruption" approach to modelling the post-disaster transition has also been proposed by Li et al. (2022), who apply priority weights to essential sectors to guard against the economic shock. In this novel study of the tourism impacts of Australia's 2019-20 mega-fires, we use the optimisation approach developed by Faturay et al. (2020a) described above, because of its application to numerous recent disasters.

2.2.3. Data collection

Tourism Research Australia (TRA) published a range of data in the National Visitor Survey (2020b) and International Visitor Survey (2020a); in order to provide a more comprehensive understanding of the losses from the bushfires, TRA provided, upon request, quarterly expenditure including day trips (personal communication, August 31, 2022). Only data from January-March 2020 was used because expenditure only started falling in that quarter. By the following quarter, the fires had been brought under control and it would not be possible to determine if any bushfire tourism losses flowed through to the following quarter because non-essential travel was banned because of the coronavirus pandemic. TRA also provided the underlying data from surveys that sought to determine the proportion of tourists who were impacted by the bushfires (personal communication, June 10 & 14, 2022). These percentages were applied to the March quarter losses to ensure no losses because of the coronavirus were included. In order to disaggregate losses by sector, the proportionate representation of tourism- and tourism-related sectors from TRA's 2018-19 State Tourism Satellite Accounts (TSA) (Austrade & Tourism Research Australia, 2019) was applied to the 2019-20 losses (Austrade & Tourism Research Australia, 2020). The UN World Tourism Organization and Australian Bureau of Statistics definitions of tourism relate to expenditure by visitors to an area where the visit is for less than a year; TSAs, which comprise expenditure on tourism and related activities of nations, include business- and education-related travel, in other words, any visits, as opposed to long-term moves. Online *Supplementary Information* SI 2.7 provides further details about the calculations of direct damages.

2.2.4. The event (gamma) matrix

Losses were divided across eight regions (each State and Territory) and 39 sectors, which included the most-affected sectors as well as other key primary, secondary and tertiary sectors. The post-disaster losses were then compared with the pre-disaster total output for the year, for the relevant sectors and regions in the MRIO and converted into a proportion. A separate gamma matrix of capital damages was also compiled, with the treatment of infrastructure, including depreciation, following the approach described in previous IO disaster studies (Faturay et al., 2020a; Lenzen et al., 2019) (see online *Supplementary Information* SI 2.6 for details); added together, these make up the final gamma matrix of proportionate losses for the economy. For example, 0.02 for South Australian Accommodation means that income in the accommodation sector in SA reduced 2% for the year; areas where no known direct damage occurred are 0. Table 1 shows the final gamma matrix ($\boldsymbol{\gamma}$) of direct losses and capital damages.

		NSW	VIC	QLD	SA	WA	TAS	ACT	NT
1	Grapes – wine	0	0	0	0	0	0	0	0
2	Apples, pears and stone fruit	0	0	0	0	0	0	0	0
3	Livestock	0	0	0	0	0	0	0	0
4	Other agriculture	0	0	0	0	0	0	0	0
5	Forestry	0	0	0	0	0	0	0	0
6	Fishing and seafood	0	0	0	0	0	0	0	0
7	Coal, oil and gas	0	0	0	0	0	0	0	0
8	Non-ferrous metal ores	0	0	0	0	0	0	0	0
9	Other mining	0	0	0	0	0	0	0	0
10	Wines	0	0	0	0	0	0	0	0
11	Other food manufacturing	0	0	0	0	0	0	0	0
12	Textiles, clothing and footwear	0	0	0	0	0	0	0	0
13	Wood and paper manufacturing	0	0	0	0	0	0	0	0
14	Automotive petrol	0.0024	0.0012	0.0015	0.0064	0.0016	0	0.0040	0.0044
15	Chemicals, petroleum and coal products nec	0	0	0	0	0	0	0	0
16	Non-metallic mineral products	0	0	0	0	0	0	0	0
17	Metals, metal products	0	0	0	0	0	0	0	0
18	Machinery appliances and equipment	0	0	0	0	0	0	0	0
19	Miscellaneous manufacturing	0	0	0	0	0	0	0	0
20	Electricity supply, gas and water	0	0	0	0	0	0	0	0
21	Residential building construction	0	0	0	0	0	0	0	0
22	Other construction	0	0	0	0	0	0	0	0
23	Rail transport	0.0007	0.0011	0.0005	0.0015	0.0011	0	0.0051	0.0019
24	Taxi transport	0.0089	0.0051	0.0065	0.0055	0.0041	0	0.0064	0.0049
25	Other road transport	0.0006	0.0004	0.0017	0.0003	0.0003	0	0.0018	0.0006
26	Air, water and other transport	0.0035	0.0024	0.0037	0.0047	0.0035	0	0.0057	0.0068
27	Transport equipment rental	0.0150	0.0190	0.0123	0.0115	0.0118	0	0.0056	0.0062
28	Travel agency and information centre services	0.0095	0.0101	0.0098	0.0137	0.0085	0	0.0091	0.0026
29	Accommodation	0.0174	0.0125	0.0106	0.0217	0.0061	0	0.0178	0.0059
30	Cafes, restaurants and take-away foods	0.0047	0.0027	0.0033	0.0028	0.0025	0	0.0022	0.0030
31	Wholesale and retail trade	0.0008	0.0004	0.0006	0.0005	0.0004	0	0.0005	0.0007
32	Ownership of dwellings	0.0005	0.0004	0.0003	0.0005	0.0003	0	0.0001	0.0001
33	Cultural and recreational services;	0.0082	0.0043	0.0047	0.0081	0.0045	0	0.0021	0.0032
34	Communication services	0	0	0	0	0	0	0	0
35	Finance, property and other business services	0	0	0	0	0	0	0	0
36	Government administration and defence	0	0	0	0	0	0	0	0
37	Education and training	0.0015	0.0010	0.0009	0.0007	0.0006	0	0.0008	0.0005
38	Health and community services	0	0	0	0	0	0	0	0
39	Personal and other services	0	0	0	0	0	0	0	0

Table 1: The gamma matrix ($\boldsymbol{\gamma}$). The gamma (event) matrix comprises direct tourism losses from Australia's 2019-20 bushfires as a proportion of total output ($\mathbf{x}$) for the 2018-19 financial year, in particular sectors and regions. Losses were calculated for Australia's States and Territories against 39 sector groupings of this study, comprising Australia's economy. Infrastructure losses were depreciated in the manner described by Faturay et al., 2020a and Lenzen et al., 2019. Regional abbreviations: New South Wales (NSW), Victoria (VIC), Queensland (QLD), South Australia (SA), Western Australia (WA), Tasmania (TAS), Australian Capital Territory (ACT), Northern Territory (NT).

As can be seen in Table 1, no losses were recorded for Tasmania (TAS) because that State recorded increased tourism expenditure (of $1.1 million). This study quantified the total impact from direct losses, across the supply chain, but did not quantify the impact of gains (in Tasmania); in the same way, insurance paid out can be seen as an economic stimulus, as can hospitalisations in providing money for the healthcare sector; these are also not included in IO disaster-analysis calculations. In this way, a standardised approach is followed in quantifying the short-term economic cost of the losses from each impacted sector.

MRIOs are based on countries' input-output tables (IOTs) in the National Accounts so the aggregated sectors were selected from 1284 sectors in the Australian Industrial Ecology Virtual Laboratory (www.ielab.info/), which are based on the Input-Output Product Classification in the Australian National Accounts (Australian Bureau of Statistics, 2009). The States and Territories were aggregated from the 2214 Statistical Area level 2 (SA2) regions (Australian Bureau of Statistics, 2011). A concordance matrix to aggregate the sectors and regions was converted into a MRIO of the Australian economy in the IELab. The IELab developed at the University of Sydney (Lenzen, et al., 2014a) was Australia's first such collaborative cloud-based platform for IO analysis. Such platforms overcome the time-consuming nature of MRIO compilation through an open-source approach, with the source data updated regularly. IELabs have now been built for Indonesia (Faturay et al., 2017), Japan (Wakiyama et al., 2020), Taiwan (Faturay et al., 2020a), China (Wang, 2017) and the United States (Faturay et al., 2020b), and the Global MRIO Lab infrastructure was used to build GLORIA on behalf of the UN International Resource Panel as the database for the open-access global Sustainable Consumption and Production Hotspot Analysis Tool (Lenzen et al., 2022).

2.2.5. Indicators for impact analysis and unravelling supply chains through production layer decomposition

The satellite account attached to the tailored MRIO was selected during the MRIO compilation in the IELab, with matrix calculations then carried out in MATLAB. In this study, the satellite account employment (in addition to the related indicator, income) was selected as an indicator for impact analysis, to be quantified along with the post-event total output ($\mathbf{x}$) and final demand ($\mathbf{y}$).

The *change* in final demand ($\Delta\mathbf{y}$) is used to calculate the employment and income impacts of the disaster using the formula $\mathbf{qLy}$, where $\mathbf{q}$ is the multiplier derived by dividing the desired indicator by pre-disaster total output $\mathbf{x}$, and $\mathbf{L}$ represents the entire supply chain $(\mathbf{I}-\mathbf{A})^{-1}$. Income data is extracted from the first row of the value-added block of the MRIO ($\mathbf{v}$), while the

aggregated total employment data is contained in the 24th row of the employment satellite account in the IELab. In both instances, the $\mathbf{q}$ matrix is calculated using element-wise multiplication so that the intensity sectors/multipliers align with the final demand sectors, enabling production layer decomposition (PLD) for a disaggregated view of impacts. The entire impact $\mathbf{qLy}$ is unravelled at each production layer through the following decomposition:

$$\underset{\text{Layer 1}}{\mathbf{qy}} + \underset{\text{Layer 2}}{\mathbf{qAy}} + \underset{\text{Layer 3}}{\mathbf{qA}^2\mathbf{y}} + \underset{\text{Layer 4}}{\mathbf{qA}^3\mathbf{y}} + \ldots + \underset{\text{Layer n}}{\mathbf{qA}^n\mathbf{y}}$$

where $\mathbf{qy}$ is the direct impact (first layer in the PLD), $\mathbf{qAy}$ is the additional impact from direct suppliers involving the $\mathbf{A}$ matrix of direct requirements, $\mathbf{qA}^2\mathbf{y}$ is the impact from suppliers of the direct suppliers and so on, to infinite (n) layers/orders of production i.e., direct suppliers as well as all indirect suppliers.

2.2.6. Limitations

Our results may be conservative because it is possible that tourists would have spent even less than anticipated in the Tourism Research Australia surveys on which this bushfire research is based, had it not been for the first COVID-19 lockdown, which then became the primary reason for slashed tourism expenditure. We calculated bushfire-related tourism expenditure losses from the National Visitor Surveys and International Visitor Surveys that were carried out from 21 January to 15 March (Tourism Research Australia, 2022), which asked tourists about the extent to which their changed behaviour occurred because of the bushfires. Had it not been for the pandemic, the bushfire impact on tourism may have measured more post-fire, without being mixed up with losses from concurrent disasters, meaning we would have identified potentially higher bushfire losses. As well, direct bushfire damages data were only available for regions, not sectors, apart from tourism-related infrastructure. Although sectoral expenditure is available in the 2019-20 ABS Tourism Satellite Account, this period included COVID-19; therefore, assumptions had to be made about bushfire-specific direct sectoral losses, based on the usual proportionate representation of tourism spend, which were then used to calculate total losses including indirect impacts (see *Supplementary Information* SI 2.7 for details about the calculation of the direct damages data).

2.3. Results

From the Tourism Research Australia quarterly data and bushfire surveys, we calculated direct losses in tourism expenditure of $1629.9 million nationwide, in addition to $112.6 million in

depreciated infrastructure (in other words, $1742 million direct losses for the year, including infrastructure). In terms of regional breakdown, these *direct* losses (including infrastructure) were: NSW - $760.5 million, VIC - $347 million, QLD - $343.7 million, SA - $113.8 million, Western Australia (WA) - $135.6 million, TAS - $0, ACT - $22.2 million and Northern Territory (NT) $19.7 million. This triggered losses across the entire supply chain totalling $2801.6 million in total output, $1561.8 million in consumption, $809.4 million in income, and employment losses of more than 7292 full-time equivalent (FTE), which impacted sectors and regions in different ways. Taking the total output losses into account as a proportion of the pre-fire total output, in 2018-19, the losses were worst in NSW, closely followed by SA, which experienced significant fires not only in the Adelaide Hills winery and day-trip region near the State's capital but also in Kangaroo Island, where almost half the island burned (Kangaroo Island Council, 2020). Next in terms of proportionate losses was NT, despite the fact that this region did not suffer catastrophic fire conditions.

2.3.1. Geographic distribution of the employment losses

The geographical spread of losses in employment are similar to losses in the other indicators measured in this study. Fig. 1 shows that almost half of the 7292 jobs lost were experienced in NSW, the most populous State, which is also where the fires were worst.

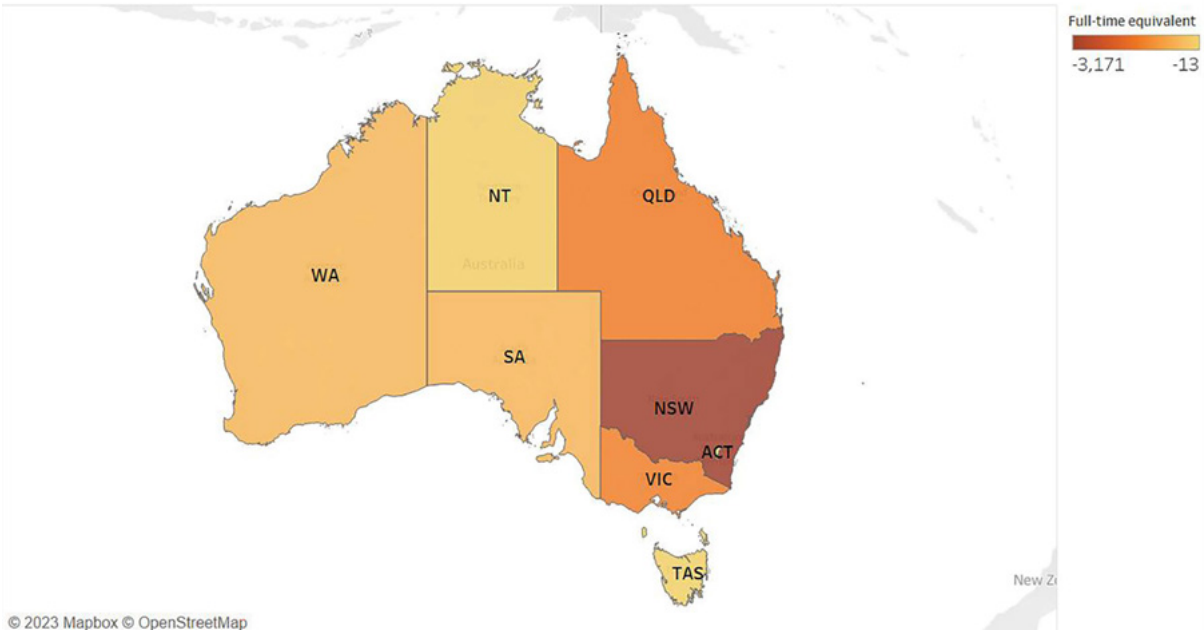


Figure 1: Losses in full-time equivalent (FTE) jobs across Australia resulting from the tourism losses because of the 2019-20 fires. The most populous State, New South Wales (NSW), suffered about twice as many losses in employment as its neighbouring eastern States, equivalent to 3171 full-time jobs. The Northern Territory (NT), although not suffering catastrophic fires, nonetheless lost 75 jobs from the short-term shock. Nationwide, more than 7292 jobs were lost. Other regions: Victoria (VIC), Queensland (QLD), South Australia (SA), Western Australia (WA), Tasmania (TAS), Australian Capital Territory (ACT)

Fig. 1 shows that although most of the employment losses were concentrated around Australia's east-coast States that also suffered the most direct tourism losses, spillovers were experienced across the nation. QLD and VIC suffered about half as much job losses as NSW, at 1499 and 1430 respectively, and SA experienced about one sixth of NSW's losses, at 516, followed by WA at 479. Tasmania, despite not suffering direct tourism damages, lost 13 jobs because of supply-chain impacts resulting from the contraction in consumption. The ACT lost substantially more jobs (110), closely followed by the NT (75 jobs).

2.3.2. Sectoral and regional hotspots

As can be seen in Fig. 2 that compares losses in consumption (final demand) and related income and employment, from an industry perspective, hospitality and transport were the worst hit overall, with the recreation and educational sectors also significantly impacted.

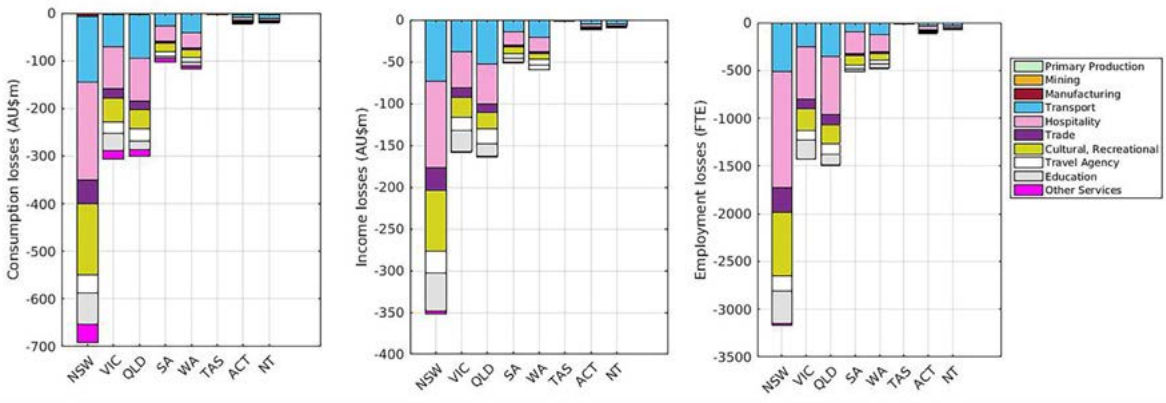


Figure 2: Losses in consumption, income and employment, across Australia's eight States and Territories and disaggregated by broad sector groupings, because of the tourism shutdown from the 2019-20 bushfires. Hospitality and transport suffered the most losses. Regional abbreviations: New South Wales (NSW), Victoria (VIC), Queensland (QLD), South Australia (SA), Western Australia (WA), Tasmania (TAS), Australian Capital Territory (ACT), Northern Territory (NT)

The "Accommodation" and "Cafes, restaurants and take-away" study sectors, which make up our aggregated hospitality grouping, together suffered the most losses in the consumption, income and employment indicators. However, disaggregating into our 39 individual sector groupings in this study, the aviation-led "Air, water and other transport" sector was the worst-hit in consumption and income (but not in employment, where "Accommodation" dominated), losing $292 million and $159 million respectively.

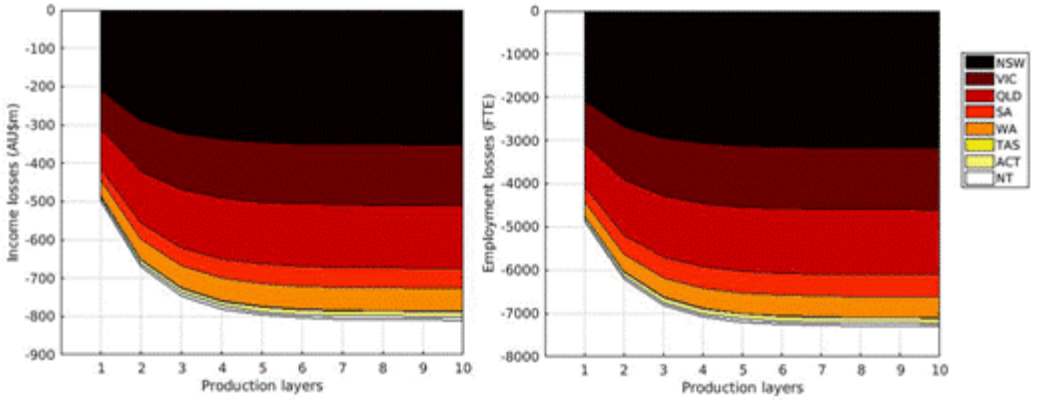
NSW shouldered the most losses, including 44% of both consumption and income impacts; NSW differed somewhat from the other regions in that the single most-impacted sector, out of the 39 sector groupings in this study, was "Cultural and recreational services" across consumption, income and employment (reducing by $148 million, $73 million and 662 jobs respectively), although when considering "Accommodation" and "Cafes, restaurants and take-

away" together as hospitality, the hospitality industry dominated NSW consumption, income and employment losses. The particularly large NSW losses in "Cultural and recreational services" is in part a reflection of the destruction of more than $200 million in Crown Lands and National Park infrastructure, (which was then depreciated - see *Methods*). These impacts including on areas such as the World Heritage Blue Mountains National Park (where approximately 82% was burnt (Australian Government Department of Agriculture, Water and the Environment, 2020)) would also have resulted in flow-on impacts to the local community, as well as more broadly, in areas such as reduced consumption of lodgings, restaurant meals and transport. Differences can also be seen between indicators for regions that suffered similar total losses. These include: VIC suffered more losses than QLD in consumption but the reverse was the case for related income and employment, with a key driver being greater losses in VIC's consumption of education and training ($37 million loss compared to $20 million). As well, WA experienced more losses than SA in consumption ($118 million compared to $102 million) and income ($60 million compared to $52 million) but not in employment (479 jobs lost compared to 516), where SA suffered particularly more losses in hospitality (229 jobs compared to 179. SA hospitality losses included from the Kangaroo Island destination the Southern Ocean Lodge, which was destroyed by the fires and for which the rebuild was estimated at $50 million (Boisvert, 2022). From a per-capita perspective, the NT was particularly impacted; for example, the NT had the smallest population in Australia in March 2020, at 245,400 people, which was more than half the TAS population of 539,600 (Australian Bureau of Statistics, 2020), however, the NT lost more income, at $9.3 million compared to $1.4 million. The underlying data on losses is in the online *Supplementary Information*.

2.3.3. Chain reactions along supply chains

In the following analysis, we discuss the impact on income and employment, which was triggered by the contraction in consumption. Fig. 3 shows that almost all the impacts were felt within about six or seven layers in the upstream supply chain, after which the additional losses per layer particularly start to level off.

a



b

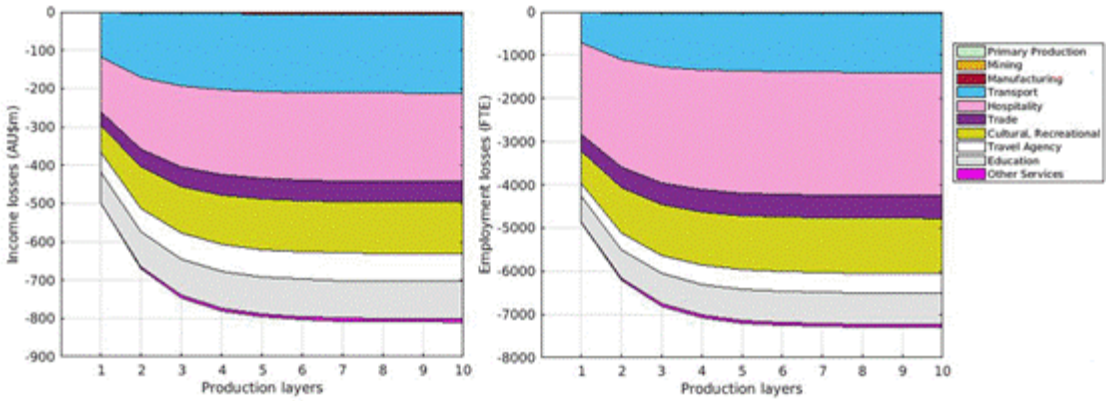


Figure 3: Production layer decomposition (PLD) of regions (a) and broad sector groupings (b). Layer 1 represents the impact from the direct tourism losses, layer 2 represents the impact from direct suppliers and so on, with the cumulative losses up to 10 layers depicted, which represent most of the losses. Employment losses measured in full-time-equivalent (FTE) jobs. Regions: New South Wales (NSW); Victoria (VIC); Queensland (QLD); South Australia (SA); Western Australia (WA); Tasmania (TAS); Australian Capital Territory (ACT); Northern Territory (NT)

The least-impacted regions tended to have a longer tail of losses because of supply-chain spillovers. In comparison, the most-impacted regions, the eastern States of NSW, VIC and QLD, experienced more losses directly or within a few orders of production.

Similarly, key industries such as transport and hospitality experienced more losses earlier on, while “Other services”, which includes sectors not directly impacted such as “Finance, property and other business services”, continued to experience significant losses further along the supply chain.

2.3.4. Regional case studies

Losses in the most-impacted State, NSW, followed a similar trend to the national results so in this section we highlight examples of divergence from the aggregated results, in the Australian Capital Territory and Tasmania. Additional disaggregation for regions and sectors and the underlying data are in the online *Supplementary Information* SI 4.

2.3.4.1. ACT

The dominance of losses in accommodation and the aviation-led transport sector in Australia's capital may in part be explained by the “fly-in-fly-out” economy.

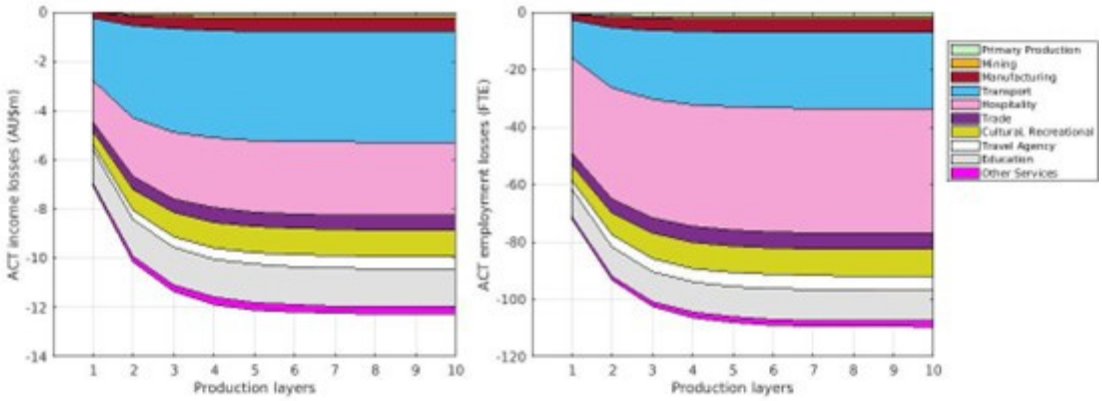


Figure 4: Production layer decomposition of the impact of tourism losses from the 2019-20 bushfires in the Australian Capital Territory, for income and full-time equivalent (FTE) employment in broad sector groupings. Although the number of upstream supply-chain interactions is theoretically infinite, results are illustrated for up to 10 orders of production, which comprise most of the losses

The ACT experienced the biggest income impact in the transport industry, led by the “Air, water and other transport” sector, which lost $3.4 million. These losses are in part because of the extreme bushfire smoke that the ACT’s capital Canberra experienced, which resulted in the airport being closed for hours on one of the worst days (Foster, 2020). “Accommodation”, as part of the hospitality industry, experienced substantially more employment losses than other sectors, equivalent to 30 jobs.

2.3.4.2. TAS

Despite Tasmania not experiencing an overall loss in direct tourism expenditure, losses from other regions flowed throughout Tasmania's economy.

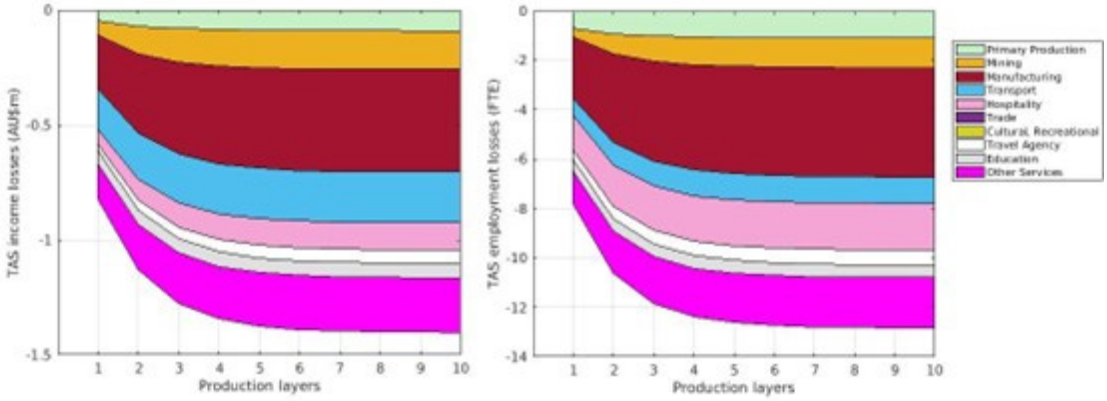


Figure 5: Production layer decomposition, across 10 broad sector groupings, of the impact of tourism losses from the 2019-20 bushfires in Tasmania. The losses are illustrated in terms of income and full-time equivalent (FTE) employment, up to 10 orders of production

As Fig. 5 shows, the losses from elsewhere in Australia flowed through Tasmania across the primary, secondary and tertiary sectors, with significant losses continuing to accumulate in upstream layers of production, particularly in the services sectors. TAS's employment indicator is notable because although the manufacturing industry in aggregate was substantially impacted in TAS, out of the 39 sectors in this study, the "Accommodation" hospitality sector suffered the most, experiencing 2 job losses in TAS.

2.4. Discussion

Tourism has been a critical driver of economic output and risks damage from climate change, particularly in countries such as Australia that are vulnerable to disasters. Tourism spend in the year prior to the fires was more than $120 billion, being responsible for the employment of 5% of Australians overall and 8.1% in rural areas, or almost one in 12 people (Tourism Australia, n.d.), and the bushfires burned worst outside of major cities because of tree cover. From a global perspective, Australia was one of the highest-yielding tourism destinations in 2018-19, with international visitors spending $44.6 billion (Tourism Australia, n.d.). Education-related travel services was Australia's fourth-biggest export in 2018-19 and, when combined with personal travel, was beaten only by iron ore and coal and was responsible for more export income than natural gas (Department of Foreign Affairs and Trade, 2020, p. 19); in fact, the federal export arm Austrade reported that its two most-impacted industries from the bushfires were tourism and

education (2020, p. 2). It should be noted that tourists are defined as any visitors who will stay for less than a year; standardised tourism satellite accounts (TSA) of tourism and related activities of nations include business- and education-related travel, meaning the official tourism statistics include not only holidaymakers but also the large and growing area of air travel generally. In Australia prior to the bushfires, "Air, water and other transport" was the main component of tourism travel, responsible for expenditure of $23.278 billion (compared to just $1.090 billion for rail transport, $1.252 billion for taxi transport, $1.854 billion for other road transport and $1.839 for motor vehicle hiring (Austrade & Tourism Research Australia, 2019).

With bushfires/wildfires increasing compared to other natural hazards (Handmer et al., 2018) and natural hazards generally projected to intensify under climate change (IPCC, 2022), it is important for countries such as Australia to quantify the economic impact of disasters as part of routine practice, that take account of supply-chain spillovers. As our research demonstrates, by including the entire supply chain, using IO analysis, total output losses identified were a 61% increase on top of the direct damages.

Our highly disaggregated results enabled us to identify differences in impacts along supply chains, which was important because the impacts were unevenly distributed. For example, in addition to the key industries of transport, hospitality and cultural and recreational services, the education sector was significantly impacted. Therefore, universities and other providers could consider planning for potential cuts to expenditure on their services in the longer term if major shutdowns to tourism become more commonplace because of increasing natural hazards in particular regions or perceptions that Australia may be unsafe. As well, although we found that the hospitality industry was the most affected overall, with "Accommodation" experiencing the most job losses, followed by "Cafes, restaurants and take-away", in terms of consumption and income, the aviation-led "Air, water and other transport" sector suffered the most out of the 39 sectors that we studied, indicating that different approaches may be taken by the government depending on policy priorities, for example in terms of jobs or income. From a regional perspective, although the States that were declared bushfire catastrophes also instigated State inquiries to help guide responses, we found that some other regions suffered significant impacts compared to their pre-fire total output. As well, supply-chain spillovers rendered some smaller regions more vulnerable to shouldering the impacts from a per-capita perspective, and this was particularly the case for the remote NT, which has the smallest population. These disaggregated results may help decision-makers in investigating certain hotspots, not only for re-building post-fire but also in terms of preparing for the next disaster.

It is also worth considering the losses suffered by "Cultural and recreational services", largely because of extensive infrastructure destruction, and spillover impacts, in National Parks that are key drawcards for tourists, for example to the World Heritage Blue Mountains in Greater Sydney. From infrastructure damage and destruction before even accounting for supply-chain impacts, we identified $275 million in losses, although these direct damages were then depreciation for the purposes of our impact analysis (see online *Supplementary Information* SI 2.6 Summary of infrastructure damage). These infrastructure losses are borne by the State governments and their repair, which would be paid by public funding, is an investment in tourism in addition to nature-based recreation generally. However, similar damages in poorer countries could be much more difficult to rectify efficiently ahead of upcoming holiday seasons, particularly in developing nations with weak local municipalities. Therefore, natural hazards may increase economic inequalities, with the burden of climate adaptation and mitigation adding to the costs of governments already struggling under business-as-usual.

Although the losses from the tourism damage that we calculated only represented a small fraction of the nation's economic output, Australia's reputation as a pristine destination could become permanently damaged in the longer term under global warming, with fewer people travelling in Australia in our peak summer holiday season; similarly, people may start to avoid other countries and regions that are increasingly in the media for their wildfires and other natural hazards. The aviation-led transport sector, which suffered among the most losses, may expect a double-hit from future impacts of climate change, with carbon-intensive industries such as air travel set to become more expensive in the low-carbon transition, making a trip "down under" less attractive. Our findings have broader implications for other nature-based destinations particularly in the Asia Pacific, which is the most disaster-prone and populous region (United Nations Office for the Coordination of Humanitarian Affairs, 2017). Countries reliant on tourism and in particular remote nations, where aviation plays a major role, are advised not only proactively to adapt their economies to worsening climate-fuelled natural hazards but also to prepare for the impacts of the necessary global transition to a low-carbon world. On the other hand, aviation globally has been increasing because of growing affluence (Lenzen et al., 2018) and it is possible that in the near future this trend will continue.

This is the first IO analysis applied to Australia's 2019-20 bushfires, with a focus on the supply-chain impacts of the reduction in tourism expenditure. Future IO studies could calculate the impact of other megafire-affected areas such as forestry or estimate the economic impact of the fires overall, from this globally unprecedented event.

2.5. Conclusion

Our novel research into the losses from the tourism shutdown resulting from Australia's 2019-20 fires found that flowing on from direct impacts of $1.7 billion, indirect impacts along supply chains resulted in $2.8 billion in total output losses and $1.6 billion in reduced consumption. The short-term drop in consumption from the unprecedented bushfires, in terms of reduced tourism expenditure during the peak holiday season, also triggered a reduction in income of $809 million and the shedding of 7292 full-time-equivalent jobs nationwide. Hospitality and the emissions-intensive transport sector were the most impacted, the latter of which is one of Australia's top exports. In particular, the accommodation sector within hospitality stood out as suffering the most job losses.

By incorporating the entire supply chain, using IO analysis, we calculated significant spill-over costs, with total output losses being an increase of 61% on top of the direct damages identified. As well, invisible impacts of the fires were identified, such as in Tasmania, which did not suffer a direct loss in tourism but nonetheless lost 13 jobs overall, with its manufacturing sectors among the most impacted, because of tourism losses suffered in other parts of the country.

This sort of comprehensive supply-chain analysis is particularly important not only in Australia but also in other nations in the disaster-prone Asia Pacific, and other regions vulnerable to fires worldwide. In line with findings that fires are increasing disproportionately because of global warming, countries that rely on nature-based tourism are among those with the most to gain from climate-change mitigation but these countries must also prepare for the impacts to community-and-industry hotspots that will result from future fires**,** in an era that has been referred to as the Pyrocene.

2.6. References

Afionis, S., Sakai, M., Scott, K., Barrett, J., & Gouldson, A. (2017). Consumption-based carbon accounting: does it have a future? *WIREs Climate Change*, *8*(1), e438. https://doi.org/10.1002/wcc.438

Austrade. (2020). *Submission 127*. Lessons to be learned in relation to the Australian bushfire season 2019-20, Senate Finance and Public Administration References Committee, Canberra, ACT, Australia. https://www.aph.gov.au/DocumentStore.ashx?id=5cbb91b2-9635-4a97-a2af-7c2cff40898c&subId=684327

Austrade & Tourism Research Australia. (2019). *Appendix: State tourism satellite accounts, 2018–19* [Data set]. Retrieved from https://www.tra.gov.au/en/data-and-research.html.

Austrade & Tourism Research Australia. (2020). *Appendix: State Tourism Satellite Accounts 2019-20* [Data set]. Retrieved from https://www.tra.gov.au/en/data-and-research.html.

Australian Bureau of Statistics. (2009). *Australian National Accounts: Input-Output Tables (Product Details), 2009-10* (ABS 5215.0.55.001). https://www.abs.gov.au/AUSSTATS/abs@.nsf/Lookup/5215.0.55.001Main+Features12009-10?OpenDocument.

Australian Bureau of Statistics. (2011). *Australian Statistical Geography Standard (ASGS)* (1270.0.55.001; Volume 1). *Main Structure and Greater Capital City Statistical Areas, July 2011*. https://www.abs.gov.au/ausstats/abs@.nsf/Previousproducts/88F6A0EDEB8879C0CA257801000C64D9?opendocument.

Australian Bureau of Statistics. (2020). *National, state and territory population*. https://www.abs.gov.au/statistics/people/population/national-state-and-territory-population/mar-2020.

Australian Government Department of Agriculture, Water and the Environment. (2020). *Gondwana Rainforests of Australia: State of conservation update: April 2020*. https://www.dcceew.gov.au/sites/default/files/documents/gondwana-rainforests-state-conservation-update-april-2020.pdf

Australian Government Department of Agriculture, Water and the Environment. (2020). *Greater Blue Mountains Area State of Conservation update: April 2020*. https://www.dcceew.gov.au/sites/default/files/documents/greater-blue-mountains-area-state-conservation-update-april-2020.pdf

Australian Government Department of Industry, Science, Energy and Resources. (2020). *Estimating greenhouse gas emissions from bushfires in Australia's temperate forests: Focus on 2019-20 - Technical update*. https://www.dcceew.gov.au/sites/default/files/documents/estimating-greenhouse-gas-emissions-from-bushfires-in-australias-temperate-forests-focus-on-2019-20.pdf

Australian Government Department of the Environment and Energy. (2019). *Quarterly update of Australia's national greenhouse gas inventory: March 2019* (Incorporating emissions from the NEM up to June 2019; Australia's National Greenhouse Accounts). https://www.dcceew.gov.au/sites/default/files/documents/nggi-quarterly-update-mar-2019.pdf

BBC. (2020, January 2). Australia fires: New South Wales declares week-long emergency. *BBC News*. https://www.bbc.com/news/world-australia-50969088

Binna Burra. (2022, June 21). QLD Government will provide funding support to rebuild the historic Binna Burra Lodge [News]. https://www.binnaburralodge.com.au/news/qld-government-will-provide-funding-support-to-rebuild-the-historic-binna-burra-lodge/

Binskin, M., Bennett, A., & Macintosh, A. (2020). *Royal Commission into National Natural Disaster Arrangements: Report*. Commonwealth of Australia. https://oia.pmc.gov.au/sites/default/files/posts/2022/11/Royal%20Commission%20int

o%20National%20Natural%20Disaster%20Arrangements%20-%20Report%20%20%5Baccessible%5D.pdf
Bočkarjova, M., Steenge, A. E., & van der Veen, A. (2004). On direct estimation of initial damage in the case of a major catastrophe: derivation of the "basic equation". *Disaster Prevention and Management: An International Journal*, *13*(4), 330-336. https://doi.org/10.1108/09653560410556555
Boer, M. M., Resco De Dios, V., & Bradstock, R. A. (2020). Unprecedented burn area of Australian mega forest fires. *Nature Climate Change*, *10*(3), 171-172. https://doi.org/10.1038/s41558-020-0716-1
Boisvert, E. (2022, February 18). Southern Ocean Lodge rebuild on Kangaroo Island starts two years after devastating bushfire. *ABC*. https://www.abc.net.au/news/2022-02-18/southern-ocean-lodge-rebuild-on-kangaroo-island-starts/100842806#:~:text=The%20lodge%20was%20destroyed%20in,its%20replacement%2C%20worth%20%2450%20million
Bourke, L. (2020, January 4). 'Out of respect': Kylie Minogue Matesong Tourism Australia ad pulled amid bushfire coverage. *Sydney Morning Herald*. https://www.smh.com.au/world/europe/out-of-respect-kylie-minogue-matesong-tourism-australia-ad-pulled-amid-bushfire-coverage-20200103-p53opl.html
Canadell, J. G., Meyer, C. P., Cook, G. D., Dowdy, A., Briggs, P. R., Knauer, J., Pepler, A., & Haverd, V. (2021). Multi-decadal increase of forest burned area in Australia is linked to climate change. *Nature Communications*, *12*(1), 6921. https://doi.org/10.1038/s41467-021-27225-4
Dalton, J. (2022, February 11). Koalas declared endangered in Australia after devastating wildfires. *The Independent*. https://www.independent.co.uk/news/world/australasia/koalas-endangered-species-australia-extinction-b1998320.html
Department of Foreign Affairs and Trade. (2020). *Trade and investment at a glance 2020*. https://www.dfat.gov.au/sites/default/files/trade-investment-glance-2020.pdf
European Commission, International Monetary Fund, Organisation for Economic Co-operation and Development, United Nations, & World Bank. (2009). *System of National Accounts 2008*. https://unstats.un.org/unsd/nationalaccount/docs/sna2008.pdf
Faturay, F., Lenzen, M., & Nugraha, K. (2017). A new sub-national multi-region input–output database for Indonesia. *Economic Systems Research*, *29*(2), 234-251. https://doi.org/10.1080/09535314.2017.1304361
Faturay, F., Sun, Y.-Y., Dietzenbacher, E., Malik, A., Geschke, A., & Lenzen, M. (2020a). Using virtual laboratories for disaster analysis: A case study of Taiwan. *Economic Systems Research*, *32*(1), 58-83. https://doi.org/10.1080/09535314.2019.1617677
Faturay, F., Vunnava, V. S. G., Lenzen, M., & Singh, S. (2020b). Using a new USA multi-region input output (MRIO) model for assessing economic and energy impacts of wind energy expansion in USA. *Applied Energy*, *261*, 114141. https://doi.org/10.1016/j.apenergy.2019.114141
Foster, A. (2020, January 23). Canberra Airport reopens after fires forced shut down. *News.com.au*. https://www.news.com.au/travel/travel-updates/incidents/too-late-to-leave-bushfires-flare-up-as-temperatures-soar/news-story/6932587f0297dd9e23eacceb4014bd34
Galbusera, L., & Giannopoulos, G. (2018). On input-output economic models in disaster impact assessment. *International Journal of Disaster Risk Reduction*, *30*, 186-198. https://doi.org/https://doi.org/10.1016/j.ijdrr.2018.04.030
Gergis, J. (2018). *Sunburnt country: The history and future of climate change in Australia*. Melbourne University Press.

Handmer, J., Ladds, M., & Magee, L. (2018). Updating the costs of disasters in Australia. *Australian Journal of Emergency Management*, *33*(2), 41-46. http://classic.austlii.edu.au/au/journals/AUJlEmMgmt/2018/36.html

Hannam, P. (2016, November 8). The 10 Sydney regions most exposed to bushfire risk. *The Sydney Morning Herald*. https://www.smh.com.au/environment/the-10-sydney-regions-most-exposed-to-bushfire-risk-20161107-gsk08y.html

Indigo Shire Council. (2020, June 23). *EXHIBIT 10-027.001 - ISC.500.001.0001 - Indigo Shire Council response to NTG-HB3-601*. Royal Commission into National Natural Disaster Arrangements, Canberra, ACT, Australia.

IPCC. (2022). *Climate Change 2022: Impacts, adaptation and vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (Eds.)]. Cambridge and New York: Cambridge University Press https://doi.org/10.1017/9781009325844

Kangaroo Island Council. (2020). *Kangaroo Island Council Annual report 2019-20* https://www.kangarooisland.sa.gov.au/__data/assets/pdf_file/0018/802341/Kangaroo-Island-Council-Annual-Report-2019-20-FINAL-web-2.pdf

Koks, E. E., Carrera, L., Jonkeren, O., Aerts, J. C. J. H., Husby, T. G., Thissen, M., Standardi, G., & Mysiak, J. (2016). Regional disaster impact analysis: Comparing input–output and computable general equilibrium models. *Natural Hazards and Earth System Sciences*, *16*(8), 1911-1924. https://doi.org/10.5194/nhess-16-1911-2016

Lenzen, M., Moran, D., Kanemoto, K., & Geschke, A. (2013). Building Eora: A global multi-region input-output database at high country and sector resolution. *Economic Systems Research*, *25*(1), 20-49. https://doi.org/10.1080/09535314.2013.769938

Lenzen, M., Geschke, A., Wiedmann, T., Lane, J., Anderson, N., Baynes, T., Boland, J., Daniels, P., Dey, C., Fry, J., Hadjikakou, M., Kenway, S., Malik, A., Moran, D., Murray, J., Nettleton, S., Poruschi, L., Reynolds, C., Rowley, H., . . . West, J. (2014a). Compiling and using input–output frameworks through collaborative virtual laboratories. *Science of The Total Environment*, *485-486*, 241-251. https://doi.org/10.1016/j.scitotenv.2014.03.062

Lenzen, M., Moran, D. D., Geschke, A., & Kanemoto, K. (2014b). A NON-SIGN-PRESERVING RAS VARIANT. *Economic Systems Research*, *26*(2), 197-208. https://dx.doi.org/10.1080/09535314.2014.897933

Lenzen, M., Geschke, A., Abd Rahman, M. D., Xiao, Y., Fry, J., Reyes, R., Dietzenbacher, E., Inomata, S., Kanemoto, K., Los, B., Moran, D., Schulte In Den Bäumen, H., Tukker, A., Walmsley, T., Wiedmann, T., Wood, R., & Yamano, N. (2017a). The Global MRIO Lab – charting the world economy. *Economic Systems Research*, *29*(2), 158-186. https://doi.org/10.1080/09535314.2017.1301887

Lenzen, M., Geschke, A., Malik, A., Fry, J., Lane, J., Wiedmann, T., Kenway, S., Hoang, K., & Cadogan-Cowper, A. (2017b). New multi-regional input–output databases for Australia: Enabling timely and flexible regional analysis. *Economic Systems Research*, *29*(2), 275-295. https://doi.org/10.1080/09535314.2017.1315331

Lenzen, M., Ya-Yen, S., Faturay, F., Yuan-Peng, T., Geschke, A., & Malik, A. (2018). The carbon footprint of global tourism. *Nature Climate Change*, *8*(6), 522-528. https://doi.org/10.1038/s41558-018-0141-x

Lenzen, M., Malik, A., Kenway, S., Daniels, P., Ka Leung, L., & Geschke, A. (2019). Economic damage and spillovers from a tropical cyclone. *Natural Hazards and Earth System Sciences*, *19*(1), 137-151. http://dx.doi.org/10.5194/nhess-19-137-2019

Lenzen, M., Li, M., Malik, A., Pomponi, F., Sun, Y.-Y., Wiedmann, T., Faturay, F., Fry, J., Gallego, B., Geschke, A., Gómez-Paredes, J., Kanemoto, K., Kenway, S., Nansai, K., Prokopenko, M., Wakiyama, T., Wang, Y., & Yousefzadeh, M. (2020). Global socio-economic losses and

environmental gains from the Coronavirus pandemic. *PLOS ONE*, *15*(7), e0235654. https://doi.org/10.1371/journal.pone.0235654

Lenzen, M., Geschke, A., West, J., Fry, J., Malik, A., Giljum, S., Milà I Canals, L., Piñero, P., Lutter, S., Wiedmann, T., Li, M., Sevenster, M., Potočnik, J., Teixeira, I., Van Voore, M., Nansai, K., & Schandl, H. (2022). Implementing the material footprint to measure progress towards Sustainable Development Goals 8 and 12. *Nature Sustainability*, *5*(2), 157-166. https://doi.org/10.1038/s41893-021-00811-6

Leontief, W. (1936). Quantitative input and output relations in the economic systems of the United States. *The Review of Economics and Statistics*, *18*(3), 105-125. https://doi.org/10.2307/1927837

Leontief, W. (1966). *Input-Output Economics*. Oxford University Press. http://ebookcentral.proquest.com/lib/usyd/detail.action?docID=4701165

Li, J., Crawford-Brown, D., Syddall, M., & Guan, D. (2013). Modeling imbalanced economic recovery following a natural disaster using input-output analysis. *Risk Analysis*, *33*(10), 1908-1923. https://doi.org/10.1111/risa.12040

Li, M., Lenzen, M., Pedauga, L. E., & Malik, A. (2022). A minimum-disruption approach to input-output disaster analysis. *Spatial Economic Analysis*, 1-25. https://doi.org/10.1080/17421772.2022.2056231

Malik, A., McBain, D., Wiedmann, T. O., Lenzen, M., & Murray, J. (2019). Advancements in Input-Output Models and Indicators for Consumption-Based Accounting. *Journal of Industrial Ecology*, *23*(2), 300-312. https://doi.org/10.1111/jiec.12771

Malik, A., Li, M., Lenzen, M., Fry, J., Liyanapathirana, N., Beyer, K., Boylan, S., Lee, A., Raubenheimer, D., Geschke, A., & Prokopenko, M. (2022). Impacts of climate change and extreme weather on food supply chains cascade across sectors and regions in Australia. *Nature Food*, *3*(8), 631-643. https://doi.org/10.1038/s43016-022-00570-3

McDonald, P. (2020, July 26). *Anatomy of a mega-fire: Black Summer* [Television broadcast]. ABC. https://www.youtube.com/watch?v=SlGmatigAy4

McIlwain, K. (2020, February 6). 'We're sorry': Plea for South Coast tourists to return after mass evacuation. *Canberra Times*. https://www.canberratimes.com.au/story/6618649/were-sorry-plea-for-south-coast-tourists-to-return-after-mass-evacuation/

Murphy, H., & van Leeuwen, S. (2021). *Australia state of the environment 2021: Biodiversity* [independent report to the Australian Government Minister for the Environment]. https://doi.org/10.26194/ren9-3639

Norman, B., Newman, P., & Steffen, W. (2021). Apocalypse now: Australian bushfires and the future of urban settlements. *npj Urban Sustainability*, *1*(2). https://doi.org/10.1038/s42949-020-00013-7

Okuyama, Y. (2007). Economic Modeling for Disaster Impact Analysis: Past, present, and future. *Economic Systems Research*, *19*(2), 115-124. https://doi.org/10.1080/09535310701328435

Okuyama, Y., & Santos, J. R. (2014). Disaster impact and input-output analysis *Economic Systems Research*, *26*(1), 1-12. https://doi.org/10.1080/09535314.2013.871505

Oosterhaven, J. (2017). On the limited usability of the inoperability IO model. *Economic Systems Research*, *29*(3), 452-461. https://doi.org/10.1080/09535314.2017.1301395

Oosterhaven, J. (2022). Negative IO Supply Shock Analyses: When Substitution Matters. In J. Oosterhaven (Ed.), *Rethinking Input-Output Analysis: A Spatial Perspective* (pp. 105-121). Springer International Publishing. https://doi.org/10.1007/978-3-031-05087-9_8

Queensland Government. (2020, August 31). *Binna Burra Road reopening marks key recovery milestone* [Press release]. https://statements.qld.gov.au/statements/90603

Rannard, G. (2020, January 8). Australia fires: Misleading maps and pictures go viral. *BBC*. https://www.bbc.com/news/blogs-trending-51020564

Richardson, H. W. (1985). Input-output and economic base multipliers: Looking backward and forward. *Journal of Regional Science*, *25*(4), 607-661. https://doi.org/10.1111/j.1467-9787.1985.tb00325.x

Rodriguez, A. (2020, January 15). Dark smoke from Australia fires is circling the Earth, NASA says. *USA Today*. https://www.usatoday.com/story/news/world/2020/01/15/australia-fires-google-earth-nasa-tracks-smoke-around-world/4476126002/

Rose, A. (1995). Input-output economics and computable general equilibrium models. *Structural Change and Economic Dynamics*, *6*(3), 295-304. https://doi.org/10.1016/0954-349X(95)00018-I

Rose, A. (2004). Economic Principles, Issues, and Research Priorities in Hazard Loss Estimation. In (pp. 13-36). Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-540-24787-6_2

Schulte in den Bäumen, H., Moran, D., Lenzen, M., Cairns, I., & Steenge, A. (2014). How severe space weather can disrupt global supply chains. *Natural Hazards and Earth System Sciences*, *14*(10), 2749-2759. https://doi.org/10.5194/nhess-14-2749-2014

Schulte in den Bäumen, H., Többen, J., & Lenzen, M. (2015). Labour forced impacts and production losses due to the 2013 flood in Germany. *Journal of Hydrology*, *527*, 142-150. https://doi.org/10.1016/j.jhydrol.2015.04.030

Steenge, A. E., & Bočkarjova, M. (2007). Thinking about Imbalances in Post-catastrophe Economies: An Input–Output based Proposition. *Economic Systems Research*, *19*(2), 205-223. https://doi.org/10.1080/09535310701330308

Swiss Re. (2021). *Natural catastrophes in 2020: Secondary perils in the spotlight, but don't forget primary-peril risks*. https://www.swissre.com/dam/jcr:ebd39a3b-dc55-4b34-9246-6dd8e5715c8b/sigma-1-2021-en.pdf

The Nobel Prize. (1973, October 18, 1973). *The prize in Economic Sciences in memory of Alfred Nobel to the father of input-output analysis* [Press release]. https://www.nobelprize.org/prizes/economic-sciences/1973/press-release/

Tourism Australia. (n.d.). The economic importance of tourism. Retrieved August 25, 2023, from https://www.tourism.australia.com/en/insights/tourism-statistics/the-economic-importance-of-tourism.html#:~:text=In%20the%20financial%20year%202018,per%20cent%20of%20Australia's%20workforce

Tourism Australia. (2020). *Submission 28*. Lessons to be learned in relation to the Australian bushfire season 2019-20, Senate Finance and Public Administration References Committee, Canberra, ACT, Australia. https://www.aph.gov.au/DocumentStore.ashx?id=f1225b83-21dd-48ac-832d-b49c5204a74b&subId=680468

Tourism Research Australia. (2020a). *International visitors in Australia: Year ending March 2020* [Summary]. Retrieved from https://www.tra.gov.au/

Tourism Research Australia. (2020b). *Travel by Australians: Year ending March 2020* [Summary]. Retrieved from https://www.tra.gov.au/

Tukker, A., & Dietzenbacher, E. (2013). Global multiregional input–output frameworks: An introduction and outlook. *Economic Systems Research*, *25*(1), 1-19. https://doi.org/10.1080/09535314.2012.761179

United Nations Office for the Coordination of Humanitarian Affairs. (2017). *Disaster response in Asia and the Pacific: A guide to international tools and services*. https://asiadisasterguide.unocha.org/images/download/ROAP_DisasterGuide.pdf

United Nations Statistics Division. (1999). *Handbook of input-output table compilation and analysis*. https://digitallibrary.un.org/record/370160?ln=en

van der Velde, I. R., van der Werf, G. R., Houweling, S., Maasakkers, J. D., Borsdorff, T., Landgraf, J., Tol, P., van Kempen, T. A., van Hees, R., Hoogeveen, R., Veefkind, J. P., & Aben, I.

(2021). Vast CO2 release from Australian fires in 2019–2020 constrained by satellite. *Nature*, *597*(7876), 366-369. https://doi.org/10.1038/s41586-021-03712-y

van Eeden, L., Nimmo, D., Mahony, M., Herman, K., Ehmke, G., Driessen, J., O'Connor, J., Bino, G., Taylor, M., & Dickman, C. (2020). *Impacts of the unprecedented 2019-20 bushfires on Australian animals*. Report prepared for WWF-Australia. https://www.wwf.nl/globalassets/pdf/wwf-impacts-of-the-unprecedented-2019-2020-bushfires-on-australian-animals.pdf

Van Oldenborgh, G. J., Krikken, F., Lewis, S., Leach, N. J., Lehner, F., Saunders, K. R., Van Weele, M., Haustein, K., Li, S., Wallom, D., Sparrow, S., Arrighi, J., Singh, R. K., Van Aalst, M. K., Philip, S. Y., Vautard, R., & Otto, F. E. L. (2021). Attribution of the Australian bushfire risk to anthropogenic climate change. *Natural Hazards and Earth System Sciences*, *21*(3), 941-960. https://doi.org/10.5194/nhess-21-941-2021

Wakiyama, T., Lenzen, M., Geschke, A., Bamba, R., & Nansai, K. (2020). A flexible multiregional input–output database for city-level sustainability footprint analysis in Japan. *Resources, Conservation and Recycling*, *154*, 104588. https://doi.org/10.1016/j.resconrec.2019.104588

Wang, Y. (2017). An industrial ecology virtual framework for policy making in China. *Economic Systems Research*, *29*(2), 252-274. https://doi.org/10.1080/09535314.2017.1313199

Wiedmann, T. (2009). Editorial: Carbon footprint and input-output analysis – An introduction. *Economic Systems Research*, *21*(3), 175-186. https://doi.org/10.1080/09535310903541256

Zhou, L., & Chen, Z. (2021). Are CGE models reliable for disaster impact analyses? *Economic Systems Research*, *33*(1), 20-46. https://doi.org/10.1080/09535314.2020.1780566

2.7. *Supplementary Information* (SI) highlights

The *Supplementary Information* (linked to from the main paper online as "Online Resource 1") is available at: https://static-content.springer.com/esm/art%3A10.1007%2Fs41885-024-00142-8/MediaObjects/41885_2024_142_MOESM1_ESM.pdf

Some highlights are below.

2.7.1. Summary of Impact information

Aspect	Region	Sectors	Example impact	Reference
Tourism	-	Multiple	• TRA survey data showed that over the March quarter internationally, 4% made changes to their travel itinerary/destinations visited because of the bushfires (a total of 14% reported their trip was impacted in some way by the bushfires, including shortening their trip). • For Australian residents, 13% were impacted in some way, with 41% of those cancelling their trips or going overseas instead.	(Personal communication, June 10, 2022) (Personal communication, June 14, 2022)

2.7.2. Summary of infrastructure damage

Aspect	Regions most impacted	Sectors	Major infrastructure (buildings, roads, transport) impacts	Reference
Parks-based recreation	NSW - Northern, Southern, South West National Parks Statewide	Cultural and recreational services	• Crown Lands: Tracks impacted - Six Foot Track, Great North Walk, Hume and Hovell Track; Zig-Zag Railway near Lithgow severely impacted, with destruction to heritage railway lines, buildings and trains • National Parks: 230 visitor precincts impacted, with a range of destroyed assets (including toilets, shelters, BBQs) Estimated AU$203.11 million	(Infrastructure NSW, 2020)
Cultural artefacts	NSW - Northern, Southern, South West	Cultural and recreational services	• 24 Aboriginal Land Council and Aboriginal Communities sites impacted Pending cost assessment at time of report	(Infrastructure NSW, 2020)
Other recreation	NSW – Snowy Valleys	Accommodation	• Selwyn Snow Resort destroyed Cost unknown	Multiple reports
Parks-based recreation	VIC - Unspecified/ Statewide	Cultural and recreational services	• Damage to buildings and infrastructure owned by Parks Victoria At least $30 million	(Bushfire Recovery Victoria, 2020), p. 10)

Parks-based recreation	SA - Kangaroo Island	Cultural and recreational services	• 98% of Flinders Chase National Park and Kelly Hill Conservation Park lost Infrastructure damage: $41 million	(State Disaster Recovery, 2020, p. iii)
Holidays/hiking	SA - Kangaroo Island	Accommodation	• Rebuild of Southern Ocean Lodge $50 million	(Boisvert, 2022, para. 4)
Holidays/hiking	QLD – Scenic Rim/Lamington National Park/Southern QLD	Accommodation	• In UNESCO-listed Gondwana rainforest near Brisbane, the historic Binna Burra Lodge and cabins were destroyed) $18 million from the State Government to help rebuild the Lodge	(Queensland Treasury, 2022, p. 11)
Parks-based recreation	QLD – Scenic Rim/Lamington National Park	Cultural and recreational services	• 35km of walking tracks damaged $1million grant for remediation works to re-open the tracks	(Queensland Reconstruction Authority, 2020, p. 14) (Queensland Government, 2020, para. 15)
Roads	QLD – Scenic Rim/Lamington National Park	Other road transport	• The cliff-side Binna Burra Road was reconstructed over almost one year $35 million project estimate	(Huxley, 2020) (Binna Burra, 2022)

2.7.3. Calculations for the gamma matrix ($\boldsymbol{\gamma}$)

Tourism losses attributed to the bushfires occurred in the January-March 2020 quarter but this period also coincided with COVID-19, when Australia started closing its international borders to select countries, culminating in a comprehensive shutdown on 20 March (Commonwealth of Australia, 2021). Calculations had to be made about losses attributed to the fires as well as to regions and sectors, from the International Visitor Survey (IVS) and National Visitor Survey (NVS) information, for the event "gamma" ($\boldsymbol{\gamma}$) matrix.

2.7.3.1. Aggregate losses in international and domestic tourism expenditure

Percentage losses for the quarter were derived from Tourism Research Australia's "Bush fires March quarter 2020" surveys, which TRA provided on request for the National Visitor Survey (NVS) (personal communication, June 14, 2022) and International Visitor Survey (IVS) (personal communication, June 10, 2022). Only data for this quarter was used because, although significant fires began in September 2019 in Queensland, tourism spend through to December 2019 by Australians continued to increase (Tourism Research Australia, 2020b) and for international visitors, spend also increased in Queensland (Tourism Research Australia, 2020a).

The bushfire questions in the survey took place from 21 January-15 March and respondents were asked about changes already realised (i.e., from Christmas 2019) and until the end of 2020 in terms of future trips planned for 2020. To avoid value judgements about how behaviour may

have changed after the borders closed to all countries because of COVID-19, no adjustment was made to the Tourism Research Australia survey findings from a particular date. However, for NVS, only figures were used for trips entirely cancelled, not trips cut short, because of a lack of data about the length of shortened trips. For IVS, "changes to travel itinerary/destinations visited" was used as the proxy inbound tourism expenditure losses rather cancellations because IVS data is gathered from international visitors at airports when they exit Australia, meaning that IVS is unable to capture international visitors who have cancelled their trip to Australia because of the bushfires (since these visitors will not show up at airports in Australia, they therefore cannot be included in the IVS).

NOTE: Tourism Research Australia provided not only expenditure on overnight stays but also for day-trips for this study, so these figures will vary from the published NVS and IVS figures that include overnight trips only.

2.7.3.2. Sectoral and regional calculations

To disaggregate the tourism losses into sectors, categories were brought across from Australia's State Tourism Satellite Accounts (TSA), with minor modifications in terms of aggregation/disaggregation of some sectors. The bushfire tourism losses for the NVS and IVS were calculated separately and then added together for each region before being apportioned to the sectors for each region. Detail about the various calculations from the NVS, IVS and TSA data are below.

2.7.3.2.1. Domestic tourists—NVS

Of the 13% impacted by the fires in the March quarter, ~41% of these cancelled their Australian trips or went overseas and we only include 75% of those surveyed, who said those losses were already realised, in order to calculate the losses for the March quarter (and after this time, most tourism losses would be because of the COVID-19 lockdown); the total change in spend by Australians for the quarter attributed to the fires is therefore 4% (.13*.75*.41). This loss percentage is applied to the summation of totals for 2019 domestic overnight and day trips of $26.029 billion, from NSW data provided by TRA (personal communication, August 31, 2022), amounting to $1.043 billion loss from the fires in domestic tourism. This loss was then allocated between the regions according to each region's proportionate representation of the total NVS quarterly losses.

NOTE: the survey in early 2020 included trips cancelled before the survey because of the bushfires ("i.e. since Christmas"), meaning a small proportion of these losses would have been carried across from the previous calendar year. However, we believe our calculations are

conservative because we did not include losses that the survey asked would be realised "Between now and end of 2020", nor trips that were "cut short" because of the fires.

2.7.3.2.2. International tourism

The 4.1% loss, using as a proxy changes to itineraries/destinations visited because of the fires, is applied to the March 2019 quarter expenditure provided by TRA (personal communication, August 31, 2022), of $14.5 billion. This amounted to $.587 billion international tourism losses from the bushfires in the March 2020 quarter, which was then allocated between the regions according to each region's proportionate representation of the total IVS quarterly losses.

2.7.3.2.3. Expenditure unallocated to any regions

"Unallocated" expenditure comprised a minor amount for NVS in 2019 of $0.087 million, and a significant change for IVS of $3082m-$4083m = $1001.1 million. These were apportioned across the regions by first obtaining the proportionate contribution of each region for NVS and IVS (excluding "Unallocated"), then adding the unallocated amounts according to the region's contribution generally and calculating the proportions again, inclusive of "Unallocated".

2.7.3.2.4. Tourism sectors

To assign State/Territory tourism losses totalling $1.630 billion for IVS+NVS to sectors, category representation in the State Tourism Satellite Accounts is generally mirrored (Austrade & Tourism Research Australia, 2020). Some sector aggregation and disaggregation had to be performed; the TSA's cultural, amusement, sporting and other recreation sectors were amalgamated into this study's "Cultural and recreational services" category, while "All other industries", which is not tourism-specific, was excluded as a separate category, with tourism sector expenditure adjusted accordingly to ensure the total remained the same. Each region's proportionate contribution of each sector was calculated. The tourism-connected industry "Automotive fuel retailing" was split into the study categories of [retail/wholesale] "Trade" and "Automotive petrol" in the proportions 14:86 according to the input-output tables (Australian Bureau of Statistics, 2022) Table 4 proportions of final uses for Petroleum and coal product manufacturing (row 39) for "margin" and "purchaser's prices" (columns AK and AL respectively).

NOTE: The proportionate representation of the year prior to the fires, 2018-19 was used to calculate the sectoral proportionate representation (Austrade & Tourism Research Australia, 2019), since the 2019-20 TSA data are likely to have been significantly impacted by the COVID-19 pandemic expenditure patterns, in particular from the time Australia comprehensively closed its borders to international travel on 20 March 2020. The 2019-20 tourism losses are then adjusted, based on the 2018-19 sector ratios.

2.7.3.2.5. Infrastructure losses

Only damage to infrastructure that could be considered a tourism asset was included. For example, Parks infrastructure within National Parks as well as accommodation was included, as was the Binna Burra Road leading to Binna Burra Lodge, which needed to be reconstructed, within Queensland's Lamington National Park. This decision was based on the definition of tourism: "Tourism comprises the activities of persons travelling to and staying in places outside their usual environment for not more than one consecutive year for leisure, business and other purposes" (Australian Bureau of Statistics, 1999, para. 3). However, the extensive damage to NSW and Victorian roads and rail was excluded; for example, the Blue Mountains rail line, where fires burnt approximately 82% of the World Heritage park. The reasoning behind this is that these assets would be used in large part by people for day-to-day activities unrelated to tourism.

Depreciation of the productive portion was applied in the same manner as outlined by Lenzen et al. (2019, p. 141) and utilised by Faturay et al. (2020, p. 69). Put simply, the approach to construct the capital damages gamma ($\boldsymbol{\gamma}$) for infrastructure losses as a proportion of pre-fire productive capital is:

1. Annualise the loss, e.g., divide the loss figure by 25.
2. Calculate the ratio $\mathbf{g}$, as mentioned in Faturay et al. for the industrial output of a sector enabled by the input of fixed capital, which is: total output ($\mathbf{x}$) for a sector divided by the gross operating surplus for the sector.
3. Multiply the answers from (1) and (2).
4. Divide the answer in (3) by the total output ($\mathbf{x}$).

This capital damages event matrix is added to the direct losses gamma, so that the final event matrix includes both "direct" and "capital damages" components.

2.7.4. *SI* References

Austrade & Tourism Research Australia. (2019). *Appendix: State tourism satellite accounts, 2018–19* [Data set]. Retrieved from https://www.tra.gov.au/en/data-and-research.html.

Austrade & Tourism Research Australia. (2020). *Appendix: State Tourism Satellite Accounts 2019-20* [Data set]. Retrieved from https://www.tra.gov.au/en/data-and-research.html.

Australian Bureau of Statistics. (1999). *Framework for Australian Tourism Statistics, 1999* (ABS 9502.0.55.001). https://www.abs.gov.au/ausstats/abs@.nsf/Previousproducts/5AA223EA8A78A311CA25697E0018FBFF?opendocument

Australian Bureau of Statistics. (2022). *Input-Output Tables, 2018-19* (5209.0.55.001) [Data set]. Australian National Accounts https://www.abs.gov.au/statistics/economy/national-accounts/australian-national-accounts-input-output-tables/2018-19/5209055001DO001_201819.xls

Binna Burra. (2022, June 21). QLD Government will provide funding support to rebuild the historic Binna Burra Lodge [News]. https://www.binnaburralodge.com.au/news/qld-government-will-provide-funding-support-to-rebuild-the-historic-binna-burra-lodge/

Boisvert, E. (2022, February 18). Southern Ocean Lodge rebuild on Kangaroo Island starts two years after devastating bushfire. *ABC*. https://www.abc.net.au/news/2022-02-18/southern-ocean-lodge-rebuild-on-kangaroo-island-starts/100842806#:~:text=The%20lodge%20was%20destroyed%20in,its%20replacement%2C%20worth%20%2450%20million

Bushfire Recovery Victoria. (2020). *Eastern Victorian fires 2019–20 State Recovery Plan* (PDF/online: ISBN 978-1-922262-34-9). State of Victoria. https://www.vic.gov.au/sites/default/files/2021-04/BRV_Statewide%20Recovery%20Plan.pdf

Faturay, F., Sun, Y.-Y., Dietzenbacher, E., Malik, A., Geschke, A., & Lenzen, M. (2020). Using virtual laboratories for disaster analysis: A case study of Taiwan. *Economic Systems Research*, *32*(1), 58-83. https://doi.org/10.1080/09535314.2019.1617677

Huxley, J. (2020, June 17). Binna Burra cliffside road rebuilt after bushfire an 'engineering feat'. *ABC*. https://www.abc.net.au/news/2020-06-17/binna-burra-road-reconstruction-a-feat-of-engineering/12357354

Infrastructure NSW. (2020, July 9). *Summary of impacted NSW assets* [Exhibit]. Royal Commission into National Natural Disaster Arrangements, Canberra, ACT, Australia.

Lenzen, M., Malik, A., Kenway, S., Daniels, P., Ka Leung, L., & Geschke, A. (2019). Economic damage and spillovers from a tropical cyclone. *Natural Hazards and Earth System Sciences*, *19*(1), 137-151. https://doi.org/http://dx.doi.org/10.5194/nhess-19-137-2019

Queensland Government. (2020, August 31). *Binna Burra Road reopening marks key recovery milestone* [Press release]. https://statements.qld.gov.au/statements/90603

Queensland Reconstruction Authority. (2020). *2019 Queensland bushfires: State Recovery Plan 2019-2022* (QRATF/20/4207; ISSN 978-0-9873118-4-9). https://www.qra.qld.gov.au/sites/default/files/2020-08/2019_qld_bushfires_recplan_2019-20_lr.pdf

Queensland Treasury. (2022). *BUDGET SPEECH: BUDGET PAPER NO. 1* [Queensland Budget]. https://s3.treasury.qld.gov.au/files/Budget_2022-23_Speech.pdf

State Disaster Recovery. (2020). *2019-20 South Australian bushfire recovery: Interim report*. Department of Premier and Cabinet, Government of South Australia. https://www.recovery.sa.gov.au/Past-Events/what-happened/2019-20-SA-Bushfire-Recovery-Interim-Report-Web.pdf

Tourism Research Australia. (2020a). *International visitors in Australia: Year ending March 2020* [Summary]. Retrieved from https://www.tra.gov.au/

Tourism Research Australia. (2020b). *Travel by Australians: Year ending March 2020 [Summary]*. Retrieved from https://www.tra.gov.au/

3. MODERN-SLAVERY SUPPLY-CHAIN ANALYSIS

Reiner, V., Malik, A., & Murray, J. (2025). Can global modern slavery be footprinted for corporate due diligence? A data analysis and review. *Journal of Industrial Ecology,* 29, 1077–1089. https://doi.org/10.1111/jiec.70037

Paper: Can modern slavery be footprinted for corporate due diligence? A data analysis and review

Abstract

Modern-slavery laws are increasingly being adopted by countries, requiring companies to demonstrate human rights due diligence. Attempts at quantifying modern slavery across the world have played a crucial role in awareness raising, and locally rich data has been used to provide insights into supply chains for specific sectors and regions but is there a tool that businesses can use wherever they are? We investigate the possibility of developing a universal, global modern-slavery satellite account for footprinting and as a first step, carry out a comprehensive review of global modern slavery data, estimates, and potential proxies. In addition to data on confirmed cases being unrepresentative of the likely population, estimates risk high sampling errors and low reproducibility. We also analyse data that might be used as "slavery-like" indicators, however none could be recommended. Such attempts at footprinting modern-day slavery are fraught because the identified supply-chain hotspots resulting from direct expenditure are based on these modern-slavery datasets that are not fit for such a purpose. Modern-slavey footprints may be misleading because the complexities and limitations of the data are not well-represented in a simple indicator, the underlying data is highly uncertain and the results simply tend to reflect poverty. Although our research highlights that there is no simple way to produce reliable estimates of global modern slavery in supply chains, continued work to build up modern-slavery data worldwide should support critical, hybrid IO-LCA studies, adding to the web of information globally to support ethical decision-making.

3.1. Introduction

Regulatory responses to address modern slavery are currently being adopted in many parts of the world. Due diligence requires businesses to consider their supply chain and what remedying action may be possible to address potential risks of illicit, modern slavery. This can be particularly complex where global supply chains are concerned, since global supply chains are inherently complex and obscured to downstream consumers. To aid responsible business practices and other reporting requirements, companies may seek technological solutions that purport to uncover modern slavery hotspots and thereby indicate where effort can be focused. However, such approaches may be fraught if the underlying data is of poor quality or is associated with high uncertainty.

In addition to *Modern Slavery Acts* and other legislation being introduced in several countries in the past few years, such as in the United Kingdom (2015) and Australia (2018), there has been growing impetus for mandatory integrated reporting including human rights (McGaughey et al., 2022). Key developments are the *Corporate Sustainability Due Diligence Directive* 2024, which

has implications for imports, and from a global perspective, the new International Sustainability Standards Board (ISSB) Standards, the first of which (IFRS S1) covers general sustainability disclosures (International Sustainability Standards Board, 2023).

A review of Australia's *Modern Slavery Act* (2018) noted that the majority of entities provided little information about their methods for identifying and responding to modern slavery risks beyond Tier 1 (direct) suppliers (Attorney-General's Department, 2022; Coward, 2021; Sinclair & Dinshaw, 2022, which accords with reports on UK's *Modern Slavery Act (*2015), suggesting that businesses struggle with responding to modern slavery in global supply chains (International Justice Mission, 2022; Lake et al., 2015).

International human rights law has been based on defining human rights indicators and then measuring how countries adhere to relevant legislation (Landman, 2004), but unlike environmental indicators that may be relatively straightforward to measure, quantifying such social phenomena has been the subject of academic debate (Barsh, 1993). These quantification issues can be seen to be particularly acute for modern slavery (Merry, 2016), which is not only difficult to detect but is an umbrella term that is not defined in international law (Davidson, 2015).

The question of whether modern slavery should be attempted to be measured at a global rather than local level has been contested by those favouring a more anthropological approach, while another school of thought favours quantitative attempts to identify, and then address, a known quantum. Yet even within the quantitative school it is widely acknowledged that there are substantial issues with the global data and estimates on modern slavery. This paper does not attempt to analyse in depth the qualitative vs quantitative theoretical debate but rather notes that in practice, modern-slavery data is already used for purposes beyond the stated intentions of the data owners, and there is only a small number of global datasets upon which estimates and footprints are based, as demonstrated in Table 1; we acknowledge the efforts that have gone into defining, and developing data on modern slavery including at the macroeconomic level, and also review the use of input-output (IO) analysis satellite development, in particular to quantify modern-slavery footprints in a tailored way for certain sectors and/or regions where high-resolution data exists. We then carry out a comprehensive analysis of global modern slavery data, estimates and potential proxies to see whether these are appropriate for universal global modern slavery IO analysis. Our data review is guided by conversations with globally, regionally and locally focused experts in trafficking as well as through consultation with modern slavery practitioners, whose information is then tested through the data analysis or literature

review; finally, we consider the research findings in terms of pragmatic steps for corporate due diligence.

3.2. A brief history of modern-slavery quantification

Much work has gone into the defining, identifying and quantifying modern slavery worldwide. The recognition that slavery continues to exist, albeit in different forms than the Transatlantic slave trade largely of Africans to America until the 19th Century, has underpinned efforts to address extreme and growing inequality. Although some countries have modern-slavery laws, "modern slavery" is not defined in international law and may include a range of exploitative practices; some legislative highlights and definitions are in Sections 1 and 2 of the online *Supplementary Information*. A rallying point of recent efforts has been the work of Bales, who has focused on highlighting the indecent practices that exist as part of the neoliberal global economic system, and attempting to quantify the scale of the problem. His highly cited number in 1999 of 27 million people in modern slavery was from a "systematic review of information" (Bales, 2017). Bales worked with the first Global Slavery Index (GSI), which increased the number to 29.8 million in 2013. Published by the foundation Walk Free (Davidson, 2015) established by Australian philanthropists, Nicola Forrest and mining magnate Andrew Forrest (Walk Free Foundation, 2013), the GSI estimate has increased a decade later to almost 50 million people living in modern slavery – which is defined as including forced labour and forced marriage by the more aggregated Global Estimates of Modern Slavery (International Labour Organization and Walk Free Foundation, 2017; International Labour Organization (ILO) et al., 2022) on which recent iterations of the GSI are based (Walk Free, 2023a). Citing global modern slavery data or estimates can be a powerful tool for advocacy (Gallagher, 2017), however, issues have been raised regarding the GSI methodology (Gallagher, 2017; Guth, 2014; Weitzer, 2014a); nonetheless, the GSI is frequently cited because it is highly disaggregated at the country level (Lavelle-Hill et al., 2021). Even officially reported cases of trafficking, which is defined in the UN Trafficking in Persons Protocol, are subject to substantial variation (Feingold, 2010, 2017); with numbers ranging from 115,324 victims in 2022 reported by the United States Trafficking in Persons (TIP) report (United States Department of State, 2023) to 450,000 victims detected between 2003-2021, as reported by the Global Report on Trafficking in Persons (GLOTIP), which is prepared by the UN (UNODC, 2023b). See Section 3.4.1.

A particular challenge is to identify modern slavery worldwide, however more straightforward is work at the micro-level, where locating vulnerabilities can be particularly effective (Weitzer,

2014b, 2015). Research into identifying and quantifying modern slavery has extended across a range of areas, as noted by Landman (2020). Examples range from focusing on regulation and liability (Campos et al., 2015; Nolan & Bott, 2018), specific sectors (Brown et al., 2021; Jackson & Decker Sparks, 2020) and countries (Phillips & Sakamoto, 2012), to local governance (LeBaron & Phillips, 2019) and globalisation (Phillips & Sakamoto, 2012), supply-chain management (Cole & Aitken, 2019; Gold et al., 2015; Hofmann et al., 2018; LeBaron, 2021; Stevenson & Cole, 2018; Stringer & Michailova, 2018) and use of satellite remote sensing (Boyd et al., 2021; Kougkoulos et al., 2021) and agent-based models (Chesney et al., 2019; Chesney et al., 2017); migration is well-studied as a risk (Latham-Sprinkle, 2019), which is growing because of climate change (Coelho et al., 2016; UNODC, 2022). Indecent employment is a common theme in the literature, and Bales and colleagues have noted the role of a sustainable development goal framework in moving beyond data challenges for holistic change (Decker Sparks et al., 2021).

Consumption-based accounting (CBA) has analysed this sub-set of labour and related issues in supply chains, in order to trace the impact of final demand to the resultant production in regions and sectors; for example, the application of industrial ecology to social footprinting was proposed (McBain, 2015; McBain & Alsamawi, 2014) and a social hotspots database developed (Norris et al., 2014), "embodied" labour/employment footprints were analysed (Alsamawi et al., 2014a; Simas et al., 2015), and a "bad labour" footprint conceptualized, with results highly aggregated because of data limitations (Simas et al., 2014), while other global studies, which used input-output (IO) analysis to incorporate the entire inter-industry supply chain, included inequality (Alsamawi et al., 2014b), occupational safety and health (Alsamawi et al., 2017), corruption (Xiao et al., 2018), and forced labour in the cotton industry, using data from the Global Estimates of Modern Slavery and population data for China and India (García-Alaminos et al., 2024). Shilling et al. (2021) constructed a global modern-slavery satellite that scaled GSI supply-chain slaves into sectors based on unskilled labour, the Global Estimates of Modern Slavery and the Social Hotspot Database forced labour risk weighting based on qualitative information (Benoit-Norris & Norris, 2015), demonstrating the applicability of IO, assuming such a composite can be relied upon.

In the next section, we discuss the IO methodology in the context of satellite development related to modern slavery, with reference to studies where rich data in particular sectors and regions has enabled tailored footprints with a high degree of resolution.

3.3. Input-output analysis and modern slavery

3.3.1. Input-output (IO) analysis and "footprint" development

Environmental supply-chain analysis is well-established, with analysis of impacts beyond scope 1 (direct) and scope 2 emissions (purchased or acquired electricity, steam, heat, and cooling) being an increasingly common requirement for companies and countries. The Greenhouse Gas Protocol (World Resources Institute & World Business Council for Sustainable Development, 2013) discusses how companies may select a system boundary, beyond which they do not quantify their impact (World Resources Institute & World Business Council for Sustainable Development, 2011), or they may use IO (World Resources Institute & World Business Council for Sustainable Development, 2013). Manually quantifying other (scope-3) emissions may introduce substantial truncation errors (Lenzen & Treloar, 2002) since the number of process inputs quickly increases and the accounting becomes onerous. In comparison, IO analysis allocates all known impacts to final demand and thus the footprints represent a more complete system boundary. Using IO, a global carbon footprint of nations was quantified years ago (Hertwich & Peters, 2009); IO has been applied to numerous environmental indicators, such as waste (Nakamura & Kondo, 2002), and air pollution (Kanemoto et al., 2014); in addition, to social indicators IO analysis has also been used to measure impacts against the sustainable development goals, including for the United Nations (Lenzen et al., 2022; Malik et al., 2024).

IO has attracted the recognition of a Nobel Memorial Prize for its creator Wassily Leontief and is the subject of a dedicated journal (Economic Systems Research), as well as numerous textbooks, e.g. (Dietzenbacher et al., 2020; Miller & Blair, 2009). For corporations, the IO techniques of structural path analysis (SPA) and production layer decomposition (PLD) can be particularly useful tools in variously indicating how far back in a supply chain one must look as well as which particular supply chains are most impactful (Huang et al., 2009). In this way, IO analysis can underpin human rights due diligence. By linking physical/satellite accounts to global, multi-region input-output (MRIO) databases, the calculated intensity per monetary unit of the indicator in question enables impacts to be tracked in association with business expenditure. The summation of impacts (direct plus indirect impacts upstream), or "footprint" is calculated as:

$$F = \mathbf{qLy} \quad (1)$$

where $\mathbf{q}$ is a vector of direct intensities, $\mathbf{L}$ is a multiplier incorporating all supply-chain interactions, and $\mathbf{y}$ is the final demand/consumption expenditure The Leontief inverse is calculated as:

$$\mathbf{L} = (\mathbf{I} - \mathbf{A})^{-1} \quad (2)$$

where $\mathbf{I}$ is the identity matrix and $\mathbf{A}$ the direct requirements matrix. Also referred to as the "technical coefficients" matrix, $\mathbf{A}$ contains the "production recipe" for each industry (the inputs required for each unit of output) and is calculated as $\mathbf{A} = \mathbf{T}\hat{\mathbf{x}}^{-1}$ where **T** is the inter-industry transaction matrix and **x** is a vector of total output. Similarly, the direct intensities ($\mathbf{q}$) are derived by dividing the indicator in question (**Q**) by the total output (**x**), where **Q** is a vector of impacts allocated to producing sectors**.**

Although IO sectors are based on averages, for impacts that may be sparsely distributed among firms, such as modern slavery, this assumption of sector homogeneity can become problematic. With more information, however, disaggregation is possible. For example, compilers of input-output tables (IOT) may create new sectors, such as renewable electricity as distinct from coal-fired electricity. In a similar manner, hybrid IO-life-cycle analysis studies enable the marrying of bottom-up information with IO databases to answer specific research questions. In the following, we point to some examples of tailored satellites that were developed for analysing slavery-like practices, where localized information supported useful supply-chain analysis.

3.3.2. IO satellites linked to modern slavery

The following are examples of IO studies that have utilized detailed information in specific areas, demonstrating the usefulness of hybrid IO, supported by bottom-up data on slavery-like practices. Examples are:

a. *Global supply chains of coltan* (Moran et al., 2015) associated purchases of coltan, which is used widely in electronic products, to funding of civil war in the Democratic Republic of Congo. Such analysis can also be useful because of the link between modern slavery and conflict minerals/mining widely noted, e.g.: (Bansal et al., 2023; Schleper et al., 2022; Sovacool, 2021). In the study, exports of columbite-tantalite ore, or coltan, out of the DRC were traced to produce an "initial estimate" of illicit flows of coltan footprint for various products.
b. *Who's afraid of Virginia Wu? US employment footprints and self-sufficiency* (Bohn et al., 2022) focuses on an area relevant to modern slavery, being foreign workers as an

integral part of affluent consumption. As part of the analysis, WIOD's Socio Economic Accounts (SEA) satellite data was used to provide employment by skill categories; the data includes estimates of informal workers.

c. *The labour footprint*: A framework to assess labour in a complex economy (Gómez-Paredes et al., 2015) – Includes a case study that incorporates an Indian government-conducted employment survey, with several indicators including forced labour estimated by considering cases of individuals in full-time work who reported zero earnings and no availability for alternate work. The research, which used Indian IO tables from the Eora MRIO database, estimate indicators for hidden indecent employment across the economy at a high degree of disaggregation. The authors recommended further research, in order to consider the practicalities of their conceived labour footprint demonstrated for India, at "different political levels and geographical regions".

In any of these cases (a-c) above, if the "satellite" of modern slavery is appropriate for a particular business, they could use the model to measure their own impact against this indicator. For example, in (c), a business could measure forced labour in Indian supply chains as a result of local purchases. Turning to the fundamental equation (1), here, $\mathbf{q}$ is a vector that includes the direct intensity of the indicator forced labour in India per sector, as estimated by Gómez-Paredes et al.(2015), the $\mathbf{L}$ matrix is Leontief's supply-chain multiplier (in this case, from the Eora MRIO database) and the stressor ($\mathbf{y}$) is the business's expenditure per sector in India (as opposed to India's total expenditure that was used by the researchers for the case study). In other words, by replacing the global stressor from the model ($\mathbf{y}$), in this case for India, with their own expenditure ($\mathbf{y}$) as the input, businesses could obtain their forced-labour impact throughout India. Of course, to use the satellites, businesses would need to harmonise their supplier-level data with the IO tables that are at the sector level, in the same way as is done with other satellites such as greenhouse gas emissions. Modern slavery, however, poses a particular challenge, in that it is highly heterogeneous, which can lead to aggregation errors when using the broad-sector averages in IO.

Although compiling satellites with detailed information, where possible, can help address this heterogeneity issue, it is particularly resource-intensive to collect data on modern slavery, and such investigations could also involve safety risks that require active management.

Regardless of the challenges of crucial data collection, the question arises, can forced labour or similar indicators be relied on at the global level? Our review of global modern-slavery data,

estimates and proxies was undertaken as a first step in the development of a potential universal, global satellite account.

3.4. Results

Table 1 presents key findings from our review of global data, estimates and potential proxies. From a regional perspective, the Global Slavery Index was carefully analysed because of the disaggregation of its estimates across numerous countries. Regarding proxies, the hazardous child labour database of the International Labour Organization (ILO) was considered because of its similarity with the worst forms of child labour; we alternatively considered low-skilled employment, as a reliable and disaggregated dataset in terms of vulnerability generally. In addition to the key databases and estimates of modern slavery listed in Table 1, the full list of proxies reviewed is in the online *Supplementary Information*.

In Section 3.4.1 we analyse key trafficking data and to what extent identified trafficking cases can be correlated with modern-slavery prevalence. As Table 1 shows, trafficking data from the Counter Trafficking Data Collaborative (CTDC), as well as modern-slavery estimates from the Global Estimates of Modern Slavery, are relied on by the Global Slavery Index in producing the most disaggregated estimate of modern slavery globally.

Name	Lead investigator(s)	Sources	Counts	Distribution	Information from the data provider
Global Report on Trafficking in Persons (GLOTIP)	United Nations Office on Drugs and Crime	Reports by UN Member States	Trafficking victims, identified according to national legislation and policy	141 regions	Its figures should not be considered representative of prevalence in a given territory
Counter Trafficking Data Collaborative (CTDC)	International Organization for Migration initiative	IOM, Recollectiv, Polaris, A21 and OTSH	Trafficking victims, identified or assisted by the contributing organizations	189 regions and 7 forced-labour and sex-trafficking types of work	It is challenging to infer to what extent trends within identified victim populations are representative of the total victim population
Global Estimates of Modern Slavery	International Labour Organization (ILO), Walk Free and International Organization for Migration (IOM)	Household surveys National survey data on forced labour; CTDC	Forced labour Forced marriage Modern slavery (forced labour + forced marriage)	5 broad regions and 7 types of work, including illicit activities	No national surveys were available for North America, so it was assimilated with the northern, southern and western Europe region There were too few cases reported in forced-marriage surveys, so a different methodology from that used for forced labour was applied
Global Slavery Index (GSI)	Walk Free	Prevalence: Global Estimates of Modern Slavery Vulnerability model for national estimates: 23 risk variables developed with input from an Expert Working Group	Modern slavery	160 regions and top goods imported by G20 countries	The sample of countries omits some of the most populous, namely China, India and Pakistan Modern slavery lacks a unifying causal theory that can be used to inform variable selection.

Table 1: Key modern slavery databases or estimates

3.4.1. Trafficking data

Trafficking has become an area of government focus (Chuang, 2014) but whether trafficking has increased is difficult to determine. Additionally, although trafficking of victims for sex tends to grab public attention, trafficking of people for non-sex labour is likely to be a bigger problem than sex trafficking (Feingold, 2009, "Most victims are trafficked into the sex industry"; Merry, 2016, p. 115, p. 115). Further details about the United States' *Trafficking Victims Protection Act* 2000 (TVPA) and the international Protocol to Prevent, Suppress and Punish Trafficking in Persons Especially Women and Children, supplementing the United Nations Convention against Transnational Organized Crime (2000), mentioned below, are in online *Supplementary Information*.

3.4.1.1. Counter Trafficking Data Collaborative (CTDC)

The CTDC's data of more than 156,000 trafficking victims or survivors across 189 countries and territories (Counter-Trafficking Data Collaborative, n.d.-a) with a timeseries of 2002-2021 is disaggregated into a total of seven forced-labour and sex-trafficking sectors, including one "Other" sector. Five data contributors are listed: IOM (UN Migration), Recollectiv (formerly Liberty Shared), Polaris, A21 and OTSH the Portuguese Observatory on Trafficking in Human Beings.

The CTDC says that testimony from survivors provide one of the best and only sources of information about trafficking and an opportunity for analysis on the profile and form of trafficking; however, it is challenging to infer to what extent trends identified in victim populations are representative of trafficking because trafficking is intended to be undetected and case data are not random samples of the population (Counter-Trafficking Data Collaborative, n.d.-a). Viewing the online dashboard of victims in the Global Synthetic Dataset (Counter-Trafficking Data Collaborative, n.d.-b) in January 2024 revealed a highly uneven distribution; this includes for the country of exploitation: North Korea (PRK) - 10 victims, United Kingdom (GBR) - 180 victims, India (IND) – 280, China (CHN) - 740 victims and the USA having the most identified, at 65,880, followed by Russia (RUS) at 11,210. Variation was also observed in the downloadable dataset (Counter-Trafficking Data Collaborative, 2021).

3.4.1.2. Global Report on Trafficking in Persons (GLOTIP)

The data portal of the United Nations Office on Drugs and Crime includes additive data of more than 450,000 victims detected between 2003 and 2021 from 141 countries, reported by Member States (UNODC, 2023b, pp. 10-11).

Data in GLOTIP is limited to individuals officially identified as trafficking victims according to national legislation and policy, who were reported to UNODC. Similar to the CTDC, GLOTIP highlights the importance of the data in providing insights into detection capability patterns and trends, rather than claiming links to prevalence. Similar to the CTDC, it highlights: “These figures shall not be considered representative of the prevalence of the crime in a given territory” (UNODC, 2023a, p. 2, p. 2).

Searching the UNODC online database for the total number of trafficking victims detected in 2020 showed great variation in numbers; these included: the United Kingdom having the most at 10,613, followed by the US at 9,854 and then India at 4,709 (UNODC, n.d.). The substantial inter-country variation can also be seen in the downloadable dataset (UNODC, 2023c).

3.4.2. Other modern slavery estimates

3.4.2.1. Global Estimates of Modern Slavery

Produced by the ILO, Walk Free and IOM (2022), the Global Estimates of Modern Slavery provides additive data on forced labour and forced marriage at the broad geographic regional level but not at a country level, across a timeseries of 2017-2021; global forced labour data is disaggregated across six economic sectors (the seventh sector, “Other”, includes non-market activities) and it was estimated that in 2021, 49.570 million slaves existed.

The forced labour estimates are based on household surveys, which included 77,914 respondents across the 68 survey countries; the survey asked about family members and including them, the total number surveyed either directly or indirectly was 628,598. The combined number of people surveyed directly or indirectly for the forced marriage estimates was 931,394 from 75 countries. This was then extrapolated into 189 countries. No national surveys were available for North America, so it was assimilated with the northern, southern and western Europe region (International Labour Organization (ILO), 2022, p. 113). Because at a global level there is no difference between place of exploitation and place of residence, to derive regional data on forced labour, a matrix was used to relate country of residence to country of exploitation using the survey data. There were too few cases reported in the surveys about forced marriage, so a different methodology was applied, using two datasets: 1. National survey data on forced labour; 2. CTDC. The odds ratios of forced commercial sexual exploitation relative to forced labour exploitation, derived from the CTDC for a given region were multiplied by forced labour data from the national surveys to obtain forced commercial sexual labour for the same region (International Labour Organization (ILO), 2022, p. 115).

3.4.2.2. Global Slavery Index

The Global Estimates' 49.570 million people in forced marriage or forced labour (produced by ILO, Walk Free and IOM) is disaggregated by GSI across 160 countries (Walk Free, 2023a). The values of the top at-risk goods imported by G20 are also estimated but this sector analysis is not suitable for global IO analysis because of its limited geographical reach; an assessment of this supply-chain information is provided in the online *Supplementary Information* SI 3). The GSI incorporates a vulnerability weighting to contribute to its risk model that allows estimates to be made at the country level, including for countries where there is no national survey. The vulnerability model is based on several variables, and has a timeseries of 2014-2021 but comparisons cannot be made between reports because of changes in methodology (Walk Free, 2023a, p. 202 & p. 208). The GSI has filled a gap in public discourse by estimating disaggregated data at the country level, and in addition to its reports, publishes their dataset (Walk Free, 2023b). Analysis in policy journals, conducted independently, have provided assessments that raised serious concerns about the GSI: in 2014 (Guth, 2014; Weitzer, 2014a) as well as in 2016 (Feingold, 2017; Gallagher, 2017). Papers co-authored by GSI funders Walk Free and/or Minderoo Foundation (also founded by Andrew and Nicola Forrest) about the initial methodology as well as more recent developments have been published in peer-reviewed non-technical and policy journals (Durgana & van Dijk, 2021; Larsen & Durgana, 2017; Zhang & Larsen, 2021); as well, a paper about the GSI, "Modelling the risk of modern slavery", was published in 2018 in the non-peer-reviewed repository SSRN (Diego-Rosell & Joudo Larsen, 2018).

After the first GSI, Gallagher called for critical examination by the counter-trafficking community, noting that at a time of funding cuts, Walk Free and its subsidiaries had stepped in, with organisations such as the ILO who may have otherwise critiqued the GSI being offered advisory roles or partnerships (Gallagher, 2014). Iterative changes to the methodology have addressed some criticisms but significant issues remain. Interviewed for this research, Feingold said that although the GSI employed talented statisticians, the primary data they worked with was problematic rendering the GSI results highly unreliable; he concludes: "It's not true that it is better to use bad data than no data" (personal communication, August 16, 2023).

The GSI notes substantial data-availability challenges: "While the sample of countries on which the estimates were based in the [Global Estimates] 2021 estimates is larger than in previous editions, there remain some regions where the coverage is limited or lacking — this specifically concerns North America and the Arab States… The sample of countries also omits some of the most populous countries, namely China, India, Pakistan…" (Walk Free, 2023a, p. 202). Despite

issues pertaining to data in those countries, the 2023 GSI found that the US, China, India and Pakistan have among the most people in modern slavery, and included in the top-10 countries from the perspective of prevalence (per 1,000 people) were Saudi Arabia, United Arab Emirates and Kuwait (Walk Free, 2023a, p. 3); methodological adjustments were made for Arab nations to account for a heightened risk of migrants there (Walk Free, 2023a, p. 3). The GSI in acknowledging the limitations of source data, says the national estimates should not be interpreted as hard findings and that the estimates have "relatively high sampling errors and a low degree of reproducibility" (p. 202).

Regarding its vulnerability index, the GSI has continued to include indicators that Gallagher criticizes, as not being indicative of modern slavery (Gallagher, 2017); Gallagher also notes that the tendency at times to rely on data points because of their availability rather than because they are the most appropriate indicators is not unique to GSI. Indicators in the "Lack of basic needs" dimension in the vulnerability index that is still used by the GSI include cell phone users, as well as tuberculosis – the latter of which Gallagher believes, is correlated to poverty rather than slavery. Davidson (2015) also raises as a criticism the GSI's link to poverty noting that some of the countries highlighted are also among the poorest, in particular, India, where much of the population live below the defined poverty line of US$1.25 per day. Davidson points out that this approach of linking poverty with vulnerability to extreme labour exploitation is contested (Phillips, 2015). Gallagher also comments that, although sexual orientation and disability rights are part of the human rights agenda, no credible link has been established with slavery (p. 4); the 2023 GSI removed disabled rights from the "Disenfranchised groups" dimension in the vulnerability index and changed the reference to sexual orientation, no longer calling out "Same sex rights" but including "LGBTI acceptance" as a variable (Walk Free, 2023a, pp. 207-8). The GSI explains its choice of variables in the vulnerability risk part of its model as being constrained by those that are published regularly regarding most of its 160 countries (Walk Free, 2023a, p. 209). Consultation with an Expert Working Group is mentioned, with detail about previous feedback referred to the 2018 GSI.

Additionally, Gallagher raises as an issue the fact that the entire slavery prevalence structure of the 2016 GSI was built on the basis of just 470 respondents who confirmed they or a family member had been in forced marriage or forced labour. The 2023 GSI did not publish this raw data but acknowledges it has a limited sample size of confirmed individual cases (Walk Free, 2023a, p. 202).

3.4.3. Proxies/“slavery-like” practices?

A review of numerous non-slavery global datasets was carried out as part of this project, many of which pertain to labour published by the ILO. The unique characteristics of two databases that were considered as potential proxies for slavery are summarized below. In general, potential proxies were found to reflect poverty rather than slavery; the exception was the ILO’s occupational safety and health statistics (OSH database), where under-reporting was believed to be particularly prevalent in developing nations (International Labour Organization, n.d.-b, "Interpretation and uses", para. 2). The over-representation of developed countries can be seen in the database on occupational fatalities (International Labour Organization, 2023a).

3.4.3.1. International Labour Organization’s hazardous child labour (from ILO’s CHILD database)

The ILO’s “Children in hazardous work by sex, age and economic activity (thousands) – annual” dataset (International Labour Organization, 2020) contains additive data covering just 26 countries and three broad sectors (agriculture, industry and services), across a timeseries of 2014-2020, based on child labour indicators using labour force and other household surveys data (International Labour Organization, n.d.-c); more than 79 million children were identified in hazardous labour in 2020.

When countries ratify the ILO Convention No. 138 and ILO Convention No. 182, they commit to formulating their own hazardous work list, and may refer, as a proxy, to the ILO Worst Forms of Child Labour Recommendation, 1999 (No. 190), supplementing ILO Convention No. 182. Article 3 of ILO Convention No. 182 sets out what comprises the *worst forms* of child labour, which includes all types of slavery and work that is generally likely to harm the health, safety or morals of children, such as the forced use of children in armed conflict, pornography and the production and trafficking of drugs (International Labour Organization, n.d.-a). Upon inquiry about missing countries from the dataset, ILOSTAT responded that this was because of data availability, rather than being reflective of the global situation on hazardous child labour (Personal communication, May 12, 2023).

3.4.3.2. Low-skilled employment

We also considered whether widely available data on low-skilled employment could be a proxy; we considered this employment data in Release 057 (Industrial Ecology Laboratory, 2022) of the Global Resource Input-Output Assessment (GLORIA) environmentally extended multi-regional input-output (MRIO) database (Lenzen et al., 2022), constructed in the Global MRIO Lab (Lenzen et al., 2017a). However, low-skilled labour is a widespread, evenly distributed characteristic of countries, while modern slavery can vary significantly even between

neighbouring countries, for example as a result of treatment of migrants ((Denney, 2023, p.12-14)).

As the GSI notes regarding the vulnerability model it developed for use in its calculations, "the field of modern slavery lacks a unifying causal theory that can be used to inform variable selection" (Walk Free, 2023a, p. 202). Potential proxies or variables correlation, regarding modern-day slavery, is an area that could benefit from further research.

3.5. Concluding discussion

Awareness of the scourge of modern-day slavery has been assisted by the development of data-collection and sharing, as well as estimates regarding the scale of the problem. The regulatory environment globally is increasingly requiring that companies demonstrate due diligence but human rights can be challenging to measure (Merry, 2016, p. 172), with activities such as trafficking in persons being particularly difficult to quantify**.** For this reason, such illicit activities cannot currently universally be measured globally in a consistent and robust manner, as required for global modern-slavery value-chain mapping. In addition to the activity being hidden, there are countries that do not participate comprehensively in efforts to quantify modern slavery in their state; this may explain why some of the bigger estimates lack or rely on limited raw data from some of the most populous countries. When such estimates move beyond a purely theoretical exercise and are considered by companies looking for a universal, global modern-slavery footprint/guidance on remedying actions, such attempts could result in unintended consequences (Guth, 2014; Satterthwaite & Moses, 2012; Ugarte et al., 2023; UNICEF, 1997, p. 23).

In this paper, we analysed published datasets, indicators and proxies for modern slavery as potential physical/satellite accounts to append to MRIO tables to underpin supply-chain analysis "footprints". Such a modern-slavery indicator could enable businesses to gain insights into supply-chain hotspots. This analysis could be useful for busy decision-makers in assessing changes to procurement, however, we found that modern slavery data upon which such analysis can be based is scant, incomplete and often published with high uncertainty; many estimates cite or use the same sources and some make further extrapolations based on these data or estimates that are not fit for such purposes. Datasets and indicators are potentially correlated with modern slavery, for example child labour and a range of human-rights variables, but these may also be linked to inequality and poverty; therefore, using such indicators as

proxies for slavery can risk painting all nations with high inequality or poverty as complicit in modern slavery, despite no such link having been demonstrated. In fact, it has been shown that modern slavery is not unique to poor countries (see, e.g., (Mitchell & Gengler, 2019; Office for National Statistics, 2020; UNICEF, 1997, p. 20)). Of particular concern is undocumented migration, which by definition escapes official record; there can also be issues with statistics on migrants generally, for example in the upper-middle-income economy of Thailand, despite major improvements on poverty generally, most migrants remain poor and are not captured in data on poverty and inequality (Domingo & Siripatthanakosol, 2023, pp. 24 & 27).

From the perspective of a potential universal modern-slavery indicator, a key challenge remains the ability to collect robust data across a large number of regions worldwide. Looking beyond the concept of *global, universal* modern slavery supply-chain analysis to more *tailored* analysis, detailed data collection and focused research could enable MRIO tables to be augmented with sectoral data in a form of hybridization, for example, as was done with coltan (Moran et al., 2015). As other specialized, hybrid lifecycle assessment/LCA MRIO studies have shown where the topic becomes specific, such as in research of sugar-sweetened beverages (Thow et al., 2021) and bioplastics (Jin et al., 2023) industries, labour-intensive, robust data collection is required. Businesses are encouraged to invest in such research, which has been demonstrated to produce insightful results based on reliable source data. Such disaggregated data may not only be of use for the particular research question but would also add to the body of available tailored data to produce a more holistic picture in aggregate.

Much has been written about the rise of the indicator culture (Espeland & Stevens, 2008; Hacking, 1990, 2014), which provides an aura of objectivity and robustness; about statistical untruths (Comaroff & Comaroff, 2006), and the fact that the simplest indicators are the most likely to succeed in terms of uptake, despite potentially losing meaning as often complex-social phenomena are converted into easily communicated quanta for organizations (March & Simon, 1958). Merry has cautioned that it may be particularly difficult to discern sources and meaning from rankings, and highlights the particular risks of composites, which can contain long interpretive chains (2011, 2016). Indicators may incorporate assumptions about cultures and peoples (e.g., from the Global South) who are excluded from the development of such measures, as targets define a new reality where activity is focused towards what is being measured (Urla, 1993).

Recent attempts to analyse modern slavery using IO analysis have been based on a desire to make use of this powerful technique for uncovering hotspots. We conclude that given available

information at the global level, it is not possible to build a robust, universal modern-slavery indicator for footprinting; we note, however, the critical role of building up the field of research of hybrid IO-LCA studies focused on specific problematic sectors or regions enabled by rich data-collection.

3.6. References

Alsamawi, A., Murray, J., & Lenzen, M. (2014a). The employment footprints of nations: Uncovering master-servant relationships. *Journal of Industrial Ecology*, *18*(1), 59-70. https://doi.org/10.1111/jiec.12104

Alsamawi, A., Murray, J., Lenzen, M., Moran, D., & Kanemoto, K. (2014b). The Inequality Footprints of Nations: A Novel Approach to Quantitative Accounting of Income Inequality. *PLOS ONE*, *9*(10), e110881. https://doi.org/10.1371/journal.pone.0110881

Alsamawi, A., Murray, J., Lenzen, M., & Reyes, R. C. (2017). Trade in occupational safety and health: Tracing the embodied human and economic harm in labour along the global supply chain. *Journal of Cleaner Production*, *147*, 187-196. https://doi.org/10.1016/j.jclepro.2016.12.110

Attorney-General's Department. (2022). *Review of Australia's Modern Slavery Act 2018: Issues Paper*. Commonwealth of Australia. https://consultations.ag.gov.au/crime/modern-slavery-act-review/user_uploads/review-modern-slavery-act-issues-paper.pdf

Bales, K. (2017). Unlocking the Statistics of Slavery. *CHANCE*, *30*(3), 4-12. https://doi.org/10.1080/09332480.2017.1383105

Bansal, V., Wallach, J., Lira Brandão, J., Lord, S., Taha, N., Akoglu, T., Kiss, L., & Zimmerman, C. (2023). An intervention-focused review of modern slave labor in Brazil's mining sector. *World Development*, *171*, 106362. https://doi.org/10.1016/j.worlddev.2023.106362

Barsh, R. L. (1993). Measuring human rights: Problems of methodology and purpose. *Human Rights Quarterly*, *15*(1), 87-121. https://doi.org/10.2307/762653

Benoit-Norris, C., & Norris, G. (2015). Chapter 6: The Social Hotspot Database. In J. Murray, D. McBain, & T. Wiedmann (Eds.). *The Sustainability Practitioner's Guide to Social Analysis and Assessment* (pp. 52-73). Common Ground Publishing.

Bohn, T., Brakman, S., & Dietzenbacher, E. (2022). Who's afraid of Virginia Wu? US employment footprints and self-sufficiency. *Economic Systems Research*, *34*(4), 469-490. https://doi.org/10.1080/09535314.2021.1935219

Boyd, D. S., Perrat, B., Li, X., Jackson, B., Landman, T., Ling, F., Bales, K., Choi-Fitzpatrick, A., Goulding, J., Marsh, S., & Foody, G. M. (2021). Informing action for United Nations SDG target 8.7 and interdependent SDGs: Examining modern slavery from space. *Humanities and Social Sciences Communications*, *8*(1), 111. https://doi.org/10.1057/s41599-021-00792-z

Brown, D., Boyd, D. S., Brickell, K., Ives, C. D., Natarajan, N., & Parsons, L. (2021). Modern slavery, environmental degradation and climate change: Fisheries, field, forests and factories. *Environment and Planning E: Nature and Space*, *4*(2), 191-207. https://doi.org/10.1177/2514848619887156

Campos, A., Huijstee, M. v., & Theuws, M. (2015). *From moral responsibility to legal liability? Modern day slavery conditions in the global garment supply chain and the need to strengthen regulatory frameworks: The case of Inditex-Zara in Brazil*. SOMO & Repórter Brasil. https://reporterbrasil.org.br/wp-content/uploads/2016/08/From-moral-responsibility-to-legal-liability.pdf

Chesney, T., Evans, K., Gold, S., & Trautrims, A. (2019). Understanding labour exploitation in the Spanish agricultural sector using an agent based approach. *Journal of Cleaner Production*, *214*, 696-704. https://doi.org/10.1016/j.jclepro.2018.12.282

Chesney, T., Gold, S., & Trautrims, A. (2017). Agent based modelling as a decision support system for shadow accounting. *Decision Support Systems*, *95*, 110-116. https://doi.org/10.1016/j.dss.2017.01.004

Chuang, J. A. (2014). Exploitation creep and the unmaking of human trafficking law. *American Journal of International Law*, *108*(4), 609-649. https://doi.org/10.5305/amerjintelaw.108.4.0609

Coelho, S., Martens, J., Cole, A., Lind, A., Lee, S., Komenda, H., & Macchiavello, M. (2016). *The climate change-human trafficking nexus*. IOM. https://publications.iom.int/system/files/pdf/mecc_infosheet_climate_change_nexus.pdf

Cole, R., & Aitken, J. (2019). Selecting suppliers for socially sustainable supply chain management:post-exchange supplier development activities as pre-selection requirements. *Production Planning & Control*, *30*(14), 1184-1202. https://doi.org/10.1080/09537287.2019.1595208

Comaroff, J., & Comaroff, J. L. (2006). Figuring crime: Quantifacts and the productionof the Un/Real. *Public Culture, 18*(1), 209-246. https://doi.org/10.1215/08992363-18-1-209

Corporate Sustainability Due Diligence Directive 2024 (EU) Directive 2024/1760. https://eur-lex.europa.eu/eli/dir/2024/1760/oj

Counter-Trafficking Data Collaborative. (n.d.-a). *FAQs*. Retrieved July 26, 2023 from https://www.ctdatacollaborative.org/page/faqs

Counter-Trafficking Data Collaborative. (n.d.-b). *Global Synthetic Data Dashboard* [Interactive dashboard]. Retrieved January 29, 2024, from CTDC. https://www.ctdatacollaborative.org/global-synthetic-data-dashboard

Counter-Trafficking Data Collaborative. (2021). *Global Synthetic Dataset* (Initiative by the IOM; time period 2002-2021; initially released Sept 2021; downloadable dataset at the link was updated in 2024) [Data set]. Retrieved April 26, 2023, from CTDC. https://www.ctdatacollaborative.org/dataset/global-synthetic-data-and-resources/resource/microdata.

Coward, A. (2021). *Moving from paper to practice: ASX200 reporting under Australia's Modern Slavery Act*. ACSI. https://acsi.org.au/wp-content/uploads/2021/07/ACSI_ModernSlavery_July2021.pdf

Davidson, J. O. C. (2015). *Modern Slavery: The margins of freedom*. Palgrave Macmillan. https://doi.org/10.1057/97811372

Decker Sparks, J. L., Boyd, D. S., Jackson, B., Ives, C. D., & Bales, K. (2021). Growing evidence of the interconnections between modern slavery, environmental degradation, and climate change. *One Earth*, *4*(2), 181-191. https://doi.org/10.1016/j.oneear.2021.01.015

Denney, L., Alffram, H., Domingo, P. and Jesperson, S. (2023). *Addressing exploitation of labour migrants in Southeast Asia: Beyond a counter-trafficking criminal justice response'* [ODI Thematic brief 2]. ODI. https://media.odi.org/documents/Thematic_brief_2_Final.pdf

Diego-Rosell, P., & Larsen, J. J. (2018). Modelling the risk of modern slavery. *SSRN*. https://doi.org/10.2139/ssrn.3215368

Dietzenbacher, E., Lahr, M. L., & Lenzen, M. (2020). *Recent Developments in Input–Output Analysis*. Edward Elgar Publishing Limited. https://doi.org/10.4337/9781786430816

Domingo, P., & Siripatthanakosol, K. (2023). *Labour migrants' vulnerability to human trafficking and labour exploitation in Southeast Asia: An analysis of Thailand*. [ODI Country study]. ODI. https://odi.cdn.ngo/media/documents/Thailand_Country_Study_for_the_website_2Fompsf.pdf

Durgana, D., & van Dijk, J. (2021). Measuring the hidden numbers of human trafficking through multiple systems estimation: Lessons learned and challenges outstanding. *Crime & Delinquency*, *67*(13-14), 2188-2212. https://doi.org/10.1177/0011128720987197

Espeland, W. N., & Stevens, M. L. (2008). A sociology of quantification. *European Journal of Sociology / Archives Européennes de Sociologie / Europäisches Archiv für Soziologie*, *49*(3), 401-436. https://doi.org/10.1017/S0003975609000150

Feingold, D. A. (2009). Think again: Human trafficking. *Foreign Policy*. https://foreignpolicy.com/2009/10/20/think-again-human-trafficking/

Feingold, D. A. (2010). Trafficking in numbers: The social construction of human trafficking data. In P. Andreas & K. M. Greenhill (Eds.), *Sex, Drugs and Body Counts: The Politics of Numbers in Global Crime and Conflict* (pp. 46-74). Cornell University Press. https://www.researchgate.net/publication/284800222_Trafficking_in_numbers_The_social_construction_of_human_trafficking_data

Feingold, D. A. (2017). Playing the numbers: The spurious promise of global trafficking statistics. *Anti-Trafficking Review*(8), 153-156. https://doi.org/10.14197/atr.201217810

Gallagher, A. (2014, November 29). The global slavery index is based on flawed data - why does no-one say so? *The Guardian*. https://www.theguardian.com/global-development/poverty-matters/2014/nov/28/global-slavery-index-walk-free-human-trafficking-anne-gallagher

Gallagher, A. T. (2017). What's wrong with the Global Slavery Index? *Anti-Trafficking Review*(8), 90-112. https://doi.org/10.14197/atr.20121786

García-Alaminos, Á., Monsalve, F., & Zafrilla, J. (2024). Disentangling social impacts in global value chains through structural path analysis: Investigating forced labor in the cotton industry. Journal of Industrial Ecology, 28(2), 303–319. https://doi.org/10.1111/jiec.13359

Gold, S., Trautrims, A., & Trodd, Z. (2015). Modern slavery challenges to supply chain management. *Supply Chain Management: An International Journal*, *20*(5), 485-494. https://doi.org/10.1108/SCM-02-2015-0046

Gómez-Paredes, J., Yamasue, E., Okumura, H., & Ishihara, K. N. (2015). THE LABOUR FOOTPRINT: A FRAMEWORK TO ASSESS LABOUR IN A COMPLEX ECONOMY. *Economic Systems Research*, *27*(4), 415-439. https://doi.org/10.1080/09535314.2014.998173

Guth, A., Anderson, R., Kinnard, K., & Tran, H. . (2014). Proper methodology and methods of collecting and analyzing slavery data: An examination of the Global Slavery Index. *Social Inclusion*, *4*(2), 14-22. https://doi.org/10.17645/si.v2i4.195

Hacking, I. (1990). *The taming of chance*. Cambridge University Press.

Hacking, I. (2014). *Why is there philosophy of mathematics at all?* Cambridge University Press. https://doi.org/10.1017/CBO9781107279346

Hertwich, E. G., & Peters, G. P. (2009). Carbon footprint of nations: A global, trade-linked analysis. *Environmental Science & Technology*, *43*(16), 6414-6420. https://doi.org/10.1021/es803496a

Hofmann, H., Schleper, M. C., & Blome, C. (2018). Conflict Minerals and Supply Chain Due Diligence: An Exploratory Study of Multi-tier Supply Chains. *Journal of Business Ethics*, *147*(1), 115-141. https://doi.org/10.1007/s10551-015-2963-z

Huang, Y. A., Lenzen, M., Weber, C. L., Murray, J., & Matthews, H. S. (2009). THE ROLE OF INPUT–OUTPUT ANALYSIS FOR THE SCREENING OF CORPORATE CARBON FOOTPRINTS. *Economic Systems Research*, *21*(3), 217-242. https://doi.org/10.1080/09535310903541348

Industrial Ecology Laboratory. (2022). *GLORIA Release 057* (Satellites include Employment (skill_low, in addition to medium- and high-skilled indicators); time period 1990-2027) [Data set]. Retrieved August 21, 2023, from https://ielab.info/labs/ielab-gloria

International Justice Mission Australia. (2022). *Spot fires in supply chains: An analysis of Australian corporate modern slavery statements and recommendations for extinguishing risk through protecting workers in South Asia*. https://ijm.org.au/wp-content/uploads/2022/05/Spot-Fires-in-Supply-Chains-Report.pdf

International Labour Organization. (n.d.-a). *Child labour statistics (CHILD database)*. Retrieved January 8, 2024, from https://ilostat.ilo.org/methods/concepts-and-definitions/description-child-labour-statistics/

International Labour Organization. (n.d.-b). *Occupational safety and health statistics (OSH database)*. Retrieved October 5, 2023, from https://ilostat.ilo.org/methods/concepts-and-definitions/description-occupational-safety-and-health-statistics/

International Labour Organization. (n.d.-c). *Statistics on child labour*. Retrieved January 8, 2024, from https://ilostat.ilo.org/topics/child-labour/

International Labour Organization. (2020). *Children in hazardous work by sex, age and economic activity (thousands) -- Annual* (CLD_XHAZ_SEX_AGE_ECO_NB_A; updated 06/07/21) [Data set]. ILOSTAT explorer. https://rshiny.ilo.org/dataexplorer48/?lang=en&id=CLD_XHAZ_SEX_AGE_ECO_NB_A

International Labour Organization. (2023). *Cases of fatal occupational injury by economic activity -- Annual* (INJ_FATL_ECO_NB_A) [Data set]. ILOSTAT explorer. https://rshiny.ilo.org/dataexplorer38/?lang=en&id=INJ_FATL_ECO_NB_A

International Labour Organization and Walk Free Foundation (2017). *Global Estimates of Modern Slavery: Forced Labour and Forced Marriage*. https://www.ilo.org/sites/default/files/wcmsp5/groups/public/%40dgreports/%40dcomm/documents/publication/wcms_575479.pdf

International Labour Organization (ILO), Walk Free, International Organisation for Migration (IOM). (2022). *Global Estimates of Modern Slavery: Forced Labour and Forced Marriage*. https://www.ilo.org/wcmsp5/groups/public/---ed_norm/---ipec/documents/publication/wcms_854733.pdf

International Sustainability Standards Board. (2023). *IFRS Sustainability Disclosure Standard: General Requirements for Disclosure of Sustainability-related Financial Information* (IFRS S1). IFRS Foundation. https://www.ifrs.org/issued-standards/ifrs-sustainability-standards-navigator/ifrs-s1-general-requirements.html/content/dam/ifrs/publications/html-standards-issb/english/2023/issued/issbs1/

Jackson, B., & Decker Sparks, J. L. (2020). Ending slavery by decarbonisation? Exploring the nexus of modern slavery, deforestation, and climate change action via REDD+. *Energy Research & Social Science*, *69*, 101610. https://doi.org/10.1016/j.erss.2020.101610

Jin, Y., Lenzen, M., Montoya, A., Laycock, B., Yuan, Z., Lant, P., Li, M., Wood, R., & Malik, A. (2023). Greenhouse gas emissions, land use and employment in a future global bioplastics economy. *Resources, Conservation and Recycling*, *193*, 106950. https://doi.org/10.1016/j.resconrec.2023.106950

Kanemoto, K., Moran, D., Lenzen, M., & Geschke, A. (2014). International trade undermines national emission reduction targets: New evidence from air pollution. *Global Environmental Change*, *24*, 52-59. https://doi.org/10.1016/j.gloenvcha.2013.09.008

Kougkoulos, I., Cakir, M. S., Kunz, N., Boyd, D. S., Trautrims, A., Hatzinikolaou, K., & Gold, S. (2021). A Multi-Method Approach to Prioritize Locations of Labor Exploitation for Ground-Based Interventions. *Production and Operations Management*, *30*(12), 4396-4411. https://doi.org/10.1111/poms.13496

Lake, Q., MacAlister, J., Berman, C., Gitsham, M., & Page, N. (2015). *Corporate approaches to addressing modern slavery in supply chains: A snapshot of current practice*. Ashridge Executive Education at Hult International Business School. https://www.ethicaltrade.org/sites/default/files/shared_resources/corporate_approaches_to_addressing_modern_slavery.pdf

Landman, T. (2004). Measuring human rights: Principle, practice, and policy. *Human Rights Quarterly*, *26*(4), 906-931.

Landman, T. (2020). Measuring Modern Slavery: Law, Human Rights, and New Forms of Data. *Human Rights Quarterly*, *42*(2), 303-331. https://doi.org/10.1353/hrq.2020.0019

Larsen, J. J., & Durgana, D. P. (2017). Measuring vulnerability and estimating prevalence of modern slavery. *CHANCE*, *30*(3), 21-29. https://doi.org/10.1080/09332480.2017.1383109

Latham-Sprinkle, J., David, F., Bryant, K., & Larsen, J. (2019). *Migrants and their vulnerability to human trafficking, modern slavery and forced labour*. http://hdl.handle.net/1854/LU-8636089

Lavelle-Hill, R., Smith, G., Mazumder, A., Landman, T., & Goulding, J. (2021). Machine learning methods for "wicked" problems: Exploring the complex drivers of modern slavery. *Humanities and Social Sciences Communications*, *8*(1), 274. https://doi.org/10.1057/s41599-021-00938-z

LeBaron, G. (2021). The Role of Supply Chains in the Global Business of Forced Labour. *Journal of Supply Chain Management*, *57*(2), 29-42. https://doi.org/10.1111/jscm.12258

LeBaron, G., & Phillips, N. (2019). States and the Political Economy of Unfree Labour. *New Political Economy*, *24*(1), 1-21. https://doi.org/10.1080/13563467.2017.1420642

Lenzen, M., Geschke, A., Abd Rahman, M. D., Xiao, Y., Fry, J., Reyes, R., Dietzenbacher, E., Inomata, S., Kanemoto, K., Los, B., Moran, D., Schulte In Den Bäumen, H., Tukker, A., Walmsley, T., Wiedmann, T., Wood, R., & Yamano, N. (2017). The Global MRIO Lab – charting the world economy. *Economic Systems Research*, *29*(2), 158-186. https://doi.org/10.1080/09535314.2017.1301887

Lenzen, M., Geschke, A., West, J., Fry, J., Malik, A., Giljum, S., Milà I Canals, L., Piñero, P., Lutter, S., Wiedmann, T., Li, M., Sevenster, M., Potočnik, J., Teixeira, I., Van Voore, M., Nansai, K., & Schandl, H. (2022). Implementing the material footprint to measure progress towards Sustainable Development Goals 8 and 12. *Nature Sustainability*, *5*(2), 157-166. https://doi.org/10.1038/s41893-021-00811-6

Lenzen, M., & Treloar, G. (2002). Embodied energy in buildings: wood versus concrete—reply to Börjesson and Gustavsson. *Energy Policy*, *30*(3), 249-255. https://doi.org/10.1016/S0301-4215(01)00142-2

Malik, A., Lenzen, M., Li, M., Mora, C., Carter, S., Giljum, S., Lutter, S., & Gómez-Paredes, J. (2024). Polarizing and equalizing trends in international trade and Sustainable Development Goals. *Nature Sustainability*. https://doi.org/10.1038/s41893-024-01397-5

March, J. G., & Simon, H. A. (1958). *Organizations*. Wiley.

McBain, D. (2015). Is Social Footprinting Relevant to Industrial Ecology? *Journal of Industrial Ecology*, *19*(3), 340-342. https://doi.org/10.1111/jiec.12260

McBain, D., & Alsamawi, A. (2014). 'Quantitative Accounting for Social Economic Indicators'. *Natural Resources Forum: Special Section on Oceans and Seas*, *38*(3), 193-202. https://doi.org/10.1111/1477-8947.12044

McGaughey, F., Voss, H., Cullen, H., & Davis, M. C. (2022). Corporate Responses to Tackling Modern Slavery: A Comparative Analysis of Australia, France and the United Kingdom. *Business and Human Rights Journal*, *7*(2), 249-270. https://doi.org/10.1017/bhj.2021.47

Merry, S. E. (2011). Measuring the world: Indicators, human rights, and global governance: with CA comment by John M. Conley. *Current Anthropology*, *52*(S3), S83-S95. https://doi.org/10.1086/657241

Merry, S. E. (2016). *The seductions of quantification: Measuring human rights, gender violence, and sex trafficking*. The University of Chicago Press. https://doi.org/10.7208/chicago/9780226261317.001.0001

Miller, R. E., & Blair, P. D. (2009). *Input-Output Analysis: Foundations and Extensions* (2nd ed.). Cambridge University Press. https://doi.org/10.1017/CBO9780511626982

Mitchell, J. S., & Gengler, J. J. (2019). What Money Can't Buy: Wealth, Inequality, and Economic Satisfaction in the Rentier State. *Political Research Quarterly*, *72*(1), 75-89. https://doi.org/10.1177/1065912918776

Modern Slavery Act 2015 (UK) c. 30. https://www.legislation.gov.uk/ukpga/2015/30/contents

Modern Slavery Act 2018 (Cth) No. 153. https://www.legislation.gov.au/C2018A00153/latest/text

Moran, D., McBain, D., Kanemoto, K., Lenzen, M., & Geschke, A. (2015). Global Supply Chains of Coltan. *Journal of Industrial Ecology*, *19*(3), 357-365. https://doi.org/https://doi.org/10.1111/jiec.12206

Nakamura, S., & Kondo, Y. (2002). Input-Output Analysis of Waste Management. *Journal of Industrial Ecology*, *6*(1), 39-63. https://doi.org/10.1162/108819802320971632

Nolan, J., & Bott, G. (2018). Global supply chains and human rights: spotlight on forced labour and modern slavery practices. *Australian Journal of Human Rights*, *24*(1), 44-69. https://doi.org/10.1080/1323238X.2018.1441610

Norris, C. B., Norris, G. A., & Aulisio, D. (2014). Efficient Assessment of Social Hotspots in the Supply Chains of 100 Product Categories Using the Social Hotspots Database. *Sustainability*, *6*(10), 6973-6984. https://doi.org/10.3390/su6106973

Office for National Statistics. (2020). *Modern slavery in the UK: March 2020*. Retrieved August 12, 2024, from https://www.ons.gov.uk/peoplepopulationandcommunity/crimeandjustice/articles/modernslaveryintheuk/march2020#measuring-modern-slavery

Phillips, N. (2015, February 17). What has forced labour to do with poverty? *openDemocracy*. https://www.opendemocracy.net/en/beyond-trafficking-and-slavery/what-has-forced-labour-to-do-with-poverty/

Phillips, N., & Sakamoto, L. (2012). Global Production Networks, Chronic Poverty and 'Slave Labour' in Brazil. *Studies in Comparative International Development*, *47*(3), 287-315. https://doi.org/10.1007/s12116-012-9101-z

Protocol to Prevent, Suppress and Punish Trafficking in Persons Especially Women and Children, supplementing the United Nations Convention against Transnational Organized Crime, Nov. 15, 2000, General Assembly resolution 55/25. https://www.ohchr.org/en/instruments-mechanisms/instruments/protocol-prevent-suppress-and-punish-trafficking-persons

Satterthwaite, M. L., & Moses, P. S. (2012). Unintended Consequences: The Technology of Indicators in Post-Earthquake Haiti. *Journal of Haitian Studies*, *18*(1), 14-49. http://www.jstor.org/stable/41715451

Schleper, M. C., Blome, C., Stevenson, M., Thürer, M., & Tusell, I. (2022). When it's the slaves that pay: In search of a fair due diligence cost distribution in conflict mineral supply chains. *Transportation Research Part E: Logistics and Transportation Review*, *164*, 102801. https://doi.org/10.1016/j.tre.2022.102801

Shilling, H. J., Wiedmann, T., & Malik, A. (2021). Modern slavery footprints in global supply chains. *Journal of Industrial Ecology*, *25*(6), 1518-1528. https://dx.doi.org/10.1111/jiec.13169

Simas, M. S., Golsteijn, L., Huijbregts, M. A. J., Wood, R., & Hertwich, E. G. (2014). The "Bad labor" footprint: Quantifying the social impacts of globalization. *Sustainability*, *6*(11), 7514-7540. https://doi.org/10.3390/su6117514

Simas, M., Wood, R., & Hertwich, E. (2015). Labor embodied in trade: The role of labor and energy productivity and implications for greenhouse gas emissions. *Journal of Industrial Ecology 19*(3), 343-356. https://doi.org/10.1016/j.rser.2013.11.046

Sinclair, A., & Dinshaw, H. (2022). *Paper Promises? Evaluating the early impact of Australia's Modern Slavery Act*. Human Rights Law Centre. https://static1.squarespace.com/static/580025f66b8f5b2dabbe4291/t/6200d3d9db51c63088d0e8e1/1644221419125/Paper+Promises_Australia+Modern+_Slavery+Act_7_FEB.pdf

Sovacool, B. K. (2021). When subterranean slavery supports sustainability transitions? power, patriarchy, and child labor in artisanal Congolese cobalt mining. *The Extractive Industries and Society*, *8*(1), 271-293. https://doi.org/10.1016/j.exis.2020.11.018

Stevenson, M., & Cole, R. (2018). Modern slavery in supply chains: a secondary data analysis of detection, remediation and disclosure. *Supply Chain Management: An International Journal*, *12*(3), 81-99. https://doi.org/10.1108/SCM-11-2017-0382

Stringer, C., & Michailova, S. (2018). Why modern slavery thrives in multinational corporations' global value chains. *Multinational Business Review*, *26*(3), 194-206. https://doi.org/10.1108/MBR-04-2018-0032

Thow, A. M., Lencucha, R. A., Rooney, K., Colagiuri, S., & Lenzen, M. (2021). Implications for farmers of measures to reduce sugars consumption. *Bulletin of the World Health Organization*, *99*(1), 41-49. https://doi.org/10.2471/blt.19.249177

Trafficking Victims Protection Act 2000. H.R. 3244. https://www.govinfo.gov/content/pkg/BILLS-106hr3244enr/pdf/BILLS-106hr3244enr.pdf

Ugarte, C., Olarreaga, M., & Saiovici, G. (2023). Child labour and global value chains. *The World Economy*, *46*(4), 941-968. https://doi.org/10.1111/twec.13401

UNICEF. (1997). *The state of the world's children*. Oxford University Press. https://www.unicef.org/media/84761/file

UNODC. (n.d.). *UNODC research: Data portal – trafficking in Persons*. Retrieved January 6, 2024, from https://dataunodc.un.org/dp-trafficking-persons

UNODC. (2022). *Climate, crime and exploitation: The gendered risks between climate-related risk, trafficking in persons and smuggling of migrants* [Policy brief]. United Nations Office on Drugs and Crime. https://www.unodc.org/documents/human-trafficking/GLO-ACTII/UNODC_Climate-TIP-SOM_Policy_Paper.pdf

UNODC. (2023a). *Data UNODC: Metadata information*. United Nations Office on Drugs and Crime. https://dataunodc.un.org/sites/dataunodc.un.org/files/metadata_trafficking_in_persons.pdf

UNODC. (2023b). *Global Report on Trafficking in Persons 2022*. United Nations Office on Drugs and Crime. https://www.unodc.org/documents/data-and-analysis/glotip/2022/GLOTiP_2022_web.pdf

UNODC. (2023c). *UNODC Research - Trafficking in Persons* [Data set]. Retrieved January 8, 2024. from dataUNODC. https://dataunodc.un.org/sites/dataunodc.un.org/files/data_glotip.xlsx.

Urla, J. (1993). Cultural politics in an age of statistics: Numbers, nations, and the making of Basque identity. *American Ethnologist*, *20*(4), 818-843. http://www.jstor.org/stable/646233

U.S. Department of State. (2023). *Trafficking in Persons Report*. Office to Monitor and Combat Trafficking in Persons. https://www.state.gov/wp-content/uploads/2023/06/2023-TIP-Report.pdf

Walk Free. (2023a). *The Global Slavery Index 2023* [Report]. Minderoo Foundation. https://cdn.walkfree.org/content/uploads/2023/05/17114737/Global-Slavery-Index-2023.pdf

Walk Free. (2023b). *Global Slavery Index 2023* [Dataset]. Minderoo Foundation. https://cdn.walkfree.org/ephemeral/2023-Global-Slavery-Index-Data-236907c0-5503-40ed-b7c8-3df6ec29ce80.zip.

Walk Free Foundation. (2013). *The Global Slavery Index 2013* [Report]. Minderoo Foundation. https://cdn.walkfree.org/content/uploads/2013/02/09125326/2013-Global-Slavery-Index.pdf

Weitzer, R. (2014a). Miscounting human trafficking and slavery. *openDemocracy*. https://www.opendemocracy.net/en/beyond-trafficking-and-slavery/miscounting-human-trafficking-and-slavery/

Weitzer, R. (2014b). New Directions in Research on Human Trafficking. *The ANNALS of the American Academy of Political and Social Science*, *653*(1), 6-24. https://doi.org/10.1177/0002716214521562

Weitzer, R. (2015). Human trafficking and contemporary slavery. *Annual Review of Sociology*, *41*(1), 223-242. https://doi.org/10.1146/annurev-soc-073014-112506

World Resources Institute & World Business Council for Sustainable Development. (2011). *Corporate Value Chain (Scope 3) Accounting and Reporting Standard: Supplement to the GHG Protocol Corporate Accounting and Reporting Standard*. Greenhouse Gas Protocol. https://ghgprotocol.org/sites/default/files/standards/Corporate-Value-Chain-Accounting-Reporing-Standard_041613_2.pdf

World Resources Institute & World Business Council for Sustainable Development. (2013). *Technical guidance for calculating scope 3 emissions: Supplement to the Corporate Value Chain (Scope 3) Accounting & Reporting Standard*. Greenhouse Gas Prootcol. https://ghgprotocol.org/sites/default/files/standards/Scope3_Calculation_Guidance_0.pdf

Xiao, Y., Lenzen, M., Benoît-Norris, C., Norris, G. A., Murray, J., & Malik, A. (2018). The Corruption Footprints of Nations. *Journal of Industrial Ecology*, *22*(1), 68-78. https://doi.org/10.1111/jiec.12537

Zhang, S. X., & Larsen, J. J. (2021). Estimating the size of the human trafficking problem: MSE and other strategies. *Crime & Delinquency*, *67*(13-14), 2169-2187. https://doi.org/10.1177/00111287211029856

3.7. *Supplementary Information* highlights

The *Supplementary Information* (linked to from the main paper online as "Supporting Information S1") is available at: https://onlinelibrary.wiley.com/action/downloadSupplement?doi=10.1111%2Fjiec.70037&file=jiec70037-sup-0001-SuppMat.docx

Some highlights are below.

3.7.1. Sector-relevant data analysed

3.7.1.1. List of Goods Produced by Child Labour or Forced Labour

Three flagship child-and forced labour data products are published by the US Department of Labour's Bureau of International Labour Affairs (ILAB) (US Department of Labor, 2022b, US Department of Labor, 2022d, US Department of Labor, 2022a), in addition to an app (US Department of Labor, 2021b) and interactive website tool (US Department of Labor, n.d.-a, US Department of Labor, n.d.-b, ILAB's Better Trade Tool, 2021b, ILAB's Better Trade Tool, 2021a, US Department of Labor, n.d.-c) that integrate data from all three. The List of Goods Produced by Child Labour or Forced Labour (US Department of Labor, 2022d, US Department of Labor, 2022b) is analysed here because information from this List is also used by the Global Slavery Index (see Section 3.7.1.2*)*.

This List is the most comprehensive of ILAB's flagship reports, and, unlike ILAB's Findings on the Worst Forms of Child Labour (US Department of Labor, 2021a, US Department of Labor, 2022a) it is not restricted to developing nations (US Department of Labor, 2022a).

The List of Goods Produced by Child Labour or Forced Labour is produced in accordance with the *Trafficking Victims Protection Reauthorization Act* (2005), as amended. The List (also referred to as the TVPRA List) requires the ILAB to develop and make available a list of goods that ILAB "has *reason to believe* are produced by forced labour or child labour in violation of international standards" (our italics) (22 USC § 7112(b)(2)(C)). Primary and secondary sources are consulted and the public can make submissions (US Department of Labor, 2022c). The 2022 List identified 158 goods from 77 countries (2022c).

The List simply comprises countries and their identified goods produced by child- or forced labour in violation of international standards. It does not contain additive data, so is unsuitable for input-output analysis.

The List excludes the US, with the purpose being to ensure identified goods are not imported into the US, as directed by statute (US Department of Labor, 2022c). “Goods” are defined by the TVPRA Procedural Guidelines as “goods, wares, articles, materials, items, supplies, and merchandise” . This does not include consideration of services that are outsourced, and in this way could be viewed as an import, e.g., call centres. However, non-domestic services are thought to be responsible for the largest share of forced labour (International Labour Organization (ILO) et al., 2022, p. 31).

3.7.1.2. GSI supply-chain information

Complementing the Global Slavery Index (GSI) slavery-prevalence estimates, the GSI links these to the supply chain by considering the top imports of the G20 from an embodied-slavery-risk perspective. This sector-based data is unsuitable as an input for global input-output analysis because it is limited to G20 countries. However, this supply-chain information was analysed here because of our analysis generally of the GSI, which has a high degree of disaggregation of modern slavery by region. The GSI list of highest-value products at risk of forced labour imported by G20 draws on ILAB’s List of Goods Produced by Child Labour or Forced Labour (see Section 3.7.1.1*)*, filtered by "forced labour”; it is amended after a literature review and the final list is then linked to trade data (Walk Free, 2023).

3.7.2. List of potential proxies analysed in this study

1. The “Bad labour” footprint [includes discussion of gender inequality] (Simas et al., 2014)
2. Cases of fatal occupational injury by economic activity -- Annual (International Labour Organization, 2023a)
3. Children in hazardous work by sex, age and economic activity (thousands) – Annual (International Labour Organization, 2020)
4. Corruption footprint of nations (Xiao et al., 2018)
5. Gini Index (World Bank Group, 2024)
6. Inflow of working age foreign citizens by sex and country of citizenship (thousands) (International Labour Organization, 2023b)
7. Informal employment by sex, age and economic activity (thousands) – Annual (International Labour Organization, 2023c)
8. Mean weekly hours actually worked per employed person by sex and economic activity – Annual (International Labour Organization, 2023d)
9. Trade union density rate (%) -- Annual (International Labour Organization, 2022)
10. World Inequality Database (World Inequality Lab, 2019)

3.7.3. *SI* References

ILAB's Better Trade Tool. (2021a). *Better trade tool_Data visualizations 2021: Top 10 countries based on 2020 US imports of goods included in ILAB lists*. Retrieved May 3, 2023, from https://public.tableau.com/app/profile/ilab.dol/viz/BetterTradeTool_datavisualizationsSeptember2021/Top10Countries

ILAB's Better Trade Tool. (2021b). *Better Trade Tool_Top 10 Goods Analysis September 2021: Top 10 ILAB Listed Goods Imported into the U.S. in 2020*. Retrieved May 3, 2023, from https://public.tableau.com/app/profile/ilab.dol/viz/BetterTradeTool_Top10GoodsAnalysisSeptember2021/Top10Goods

International Labour Organization. (2020). Children in hazardous work by sex, age and economic activity (thousands) -- Annual (CLD_XHAZ_SEX_AGE_ECO_NB_A; updated 06/07/21) [Data set]. https://rshiny.ilo.org/dataexplorer48/?lang=en&id=CLD_XHAZ_SEX_AGE_ECO_NB_A.

International Labour Organization. (2022). Trade union density rate (%) -- Annual (ILR_TUMT_NOC_RT_A; time period 2009-2020) [Data set]. Retrieved from ILOSTAT explorer. https://rshiny.ilo.org/dataexplorer47/?lang=en&id=ILR_CBCT_NOC_RT_A.

International Labour Organization. (2023a). Cases of fatal occupational injury by economic activity -- Annual. (INJ_FATL_ECO_NB_A; time period 1970-2022) [Data set]. Retrieved October 6, 2023, from ILOSTAT explorer. https://rshiny.ilo.org/dataexplorer38/?lang=en&id=INJ_FATL_ECO_NB_A.

International Labour Organization. (2023b). Inflow of working age foreign citizens by sex and country of citizenship (thousands) -- Annual. (MFL_NCIT_SEX_CCT_NB_A; time period 1980-2022) [Data set]. Retrieved October 24, 2023, from ILOSTAT explorer. https://rshiny.ilo.org/dataexplorer9/?lang=en&id=MFL_NCIT_SEX_CCT_NB_A.

International Labour Organization. (2023c). Informal employment by sex, age and economic activity (thousands) -- Annual (EMP_NIFL_SEX_AGE_ECO_NB_A; time period 1999-2022; updated 04/08/2023) [Data set]. Retrieved May 17, 2023, from ILOSTAT explorer. https://rshiny.ilo.org/dataexplorer27/?lang=en&id=EMP_NIFL_SEX_AGE_ECO_NB_A

International Labour Organization. (2023d). Mean weekly hours actually worked per employed person by sex, age and economic activity -- Annual. (HOW_TEMP_SEX_AGE_ECO_NB_A; time period 1976-2023) [Data set]. Retrieved October 22, 2023, from ILOSTAT explorer. https://rshiny.ilo.org/dataexplorer32/?lang=en&id=HOW_TEMP_SEX_AGE_ECO_NB_A.

International Labour Organization (ILO), Walk Free and International Organization for Migration, & (IOM). (2022). Global Estimates of Modern Slavery: Forced labor and Forced Marriage. https://www.ilo.org/sites/default/files/wcmsp5/groups/public/%40ed_norm/%40ipec/documents/publication/wcms_854733.pdf

Simas, M. S., Golsteijn, L., Huijbregts, M. A. J., Wood, R., & Hertwich, E. G. (2014). The "Bad labor" footprint: Quantifying the social impacts of globalization. *Sustainability, 6*(11), 7514-7540. https://doi.org/10.3390/su6117514

Trafficking Victims Protection Reauthorization Act 2005, Pub. L. 109-164, 22 USC § 7101 note. https://www.congress.gov/109/statute/STATUTE-119/STATUTE-119-Pg3558.pdf

U.S. Department of Labor. (n.d.-a). *Better Trade Tool*. https://www.dol.gov/agencies/ilab/better-trade-tool

U.S. Department of Labor. (n.d.-b). *Better trade tool: At a glance - US world imports from 2016-2021*. https://public.tableau.com/app/profile/ilab.dol/viz/AtaGlanceU_S_WorldImports2016-2021/AtaGlance2016-2021

U.S. Department of Labor. (n.d.-c). *Better trade tool: Classification methodology*. Bureau of International Labor Affairs. https://www.dol.gov/sites/dolgov/files/ILAB/Better-Trade-Tool-Classification-Methodology-09-03-2021.pdf

U.S. Department of Labor. (2021a). *Findings on the worst forms of child labor.* Bureau of International Labor Affairs. Retrieved May 3, 2023, from https://www.dol.gov/agencies/ilab/resources/reports/child-labor/findings

U.S. Department of Labor. (2021b). *Sweat & Toil* [Mobile app]. App Store. https://www.dol.gov/general/apps/ilab

U.S. Department of Labor. (2022a). *2021 FINDINGS ON THE WORST FORMS OF CHILD LABOR*. Bureau of International Labor Affairs. https://www.dol.gov/sites/dolgov/files/ILAB/child_labor_reports/tda2021/2021_TDA_Big_Book.pdf

U.S. Department of Labor. (2022b). *List of Goods (Excel)*. Bureau of International Labor Affairs. https://www.dol.gov/sites/dolgov/files/ILAB/child_labor_reports/tda2022/2022ListofGoodsExcel.xlsx

U.S. Department of Labor. (2022c). *LIST OF GOODS PRODUCED BY CHILD LABOR OR FORCED LABOR* [Report]. Bureau of International Labor Affairs. https://www.dol.gov/sites/dolgov/files/ilab/child_labor_reports/tda2021/2022-tvpra-list-of-goods-v3.pdf

U.S. Department of Labor. (2022d). *List of Products Produced by Forced or Indentured Child Labor (Excel Format)*. Retrieved May 3, 2023, from Bureau of International Labor Affairs. https://www.dol.gov/agencies/ilab/reports/child-labor/list-of-products

Walk Free. (2023). *The Global Slavery Index 2023* [Report]. Minderoo Foundation. https://cdn.walkfree.org/content/uploads/2023/05/17114737/Global-Slavery-Index-2023.pdf

World Bank Group. (2024). *Gini index* (SI.POV.GINI; last updated 28/06/2024; time period 1960-2023] [Data set]. Retrieved August 5, 2024, from WORLD BANK GROUP. https://api.worldbank.org/v2/en/indicator/SI.POV.GINI?downloadformat=csv.

World Inequality Lab. (2019). *Fig5.1_WorldMap2019* [Data set]. Retrieved August 15, 2023, from *WORLD INEQUALITY DATABASE (WID*). https://wid.world/data/.

Xiao, Y., Lenzen, M., Benoît-Norris, C., Norris, G. A., Murray, J., & Malik, A. (2018). The Corruption Footprints of Nations. *Journal of Industrial Ecology*, *22*(1), 68-78. https://doi.org/10.1111/jiec.12537

4. NOVEL DOWNSTREAM FRAMEWORK FOR ORGANISATIONS

Reiner, V. (*under review*). Income-based responsibility for organisations: A framework and demonstration of corporate sales-chain analysis.

Paper: Income-based responsibility for organisations: A framework and demonstration of corporate sales-chain analysis

Abstract

The emergence of global, interoperable standards and requirements regarding greenhouse gas emissions reporting has brought into focus the impact from corporate customers. Increasingly, regulations include reporting of indirect, ”scope-3” emissions. Many organisations exclude downstream emissions if transport and use/disposal of a product are deemed immaterial or unknown. Input-output analysis (IO) is a popular method for calculating upstream impacts including from corporate purchases but no paper previously described enabled environmental impact associated with a specific organisation’s *sales* . This paper extends “income-based” IO analysis to the enterprise level with a focus on carbon emissions. The hybrid IO/life-cycle analysis (LCA) framework shows how seemingly low-emissions-intensive outputs such as services could have substantial impact if associated with emissions-intensive production. IO emission factors are commonly used for “spend-based” calculations upstream; this research underscores the role that income-based emission factors could play in facilitating calculations downstream, as part of comprehensive, whole-of-value-chain reporting.

4.1. Introduction

Organisations have in the main struggled to calculate enabled emissions from the sales that they make for production downstream, or in other words, their impact down the inter-industry sales chain. Upstream this has proven to be less of an issue, with input-output (IO) analysis commonly employed to quantify impact from the perspective of the inter-industry supply chain driven by organisational purchases.

The value of upstream supply-chain analysis has been demonstrated over decades, with so-called consumption-based accounting (CBA) providing insights beyond the producer (PBA) / territorial perspective (Malik et al., 2019; Peters, 2008; Tukker et al., 2020, p. 621). To these perspectives has been added downstream, “income-based” responsibility (Marques et al., 2012), which has shown that when looking at income rather than expenditure on a global level, greenhouse gas emissions were largely attributed to just a few fossil-fuel exporting nations. Many studies now consider consumption-, production and income-based perspectives, in a three-tiered approach e.g. (Chen et al., 2017; Li et al., 2022; Sanguinet & Azzoni, 2024).

This paper is the result of an organisation-wide project at the University of Sydney focused on the new International Sustainability Standards Board (ISSB)’s Climate-related Disclosures (International Sustainability Standards Board, 2023), to prepare for anticipated mandatory

scope-3 emissions reporting, which requires organisations to estimate emissions in their value chain. The decision was taken to take a leadership position rather than simply focus on compliance, and use comprehensive, environmentally extended input-output (EEIO) analysis (Leontief, 1970) not only upstream but also for downstream calculations (Ghosh, 1958), in line with the Greenhouse Gas Protocol to which the ISSB defers (World Business Council for Sustainable Development & World Resources Institute, 2004; World Resources Institute & World Business Council for Sustainable Development, 2011). The GHG Protocol defines three "scopes" of emissions (World Business Council for Sustainable Development & World Resources Institute, 2004)[4] and specifically for "scope-3" indirect emissions it identifies upstream and downstream categories for reporting against. As the first university to this author's knowledge to investigate a comprehensive analysis for its reporting purposes downstream, the real-world impact of the lack of such investigation became evident. In Australia, for example, some neighbouring universities accept payment for coal research (ACARP, 2024) including those that are "divesting" or have already divested regarding financed investments. This narrow view of income-based responsibility i.e., limited to direct investments, can be seen from the fact that no universities had at the time of writing disclosed emissions in the important downstream GHG Protocol categories of Processing- and Use of Sold Products, which could result largely from research i.e., production based on knowledge-exchange. As shown in Table 1, there have been broadly two parallel arguments regarding the interpretation of the supply-side model, however the efficacy of downstream IO analysis depends upon the interpretation relating to its intended use.

In the research I present in this paper, the aim is not to forecast supply-"driven" quantity changes downstream such as bottlenecks e.g. (Altimiras-Martin, 2024). The aim is to describe relationships, in this case, the emissions a reporting entity enabled e.g., allocating responsibility for the production impacts to the reporting entity by analysing the reporting entity's downstream carbon footprint. As well, it is not the intent in this paper to explore in-depth theoretical arguments, but to describe a hybrid [lifecycle analysis] LCA-IO downstream calculus and broad framework for establishing a corporate carbon footprint that can complement the well-established concept of the upstream LCA-IO corporate carbon footprint, in other words a scalable model that is aligned with the most recent update of the Greenhouse Gas Protocol (World Resources Institute & World Business Council for Sustainable

[4] Scope-1 emissions, from sources owned or controlled by the reporting entity; scope-2 emissions, from purchased or acquired electricity, steam, heat or cooling; and scope-3 emissions, which is all other indirect emissions.

Development, 2013). The GHG Protocol allows EEIO emission factors to be used as an approach to scope-3 calculations and accepts double-counting as "by definition" part of scope-3 analysis (2011, p. 108). The use of the downstream (Ghosh) model as a descriptive tool mirrors the full inter-industrial lifecycle perspective of the upstream (Leontief) model, *ex-post,* and therefore also easily allows for modifications such as regarding double-counting in a consistent manner, as detailed later in this paper.

A country or corporation's shared responsibility as a consumer and producer can be considered variously as: regarding its demand (purchases) in terms of final consumption driving upstream impact, and its supply (sales) regarding primary inputs and enabled downstream impact (Lenzen & Murray, 2010, pp. 263-265); however regarding the latter, no paper has previously been published that demonstrates in a generalised way from an environmental perspective this income-based hybrid [lifecycle assessment] LCA-IO approach for an organisation. In terms of greenhouse gas (GHG) emissions, at the time of writing, IO spend-based emission factors to facilitate calculations by carbon accountants and non-IO technicians were commonly recommended or provided without their downstream, income-based equivalents e.g., (United Kingdom Government Department for Energy Security & Net Zero, 2025; United States Environmental Protection Agency, n.d.; World Resources Institute & World Business Council for Sustainable Development, 2013). IO analysis offers a relatively straightforward solution to new mandatory scope-3 reporting requirements including downstream, while providing insights throughout the inter-industry sales chain.

In developing this framework of for generalised income-based IO analysis at the organisational level, international Standards and systems were consulted, in particular ISIC, the International Standard Industrial Classification of All Economic Activities (Task team on ISIC, 2024; United Nations Department of Economic and Social Affairs, 2008) and the System of National Accounts (Commission of the European Communities - Eurostat et al., 1993; European Communities et al., 2009). To clarify unique downstream circumstances, it is considered: whether to treat the public sector as market or non-market – this is particularly relevant to organisations for whom the public sector is a key income provider; and how to distinguish aggregated service sectors that include sectors whose impact may be substantial from a downstream perspective. The framework is then demonstrated using a university case study, testing alternate scenarios and calculating emissions against the GHG Protocol's downstream categories. These key framework considerations could theoretically be applied to a range of IO downstream methods. However, the standard "income-based" IO method underpins the analysis in this paper, as the most widely used IO method downstream, which is demonstrated

as robust as well as being accessible to non-experts through the provision of income-based emission factors.

Australia is an early adopter of the disclosures aligned to the IFRS sustainability Standards (Australian Accounting Standards Board, 2024). In the State of New South Wales (NSW), an early jurisdictional response for NSW-government and related entities did not indicate any scope-3 exclusions (State of New South Wales (NSW Treasury), 2023), and the University of Sydney was included in phase I of a staggered approach to mandatory climate-related disclosures. As part of the University's preparatory efforts, the framework described in this paper was developed, enabling hybrid IO-LCA downstream in a way that lends itself to reproducibility. This paper presents a novel framework in order to make comprehensive downstream due diligence widely accessible, by demonstrating a methodology for IO analysis based on an organisation's income.

In summary, this paper: presents a novel framework for generalised income-based IO analysis at the organisational level; applies income-based emission factors for calculating emissions across GHG Protocol categories downstream; and discusses additional calculations that may be made separately to the IO analysis to address the GHG Protocol comprehensively including from activities treated as exogenous to intermediate production i.e., GHG Protocol Category 15: Investments. This paper is set out as follows: following this overview, the theoretical foundation for this study is laid out through a literature review of downstream IO analysis including a note on the use of value added rather than its sub-set profit (Section 2); the methods section is divided into a summary of IO downstream calculus, a presentation of this study's framework, and the application of the framework to a case study (Section 3); the results are then detailed (Section 4); and in the concluding discussion, important outcomes of the decisions taken in developing the framework are highlighted along with key findings, and next steps are considered for corporate reporting downstream (Section 5).

4.2. Literature review: A brief history of downstream, “sales-chain” analysis

To summarise the broad perspectives in Table 1 (next page), there is the approach of Ghosh IO analysis as causative i.e., an *ex-ante quantity* model, which has been demonstrated to be implausible (Oosterhaven, 1988) or alternatively a *“price”* interpretation (Dietzenbacher, 1997); or otherwise as a *descriptive* model that can retrospectively *associate responsibility* for impacts, which have already occurred (*ex-post)*, with past activity based on the known state of the economy as a static model. Comparing both Leontief (upstream) and Ghosh (downstream) models, it has elsewhere been shown in regard to closed IO models (Manestra & Sancho, 2013; 2020) that neither is necessarily better and that whatever may seem to be pathological in the Ghosh model (Oosterhaven, 2012) because of mathematical symmetry can similarly be found in the Leontief model).

4.2.1. IO analysis and corporate reporting

IO analysis was conceived in the 1930s to show the inter-relationships in the economy (Leontief, 1936), rose to prominence during the oil shocks that highlighted the importance of upstream supply chains linked to final consumption, and its creator Wassily Leontief was recognised with a Nobel Prize in 1973. Moving from industry-level analysis, hybrid analysis including micro-level information is now well-established in terms of using organisational expenditure to measure an organisation’s indirect impact (e.g. economic, environmental and/or social) incorporating the entire inter-industry supply-chain. Such enterprise IO analysis upstream has included for research departments (Wood & Lenzen, 2003), conceptualising IO corporate reporting generally (Huang et al., 2009), industry-focused in terms of timber (Alvarez et al., 2019) and health (Keil, 2023) and undertaken at universities such as Sydney (Baboulet & Lenzen, 2010), Yale (Thurston & Eckelman, 2011), NTNU, the Norwegian University of Technology and Science (Larsen et al., 2013), Cornell (Sun et al., 2022) and several Danish universities (Stridsland et al., 2023).

Reference	Argument
(Ghosh, 1958)	*Alternative* to demand-driven Leontief model i.e., *allocation* and scarcity in relation to consumption rather than *technical requirements* for production. Relevant to cases of monopolistic market/centrally planned economy, supply restrictions
(Oosterhaven, 1988)	The model may only be used, if carefully interpreted, in *descriptive* analyses. *Any causal interpretation or application leads to at best meaningless*, but probably nonsensical results
(Gruver, 1989)	Ghosh may be *reasonable for approximating the effect of small changes* - since the implied production relation may be interpreted as a cost minimising choice for a standard constant-returns-to-scale production function linearised around the initial solution under the assumption that relative prices are unchanged
(Rose & Allison, 1989)	Requiring production coefficients to remain fixed is unnecessarily restrictive given extensive use of approximation methods in mathematics, economics, regional science. Simulations… region are shown to result in changes in the corresponding production coefficients *well within conventional tolerance levels*
(Oosterhaven, 1989)	Gruver's production function provides a theoretical foundation for the supply model *only in a most trivial case.* And small input-coefficient changes discussed in Rose and Allison provide an insufficient excuse for using the supply model for impact studies; e*mployment estimates may be quite different* depending on the approach used.
(Dietzenbacher, 1997)	The "supply-driven" model becomes plausible once it is interpreted as a "price" model i.e., sectoral *output values change* due to price changes, which are caused by price changes for the primary inputs. As the dual to the Ghosh price model, the Ghosh quantity model is derived, which is equivalent to the demand-driven (or Leontief quantity) model, which is the dual of the Leontief price model. The Ghosh and Leontief models can be viewed as each others' mirror-image.
(Gallego & Lenzen, 2005)	Shared producer and consumer responsibility. Viewing *responsibility as a metric*, IO analysis is not used as a causal (quantity or price) impact model, but rather as a *descriptive* tool, *ex-post*… for distributing responsibility for resource use and pollution caused during industrial *production*.
(De Mesnard, 2009)	Dietzenbacher's interpretation (1997)—the Ghosh model… is able to serve for cost-push exercises——is fine… However… the familiar dual Leontief model of production prices performs the same task in a much simpler way.
(Lenzen & Murray, 2010; Marques et al., 2012)	The Ghosh model can address environmental responsibility from a downstream perspective*, with sales interpreted as quantities but strictly ex-post*. Presents nomenclature for downstream carbon footprints and "income-based" responsibility.
(Guerra & Sancho, 2011)	An *alternative closure* rule in line with the original allocation rules defined by Ghosh solves, to some extent, the implausibility problem because then value-added is correctly computed and responsive to allocation changes.
(Oosterhaven, 2012)	*Guerra & Sancho's extension makes it more problematic*. The prime reason is that complementarities between inputs are negated, not only for firms, but now also for households. Consequently, industry and aggregate output may now increase, while corresponding value added decreases, and vice versa.
(Manresa & Sancho, 2013, 2020)	The anomalous pathological economic behaviour reported by Oosterhaven (2012) for the closed Ghosh model has a parallel counterpart in the closed Leontief model.
(Oosterhaven, 2024)	Reiterates and elegantly proves the Ghosh price model (Dietzenbacher, 1997) and additionally proves that the demand-driven IO quantity model of Leontief may similarly be re-interpreted as the almost unknown revenue-pull IO price model.
(Altimiras-Martin, 2024)	Proposes an alternative Ghosh quantity model that endogenises the consumption of all primary inputs except the one driving the model… hopefully rekindling "supply-driven" analyses… e.g. to identify productive bottlenecks from a supply perspective.

Table 1: Summary of downstream IO papers and discourse.

4.2.2. Downstream IO conception and early days

However, IO *downstream,* which is focused on impacts by customers (not suppliers) as a result of our activities as producers (not consumers) is underutilised. IO analysis was initially conceived to incorporate all inter-industry upstream *supply-chain* inputs into to a product driven by final demand, however it did not consider the approach, conversely, of primary inputs associated with all inter-industry downstream *sales-chain* outputs. Ghosh (1958) postulated such an alternative approach for IO calculus where supply predominates rather than demand. Ghosh reasoned that this would be applicable to centrally planned economies, where monopolies dominated or in situations of scarcity and rationing (e.g., of capital or labour), for example. In this way, one could associate an IO matrix with two sets of coefficients; one was the production-side fixed technical coefficients, which was conceived by Leontief, and the other, that Ghosh proposed, was the supply-side fixed allocation coefficients, which have later also been called "sales" coefficients. Gallego & Lenzen (2005) infer that Ghosh perceived the allocation matrix a_{ij} as representing *value* coefficients, however they were subsequently employed as *quantity* coefficients.

Oosterhaven (1988) convincingly demonstrated that the Ghosh model from a causative quantity perspective was largely implausible, with the assumption of perfectly elastic demand meaning that factories could work without labourers or cars could drive without petrol, and that input ratios could in principle assume any value depending on supply. "So, the essential notion of production requirements, i.e., the production function, is actually abandoned" (p. 207)." He did, however, note the Ghosh model's *descriptive* uses while warning against *ex-ante* interpretations such as pertaining to shortages: "The descriptive device… may be used as long as it is not mistaken to indicate the causal effect" (p. 209).

4.2.3. Revival of the Ghosh model

A substantial counter response came a decade later from Dietzenbacher (1997), who noted that this critique was correct only when the Ghoshian model was assumed to relate to changes in the *quantity* of total output; if, however, it was interpreted as describing changes in output *values due to price changes,* then this Ghoshian "price" model yielded equivalent results to a Leontief price model, while also allowing for meaningful interpretation of the inverse matrix in terms of multipliers. Further, Dietzenbacher showed that the dual of the Ghosh price model is the Ghosh quantity model, which is equivalent to the traditional Leontief quantity model. Dietzenbacher in his vindication of the Ghosh model reinterpreted as a price model, concluded that the Ghosh (price) model and the traditional Leontief (quantity) model are each other's

With the value chain now being considered not just from an upstream perspective, the concept of producer and consumer responsibility was initially explored (Gallego & Lenzen, 2005; Lenzen et al., 2007; Lenzen & Murray, 2010; Rodrigues & Domingos, 2008; Rodrigues et al., 2006). Rodrigues et al., for example, reasoned that the environmental pressure from a product related to economic flow could be divided into its past (upstream) and future (downstream). Gallego & Lenzen (2005, p. 366) showed that in addition to IO analysis having being considered for *causal* (quantity or price) impact analysis, it could alternatively be used as a *descriptive* tool, *having responsibility as a metric*, and applied in an "*ex-post* manner for distributing responsibility for resource use and pollution caused during industrial production".[5] In considering how flows could be divided and responsibility assigned, Gallego & Lenzen discussed shortcomings of a previous attempt to include producers and consumers in an IO-type impact model, being the total-flow model. The total-flow concept arose out of the limitation of the classical Leontief model to account not for *total* industrial output but rather the fraction delivered into *final demand*. Total flow also accounted for intermediate transactions, however its non-additivity meant that the total-flow coefficient matrix could not be expressed as the sum of an infinite power series and also, one should consider in principle only one sector at a time (Szyrmer, 1992, in Gallego & Lenzen, 2005).

In a subsequent paper, Lenzen (2008) also demonstrated how the so-called "shared responsibility" approach could provide a solution to double-counting, through mutually exclusive and collectively exhaustive portions of responsibility shares. Previously, Lenzen et al. (2007) explained their recommendation for pegging responsibility shares to "total value added" because of its invariance properties. Although the GHG Protocol has recognised that double-counting by an organisation between scope-3 categories (e.g., upstream and downstream categories) may fulfil particular aims such as to drive value-chain reductions; if, however, the double-counting is addressed, the organisation should explain where the emissions remain reported and where adjustments have been made, using cross references if necessary (World Resources Institute & World Business Council for Sustainable Development, 2013, p. 57).

4.2.4. "Income-based" analysis adds to consumption- and production-based perspectives

Lenzen & Murray (2010) established a framework including terminology for IO "downstream carbon footprints", explaining that the environmentally extended IO Ghosh model extends

[5] The authors acknowledged the implausibility however from a causal quantity perspective: "*Ex ante*, the Ghosh model cannot be interpreted in a physical, causal sense: supply-side multipliers [G_{ij}] do not quantify the amount of output generated by an injection of primary inputs" (p. 368).

beyond traditional notions of downstream emissions, i.e., commonly associated with final *use* and *disposal* of our products, to *enabled* emissions incorporating the entire inter-industry sales chain. The authors (p. 264) discussed how the Ghosh model could be used in corporate reporting: "An analyst would specify the dollar bill of compensation payments for primary inputs **v** (labour, capital) into the companies, and use the downstream input–output calculus to determine the associated emissions."[6] Then in a case study, Lenzen et al. (2010) used income as an exogenous input in order to analyse aspects of the University of Sydney's *financial* operations though a nested IO (but not environmentally extended) enterprise model under various levels of closure. Marques et al. (2012) went on to distinguish by name, downstream responsibility as "income-based", because "primary inputs are provided for "a salary, or, in a broader view, an income" (p. 59). It should be noted that the GHG Protocol technical guidance on scope-3 calculations was developed about the same time (Marques et al., 2013; World Resources Institute & World Business Council for Sustainable Development, 2013), which may explain the lack of downstream emission factors in the guidance. For example, although the GHG Protocol includes seven downstream categories for corporate reporting, its technical guidance only includes the option of using EEIO emission factors from a "spend-based" perspective (World Resources Institute & World Business Council for Sustainable Development, 2013, p. 104). The supplement to the scope-3 Standard does not mandate the reporting of downstream emissions from all *indirect*-use phases of a product, with the Protocol reasoning that in some cases, the eventual end use of intermediate products and therefore associated emissions may be unknown and in those cases, exclusions are justified (World Resources Institute & World Business Council for Sustainable Development, 2011, p. 60).

Following the revival of the Ghosh model (Dietzenbacher, 1997) and the developmental phase of income-based IO analysis (Gallego & Lenzen, 2005; Lenzen & Murray, 2010; Marques et al., 2012), there have been numerous downstream IO studies, mostly income-based. Some studies are solely on income-based applications while others now consider consumption- and income-based perspectives. Xu et al. (2019) whose study uses income-based accounting for mitigation analysis of emissions from urban agglomeration in China, provide a comprehensive summary of previous income-based studies, which they said "proved" the effectiveness of the model; further, Xu et al. cite numerous studies that indicate that urban carbon emissions closely

[6] Lenzen & Murray (2010, p. 264) noted the appropriateness of taking an *ex-post* perspective, given the assumptions in classical IO analysis of fixed sales- and technical coefficients and therefore perfectly elastic supply and demand: "These assumptions limit its capability to evaluate future scenarios. As a consequence of this methodological shortcoming, most input–output models are applied to static as opposed to dynamic problems."

correlate with gross domestic product (GDP). These income-based studies take the Ghosh model as a given although some acknowledge its limitations. For example, Chen et al. (2017, p. 226), who tackled the lack of information about city-induced emissions by conducting a case study of Australia, describe both the upstream, backward linkages and the downstream, forward linkages as "well-established", while Steininger et al. (2016) consider various carbon accounting approaches, including those described above, and conclude that although none are perfect, each offers valuable contributions.

Subsequent studies, focused solely on income-based analysis, include: the carbon impact of capital and labour in France (Pottier & Le Treut, 2023), global methane emissions with a focus on structural decomposition analysis (Cheng et al., 2023), household carbon footprints in the United States (Starr et al., 2023) and water scarcity risk in Chinese cities (Fu et al., 2024). Recent studies that consider income- along with other perspectives such as consumption- and/or production-based (territorial) include: Chinese air pollution and inequality (Guan et al., 2019), global mercury emissions (Qi et al., 2019), Jing-Jin-Ji region's energy-related PM2.5 emissions between 2002-2015 (Li et al., 2021), Chinese carbon emissions with a focus on different production layers (Li et al., 2021), global trends and drivers of Polycyclic Aromatic Hydrocarbons emissions (Li et al., 2022), Brazilian regional production chains and carbon emissions between 2011-2018 (Sanguinet & Azzoni, 2024), and road-transportation carbon emissions using China as a case study (Liu & Zhou, 2025).

4.2.5. Recent discourse, research gap

In parallel, discourse about the Ghosh model has continued e.g., De Mesnard (2009) observed that the model was not the only way to conduct cost-push exercises and was therefore of limited interest; Guerra & Sancho (2011) proposed a remedy to what they refer to as the "alleged implausibility" of the Ghosh *quantity* model, which was then counteracted by Oosterhaven (2012) as even more implausible. More recently, Oosterhaven (2024) proposed a set of ultimate IO equations from the demand and supply sides, with a focus on inflationary processes. Another recent alternative downstream model was proposed by Altimiras-Martin (2024); Altimiras-Martin, who demonstrated how the Ghosh and Leontief models convey the same information from different "perspectives", proposed a reformulated Ghosh quantity model, which endogenises the consumption of all primary inputs except the one driving the model, with the total-requirements matrix being calculated as a function of the exogenous primary input. Nonetheless, the fact remains that the Ghosh model *ex-post* is useful from a *descriptive* perspective (Piñero et al., 2019).

In addition to Lenzen et al. (2010) who used income and expenditure inputs to analyse teaching and research scenarios at a university, only one IO study that considered an organisation's downstream impact has been identified (Gómez et al., 2016), but rather than using income, it used expenditure to demonstrate both upstream and downstream impact, which was achieved by transposition of columns and rows in Leontief inverse matrix, like global-level studies such as Meng et al. (2018). Such an approach does not analyse organisational responsibility in relation to its income but rather attributes all responsibility to expenditure decisions. A research gap therefore was identified regarding generalised income-based responsibility at the enterprise level, for downstream IO analysis linked to an organisation's *sales*, to complement well-established upstream IO analysis linked to an organisation's purchases. As is shown in Section 4.3.1, an added benefit is that such a Ghoshian approach enables the relatively straightforward use of income-based emission factors in concert with organisational income for non-experts to calculate downstream scope-3 emissions.

4.2.6. Clarifying note on value added, profit and shared responsibility

Before moving to the technical section, some literature is highlighted that supports the use of an organisation's total income (rather than, for example, profit) as a proxy for primary inputs ($\mathbf{v}$).

Lenzen et al. (2007) considered the question of whether gross operating surplus (GOS) would be a better variable for responsibility share as the only discretionary component of value added. Those authors conclude, "a disadvantage of the surplus-pegging method is that it does not have the same invariance property as the standard Leontief formulation" (p. 37 and proven in their Appendix A). Later, Lenzen & Murray (2010), who discuss downstream responsibility in terms of sales ($\mathbf{v}$), note earlier analysis that demonstrates symmetrically that taking full producer (or full consumer) responsibility could lead to multiple-counting throughout the value chain (Lenzen, 2008). In addition to the previous discussion of consistent approach to shared responsibility as a solution to double-counting, in Section 4.2.2, a post-calculation adjustment for the GHG Protocol is discussed in Section 4.3.2.3.1. Value added is also discussed by Dietzenbacher & Lahr (2013, p. 347) as commonly being employed to measure impacts of economic change. They explain that in comparison: "measurement of profit-type income is rather problematic in static economic models. This is because such income is in reality quite volatile from one year to the next since it moves with the business cycle and, thus, sometimes runs negative for certain industries."

4.3. Material and methods

4.3.1. IO supply-side calculus

The IO calculus used in this research for allocating environmental responsibility (for GHG emissions) is described below; here, the supply-side model for corporate reporting is used descriptively *ex-post* (Gallego & Lenzen, 2005; Lenzen & Murray, 2010).[7]

In the Ghoshian model, the downstream-equivalent coefficients matrix $\mathbf{B}$ is described as the inverse of the Leontief direct requirements/technical coefficients matrix $\mathbf{A}$ (Ghosh, 1958, p. 62).

$$\mathbf{B} = \hat{\mathbf{x}}^{-1}\mathbf{T} \quad (1)$$

where $\mathbf{T}$ is the matrix of interindustry transactions, $\mathbf{x}$ is *total input*, and the hat symbol (^) represents a diagonal matrix. Here, the *rows* of *direct* allocation/sales coefficients in $\mathbf{B}$ show the output across sectors per unit sectoral input. The transposition from the demand-side "production recipe" columns in $\mathbf{A}$ to the supply-side sales rows in $\mathbf{B}$ is achieved through the pre-multiplication of $\mathbf{T}$.

Following the calculus for the famous Leontief inverse ($\mathbf{L}$), the Ghoshian inverse is then:

$$\mathbf{G} = (\mathbf{I} - \mathbf{B})^{-1} \quad (2)$$

where the rows of *total* allocation/sales coefficients in $\mathbf{G}$ show the output across sectors, both direct and indirect, associated per unit primary input.

Next, for the environmental extension, a direct-intensities vector ($\mathbf{q}$) of size $1 \times N$ is calculated from a satellite of size $1 \times N$ ($\mathbf{Q}$): of physical quantities of GHG emissions:

$$\mathbf{q} = \mathbf{Q}\hat{\mathbf{x}}^{-1} \quad (3)$$

where the column vector of direct emission factors are impact production factors per unit sectoral *output*.

The EEIO downstream impact can then be calculated as factor impacts:

$$F = \mathbf{v}\mathbf{G}\mathbf{q}' \quad (4)$$

(see, for example, Xu et al. (2019)). Here $\mathbf{v}$ is a row vector of primary inputs the prime symbol ($'$) denotes transposition. The equation is then re-arranged so that, rather than producing a scalar

[7] Following Gallego & Lenzen's use of the Ghosh model as descriptive tool for allocating environmental *responsibility* as a metric*, ex-post* (2005), Lenzen & Murray (2010) in the context of establishing a framework for quantifying downstream carbon footprints, interpret sales as quantities, but strictly *ex-post*.

for GHG Protocol scope-3 categories (see Section 4.3.2.3), it is disaggregated to yield sectoral results. Below, equations (5) and (6) are the Ghosh equivalent of the Leontief production vs consumption perspectives (Malik et al., 2022; Miller & Blair, 2022), which Miller & Blair demonstrated in aggregate sum to the same amount.

To view emissions from the perspective of emitting industries ($\mathbf{q}$):

$$\mathbf{F} = (\mathbf{vG})' \circ \mathbf{q}' \tag{5}$$

To view emissions from the perspective of primary inputs:

$$\mathbf{F} = \mathbf{v}' \circ \mathbf{Gq}' \tag{6}$$

where the Hadamard symbol (°) represents element-wise multiplication and where, paraphrasing Chen et al. (2017), the downstream vector of *total* intensities, which is referred to here as carbon forward multipliers ($\mathbf{CFM}$), is calculated as:

$$\mathbf{CFM} = \mathbf{Gq}' \tag{7}$$

This total-intensity vector comprises allocations of sectoral emission-intensities per unit primary input, thereby coupling the direct environmental intensities per sector with the sectoral sales-chain multiplier.

The Ghosh inverse calculated in equation (2) can be decomposed per order of production (Layer) through a power series $\mathbf{G} = \mathbf{I} + \mathbf{B} + \mathbf{B}^2 + \mathbf{B}^3 + \ ...^{\infty}$ where $\mathbf{I}$ is an identity matrix. This translates in the downstream EEIO calculus (equation (4)) as $F = \mathbf{v}(\mathbf{I} + \mathbf{B} + \mathbf{B}^2 + \mathbf{B}^3 + \cdots^{\infty})\mathbf{q}'$, which can be expanded into a production layer decomposition (PLD) as described by Li et al. (2021):

$$F = \underset{\text{Layer 1}}{\mathbf{vq}'} + \underset{\text{Layer 2}}{\mathbf{vBq}'} + \underset{\text{Layer 3}}{\mathbf{vB}^2\mathbf{q}'} + \underset{\text{Layer 4}}{\mathbf{vB}^3\mathbf{q}'} + \cdots \underset{\text{Layer n}}{\mathbf{vB}^n\mathbf{q}'} \tag{8}$$

In this paper, the PLD in equation (8) is decomposed, for analysis to a higher degree of resolution, from the emitting-industries perspective (equation (5)) such that:

$$\mathbf{F} = \underset{\text{Layer 1}}{\mathbf{v}' \circ \mathbf{q}'} + \underset{\text{Layer 2}}{(\mathbf{vB})' \circ \mathbf{q}'} + \underset{\text{Layer 3}}{(\mathbf{vB}^2)' \circ \mathbf{q}'} + \underset{\text{Layer 4}}{(\mathbf{vB}^3)' \circ \mathbf{q}'} + \cdots \underset{\text{Layer n}}{(\mathbf{vB}^n)' \circ \mathbf{q}'} \tag{9}$$

Of course, specific sales chains could also be analysed using structural path analysis (SPA) such that for a simple one-stage sales chain for example, paraphrasing Lenzen & Murray (2010),

if defining emissions intensity as q_j, $F = v_j q_j$, with our downstream responsibility calculated from our customer's emissions and the fraction of our sales in our customer's input.[8]

In summary, the Ghosh model's justified use as a *descriptive device* (but not as an *ex-ante quantity* model), as initially identified by Oosterhaven (1988) and later defined from an *ex-post* perspective for distributing responsibility (Gallego & Lenzen, 2005; Lenzen & Murray, 2010), has potential as a powerful tool. In this paper, to complement well-established upstream corporate supply-chain analysis, it is shown how to perform the dual responsibility allocation downstream of corporate sales-chain analysis, for annual reporting pertaining to corporate purchases and sales that have already taken place.

Mirroring the approach in upstream hybrid IO-LCA enterprise calculations, where *organisational expenditure is used as a proxy for final demand*, in the downstream equivalent $Q = \mathbf{vGq}'$, *organisational sales/receipts are used as a proxy for primary inputs* ($\mathbf{v}$) in this study, following Lenzen et al. (2010) whose case study analysed financial, not environmental impacts, and the generalised downstream approach described by Lenzen & Murray (2010). No paper has detailed how to obtain the vector $\mathbf{v}$ representing an organisation's relevant income per sector. The novel framework is described in the sections that follow.

4.3.2. Framework for measuring organisational income-based impact

Here, a novel framework is developed for income-based IO analysis at the enterprise level:

1. Decision-making is discussed regarding how to harmonise organisational sales with the sectors to which our customers belong, in order to calculate the enabled production downstream; a special case is highlighted regarding membership organisation service providers focused on high-intensity sectors downstream (Section 4.3.2.1).

2. An approach regarding the treatment of public-sector grants as non-market (i.e. the drivers are *political*) is presented, which is important for organisations that may be reliant on such income (Section 4.3.2.2).

Then:

3. The framework is discussed in relation to the global scope-3 Standard, the GHG Protocol. It is shown how to apply IO analysis across GHG Protocol categories downstream. Also

[8] "Mathematically speaking, the downstream responsibility Q_j^{down} of a supplier (for example a worker or an investor) who sells to us an amount v_j of primary inputs j (for example labour or capital), for our emissions Q_j, is calculated from a) our emissions Q_j, and b) the fraction v_j/x_j of our supplier's sales v_j in our input x_j" (Lenzen & Murray, 2010, p. 265).

discussed are activities that are not related to inter-industry production and therefore where non-IO calculations may be undertaken e.g., for Category 15 Investments (Section 4.3.2.3).

4.3.2.1.Harmonising organisational sales with customer sectors for production downstream

In order to undertake the IO calculus, it must first be determined how to harmonise the organisation's sales with customer sectors, in formulating the primary-inputs vector ($\mathbf{v}$) as the starting point for allocating downstream responsibility.

Recall that upstream, the harmonisation of organisational expenditure with sectors can be relatively intuitive e.g., it tends to be clear which are the *sectors that supply us*, whether it be emissions-intensive sectors such as energy or lower-emissions services sectors. Downstream, conversely, it is the *sectors we sell* to, viewed from the perspective of enabled emissions. In some cases, the sectors that our direct customers belong to may be easy to ascertain from receipts. However in many cases, details about the business are required or discussion with subject-matter experts, in order to map appropriately the destination of our outputs with the receiving sectors from which our customers originate.

Just as upstream, products we purchase can be seen to include embodied supply-chain emissions, downstream, products we sell can be seen to include enabled sales-chain emissions. As noted in Section 4.2, equity concerns regarding income-based IO downstream may be addressed through "shared responsibility", for example in terms of value-added (Lenzen et al., 2007, pp. 34-35). However, the GHG Protocol did not at the time of writing consider a value-added approach to shared-responsibility, although it did allow for adjustments to address double-counting of an organisation's emissions (World Resources Institute & World Business Council for Sustainable Development, 2013, p. 111).

So how does the production cycle downstream compare to upstream visually?

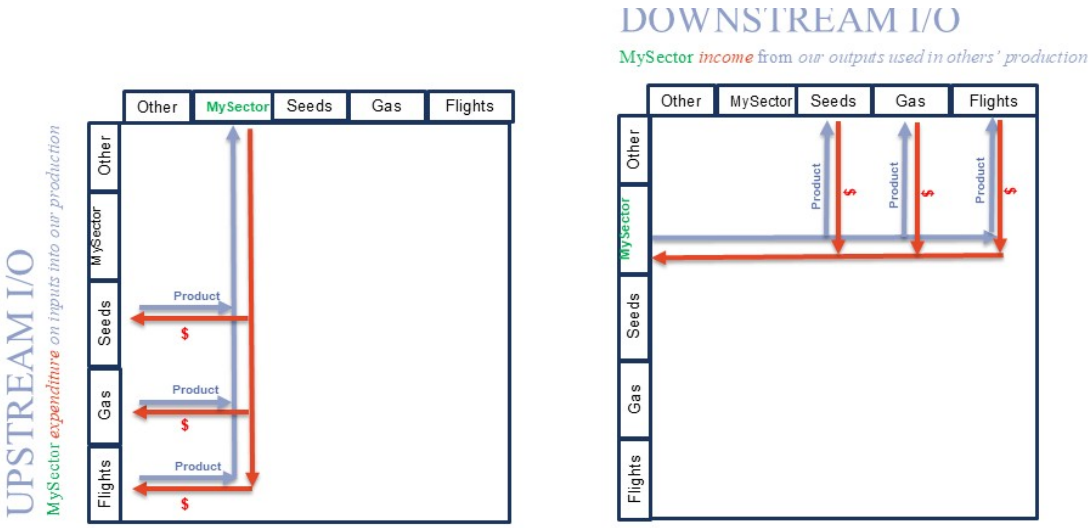


Figure 1: Upstream vs downstream: The cycle of inter-industry production

As can be seen in Fig. 1, the left-hand inter-industry table is the Leontief model, where the sectoral contributions to MySector's production is a combination of the inputs listed in the various rows (in return, MySector pays those suppliers for their products). The right-hand inter-industry table is the Ghosh model. Here, rather than buying product, MySector sells product, which is a combination of the outputs listed in the various columns (in return, MySector receives payment for sales of its product). In other words, for the inter-industry value chain upstream: what sectors supply MySector and downstream: to which sectors MySector sells.

Using a simple example, if we received income from the pharmaceutical industry for research to enable their development of new medicines, we harmonise this income with the pharmaceutical industry. A seemingly more complicated example becomes straightforward if we continue to focus on *which sector our customer is from*. For example, if we undertook research for an iron-ore mining company to develop autonomous mining technology, we harmonise this income with the iron-ores extraction sector; the *customer is from the iron-ores sector* and as a result of the income we received from them, we *enabled them to mine iron ore*.

It is, however, important to bear in mind that for highly aggregated sectors such as umbrella services sectors, the downstream impact could vary greatly depending on the final-destination sector that our product enabled, compared to upstream. In this case, bottom-up information may be used to provide a more appropriate sector harmonisation; this is in line with the spirit of ISIC, which supports flexibility where required: "If a particular economic sector is economically of great importance or has developed important specializations that are not separately

identified in ISIC, the relevant part of the classification can be further disaggregated" (Task team on ISIC, 2024, p. 30).

4.3.2.1.1. Special case: certain membership organisations

Detail may become important where our outputs are not related to positive change, facilitating emissions-intensive business-as-usual. Take, for example, a (service) cattle or coal membership organisation. Such levied trade associations were at the time of writing grouped by international frameworks in aggregate regardless of the sector they are ultimately focused on, for example, ISIC Revision 4 groups trade associations into Section S "Other service activities"/9411 "Activities of business and employers membership organizations", which includes "activities of organizations whose members' interests centre on the development and prosperity of enterprises in a particular line of business" (United Nations Department of Economic and Social Affairs, 2008, p. 263). This differs from what ISIC refers to as support activities to agriculture (p. 73) or mining support service activities (p. 84), which are grouped variously with agriculture and mining.

Regarding trade associations, from an upstream perspective, such service *activities* are relatively low-emissions intensive. However, the *ultimate impact downstream* is emissions from cattle or coal production. Although the inter-industry transactions in IO tables ultimately reflect this in the "service" contributions to the cattle or coal sectors, the grouping of all trade associations regardless of type does not reflect their heterogeneity from a downstream perspective. Therefore it could be argued that if we know we enabled, for example, cattle-raising- or coal-mining activities, a more appropriate reflection is that our sale to the trade association in question should be harmonised with the ultimate-destination emissions-intensive sector being enabled (e.g., cattle raising/coal mining).

An exception, however, may involve cases of emissions-intensive industries in transition. For example, sales of research into reducing cattle methane emissions, to a cattle trade association, could be argued to have as much potential to *reduce emissions* as sales to the same association to increase cattle productivity may have on potential to *increase emissions*; in such a case, it is recommended that the sales remain harmonised with the relevant service sector, rather than being upgraded to the final-destination sector.

4.3.2.2. Approach to the public sector

The starting point is that *non-grant* income from the public sector can be considered as related to market production and therefore be included in the IO analysis. An example of non-grant public-sector income is funded research positions for university academics co-located at a

public hospital. As such, non-grant payments are made for outputs that the paying customer *uses* in the production process, in this case, research for production. This meets the definition of economic production by ISIC, whose focus is on the *type* of activity regardless of *who* is the producer:

"ISIC is a classification according to kind of economic activity [regarding]... units engaged in economic production as defined by SNA, which states: 'Economic production is an activity carried out under the control and responsibility of an institutional unit that uses inputs of labour, capital, and goods and services to produce outputs of goods and services' (2008 SNA, para. 6.24)"(Task team on ISIC, 2024, p. 6).

SNA specifies that in addition to producers using the output for production, a feature of market production includes that the producer unit has "imputed expenditure on the output" (European Communities et al., 2009, p. 110).

A benefit of including all non-grant income is that it is not necessary to distinguish between such income as being derived from the public sector, as opposed to income provided by the private sector.

But what about *grant* income, where the public sector also uses the outputs it pays for as a producer? In an ideal world with perfect information, the approach to such public-sector grant income is that it may, potentially, also be classified according to the producing sector. In reality however, identifying which grant income is part of inter-industry market activity (where the paying customer uses the output for production) may be complicated. Such grants may not be clearly named nor information forthcoming in a timely manner to align with annual reporting. Putting aside the question of grant income that *may* be identified as linked to *production* for the time being, what about untied, general-purpose public-sector grants? SNA views public-sector activities as "based on political and social considerations rather than on profit-maximization" (European Communities et al., 2009, p. 435). Therefore public-sector provided *grant income for the commons* can be justifiably treated as *non-market* and therefore excluded from the IO analysis. SNA clarifies: "Non market output consists of goods and individual or collective services produced by non-profit institutions serving households (NPISHs) or government that are supplied free, or at prices that are not economically significant" (European Communities et al., 2009, p. 110). An example of non-market grant income from this perspective is untied grants for university infrastructure, which may be seen as supporting the provision of education and research for public wellbeing.

Considering the various challenges and perspectives, a hybrid approach is taken to the public sector and its components, including government, non-profit institutions and also university research and development (R&D), to reflect variously parts of SNA and ISIC. Definitions and further information about the treatment of the public sector by SNA and ISIC, which take opposing viewpoints, are in Section 4.7.3. Below, the approach to the public sector developed for this novel enterprise framework is summarised.

1. **Exclude public-sector *grants*** (SNA aligned; no need to identify cases of market production)*:*
    - Government grants treated as non-market and therefore excluded from the IO analysis. Also excluded as part of the public sector are:
    - Non-profit institutions (NPI) grants (NPIs treated as a proxy for households or government). The SNA notes that NPIs can act as non-market or market actors, but that only NPIs serving corporations (which behave like corporations), termed "quasi-corporations" are considered as intermediate/market producers. An example of a quasi-corporation is a trade association (European Communities, International Monetary Fund, Organisation for Economic Co-operation and Development, United Nations & World Bank, 2009, p. 455). See Table 3 for an example of decision-making regarding whether or not an NPI may be a quasi-corporation; further information on NPIs is in Section 4.7.3.4.
    - University grants*; University* research and development (R&D) is considered non-market and therefore excluded, as opposed to commercial R&D, which is market (European Communities et al., 2009, p. 119).
2. **Include public-sector *non-grant income*** (ISIC aligned; no need to distinguish between public and private customers):

Here, in the same way as in *upstream* IO analysis our demand (expenditure) is viewed as the driving force for production, *downstream* our sales (income) are associated with enabled production by our customers. This is distinct from the approach to income from public-sector *grants* (excluded in 1 above), which is viewed as being underpinned by non-market considerations. In addition to the relative ease of implementation of 1 + 2 above, in the University case-study results (Section 4.4), the inclusion or exclusion of the public sector does not make a meaningful difference in terms of hotspots.

4.3.2.3. GHG Protocol downstream categories

The GHG Protocol defines 15 scope-3 categories, including seven downstream categories: 9 – Downstream Transportation and Distribution; 10 – Processing of Sold Products; 11 – Use of Sold

Products; 12 End-of-life Treatment of Sold Products; 13 Downstream Leased Assets; 14 Franchises and 15 Investments. Some highlights are below and further details that had been prepared to assist future anticipated auditing is in Section 4.7.1.

From an IO perspective, not all GHG Protocol scope-3 categories relate to intermediate/inter-industry production, so it is important to identify where non-IO calculations may be undertaken. Since investment does not tend to be treated as part of intermediate production, investment income is excluded from IO analysis and therefore any emissions from investments can be calculated separately. Similarly, households tend to be treated as exogenous to intermediate production in IO analysis; the GHG Protocol provides for emissions from customer travel to retail stores to be optionally included (World Resources Institute & World Business Council for Sustainable Development, 2013, p. 103), so any emissions from households travel can be calculated separately using non-IO methods. After harmonising relevant organisational income with sectors as described in Sections 4.3.2.1-4.3.2.2 and calculating the total emissions downstream from inter-industry production, using IO analysis, this can be further disaggregated between the relevant GHG Protocol downstream categories.

Category 12 End-of-Life Treatment of Sold Products is interpreted as relating to income from waste-related sectors from an inter-industry perspective; similarly category 11 Use of Sold Products is treated from an inter-industry perspective, noting that the GHG Protocol acknowledges that category 11 can be used to record *indirect use*-phase emissions (World Resources Institute & World Business Council for Sustainable Development, 2013, p. 113). Emissions for categories where income is identified can be calculated using equation (6). For categories where no income is received, the emissions will be zero. For example, if no *income* had been received from leasing assets, then the emissions in category 13 Downstream Leased Assets would be zero. The remaining emissions downstream from the total calculated using IO analysis are apportioned between the aggregated categories 10-11 for processing and use of products. Emissions from these remaining two categories could be calculated from the *proportions* of, for direct-customer use, $\mathbf{vq}$ (Layer 1 in the production-layer decomposition equations (8-9)), compared to the rest of the sales chain as the processing component ($\mathbf{vGq}' - \mathbf{vq}'$). Alternatively, the emissions for these two categories could be calculated variously as the *sum* of $\mathbf{vq}$ per remaining sector that attracted income, for category 11 Use of Sold Products, and the sum of ($\mathbf{vGq}' - \mathbf{vq}'$) for those remaining sectors that attracted income, for category 10 Processing of Sold Products; this alternative approach is also accessible to the non-expert, through the use of emission factors including the total forward multipliers ($\mathbf{CFM}$) in equation (7), which does not involve large calculations including the Ghosh inverse ($\mathbf{G}$). Note: the University

of Sydney has disclosed its audited scope-3 emissions across GHG Protocol categories incorporating the approach of this pilot 2022 framework, which demonstrates its reproducibility because the disclosure is subject to recalculation as part of the assurance process; for example see the first disclosure (The University of Sydney, 2025).

4.3.2.3.1. Double-counting adjustment

Assuming that emissions are separately recorded against *upstream* GHG Protocol categories, an organisation may finds double-counting between scope-3 categories i.e., the reporting entity's upstream and downstream scope-3 emissions pertaining to the same sector, to be useful in terms of providing a comprehensive value-chain perspective (World Resources Institute & World Business Council for Sustainable Development, 2011, p. 108). If, however, the intention is that emissions in the 15 scope-3 categories sum to the reporting entity's total inter-industry value-chain emissions, i.e.,, there cannot be double-counting, then adjustments may be made. Given that IO analysis upstream and downstream refers to the same pool of global GHG emissions but from different total-lifecycle perspectives, such double-counting could occur where the reporting entity calculates its emissions upstream from a particular sector and then calculates emissions downstream attributed to the same sector. In such instances, any additional calculations could be made as advised by the GHG Protocol (World Resources Institute & World Business Council for Sustainable Development, 2013, p. 111); the Protocol does not specify how such adjustment(s) should be made, only that the reporting entity's approach should be transparent (World Resources Institute & World Business Council for Sustainable Development, 2011, p. 57).

4.3.3. Data and application: University case study

The University had 199 unique revenue class codes, encompassing almost 300,000 separate line items for the period of January to December 2022. The vast majority of the income classes were for fees from students (households, exogenous to intermediate production, see Section 4.3.3.1) and government grants (non-market) and so were excluded from the IO analysis (although an alternative scenario including public-sector grants was also tested (Section 4.3.3.3)). Nonetheless, about 35,000 line items of eligible income were included, which needed to be harmonised with sectors in the MRIO database [Global Resource Input-Output Assessment] GLORIA (Lenzen et al., 2017; Lenzen et al., 2022). See Table 2 for a summary of the approach taken regarding which key income streams were treated as exogenous and which were included, as part of market production, for the IO calculus. Although the broad framework presented in this paper could be applied to other IO databases, for example focusing on national rather than global IO data, GLORIA was chosen as fulfilling particular University of Sydney requirements. These were: to facilitate international benchmarking and analysis and

consider reputation in terms of collaborations (i.e., UNEP in providing the underlying MRIO and GHG data for the Sustainable Consumption and Production Hotspot Analysis Tool https://scp-hat.org/). GLORIA's low levels of uncertainty, including for the case-study country Australia (Lenzen et al., 2022, Supplementary Information, p. 62), was also taken into account. As well, comparability between key global MRIO databases generally was considered including EORA, which was used as the initial estimate for GLORIA (Moran & Wood, 2014; Owen et al., 2014). The GHG Protocol's Accounting and Reporting Principles (World Resources Institute & World Business Council for Sustainable Development, 2011) were considered in terms of prioritisation for accuracy and also transparency in ensuring efficient comprehensive reporting.

4.3.3.1. Emissions from activities unrelated to intermediate production

To report on emissions in GHG Protocol category 15 Investments and 9 Downstream Transportation and Distribution (relevant to flights to Sydney by international students), process-based approaches were taken; these emissions unrelated to intermediate production were added to the University's emissions that were calculated using IO analysis (see below, Section 4.3.3.2). Income from international students accounted for about half the University's income (The University of Sydney, 2023), suggesting that emissions from international students' travel to the "retail outlet", should be optionally calculated (World Resources Institute & World Business Council for Sustainable Development, 2013, p. 103). The approach of Heller, Sun, Guo and Malik (2022) was followed in relying on the online ICAO Carbon Emissions Calculator (International Civil Aviation Organization, n.d.), based on commencing students and assuming the most direct route was taken, in Economy class; and emissions were assigned to the students' country of residence. Similarly, since investment was treated as exogenous to intermediate production, investment income (The University of Sydney, 2023) was excluded from the IO analysis, with the estimated financed emissions that were calculated by an external consultant using non-IO methods (The University of Sydney, 2022) used for GHG Protocol category 15.

4.3.3.2. Emissions from intermediate production

In the following, rebalanced multi-region, input-output (MRIO) tables are used from 2021; in this paper, the indicator reported on is GHG emissions. The latest version at the time, GLORIA Release 059 (Lenzen & Li, 2024; Schandl et al., 2024), distinguished 120 sectors and 164 regions.

Following and building on prior work (Lenzen et al., 2010; Lenzen & Murray, 2010), the University of Sydney's revenue data was extracted from the general ledger from which to compile the

value-added ($\mathbf{v}$) matrix.[9] As with Baboulet & Lenzen (2010), concordance matrices were used to harmonise the University's unique class codes to sectors, in order to perform the IO analysis. Simultaneously, an upstream (spend-based) analysis was undertaken for the University by Reiner & Malik (*under review*) but downstream, the harmonisation of income to sectors described in this paper required less detailed analysis because income included in the IO analysis represented a minority of the total (expenditure plus income) used in the IO analyses; as well, income that the University received tended to be from relatively low-emissions sectors.

In order to perform the analysis efficiently for the pilot study, all income was harmonised with Australian sectors; an exception to the general focus on Australia was made regarding international student travel (see Section 4.3.3.1 "Emissions from activities unrelated to intermediate production"), because of the large number of students who had a different primary country of residence and the emissions intensity of aviation. Downstream, the sector harmonisation was generally not straightforward, since it had to be determined for each class code, which sectors paid for the University's outputs. For example, a substantial amount of the University's income was from consultancy or contract research. For each of these class codes (e.g., 2115 Research Grants Industry; 2117 Research Grants Overseas etc.) the proportionate representation of the various sectors for which the research was performed had to be estimated. In some cases, University subject-matter experts provided an estimated breakdown. For most classes, a process was required in order to estimate the sectoral composition of classes in a way that was not only effective but also efficient. This harmonisation was undertaken through prioritisation, noting that the GHG Protocol stresses the importance of efficient yet effective reporting in addition to continuous improvement (World Business Council for Sustainable Development & World Resources Institute, 2004, p. 59). Most time was spent on analysing the classes representing the most income or that included the most high-emissions intensive sectors (for example, relating to agricultural research). Of those, the key contributors per class were harmonised with GLORIA sectors. Where this was not immediately clear and a class represented less than 1% of the downstream income included in the IO analysis, the income was harmonised with "Professional, scientific and technical services". Trade margins were calculated (Australian Bureau of Statistics, 2024a, 2024b) for the class 2600 Farm Sales, since the agricultural sales were made via Australian broking agencies.

Because of material income received from a member-based trade association *serving* the cattle industry, which is high-emissions intensity (Intergovernmental Panel on Climate Change, 2022),

[9] In this study, the Ghosh model is interpreted as a descriptive model strictly *ex-post*.

further investigation was undertaken to determine whether the research income should be harmonised with the umbrella "Other services" sector, which includes trade associations, or instead be harmonised with "Raising of cattle" to reflect traditional meat production (as discussed generally in Section 4.3.2.1.1). The analysis indicated that similar amounts of the University's research income from this trade association was for projects variously on projects to (a) increase profitability (i.e., from increased cattle production); (b) reduce methane emissions; and (c) reduce animal mental- and physical ill-health, which could potentially also result in improvements in profitability (a) and environmental sustainability (b). Since productivity increases and methane decreases would have opposite impacts on emissions, and the impact of other research in (c) was unclear regarding emissions, it was decided that it was unlikely there would be any substantial net increase in meat emissions (and potentially there would be a decrease); therefore, all of this trade-association income was harmonised with the aggregated services sector rather than being upgraded to cattle-raising.

4.3.3.2.1. Hypothetical situation: Cattle research switches to enabling traditional production

However, to illustrate what would have been the impact downstream in a hypothetical situation where all the University's research for the livestock-focused trade association had been for *traditional* cattle raising (rather than also to reduce cattle methane emissions, for example), a second calculation was made where this income was switched from being harmonised with the "Other services" sector instead to being harmonised with "Raising of cattle".

CUSTOMER/GHG CATEGORY AS RELEVANT	**POSSIBLE INTERMEDIATE USE?**	***IF POSSIBLE INTERMEDIATE USE*, IO OR Non-Market?**	**COMMENT**
Student	No		Households treated as exogenous
Government	Depends on circumstance	Public-sector grants: Non-Market Non-grant income: IO	SNA approach: separates public from non-public. ISIC approach: focused on activities, not who is the customer.
Bequest	No		Households treated as exogenous
Individual Grant	No		Households treated as exogenous
Non-profit Institution (NPI)	Depends on circumstance (assuming not a quasi-corporation)	Public-sector grants: Non-Market Non-grant income: IO	SNA approach: separates public from non-public. ISIC approach: focused on activities, not who is the customer.
Quasi-corporation NPI	Yes	IO	SNA, like ISIC, treats these as corporations (non-public).
Research institute NPI	Yes	Public-sector grants: Non-Market Non-grant income: IO	SNA approach: separates public from non-public. ISIC approach: focused on activities, not who is the customer.
Teaching grants (for students)	No		Households treated as exogenous
Operational grants (from government)	Yes	Public-sector grants: Non-Market	SNA approach: separates public from non-public.
Industry research grant	Yes	IO	
Consulting	Yes	IO	
Shared research grant paid by another university (NPI)	Yes	Public-sector grants: Non-Market	SNA approach: separates public from non-public.
Funded research position (NPI)	Yes	IO	ISIC approach: focused on activities, not who is the customer.
Sale of goods to business	Yes	IO	
Downstream leased assets	Yes	IO	
Franchises	Yes	IO	Only relevant if franchised operations.
Investments	No		Treated as exogenous

Table 2: Categorisation of key income streams for potential downstream input-output analysis, with a focus on customer categories that were considered for the University of Sydney case study.

	NPI Research Institute: Cooperative Research Centre (CRC)	**NPI Member-based trade association**
Focused on a particular subset of other market producers?	NO – serves the general public	YES – serves the particular industry of its members
Funded by enterprises?	NO – government & donations	YES – levied

Table 3: Two examples representing different extremes, being a non-profit institution (NPI) research institute (left-hand column) and a trade association (right-hand column), tested against various requirements in the System of National Accounts (SNA) in forming the decision regarding whether the NPI is a quasi-organisation, based on affirmative responses (or otherwise) to the quest

4.3.3.3. Testing the alternate scenario: Including Pubic-sector grants

In order to test the robustness of the framework proposed in terms of excluding all public-sector grants from the IO analysis (Section 4.3.2.2), an alternative was analysed (however, *generic* grants such as for systemic research remained excluded, as not being linked to a paying customer who would use the purchased outputs). In general, 48.4% was included according to estimates of *applied* research (Ferguson, 2022, "Expenditure by type of activity") unless the grants were in partnership with industry in which case 100% tended to be included. Public-sector grants were generally harmonised with low-emissions intensive industries such as “Government; social security; defence; public order” or “Professional, scientific and technical services”.

4.4. Results

This Section presents GHG Protocol category results (4.1), emissions disaggregated by broad sector groupings and key sectors (4.2), alternate-scenario results to test the framework by including public-sector grants (4.3) and hypothetical results in the event that all income from the cattle-related trade association had been for traditional production rather than having a strong focus on assisting the industry’s low-carbon transition (4.4).

For the University of Sydney case study, because the key inter-industry customers were not from high-emissions-intensive sectors, the emissions calculated as part of IO analysis downstream were relatively small (but see Section 4.4.4 for a hypothetical comparison). Two key activities not associated with inter-industry production, being the relatively high-intensity financial *investments* and flights by international *students*, were the University’s hotspots downstream; these were calculated using non-IO methods.

4.4.1. GHG Protocol scope-3 emissions downstream

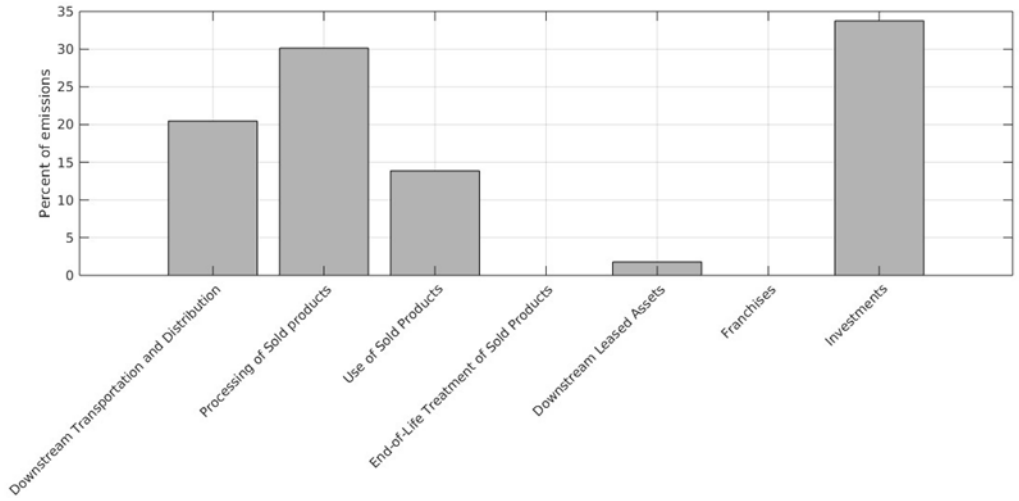


Figure 2: University of Sydney emissions across GHG Protocol scope-3 downstream categories 9-15, from the 2022 pilot. *The middle categories represent emissions from the inter-industry sales-chain*, calculated using IO analysis, while emissions in the first and last categories were calculated using non-IO methods, since no income was received from transport-related sectors and investment is exogenous to intermediate production. Percentages rather than physical quantities of emissions are provided because the information in this report is not an official or endorsed disclosure of the University of Sydney and has not been internally reviewed or approved by the University or subjected to an assurance process; no reliance should be placed on the information

Fig. 2 shows the proportionate contribution of the University's downstream emissions per GHG Protocol downstream category in 2022 (GHG Protocol scope-3 categories 9-15), applying Section 4.3.2.3 of this framework. No emissions were recorded for category 12 End-of-Life Treatment of Sold Products because no income was received from the waste sector; as well, no emissions were recorded for category 14 Franchises because the University has no franchises. The relatively small proportion of emissions from inter-industry sales to direct customers (Use of Sold Products) compared to the rest of the sales chain (Processing of Sold Products) is evidence that the University cannot easily exert substantial influence on reducing the downstream inter-industry emissions, since the sectors the University sold directly to tended to be low-emissions-intensive, for example, services sectors.

4.4.2. Disaggregating impact according to emitting industries

The relatively small proportion of the University's emissions from inter-industry production is further evidenced in Fig. 3, which decomposes the sales chain according to equation (4) ($\mathbf{vG} \circ \mathbf{q}$) in order to assess hotspots per sector as a result of *all* sectoral customers' payments to the University; for example, as is highlighted in the bar chart (left-hand panel), one of the top sectors downstream was electricity, although the University did not gain any income from sales to the electricity sector. In other words, the University's downstream emissions includes from customers consuming traditional electricity to use the outputs, as well as manufacturing enabled by the University's sales, for example through licences and royalties. The University derived some income from research for the relatively high-emissions-intensive cropping sector; almost all the emissions in this sector came from the University's direct customers (at Layer 1 in the production layer decomposition (PLD), right-hand panel), rather than increasing significantly at subsequent downstream production layers. In the PLD, the emissions from international student travel and financed investments were added at production-layer 0. See Section 4.7.2 for the sectoral aggregator.

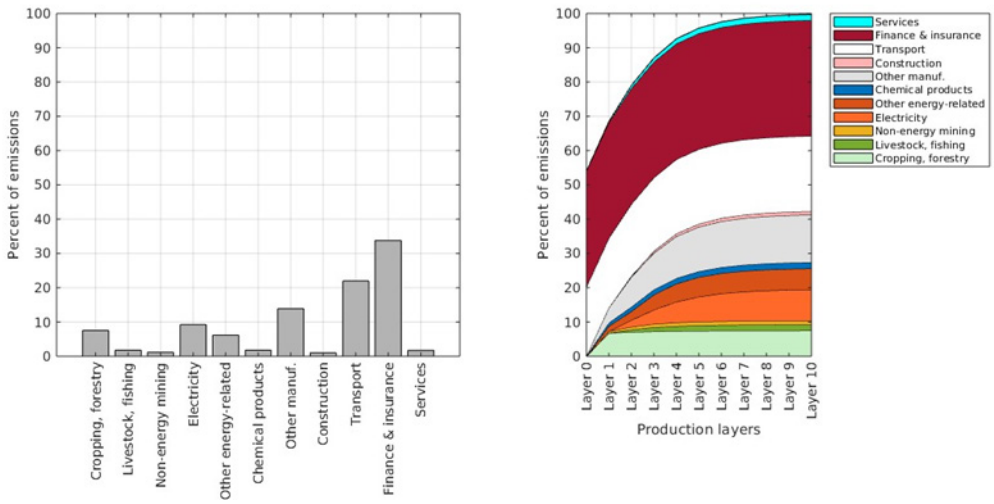


Figure 3: University of Sydney GHG emissions downstream in 2022 by key sectors and broad sector groupings, calculated from the perspective of emitting industries ($\mathbf{vG} \circ \mathbf{q}$). The right-hand panel is a production layer decomposition (PLD), with inter-industry sales-chain effects from Layer 1 onwards, and emissions from financed investments and international student travel added at production-layer 0. Percentages rather than physical quantities of emissions are provided because the information in this report is not an official or endorsed disclosure of the University

4.4.3. Alternate scenario shows the Framework is robust

To test the robustness of the framework that excludes public-sector grants, alternatively, emissions that may have been enabled from a substantial public-sector-as-producer were also estimated (from alternative-data Section 4.3.3.3). This alternate scenario more than doubled the income included in the IO analysis (in the primary-inputs matrix $\mathbf{v}$); however, the University's emissions from downstream production in this scenario only increased by about the same amount as the total emissions from financed investments. As well, the downstream emissions from intermediate use of the University's output were distributed throughout the sales chain.

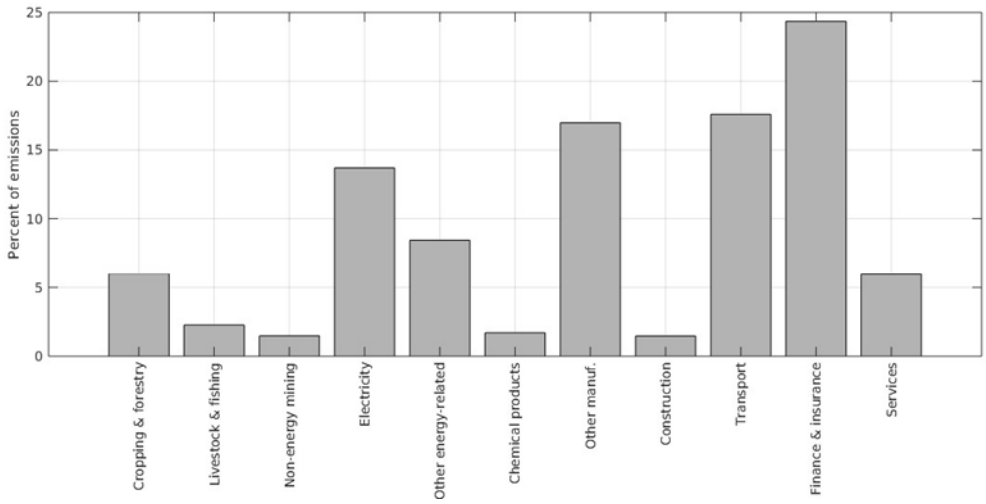


Figure 4: The University of Sydney's downstream emissions in 2022, including from public-sector grants. In this alternate scenario where public-sector grants are included as part of market activity, the most emissions still come from the Transport and Finance/Insurance sectors, mostly from international *student* aviation and financed *investment,* rather than the inter-industry sales chain. Proportionate emissions from production remain similar to the University's emissions in Fig. 3 calculated by excluding the public sector as non-market. An exception is the umbrella aggregated Services sector, which increased more than the other sectors, since the public sector is largely made up of services such as healthcare, education, and government. Percentages rather than physical quantities of emissions are provided because the information in this report is not an official or endorsed disclosure of the University

4.4.4. Hypothetical situation of all cattle research being for traditional production

The results would be substantially altered if all income from the livestock-focused trade association had been for traditional production (from hypothetical data Section 4.3.3.2.1), rather than a substantial amount of the University's research being to reduce methane, for example from burps/farts.

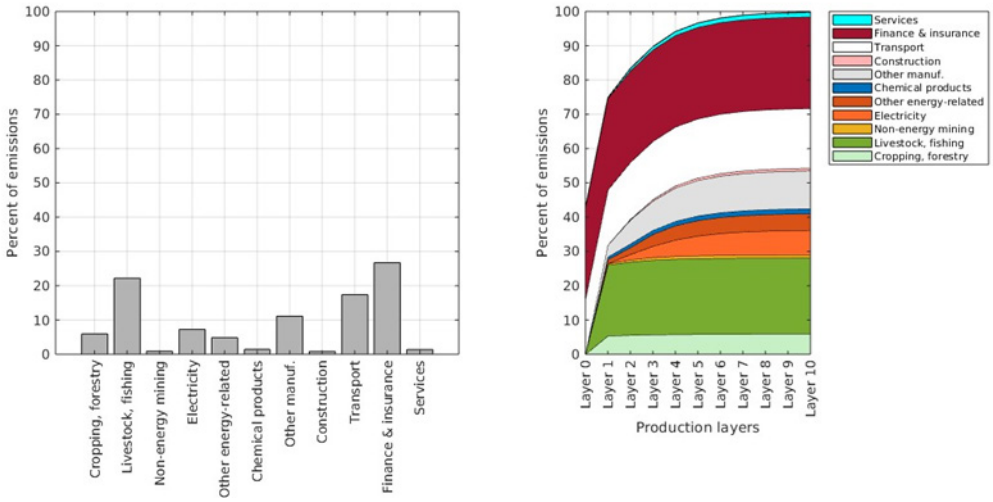


Figure 5: A hypothetical example of potential University of Sydney downstream emissions in 2022 if all livestock research had been for traditional cattle production. Emissions by key sectors and broad sector groupings are calculated from the perspective of emitting industries ($\mathbf{vG} \circ \mathbf{q}$). The right-hand panel is a production layer decomposition (PLD), with inter-industry sales-chain effects from Layer 1 onwards, and emissions from financed investments and international student travel added at production-layer 0. Percentages rather than physical quantities of emissions are provided because the information in this report is not an official or endorsed disclosure of the University

As highlighted in the Fig. 5 bar chart, in this hypothetical situation, the downstream livestock sector becomes almost the top source of sales-chain emissions. Looking at orders of production downstream, it can be seen in the PLD that almost all the livestock emissions would be at Layer 1, from direct sales to the trade association of research to increase cattle production. This hypothetical situation, compared to that described in Section 4.4.2, would have resulted in a 57% increase in emissions along the *inter-industry* sales chain and a 26% increase in terms of *total* downstream emissions.

4.5. Discussion and conclusion

This is to the author's knowledge the first time that income-based EEIO has been directed at the level of an individual organisation and the results published. This hybrid IO-LCA enterprise study provides a framework for organisations to use IO analysis downstream. The use of IO analysis downstream has, to date, not enjoyed the same worldwide utilisation as upstream IO analysis but it could play a critical role in the emerging landscape of mandatory corporate reporting.

The novel framework takes two important positions: One is to treat *public-sector grants* as non-market, meaning such income is excluded from the IO analysis. In this sense, organisations can be seen as reactive to public-sector political agendas rather than as responsible actors in public-sector production; one reason for this calculation approach is that it can be difficult to identify where the public-sector grantor also *uses* the output, as required to meet the definition

of market *production* (European Communities et al., 2009, p. 630). Future research could analyse the association between the public sector and enabled emissions. The second framework decision is that in cases where organisational outputs may be for a customer whose services are focused on an emissions-intensive sector, then an accurate representation of the impact of this income is to harmonise it with the final-destination sector; an example is research for a cattle or coal member-based trade association. This position reflects the utility of the hybrid IO-LCA approach in making use of superior process-based information where it exists, in this case being that the income is ultimately associated with emissions-intensive production (of cattle/coal). Although exceptions may be made for low-carbon-transition activities, such as research into reducing cattle methane emissions, the same may not be said for research into carbon capture and storage for example, noting the controversy that surrounds its efficacy; therefore it is not recommended that such income be used as a counterbalance against the upgrading of any coal-supporting research to the relevant coal sector, where the ultimate aim of such research is to support the viability/profitability of coal production. Clearly, these sort of decisions should be justified and subjected to scrutiny as part of the scope-3 reporting process. The key point is that using IO analysis, we can gain insights into our impact as suppliers regarding emissions down our sales chain; the approach advocated for here is also in the spirit intended by ISIC regarding flexibility where required (Task team on ISIC, 2024, p. 30), in this instance being in response to the increased focus on *downstream* responsibility.

The case study of the University of Sydney found that emissions from the inter-industry sales chain, calculated using IO analysis, were not substantial in comparison to emissions from high-intensity activities of financed emissions and international student travel, which are also linked to substantial University income. However, this would not have been the case if the focus of the research for a livestock trade association had been to enable *traditional* cattle production, rather than to support the *low-carbon* transition. The case study demonstrated the robustness of the framework for the knowledge organisation regardless of whether public-sector grants were included as part of market activity, underpinned by the assumption that the public-sector customer would tend to be focused on relatively low-emissions production.

In extending beyond end-of-chain notions of downstream responsibility as limited to a product's transport, final use and disposal, IO analysis shows how seemingly low-emissions-intensive activities may have enabled high-emissions-intensive production, depending on the sectors to whom we sold. In this respect, there is a significant missed opportunity in the fact that at the time of writing, no other Australian university for example had reported on (and therefore better managed) their emissions-enabling research, in the GHG Protocol downstream

categories 11 and 10 for Use- and Processing of Sold Products. Australia is one of the largest exporters of coal (Department of Industry Science and Resources, 2025), whose production is assisted by institutions that accept funding for coal research. In the latest annual funding round at the time of writing of the levied Australian Coal Association Research Program, 142 university projects are listed (ACARP, 2024), Using IO analysis to calculate downstream emissions therefore could highlight where a *divestment-style approach to all income* generation (not just from investments) could add weight to social license to operate and support a low-carbon economy.

With downstream IO analysis having become well-established in the past couple of decades, it has become clear that the insights from downstream analysis are distinct from those afforded from an upstream perspective. Nonetheless, the common practice of IO analysis upstream has to date not extended to IO downstream for organisations. Downstream, income-based emission factors could add to the carbon-accounting toolkit, complementing spend-based emission factors and making IO analysis accessible for all organisations. In this paper, the enterprise-level research into downstream value-chain emissions highlights the crucial role that incorporating the entire inter-industry sales chain can play, using IO analysis. This novel framework focused on income-based environmental responsibility for organisations provides a standardised approach for sustainability reporting downstream to support routine whole-of-value-chain disclosures.

4.6. References

ACARP. (2024). *ACARP 2024*. https://www.acarp.com.au/Media/ACARP%202024%20Report.pdf

Altimiras-Martin, A. (2024). A supply-driven model consuming simultaneously all primary inputs: unfolding analytical potential beyond the Ghosh model. *Economic Systems Research, 36*(2), 249-264. https://doi.org/10.1080/09535314.2022.2137008

Alvarez, S., Tobarra, M.-A., & Zafrilla, J.-E. (2019). Corporate and Product Carbon Footprint under Compound Hybrid Analysis: Application to a Spanish Timber Company. *Journal of Industrial Ecology, 23*(2), 496-507. https://doi.org/10.1111/jiec.12759

Australian Accounting Standards Board. (2024). Australian Sustainability Reporting Standards AASB S1 and AASB S2 are now available on the AASB Digital Standards Portal [News]. https://aasb.gov.au/news/australian-sustainability-reporting-standards-aasb-s1-and-aasb-s2-are-now-available-on-the-aasb-digital-standards-portal/

Australian Bureau of Statistics. (2024a). *Australian National Accounts: Input-Output Tables, 2022-23* (ABS 5209.0.55.001) [Data set], *Table 4. Reconciliation of flows at basic prices and at purchasers' prices by product group*. https://www.abs.gov.au/statistics/economy/national-accounts/australian-national-accounts-input-output-tables/2022-23/520905500104.xlsx

Australian Bureau of Statistics. (2024b). *Australian National Accounts: Input-Output Tables, 2022-23* (ABS 5209.0.55.001) [Data set], *Table 23. Wholesale margin on supply by product group by using industry and final use category*. https://www.abs.gov.au/statistics/economy/national-accounts/australian-national-accounts-input-output-tables/2022-23/520905500123.xlsx

Baboulet, O., & Lenzen, M. (2010). Evaluating the environmental performance of a university. *Journal of Cleaner Production, 18*(12), 1134-1141. https://doi.org/10.1016/j.jclepro.2010.04.006

Chen, G., Hadjikakou, M., & Wiedmann, T. (2017). Urban carbon transformations: unravelling spatial and inter-sectoral linkages for key city industries based on multi-region input–output analysis. *Journal of Cleaner Production, 163*, 224-240. https://doi.org/10.1016/j.jclepro.2016.04.046

Cheng, X., Wu, X., Guan, C., Sun, X., & Zhang, B. (2023). Impacts of production structure changes on global CH4 emissions: Evidences from income-based accounting and decomposition analysis. *Ecological Economics, 213*, 107967. https://doi.org/10.1016/j.ecolecon.2023.107967

Commission of the European Communities - Eurostat, International Monetary Fund, Organization for Economic Co-operation and Development, United Nations, & World Bank. (1993). *System of National Accounts*. https://unstats.un.org/unsd/nationalaccount/docs/sna2008.pdf

De Mesnard, L. (2009). IS THE GHOSH MODEL INTERESTING? *Journal of Regional Science, 49*(2), 361-372. https://doi.org/10.1111/j.1467-9787.2008.00593.x

Department of Industry, Science and Resources. (2025). *Commonwealth of Australia Resources and Energy Quarterly: June 2025*. Office of the Chief Economist. https://www.industry.gov.au/sites/default/files/2025-06/resources-and-energy-quarterly-june-2025.pdf

Dietzenbacher, E. (1997). In Vindication of the Ghosh Model: A Reinterpretation as a Price Model. *Journal of Regional Science, 37*(4), 629-651. https://doi.org/10.1111/0022-4146.00073

Dietzenbacher, E., & Lahr, M. L. (2013). EXPANDING EXTRACTIONS. *Economic Systems Research, 25*(3), 341-360. https://doi.org/10.1111/0022-4146.00073

European Communities, International Monetary Fund, Organisation for Economic Co-operation and Development, United Nations, & World Bank. (2009). System of National Accounts 2008. https://unstats.un.org/unsd/nationalaccount/docs/sna2008.pdf

Ferguson, H. (2022, February 17). *University research funding: a quick guide.* Parliament of Australia. https://www.aph.gov.au/About_Parliament/Parliamentary_departments/Parliamentary_Library/Research/Quick_Guides/2021-22/UniversityResearchFunding

Fu, Z., Sun, S., & Konar, M. (2024). Hydro-Economic Risk and Resilience to Supply Chain Water Scarcity in Chinese Cities. *Environmental Science & Technology, 58*(49), 21578-21588. https://doi.org/10.1021/acs.est.4c08472

Gallego, B., & Lenzen, M. (2005). A consistent input–output formulation of shared producer and consumer responsibility. *Economic Systems Research, 17*(4), 365-391. https://doi.org/10.1080/09535310500283492

Ghosh, A. (1958). Input-Output Approach in an Allocation System. *Economica, 25*(97), 58-64. https://doi.org/10.2307/2550694

Gómez, N., Cadarso, M.-Á., & Monsalve, F. (2016). Carbon footprint of a university in a multiregional model: the case of the University of Castilla-La Mancha. *Journal of Cleaner Production, 138*, 119- https://doi.org/10.1016/j.jclepro.2016.06.009

Gruver, G. W. (1989). ON THE PLAUSIBILITY OF THE SUPPLY—DRIVEN INPUT-OUTPUT MODEL: A THEORETICAL BASIS FOR INPUT-COEFFICIENT CHANGE. *Journal of Regional Science, 29*(3), 441-450. https://doi.org/10.1111/j.1467-9787.1989.tb01389.x

Guan, Y., Huang, G., Liu, L., Zhai, M., & Xu, X. (2019). Measurement of air-pollution inequality through a three-perspective accounting model. *Science of The Total Environment, 696*, 133937. https://doi.org/10.1016/j.scitotenv.2019.133937

Guerra, A.-I., & Sancho, F. (2011). REVISITING THE ORIGINAL GHOSH MODEL: CAN IT BE MADE MORE PLAUSIBLE? *Economic Systems Research, 23*(3), 319-328. https://doi.org/10.1080/09535314.2011.566261

Heller, R. F., Ya-Yen, S., Guo, Z., & Malik, A. (2022). Impact on carbon emissions of online study for a cohort of overseas students: A retrospective cohort study [version 5; peer review: 2 approved, 1 approved with reservations]. *F1000Research, 10:849*. https://doi.org/10.12688/f1000research.55156.5

Huang, Y. A., Lenzen, M., Weber, C. L., Murray, J., & Matthews, H. S. (2009). THE ROLE OF INPUT–OUTPUT ANALYSIS FOR THE SCREENING OF CORPORATE CARBON FOOTPRINTS. *Economic Systems Research, 21*(3), 217-242. https://doi.org/10.12688/f1000research.55156.5

International Civil Aviation Organization. (n.d.). *ICAO Carbon Emissions Calculator*. Retrieved May 29, 2024, from https://www.icao.int/environmental-protection/Carbonoffset/Pages/default.aspx

International Sustainability Standards Board. (2023). *IFRS Sustainability Disclosure Standard: Climate-related Disclosures* (ISSB Standard No. IFRS S2)

Keil, M. (2023). The greenhouse gas emissions of a German hospital - A case study of an easy-to-use approach based on financial data. *Cleaner Environmental Systems, 11*, 100140. https://doi.org/10.1016/j.cesys.2023.100140

Larsen, H. N., Pettersen, J., Solli, C., & Hertwich, E. G. (2013). Investigating the Carbon Footprint of a University - The case of NTNU. *Journal of Cleaner Production, 48*, 39-47. https://doi.org/10.1016/j.jclepro.2011.10.007

Lenzen, M., Murray, J., Sack, F., & Wiedmann, T. (2007). Shared producer and consumer responsibility — Theory and practice. *Ecological Economics, 61*(1), 27-42. https://doi.org/10.1016/j.ecolecon.2006.05.018

Lenzen, M. (2008). Double-Counting in Life Cycle Calculations. *Journal of Industrial Ecology, 12*(4), 583-599. https://doi.org/10.1111/j.1530-9290.2008.00067.x

Lenzen, M., Benrimoj, C., & Kotic, B. (2010). INPUT–OUTPUT ANALYSIS FOR BUSINESS PLANNING: A CASE STUDY OF THE UNIVERSITY OF SYDNEY. *Economic Systems Research, 22*(2), 155-179. https://dx.doi.org/10.1080/09535314.2010.484012

Lenzen, M., Geschke, A., Abd Rahman, M. D., Xiao, Y., Fry, J., Reyes, R., . . . Yamano, N. (2017). The Global MRIO Lab – charting the world economy. *Economic Systems Research, 29*(2), 158-186. https://doi.org/10.1080/09535314.2017.1301887

Lenzen, M., Geschke, A., West, J., Fry, J., Malik, A., Giljum, S., . . . Schandl, H. (2022). Implementing the material footprint to measure progress towards Sustainable Development Goals 8 and 12. *Nature Sustainability, 5*(2), 157-166. https://doi.org/10.1038/s41893-021-00811-6

Lenzen, M., & Li, M. (2024). *GLORIA MRIO database Release 059* [Release notes]

Lenzen, M., & Murray, J. (2010). Conceptualising environmental responsibility. *Ecological Economics, 70*(2), 261-270. https://doi.org/10.1016/j.ecolecon.2010.04.005

Leontief, W. (1936). Quantitative input and output relations in the economic systems of the United States. *The Review of Economics and Statistics, 18*(3), 105-125. https://doi.org/10.2307/1927837

Leontief, W. (1970). Environmental Repercussions and the Economic Structure: An Input-Output Approach. *The Review of Economics and Statistics, 52*(3), 262-271. https://doi.org/10.2307/1926294

Li, J., Huang, G., Li, Y., Liu, L., & Sun, C. (2021). Unveiling Carbon Emission Attributions along Sale Chains. *Environmental Science & Technology, 55*(1), 220-229. https://doi.org/10.1021/acs.est.0c05798

Li, R., Hua, P., & Krebs, P. (2022). Global Trends and Drivers in Consumption- and Income-Based Emissions of Polycyclic Aromatic Hydrocarbons. *Environmental Science & Technology, 56*(1), 131-144. https://doi.org/10.1021/acs.est.1c04685

Li, Y., Chen, B., Fang, D., Zhang, B., Bai, J., Liu, G., & Zhang, Y. (2021). Drivers of energy-related PM2.5 emissions in the Jing-Jin-Ji region between 2002 and 2015. *Applied Energy, 288*, 116668. https://doi.org/10.1016/j.apenergy.2021.116668

Liu, X., & Zhou, X. (2025). Determinants of carbon emissions from road transportation in China: An extended input-output framework with production-theoretical approach. *Energy, 316*, 134493. https://doi.org/10.1016/j.energy.2025.134493

Malik, A., McBain, D., Wiedmann, T. O., Lenzen, M., & Murray, J. (2019). Advancements in Input-Output Models and Indicators for Consumption-Based Accounting. *Journal of Industrial Ecology, 23*(2), 300-312. https://doi.org/10.1111/jiec.12771

Malik, A., Lenzen, M., Lane, J., Lam, K. L., Harding, O. M., & Geschke, A. (2022). Carbon footprint and voting preferences of a council. *Resources, Conservation and Recycling, 186*, 106535. https://doi.org/10.1016/j.resconrec.2022.106535

Manresa, A., & Sancho, F. (2013). Supply and demand biases in linear interindustry models. *Economic Modelling, 33*, 94-100. https://doi.org/10.1016/j.econmod.2013.03.025

Manresa, A., & Sancho, F. (2020). A follow-up note on the plausibility of the Leontief and Ghosh closed models. *Economic Systems Research, 32*(1), 166-172. https://doi.org/10.1080/09535314.2019.1650331

Marques, A., Rodrigues, J., Lenzen, M., & Domingos, T. (2012). Income-based environmental responsibility. *Ecological Economics, 84*, 57-65. https://doi.org/10.1016/j.ecolecon.2012.09.010

Marques, A., Rodrigues, J., & Domingos, T. (2013). International trade and the geographical separation between income and enabled carbon emissions. *Ecological Economics, 89*, 162-169. https://doi.org/10.1016/j.ecolecon.2013.02.020

Meng, B., Peters, G. P., Wang, Z., & Li, M. (2018). Tracing CO2 emissions in global value chains. *Energy Economics, 73*, 24-42. https://doi.org/10.1016/j.eneco.2018.05.013

Miller, R., & Blair, P. (2022). *Input–Output Analysis: Foundations and Extensions - Third Edition* (3rd ed.). New York, NY: Cambridge University Press.
Moran, D., & Wood, R. (2014). CONVERGENCE BETWEEN THE EORA, WIOD, EXIOBASE, AND OPENEU'S CONSUMPTION-BASED CARBON ACCOUNTS. *Economic Systems Research, 26*(3), 245-261. https://doi.org/10.1080/09535314.2014.935298
Oosterhaven, J. (1988). ON THE PLAUSIBILITY OF THE SUPPLY-DRIVEN INPUT-OUTPUT MODEL. *Journal of Regional Science, 28*(2), 203-217. https://doi.org/10.1111/j.1467-9787.1988.tb01208.x
Oosterhaven, J. (1989). THE SUPPLY-DRIVEN INPUT-OUTPUT MODEL: A NEW INTERPRETATION BUT STILL IMPLAUSIBLE. *Journal of Regional Science, 29*(3), 459-465. doi:https://doi.org/10.1111/j.1467-9787.1989.tb01391.x
Oosterhaven, J. (2012). ADDING SUPPLY-DRIVEN CONSUMPTION MAKES THE GHOSH MODEL EVEN MORE IMPLAUSIBLE. *Economic Systems Research, 24*(1), 101-111. https://doi.org/10.1080/09535314.2011.635137
Oosterhaven, J. (2024). Price re-interpretations of the basic IO quantity models result in the ultimate input-output equations. *Economic Systems Research, 36*(2), 191-200. https://doi.org/10.1080/09535314.2022.2159792
Owen, A., Steen-Olsen, K., Barrett, J., Wiedmann, T., & Lenzen, M. (2014). STRUCTURAL DECOMPOSITION APPROACH TO COMPARING MRIO DATABASES. *Economic Systems Research, 26*(3), 262-283. https://doi.org/10.1080/09535314.2014.935299
Peters, G. P. (2008). From production-based to consumption-based national emission inventories. *Ecological Economics, 65*(1), 13-23. https://doi.org/10.1016/j.ecolecon.2007.10.014
Piñero, P., Bruckner, M., Wieland, H., Pongrácz, E., & Giljum, S. (2019). The raw material basis of global value chains: allocating environmental responsibility based on value generation. *Economic Systems Research, 31*(2), 206-227. https://doi.org/10.1080/09535314.2018.1536038
Pottier, A., & Le Treut, G. (2023). Quantifying GHG emissions enabled by capital and labor: Economic and gender inequalities in France. *Journal of Industrial Ecology, 27*(2), 624-636. https://doi.org/10.1111/jiec.13383
Qi, J., Wang, Y., Liang, S., Li, Y., Li, Y., Feng, C., . . . Yang, Z. (2019). Primary Suppliers Driving Atmospheric Mercury Emissions through Global Supply Chains. *One Earth, 1*(2), 254-266. https://doi.org/10.1016/j.oneear.2019.10.005
Reiner, V., & Malik, A. (*under review*). Scope-3 emissions and Nature impact throughout the value chain: An approach to mandatory environmental due diligence.
Rodrigues, J., & Domingos, T. (2008). Consumer and producer environmental responsibility: Comparing two approaches. *Ecological Economics, 66*(2), 533-546. https://doi.org/10.1016/j.ecolecon.2007.12.010
Rodrigues, J., Domingos, T., Giljum, S., & Schneider, F. (2006). Designing an indicator of environmental responsibility. *Ecological Economics, 59*(3), 256-266. https://doi.org/10.1016/j.ecolecon.2005.10.002
Rose, A., & Allison, T. (1989). ON THE PLAUSIBILITY OF THE SUPPLY-DRIVEN INPUT-OUTPUT MODEL: EMPIRICAL EVIDENCE ON JOINT STABILITY. *Journal of Regional Science, 29*(3), 451-458. https://doi.org/10.1111/j.1467-9787.1989.tb01390.x
Sanguinet, E. R., & Azzoni, C. R. (2024). Carbon emissions drivers in Brazilian regional production chains: Value-added and consumption-based approaches. *Regional Science Policy & Practice, 16*(8), 100015. https://doi.org/10.1016/j.rspp.2024.100015
Schandl, H., Marcos-Martinez, R., West, J., Miatto, A., Lutter, S., Lieber, M., . . . Fischer-Kowalski, M. (2024). Global material flows and resource productivity: The 2024 update. *Journal of Industrial Ecology, 28*(6), 2012-2031. https://doi.org/10.1111/jiec.13593

Starr, J., Nicolson, C., Ash, M., Markowitz, E. M., & Moran, D. (2023). Income-based U.S. household carbon footprints (1990–2019) offer new insights on emissions inequality and climate finance. *PLOS Climate, 2*(8), e0000190. https://doi.org/10.1371/journal.pclm.0000190

State of New South Wales (NSW Treasury). (2023). *NSW Treasury Policy and Guidelines – Annual Reporting Requirements: TPG 23-10*. (NSW Treasury Publication No. TPG23-10). NSW Treasury, NSW Government. https://arp.nsw.gov.au/assets/ars/attachments/tpg23-10-annual-reporting-requirements-v2.pdf

Steininger, K. W., Lininger, C., Meyer, L. H., Muñoz, P., & Schinko, T. (2016). Multiple carbon accounting to support just and effective climate policies. *Nature Climate Change, 6*(1), 35-41. https://doi.org/10.1038/nclimate2867

Stridsland, T., Stounbjerg, A., & Sanderson, H. (2023). A hybrid approach to a more complete emissions inventory: a case study of Aarhus University. *Carbon Management, 14*(1). https://doi.org/10.1038/nclimate2867

Sun, L., Kaufman, M. F., Sirk, E. A., Durga, S., Mahowald, N. M., & You, F. (2022). COVID-19 impact on an academic Institution's greenhouse gas inventory: The case of Cornell University. *Journal of Cleaner Production, 363*, 132440. https://doi.org/10.1016/j.jclepro.2022.132440

Task team on ISIC. (2024). *Introduction of the Standard Industrial Classification of All Economic Activities, Revision 5 (ISIC Rev.5) - (Part of forthcoming UN publication)*. https://unstats.un.org/unsd/classifications/Econ/Download/In%20Text/ISIC5_Intro_11Mar2024.pdf

The University of Sydney. (2022). *Investment and Capital Management Investment Report 2022*. https://www.sydney.edu.au/content/dam/corporate/documents/about-us/governance-and-structure/our-portfolios/investment-and-capital-management-report-2022.pdf

The University of Sydney. (2023). *Annual Report 2022*. https://www.sydney.edu.au/content/dam/corporate/documents/about-us/values-and-visions/annual-report/university-of-sydney-2022-annual-report.pdf

The University of Sydney. (2025). University of Sydney first in Australia to release full climate-related financial disclosure [News]. https://www.sydney.edu.au/news-opinion/news/2025/07/21/sydney-releases-full-climate-related-financial-disclosure.html

Thurston, M., & Eckelman, M. J. (2011). Assessing greenhouse gas emissions from university purchases. *International Journal of Sustainability in Higher Education, 12*(3), 225-235. https://doi.org/10.1108/14676371111148018

Tukker, A., Pollitt, H., & Henkemans, M. (2020). Consumption-based carbon accounting: sense and sensibility. *Climate Policy, 20*(sup1), S1-S13. https://doi.org/10.1080/14693062.2020.1728208

United Kingdom Government Department for Energy Security & Net Zero. (2025). *UK Government GHG Conversion Factors for Company Reporting* GOV.UK. https://assets.publishing.service.gov.uk/media/6846a4f55e92539572806125/ghg-conversion-factors-2025-full-set.xlsx

United Nations Statistics Division. (2008). International Standard Industrial Classification of All Economic Activities (ISIC) Rev.4. https://unstats.un.org/unsd/classifications/Econ/Download/In%20Text/ISIC5_Intro_11Mar2024.pdf

United States Environmental Protection Agency. (n.d.). Scope 3 Inventory Guidance. Retrieved March 5, 2025, from https://www.epa.gov/climateleadership/scope-3-inventory-guidance

Wood, R., & Lenzen, M. (2003). An application of an improved ecological footprint method and structural path analysis in a comparative institutional study. *Local Environ., 8*(4), 365. https://doi.org/10.1080/13549830306670

World Business Council for Sustainable Development & World Resources Institute. (2004). *The Greenhouse Gas Protocol: A Corporate Accounting and Reporting Standard - REVISED EDITION*. https://ghgprotocol.org/sites/default/files/standards/ghg-protocol-revised.pdf

World Resources Institute & World Business Council for Sustainable Development. (2011). *Corporate Value Chain (Scope 3) Accounting and Reporting Standard: Supplement to the GHG Protocol Corporate Accounting and Reporting Standard*. https://ghgprotocol.org/sites/default/files/standards/Corporate-Value-Chain-Accounting-Reporing-Standard_041613_2.pdf

World Resources Institute & World Business Council for Sustainable Development. (2013). *Technical guidance for calculating scope 3 emissions: Supplement to the Corporate Value Chain (Scope 3) Accounting & Reporting Standard*. https://ghgprotocol.org/sites/default/files/standards/Scope3_Calculation_Guidance_0.pdf

Xu, L., Chen, G., Wiedmann, T., Wang, Y., Geschke, A., & Shi, L. (2019). Supply-side carbon accounting and mitigation analysis for Beijing-Tianjin-Hebei urban agglomeration in China. *Journal of Environmental Management, 248*, 109243. https://doi.org/10.1016/j.jenvman.2019.07.014

4.7. *Supplementary Information*

4.7.1. Greenhouse Gas Protocol categories downstream details

Below is an edited excerpt from documentation that had been prepared in anticipation of future assurance, and extended for this paper.

The seven downstream categories: 9 – Downstream Transportation and Distribution; 10 – Processing of Sold Products; 11 – Use of Sold Products; 12 End-of-life Treatment of Sold Products; 13 Downstream Leased Assets; 14 Franchises and 15 Investments: are discussed in descending order.

4.7.1.1. Investments (Category 15)

Calculated separately to the IO calculations (i.e., by hiring a consultant for the process-based analysis), because investment is treated as exogenous to intermediate production in conventional IO analysis.

4.7.1.2. Franchises (Category 14)

Not relevant for the University because it does not have any franchises.

Although the University receives some licenses and royalties, these are from use of IP rather than company franchises as such.

4.7.1.3. Downstream Leased Assets (Category 13)

A concordance was drawn up in the same way as was done for the gross GHG emissions but with just one class code relevant to the University's downstream leased assets in 2022 (being for rental accommodation) using the Main Text equation (4). Alternatively, the emissions for this category could be simply calculated from equation (6) by multiplying the income earned ($\mathbf{v}$) from the GLORIA sector, Property and Real Estate (for rental accommodation), by the total intensity/carbon forward multiplier ($\mathbf{CFM}$) in equation (7) for that sector.

4.7.1.4. End-of -Life Treatment of Sold Products (Category 12)

Not relevant for the University because it did not receive any income from the waste or materials-recovery sectors.

The GHG Protocol notes that end-of-life treatment methods discussed for the upstream category 5 Waste Generated in Operations also apply to this category (World Resources Institute & World Business Council for Sustainable Development, 2013, p. 125), which include

recycling. The GHG Protocol notes that Category 12 can relate to intermediate, rather than final products (p. 125).

4.7.1.5. Categories 11 & 10 Use- and Processing of Sold Products

See the end of this Section (4.7.1) regarding intermediate "Residual Categories".

4.7.1.6. Downstream Transportation and Distribution (Category 9)

i) Regarding emissions from intermediate production, the same approach was taken as for Section 4.7.1.3 in terms of multiplying the income from producers in the relevant sector(s) by the total intensity for that sector(s).

ii) Regarding households' travel to the "retail" outlet as an optional addition (World Resources Institute & World Business Council for Sustainable Development, 2013, p. 103), these were added to the emissions calculated in (i); the calculation of emissions from travel by the University's international students are discussed in the Main Text "Emissions from activities unrelated to intermediate production" Section (4.3.3.1) but generally followed Heller et al. (2022).

4.7.1.7. Residual categories of production (Categories 11 & 10)

i) Step 1: The remaining downstream emissions are calculated. For the University, this was gross downstream emissions from the inter-industry sales chain less emissions from leases and transport/distribution (Sections 4.7.1.3 & 4.7.1.6(i)).

ii) Step 2: These remaining emissions were then apportioned between the remaining two categories 10 Processing of Sold Products and 11 Use of Sold Products, according to their relative proportions of the gross downstream emissions from the inter-industry sales chain calculated using equation (4) in the Main Text, with direct customers (users) of our product denoted by $\mathbf{v} * \mathbf{q}$ as Layer 1 in the production layer decomposition equation (8) in the Main Text. In this way, we are able to calculate the emissions variously from direct Use of Sold Products ($\mathbf{vq}$ proportion of the remaining downstream emissions) and downstream Processing of Sold Products, which comprises the remainder of the emissions downstream from the inter-industry sales chain.

4.7.2. Concordance of the 120 GLORIA sectors to key sectors/groupings for visualisation

Lfd_Nr	Sector_names	**Cropping and forestry**	**Raising animals & seafood**	**Non-Energy Mining**	**Electricity**	**Other Energy-Related Activities**	**Chemical products**	**Food Manufacturing**	**Other Manufacturing**	**Construction**	**Transport**	**Services**
1	Growing wheat	1	0	0	0	0	0	0	0	0	0	0
2	Growing maize	1	0	0	0	0	0	0	0	0	0	0
3	Growing cereals n.e.c.	1	0	0	0	0	0	0	0	0	0	0
4	Growing leguminous crops and oil seeds	1	0	0	0	0	0	0	0	0	0	0
5	Growing rice	1	0	0	0	0	0	0	0	0	0	0
6	Growing vegetables roots tubers	1	0	0	0	0	0	0	0	0	0	0
7	Growing sugar beet and cane	1	0	0	0	0	0	0	0	0	0	0
8	Growing tobacco	1	0	0	0	0	0	0	0	0	0	0
9	Growing fibre crops	1	0	0	0	0	0	0	0	0	0	0
10	Growing crops n.e.c.	1	0	0	0	0	0	0	0	0	0	0
11	Growing grapes	1	0	0	0	0	0	0	0	0	0	0
12	Growing fruits and nuts	1	0	0	0	0	0	0	0	0	0	0
13	Growing beverage crops coffee tea etc	1	0	0	0	0	0	0	0	0	0	0
14	Growing spices aromatic drug and pharmaceutical crops	1	0	0	0	0	0	0	0	0	0	0
15	Seeds and plant propagation	1	0	0	0	0	0	0	0	0	0	0
16	Raising of cattle	0	1	0	0	0	0	0	0	0	0	0
17	Raising of sheep	0	1	0	0	0	0	0	0	0	0	0
18	Raising of swine pigs	0	1	0	0	0	0	0	0	0	0	0
19	Raising of poultry	0	1	0	0	0	0	0	0	0	0	0
20	raising of animals n.e.c.; services to agriculture	0	1	0	0	0	0	0	0	0	0	0
21	Forestry and logging	1	0	0	0	0	0	0	0	0	0	0
22	Fishing	0	1	0	0	0	0	0	0	0	0	0
23	Crustaceans and molluscs	0	1	0	0	0	0	0	0	0	0	0

24	Hard coal	0	0	0	0	1	0	0	0	0	0	0
25	Lignite and peat	0	0	0	0	1	0	0	0	0	0	0
26	Petroleum extraction	0	0	0	0	1	0	0	0	0	0	0
27	Gas extraction	0	0	0	0	1	0	0	0	0	0	0
28	Iron ores	0	0	1	0	0	0	0	0	0	0	0
29	Uranium ores	0	0	1	0	0	0	0	0	0	0	0
30	Aluminium ore	0	0	1	0	0	0	0	0	0	0	0
31	Copper ores	0	0	1	0	0	0	0	0	0	0	0
32	Gold ores	0	0	1	0	0	0	0	0	0	0	0
33	Lead zinc silver ores	0	0	1	0	0	0	0	0	0	0	0
34	Nickel ores	0	0	1	0	0	0	0	0	0	0	0
35	Tin ores	0	0	1	0	0	0	0	0	0	0	0
36	Other non-ferrous ores	0	0	1	0	0	0	0	0	0	0	0
37	Quarrying of stone sand and clay	0	0	1	0	0	0	0	0	0	0	0
38	Chemical and fertilizer minerals	0	0	1	0	0	0	0	0	0	0	0
39	Extraction of salt	0	0	1	0	0	0	0	0	0	0	0
40	Mining and quarrying n.e.c; services to mining	0	0	1	0	0	0	0	0	0	0	0
41	Beef meat	0	0	0	0	0	0	1	0	0	0	0
42	Sheep meat	0	0	0	0	0	0	1	0	0	0	0
43	Pork	0	0	0	0	0	0	1	0	0	0	0
44	Poultry meat	0	0	0	0	0	0	1	0	0	0	0
45	Other meat products	0	0	0	0	0	0	1	0	0	0	0
46	Fish products	0	0	0	0	0	0	1	0	0	0	0
47	Cereal products	0	0	0	0	0	0	1	0	0	0	0
48	Vegetable products	0	0	0	0	0	0	1	0	0	0	0
49	Fruit products	0	0	0	0	0	0	1	0	0	0	0
50	Food products and feeds n.e.c.	0	0	0	0	0	0	1	0	0	0	0
51	Sugar refining cocoa chocolate and confectionery	0	0	0	0	0	0	1	0	0	0	0
52	Animal oils and fats	0	0	0	0	0	0	1	0	0	0	0
53	Vegetable oils and fats	0	0	0	0	0	0	1	0	0	0	0
54	Dairy products	0	0	0	0	0	0	1	0	0	0	0
55	Alcoholic and other beverages	0	0	0	0	0	0	1	0	0	0	0

56	Tobacco products	0	0	0	0	0	0	1	0	0	0	0
57	Textiles and clothing	0	0	0	0	0	0	0	1	0	0	0
58	Leather and footwear	0	0	0	0	0	0	0	1	0	0	0
59	Sawmill products	0	0	0	0	0	0	0	1	0	0	0
60	Pulp and paper	0	0	0	0	0	0	0	1	0	0	0
61	Printing	0	0	0	0	0	0	0	1	0	0	0
62	Coke oven products	0	0	0	0	1	0	0	0	0	0	0
63	Refined petroleum products	0	0	0	0	1	0	0	0	0	0	0
64	Nitrogenous fertilizers	0	0	0	0	0	0	0	1	0	0	0
65	Non-nitrogenous and mixed fertilizers	0	0	0	0	0	0	0	1	0	0	0
66	Basic petrochemical products	0	0	0	0	0	0	0	1	0	0	0
67	Basic inorganic chemicals	0	0	0	0	0	1	0	1	0	0	0
68	Basic organic chemicals	0	0	0	0	0	1	0	1	0	0	0
69	Pharmaceuticals and medicinal products	0	0	0	0	0	0	0	1	0	0	0
70	Dyes paints glues detergents and other chemical products	0	0	0	0	0	1	0	0	0	0	0
71	Rubber products	0	0	0	0	0	0	0	1	0	0	0
72	Plastic products	0	0	0	0	0	0	0	1	0	0	0
73	Clay building materials	0	0	0	0	0	0	0	1	0	0	0
74	Other ceramics n e c	0	0	0	0	0	0	0	1	0	0	0
75	Cement lime and plaster products	0	0	0	0	0	0	0	1	0	0	0
76	Other non metallic mineral products n e c	0	0	0	0	0	0	0	1	0	0	0
77	Basic iron and steel	0	0	0	0	0	0	0	1	0	0	0
78	Basic aluminium	0	0	0	0	0	0	0	1	0	0	0
79	Basic copper	0	0	0	0	0	0	0	1	0	0	0
80	Basic gold	0	0	0	0	0	0	0	1	0	0	0
81	Basic lead zinc silver	0	0	0	0	0	0	0	1	0	0	0
82	Basic nickel	0	0	0	0	0	0	0	1	0	0	0
83	Basic tin	0	0	0	0	0	0	0	1	0	0	0
84	Basic non-ferrous metals n.e.c.	0	0	0	0	0	0	0	1	0	0	0
85	Fabricated metal products	0	0	0	0	0	0	0	1	0	0	0

86	Machinery and equipment	0	0	0	0	0	0	0	1	0	0	0
87	Motor vehicles trailers and semi trailers	0	0	0	0	0	0	0	1	0	0	0
88	Other transport equipment	0	0	0	0	0	0	0	1	0	0	0
89	Repair and installation of machinery and equipment	0	0	0	0	0	0	0	0	0	0	1
90	Computers electronic products optical and precision instruments	0	0	0	0	0	0	0	1	0	0	0
91	Electrical equipment	0	0	0	0	0	0	0	1	0	0	0
92	Furniture and other manufacturing n e c	0	0	0	0	0	0	0	1	0	0	0
93	Electric power generation transmission and distribution	0	0	0	1	0	0	0	0	0	0	0
94	Distribution of gaseous fuels through mains	0	0	0	0	1	0	0	0	0	0	0
95	Water collection treatment and supply sewerage	0	0	0	0	0	0	0	0	0	0	1
96	Waste collection treatment and disposal	0	0	0	0	0	0	0	0	0	0	1
97	Materials recovery	0	0	0	0	0	0	0	1	0	0	0
98	Building construction	0	0	0	0	0	0	0	0	1	0	0
99	Civil engineering construction	0	0	0	0	0	0	0	0	1	0	0
100	Wholesale and retail trade repair of motor vehicles and motorcycles	0	0	0	0	0	0	0	0	0	0	1
101	Road transport	0	0	0	0	0	0	0	0	0	1	0
102	Rail transport	0	0	0	0	0	0	0	0	0	1	0
103	Transport via pipeline	0	0	0	0	0	0	0	0	0	1	0
104	Water transport	0	0	0	0	0	0	0	0	0	1	0
105	Air transport	0	0	0	0	0	0	0	0	0	1	0
106	Services to transport	0	0	0	0	0	0	0	0	0	1	0
107	Postal and courier services	0	0	0	0	0	0	0	0	0	1	0
108	Hospitality	0	0	0	0	0	0	0	0	0	0	1
109	Publishing	0	0	0	0	0	0	0	0	0	0	1

110	Telecommunications	0	0	0	0	0	0	0	0	0	0	1
111	Information services	0	0	0	0	0	0	0	0	0	0	1
112	Finance and insurance	0	0	0	0	0	0	0	0	0	0	1
113	Property and real estate	0	0	0	0	0	0	0	0	0	0	1
114	Professional scientific and technical services	0	0	0	0	0	0	0	0	0	0	1
115	Administrative services	0	0	0	0	0	0	0	0	0	0	1
116	Government social security defence public order	0	0	0	0	0	0	0	0	0	0	1
117	Education	0	0	0	0	0	0	0	0	0	0	1
118	Human health and social work activities	0	0	0	0	0	0	0	0	0	0	1
119	Arts entertainment and recreation	0	0	0	0	0	0	0	0	0	0	1
120	Other services	0	0	0	0	0	0	0	0	0	0	1

4.7.3. Public-sector definitions

4.7.3.1. Analysis of ISIC, SNA

In the following, the International Standard Industry Classification of all economic activities (ISIC) and the System of National Accounts (SNA) are discussed. The ISIC is the most widely used *classification* in economic statistics, while the SNA is the international *standard for compilation of national accounts* statistics and reporting of national accounting data, and is based on input-output tables (IOT).

4.7.3.1.1. ISIC

The ISIC, which is produced by the United Nations, is the most widely used classification system: "As an international standard classification, ISIC is the primary tool for collecting and presenting internationally comparable statistics by economic activity" (Task team on ISIC, 2024, p. 30). The UN's Central Product Classification (CPC) follows a similar approach to ISIC but rather than being based on activities it is based on the products, with a reference to the ISIC class in which the good or services are mainly produced (Task team on ISIC, 2024, p. 6).

4.7.3.1.2. SNA

The SNA's focus is on facilitating analysis and decision-making through standardised accounting information, and is not only published by the UN but also be the European Commission, International Monetary Fund, Organisation for Economic Co-operation and Development and the World Bank. The SNA was adopted at the United Nations Statistical Commission as the international standard for compiling national accounts statistics. (European Communities et al., 2009, p. iiv). In addition to flow accounts and balance sheets, the SNA includes a section on input-output tables (detailed information on IO analysis by the United Nations Statistics Division is in the "Handbook of input-output table compilation and analysis" (1999), as the international guidelines for IO analysis). The SNA is "the internationally agreed standard set of recommendations on how to compile measures of economic activity in accordance with strict accounting conventions based on economic principles… that comprise the internationally agreed standard for measuring such items as gross domestic product (GDP)" (European Communities et al., 2009, p. 1).

4.7.3.2. Kind of ownership and economic producers

The discrepancy between SNA and ISIC in their approach to economic producers is highlighted by ISIC:

ISIC does not draw distinctions according to kind of ownership of a producing unit or type of legal organization because such criteria do not relate to the characteristics of the activity itself. Units engaged in the same kind of economic activity are classified in the same category of ISIC, irrespective of whether they are unincorporated enterprises, (part of) incorporated enterprises or government units, foreign controlled or have a parent enterprise that consists of more than one establishment. Therefore, a strict link between ISIC and the Classification of Institutional Sectors in SNA does not exist (Task team on ISIC, 2024, p. 7).

4.7.3.3. Public-sector as part of the market?

It is generally acknowledged that government is unlike industry (market), however the treatment of government by classification systems, notably the SNA, ISIC and related Central Product

Classification (CPC) varies substantially (European Communities et al., 2009; Miller & Blair, 2022; United Nations Statistics Division, 2015).

Both the SNA and ISIC agree on unique characteristics of governments globally as providing administrative services, compulsory social security and defence. For other activities, however, the ISIC does not make a distinction, while noting that not only government bodies but also private units performing typical "public administration activities" may be classified for example in section P (Education). "In general, ISIC does not differentiate between market and non-market activities. However, it should be emphasized that this distinction continues to be an important feature of SNA" (Task team on ISIC, 2024, p. 7).

The 1993 SNA describes government units as: "unique kinds of legal entities established by political processes which have legislative, judicial or executive authority over other institutional units within a given area" (Commission of the European Communities - Eurostat et al., 1993, p. 122), where "the range of goods and services produced by government units varies greatly from one country to another (p. 123). The 2008 SNA explains: "In order to analyse the full impact of government on the economy, therefore, it is useful to form a sector consisting of all the units of general government and all public corporations. This composite sector is referred to as the public sector (European Communities et al., 2009, p. 435).

An exception is made for quasi-corporations – unincorporated enterprises that act like corporations and are treated as such in the SNA. However:

> "If they function like corporations, they must keep complete sets of accounts. Indeed, the existence or possibility to construct a complete set of accounts, including balance sheets, for the enterprise is a necessary condition for it to be treated as a separate institutional unit, otherwise it would not be feasible from an accounting point of view to distinguish the quasi-corporation from its owner" (European Communities et al., 2009, p. 440).

The 1993 SNA highlights the importance of unit integration with government as a distinguishing factor identifying whether something should be treated as government or a quasi-corporation:

> "the producer units that remain integrated with the government units that own them are those that cannot be treated as quasi-corporations. Such units remain within the general government sector. They are likely to consist largely, or entirely, of non-market producers: that is, producers most or all of whose output is supplied to other units free, or at prices that are not economically significant" (Commission of the European Communities - Eurostat et al., 1993, p. 124).

Following the ISIC and CPC, the aggregated government sector in the MRIO used for this study GLORIA (Lenzen et al., 2017; Lenzen et al., 2022) consists of administrative government services, social security and public order/safety/defence. The question for the purposes of organisational impact analysis, is if we consider government:

1. as one extensive public sector, not a market "producer"; or
2. as only uniquely providing administrative, social security and defence services, while the remainder of activities should be classified with the relevant industry i.e., health.

4.7.3.4: Non-profit institutions (NPIs)

Non-profit institutions (NPIs) are characterised by the System of National Accounts (SNA) according to whether they are market or non-market actors (Commission of the European Communities - Eurostat et al., 1993). Further, the SNA 2008 chapter on NPIs clearly delineates them into key categories, which can be summarised as either:

1. corporate focused (market);
2. non-profit institutions serving households (Government-controlled non-market or household-focused market or non-market final demand).(European Communities et al., 2009, p. 455).

Only (1) is considered as an economic inter-industry producer; put simply:
"When the fees charged are regarded as being economically significant, the NPIs concerned are treated as providing market services and are allocated to the corporations sectors. Otherwise the NPIs fall into the institutional sector of NPISHs [final demand] " (European Communities et al., 2009, p. 455).

4.7.3.4.1: Corporation-focused ("quasi-corporations")

1. product provided to *corporations;*
2. this output is *sold to the corporations concerned* and treated as intermediate (market *producer*). (European Communities et al., 2009, p. 455).

"Some NPIs produce services for corporations typically charging fees (sometimes described as subscriptions) intended to cover costs. They are often set up as associations that provide services exclusively to members. The level of fees charged, the price of membership, typically satisfies the SNA criteria of economically significant prices. For this reason these NPIs are allocated to the corporations sectors. An example of an NPI serving corporations is a trade association." (European Communities et al., 2009, p. 455).

4.7.3.4.2. Non-corporate focused

a. government-controlled (e.g., research institute whose officers are appointed- or objectives determined- by government) - Services to individuals OR collective services, provided on non-market basis – treated as Government; or otherwise;

b. non-profit institutions serving households (NPISH):
    i. individual households at market (economically significant) prices – Allocated to Corporate sector; Household Final demand;
    ii. Individual households free or non-economically significant prices – Allocated to NPISH; Household final consumption from social transfers in kind;
    iii. Collective services free or not economically significant prices **–** Final consumption of NPISH (European Communities et al., 2009, p. 455).

4.7.3.4.2.1. Universities and research institutes

Activities by university NPIs may be treated as market or non-market. The SNA identifies variously:

> "Schools, colleges, universities, clinics, hospitals, etc. constituted as NPIs are *market producers when they charge fees which are based on their production costs* and which are sufficiently high to have a significant influence on the demand for their services" (European Communities et al., 2009, p. 73). This would include sales of goods to industry.

In terms of grant income for research:

> "Research and development undertaken by government units, universities, non-profit research institutes, etc. is non-market production" [for example, university research paid by government grants]; however: "Research and development undertaken by specialized *commercial research* laboratories or institutes is valued by receipts from sales, contracts, commissions, fees, etc. in the usual way" (European Communities et al., 2009, p. 119). As a de facto for commercial research laboratories or institutes, this implies that university research *for commercial purposes* should be treated as market, not non-market production.

The case of research institutes can appear complex, e.g., Cooperative Research Centres (CRCs) in Australia are set up as companies. Organisations can apply for approved research institute status[10] (dependent on meeting certain criteria) and receive deductable gift recipient (DGT) endorsement. In the framework presented in this paper, non-government industry bodies that have a statutory authority agreement with the government are classified as quasi-corporations i.e., grant income from them is not excluded as public sector, but CRC research institutes are treated as non-market i.e., income from those is excluded as part of the public sector.

See Table 3 in the Main Text for a decision-tree in assessing whether an NPI may be a research institute, at the one extreme as part of the public sector, or a quasi-corporation, which is treated as a market NPI.

4.7.4. *SI* References

Commission of the European Communities - Eurostat, International Monetary Fund, Organization for Economic Co-operation and Development, United Nations, & World Bank. (1993). System of National Accounts. https://unstats.un.org/unsd/nationalaccount/docs/1993sna.pdf

European Communities, International Monetary Fund, Organisation for Economic Co-operation and Development, United Nations, & World Bank. (2009). System of National Accounts 2008. https://unstats.un.org/unsd/nationalaccount/docs/sna2008.pdf

Ferguson, H. (2022, February 17). *University research funding: a quick guide.* Parliament of Australia. https://www.aph.gov.au/About_Parliament/Parliamentary_departments/Parliamentary_Library/Research/Quick_Guides/2021-22/UniversityResearchFunding

Heller, R. F., Ya-Yen, S., Guo, Z., & Malik, A. (2022). Impact on carbon emissions of online study for a cohort of overseas students: A retrospective cohort study [version 5; peer

[10] https://www.ato.gov.au/businesses-and-organisations/not-for-profit-organisations/getting-started/in-detail/types-of-dgrs/a-k/approved-research-institutes-applicants

review: 2 approved, 1 approved with reservations]. *F1000Research, 10:849*. https://doi.org/10.12688/f1000research.55156.5

Lenzen, M., Geschke, A., Abd Rahman, M. D., Xiao, Y., Fry, J., Reyes, R., Dietzenbacher, E., Inomata, S., Kanemoto, K., Los, B., Moran, D., Schulte In Den Bäumen, H., Tukker, A., Walmsley, T., Wiedmann, T., Wood, R., & Yamano, N. (2017). The Global MRIO Lab – charting the world economy. *Economic Systems Research*, *29*(2), 158-186. https://doi.org/10.1080/09535314.2017.1301887

Lenzen, M., Geschke, A., West, J., Fry, J., Malik, A., Giljum, S., Milà I Canals, L., Piñero, P., Lutter, S., Wiedmann, T., Li, M., Sevenster, M., Potočnik, J., Teixeira, I., Van Voore, M., Nansai, K., & Schandl, H. (2022). Implementing the material footprint to measure progress towards Sustainable Development Goals 8 and 12. *Nature Sustainability*, *5*(2), 157-166. https://doi.org/10.1038/s41893-021-00811-6

Miller, R., & Blair, P. (2022). *Input–Output Analysis: Foundations and Extensions - Third Edition* (3rd ed.). Cambridge University Press. https://doi.org/10.1017/9781108676212

Task team on ISIC. (2024). *Introduction of the Standard Industrial Classification of All Economic Activities, Revision 5 (ISIC Rev.5) - (Part of forthcoming UN publication)*. https://unstats.un.org/unsd/classifications/Econ/Download/In%20Text/ISIC5_Intro_11Mar2024.pdf

United Nations Statistics Division. (1999). *Handbook of input-output table compilation and analysis*. https://digitallibrary.un.org/record/370160?ln=en

United Nations Statistics Division. (2015). *Central Product Classification (CPC)*. https://unstats.un.org/unsd/classifications/unsdclassifications/cpcv21.pdf

World Resources Institute & World Business Council for Sustainable Development. (2013). *Technical guidance for calculating scope 3 emissions: Supplement to the Corporate Value Chain (Scope 3) Accounting & Reporting Standard*. https://ghgprotocol.org/sites/default/files/standards/Scope3_Calculation_Guidance_0.pdf

5. COMPREHENSIVE AND HOLISTIC CLIMATE-AND-SUSTAINABILITY DUE DILIGENCE

Reiner, V., & Malik, A. (*under review*). Scope-3 emissions and Sustainability impact throughout the value chain: An approach to mandatory environmental due diligence.

Paper: Scope-3 emissions and Sustainability impact throughout the value chain: An approach to mandatory environmental due diligence

Abstract

This study applies and extends input-output (IO) analysis to new environmental reporting frameworks for integrated and standardised analysis that is comprehensive, while incorporating process-based data where practicable. This hybrid IO-LCA (life cycle analysis) research is the first to describe the application of spend-based- with income-based IO analysis across scope-3 Greenhouse Gas Protocol categories for an organisation; using the same underlying data, the research also measures general sustainability-related indicators. By undertaking a Climate- and Nature impact assessment, the method is in alignment with the International Sustainability Standards Board (ISSB), and regional adaptations/ legislation, holistically. In the case study, all direct suppliers' electricity emissions linked to the University's expenditure were calculated in a relatively straightforward manner, estimated as totalling more than the University's reported scope-1 emissions; for the study indicators, comprising greenhouse gas emissions, land use and bluewater consumption indirect impact represented 90% of the total footprint on average. The IO framework presented in this study could be applied by organisations to calculate their inter-industry upstream and downstream impact, based on their estimated expenditure and income per sector. Having demonstrated how scope-3 emissions could be calculated for comprehensive corporate reporting using upstream- and downstream IO emission factors, mandating the scope-3 approach promptly within a continuous improvement context becomes paramount. By making IO analysis mandatory for scope-3 due diligence, organisations can be ambitious in their disclosures on a level playing field. The fact that IO analysis incorporates all inter-industry emissions suggests a role for some form of relief within a whole-of-value-chain due-diligence framework.

5.1. Introduction

Scope-3 emissions are generally regarded as more difficult to measure than emissions from a reporting entity's direct combustion of fossil fuels (scope 1) or from purchased or acquired electricity, steam, heat or cooling (scope 2); the Greenhouse Gas Protocol has defined scope-3 emissions as all other value-chain emissions that result from a company's activities (World Business Council for Sustainable Development & World Resources Institute , 2004). Mandatory reporting of scope-3 emissions, which can account for more than 90% of an organisation's emissions (Greenhouse Gas Protocol, 2022, p. 2), is becoming increasingly common worldwide; concurrently, there is increasing pressure regarding other sustainability-related reporting, of Nature indicators. General-sustainability reporting as opposed to climate reporting among Australian universities provides a good example of the situation, where reporting at the time of writing was *voluntary.* Some universities report on some sustainability measures and some separately report on some scope-3 emissions. At the University of Sydney, its first sustainability strategy sought to commence environmental reporting and draw internally on its academic pioneers in global supply-chain "footprinting", using input-output (IO) analysis to quantify all inter-industry scope-3 emissions, as well as investigate biodiversity-related impacts, holistically. The coronavirus pandemic delayed the commencement but the project was revisited in anticipation of mandatory reporting and to play a leadership role, with the University's first climate-related disclosure including emissions calculations for all GHG Protocol scope-3 categories (The University of Sydney, 2025); the methods application and development as part of a holistic pilot study for 2022, which preceded the disclosure, is the focus of this paper.

Although this paper includes details of the data-collection efforts for the University of Sydney case study for completeness, such data challenges and the individual solutions trialled may vary depending on the organisation. The contribution of this paper lies in the broad framework for organisations presented: for hybrid LCA-IO analysis upstream and downstream for comprehensive due diligence including the entire inter-industry value chain based on the reporting entity's estimated expenditure and income per sector.

5.1.1. Environmental due-diligence frameworks

The International Sustainability Standards Board (ISSB) Sustainability Disclosure Standards includes mandatory reporting of scope-3 emissions upstream and downstream from the second year. The ISSB Standards came into effect for annual reporting periods beginning on or after 1 January 2024. The ISSB brings together key sustainability standards, with interoperability

work such as with the European Sustainability Reporting Standards (IFRS, 2024) and with the ISSB including the [Task Force on Climate-related Financial Disclosures] TCFD (IFRS, n.d.-a) and the [Taskforce on Nature-related Financial Disclosures] TNFD (2025). The ISSB's first Standards published by IFRS, IFRS S1 *General Requirements for Disclosure of Sustainability-related Financial Information* International Sustainability Standards Board, 2023b), and IFRS S2 *Climate-related Disclosures* (International Sustainability Standards Board, 2023a), were issued within two years of the ISSB's formation. A visual summary of the emerging global architecture for Climate- and Nature corporate reporting has been provided by the TNFD (2023, p. 20); in this paper we use "due diligence" generally to describe current or expected mandatory-reporting regimes. The climate-disclosure landscape is fast-moving and evolving. For example, recent amendments have been announced aimed at simplification regarding the ISSB's IFRS S2 (IFRS, 2025), as well as the Corporate Sustainability Reporting Directive and the Corporate Sustainability Due Diligence Directive (European Commission, 2025). Australia has been an early adopter of key elements of the ISSB Standards (IFRS, n.d.-b, n.d.-c), which prompted this study. Australian jurisdictional market regulation is detailed by Simnett, et al., (2024). At the time of writing, in Australia for reporting periods from 1 January 2025 many large organisations were required to prepare their disclosures under the AASB S2 *Climate-related Disclosures* (Australian Accounting Standards Board, 2024a), which is aligned with IFRS S2 (International Sustainability Standards Board, 2023a) , while AASB S1 *General Requirements for Disclosure of Sustainability-related Financial Information [voluntary]* (Australian Accounting Standards Board, 2024b) incorporates IFRS S1 (International Sustainability Standards Board, 2023b). However at the sub-national level in the State of New South Wales, recent amendments to NSW Treasury's reporting framework for climate-related financial disclosures, have been made to reflect concern from stakeholder feedback; for NSW government annual-reporting "entities" (State of New South Wales (NSW Treasury), 2024), scope-3 emissions were excluded "at this point" because of lack of readiness (State of New South Wales (NSW Treasury), 2025, p. 43).

5.1.2. A brief overview of general-sustainability- and scope-3 reporting

Climate- and Nature due diligence provides an opportunity for integrated reporting of businesses to address national and global efforts on the sustainability development goals (Lu et al., 2015), while focusing corporate social responsibility on priorities such as climate inaction as a threat to SDG progress (Mackay et al., 2025) Approaches to reporting have varied widely, for sustainability generally (Troshani & Rowbottom, 2024) as well as the carbon-footprint (CF) in particular (Downie & Stubbs, 2012; García-Alaminos et al., 2022; Helmers et al., 2021; Onat et

al., 2025; Stridsland & Sanderson, 2023). Looking at value-chain analysis of indirect emissions, most reporting has focused upstream analysis i.e., emissions from suppliers, rather than downstream emissions from customers, which has traditionally been considered as less intuitive. For example, the GHG Protocol refers to IO-based emissions calculations as "spend-based" (World Resources Institute & World Business Council for Sustainable Development, 2013, p. 21), since at the time of the organisation's development of standards and guides, the income-based, downstream equivalent to upstream emission factors had only just started to be conceived (Marques et al., 2013). In terms of traditional process-based, lifecycle assessment (LCA) approaches that rely on locally collected data, the GHG Protocol notes that a disadvantage is its lack of comparability because the data as well as the system boundary within which to measure the GHG emissions are chosen by the practitioner. The GHG Protocol has dealt with the question of whether to use detailed process-based, LCA, or boundary-free industry-average IO analysis, by noting the value of hybrid analysis: "Companies may combine the top down [environmentally extended IO] EEIO approach with the bottom-up, process-based approach to leverage the benefits of both approaches" (World Resources Institute & World Business Council for Sustainable Development, 2013, p. 18). Table 1 highlights some advantages and disadvantages of IO versus process-based approaches according to the GHG Protocol; it should be noted that in recent years, models have developed substantially regarding multi-region (MRIO databases), and improvements in data and supercomputing have supported high-resolution analysis and reporting (Tukker & Dietzenbacher, 2013; Malik et al., 2019). Hybrid IO-LCA calculations mean that bottom-up data can be used where practicable, with IO analysis covering all higher-order supply chains (Lenzen, 2000). Upstream IO analysis is now well-established and has been demonstrated and discussed at various levels, e.g., corporate (Huang et al., 2009), local council (Malik et al., 2022), municipality (Larsen & Hertwich, 2010) and local health district (Malik et al., 2024).

Environmentally extended IO analysis (EEIO)	**Process-based (LCA)**
Comprehensive coverage	Lack of comparability as the system boundary and the data are selected by the practitioner
Simplicity of method and application	Collection of data may be time, cost, and labor intensive
Lacks specificity and accuracy of process-based approaches	High level of specificity and focus
Time and cost savings as data requirements are less onerous than in a process-based approach.	Data requirements may render large-scale, multi-product analysis impractical.

Table 1: An excerpt of advantages and disadvantages of IO vs process-based approaches, from the GHG Protocol's scope-3 technical guidance (World Resources Institute & World Business Council for Sustainable Development, 2013, p. 17)

Among universities, whose academics are focused on ”wicked” challenges in terms of society’s major challenges, IO analysis has been used by several to measure their greenhouse gas (GHG) emissions, which are discussed below. However, as with other organisations, the focus of analysis of university environmental measurement has traditionally been on GHG emissions rather than on holistic quantification of Climate *and* Nature indicators, although Baboulet & Lenzen (2010) calculated the upstream impact of the University of Sydney across several indicators. Section 5.2 discusses IO methodology. Sun et al. (2022) quantified Cornell University’s scope-3 emissions with a focus on procurement expenditure, i.e., upstream suppliers. García-Alaminos et al. (2022), who propose a model that focuses on upstream emissions but does not extend downstream, provide a good review of earlier university carbon footprints (CF). Similarly, in a review article, Stridsland and Sanderson (2023) note that many universities still rely on LCA; those authors recommend a spend-based approach, however, by not extending from expenditure also to include income, such an approach is limited to upstream (but not also downstream) IO analysis. Stridsland et al. (2024) report on a consortium of Danish universities, who consider downstream emissions reporting as part of the GHG Protocol but do not attempt to quantify them in phase I of the project. In terms of leadership in general-sustainability reporting, the Nature Positive Universities Alliance, which was announced at the United Nations Biodiversity Conference (COP15) in 2022, used as an exemplar the University of Oxford “biodiversity footprint” (Bull et al., 2022). In their assessment, Bull et al. noted the challenges of standardisation: "Quantifying the impacts of an organisation’s activities on biodiversity trends is not standardised like the contributions it makes to climate change" (Bull et al., 2022, Supplementary Information, p. 14). However, biodiversity impact can be quantified in a standardised way, using economic data from IO analysis to underpin the value-chain calculations (Irwin et al., 2022; Lenzen et al., 2012).

Moving from analysis of economic drivers from a consumer to a producer perspective, Ghosh (1958) formulated the downstream equivalent to upstream IO analysis, which incorporates the entire inter-industry sales chain, but the method was the substantially critiqued and it was not until decades later that a reinterpretation provided “vindication” for the Ghosh model (Dietzenbacher, 1997). This was followed by substantial update of Ghoshian calculus as part of a more holistic approach to consumer and producer responsibility generally (Gallego & Lenzen, 2005) and focusing on downstream environmental impacts specifically (Lenzen & Murray, 2010). Gallego & Lenzen highlighted that *ex-post,* the Ghosh model could be used descriptively to re-trace embodiments of primary inputs [e.g., income] in downstream sales (2005, p. 368). Such an approach was distinguished as “income-based” (Marques et al., 2012) and numerous

researchers then undertook a variety of integrated analysis including an income-based perspective at the macroeconomic level e.g. (Chen et al., 2017; Cooper et al., 2021; Guan et al., 2019), with Lenzen et al. (2010) performing downstream IO analysis for financial but not environmental indicators for the University of Sydney. Extending this to generalised IO analysis at the organisational level, Reiner (*under review*) detailed a framework regarding unique considerations and approaches to consider when replacing global, national, sub-national or industry-level primary inputs with a particular organisation's income data in order to undertake such a downstream hybrid IO-LCA calculation. Although some academic discourse continues to suggest potential improvements regarding the Ghoshian model, from a value-chain perspective regarding the types of accounts it has been said that "only one of them is of importance: the expenditure and revenue account" (Leontief, 1936, p. 106); inter-industry impact based on this set of accounts may be estimated in a relatively straightforward manner through the use of spend-based and income-based multipliers.

For this study, we (a) follow the general approaches of Baboulet & Lenzen (2010) to calculate an organisation's *upstream* environmental impacts based on expenditure, and Lenzen et al. (2010) to calculate an organisation's *downstream* financial impacts based on income; (b) incorporate the *environmentally extended* income-based downstream enterprise framework (Reiner, *under review*), which has a focus on Climate reporting; and (c) extend (b) to new Climate- and *Nature* due-diligence requirements *upstream and downstream* holistically. Taking a hybrid IO-LCA approach, we present GHG emissions, land use and bluewater consumption impacts for the University of Sydney's activities in 2022 upstream, using spend-based IO analysis, and downstream (income-based IO analysis). Scope-3 emissions are reported across the 15 GHG Protocol categories. We use the Global Resource Input-Output Assessment (GLORIA) database (Lenzen et al., 2022; Schandl et al., 2024) of 120 sectors and 164 regions. This paper is set out as follows: A brief history and background to IO analysis is provided in Section 5.2. This is followed by a case study undertaking a holistic enterprise Climate- and Nature study using IO analysis in Sections 5.3-5.4, drawing on the income-based framework for organisations (Reiner, *under review*), and adding upstream calculations including for GHG Protocol categories. We demonstrate the practical decisions that can result from such integrated analysis to a high degree of resolution and conclude by discussing implications for sustainability due diligence with a focus on GHG accounting in Sections 5.5-5.6.

5.2. Input-output (IO) methodology

5.2.1. The development and application of IO analysis

IO analysis was developed by Wassily Leontief from the 1930s to describe the inter-relationships in the economy, initially for a single country and later for multiple countries (Leontief, 1974). IO analysis rose to prominence during the 1970s oil shocks and Leontief won a Nobel Prize in 1973. Leontief had detailed his construction of a "*Tableau Economique* of the American economy" for 1919, a breakthrough at the time that used real rather than fictitious numbers to dissect the economic system into classes of independent units and comprised only a handful of sectors (Leontief, 1936). Central to IO is the concept of economic equilibrium, with a fundamental accounting assumption that the total expenditure of all organisations and households must equal the sum total of their revenue (including savings and borrowing). Already in the early days Leontief described how so-called market "externalities" could be considered part of the economic structure, demonstrating how embodied pollution can be traced alongside the flow of goods and services via technical coefficients (Leontief, 1970). This extension is referred to as environmentally extended input-output analysis (EEIO). Also referred to as consumption-based accounting (CBA), Leontief's IO analysis from an upstream perspective traces the impact of economic activity back to demand. An alternative approach to IO analysis proposed by Ghosh (1958) from a downstream perspective describes the impact of economic activity as associated with supply, as discussed previously in Section 5.1.2.

In recent years, the accuracy and applicability of IO analysis has improved substantially because of increased data availability as well as developments in human and technological resourcing through virtual collaborative infrastructure and supercomputers that analyse billions of supply chains (Lenzen et al., 2017a; Lenzen et al., 2017b; Malik et al., 2019). A benefit of such global databases is that they can enable comparison of a range of indicators worldwide in a standardised manner, while incorporating spillover effects from substantial international trade (Kanemoto et al., 2014), in alignment with frameworks such as the sustainable development goals (SDGs). Today, IO tables (IOTs) are central to the almost universal System of National Accounts (Commission of the European Communities - Eurostat et al., 1993) of countries' statistical agencies; IO analysis is governed by UN standards (United Nations Statistics Division, 1999, 2018) and underpins modern analysis such as through the global value chains (GVC) dashboard (World Trade Organization, n.d.) and the development of widely used multipliers (Guannan Miao et al., 2024; ten Raa, 2017). IO analysis has been said to be one of the most widely applied methods in economics (Miller & Blair, 2022, p. 1). Environmentally

extended IO analysis is also used to develop emission factors, which the GHG Protocol has referred to as spend-based or EEIO emission factors (World Resources Institute & World Business Council for Sustainable Development, 2013, p. 21)..

5.2.2. Key environmentally extended IO calculus

The detailed MRIO database GLORIA Release 059 that we used had $N = 164 \times 120 = 19{,}680$ region/sector pairs (Section 5.3 Data and calculations). We converted each of the selected indicators (GHG emissions, Land Use and Bluewater Consumption) from the relevant rows of the environmentally extended satellite of physical accounts ($\mathbf{Q}$) into an $1 \times N$ indicator e.g., $\mathbf{Q}_{\text{GHGs}}$, $\mathbf{Q}_{\text{LandUse}}$, $\mathbf{Q}_{\text{Bluewater}}$. We subjected this system per indicator to IO analysis (discussed in Sections 5.1.2-5.2.1). In IO calculus, upstream embodied impact, which may be called a footprint (F) can be described as:

$$F = (\mathbf{Q}\hat{\mathbf{x}}^{-1})(\mathbf{I} - \mathbf{T}\hat{\mathbf{x}}^{-1})^{-1}\mathbf{y} \quad \text{(1a)}$$

(detailed below) where the impact can be summarised as being as a function of the total-intensity multiplier $(\mathbf{Q}\hat{\mathbf{x}}^{-1})(\mathbf{I} - \mathbf{T}\hat{\mathbf{x}}^{-1})^{-1}$ driven by the vector of final demand ($\mathbf{y}$), which is in monetary units:

$$F = \mathbf{m}\mathbf{y} \quad \text{(1b)}$$

where $\mathbf{m}$ is a vector of size $1 \times N$ and $\mathbf{y}$ is sized $N \times 1$. Although the result in equations (1a) and in (1b) is a scalar (F), the footprints in later equations are decomposed by sectoral contributions. For GHG emissions, the total intensities in the vector of backward multipliers upstream ($\mathbf{m}$) are also referred to as scope-3 spend-based emission factors (an exception is with electricity emissions, where the GHG Protocol calls out inter-industry "scope-2" emissions, see Section 5.3.6.2). The $1 \times N$ vector of direct-intensities ($\mathbf{Q}\hat{\mathbf{x}}^{-1}$), often denoted as ($\mathbf{q}$), is defined where each element is associated with one unit of gross output x_j of sector j (the hat symbol represents vector diagonalisation). The total-requirements matrix $(\mathbf{I} - \mathbf{T}\hat{\mathbf{x}}^{-1})^{-1}$ is the famous Leontief inverse ($\mathbf{L}$) that elegantly encapsulates the entire upstream inter-industry supply chain. In calculating $\mathbf{L}$, $\mathbf{I}$ is an identity matrix and $\mathbf{T}$ is the matrix of intermediate transactions. The direct-requirements matrix ($\mathbf{T}\hat{\mathbf{x}}^{-1}$), also called the $\mathbf{A}$ matrix, comprises technical coefficients of inputs directly required per unit of output of a sector. IO analytical techniques possible from equation (1a) that provide insights into hotspots throughout the supply chain, include production layer decomposition (PLD) and structural path analysis (SPA). In PLD, it can be seen how far back in the supply chain the hotspots lie; the supply chain is decomposed through a Taylor expansion of $\mathbf{L}$ into different production layers such that:

$$\mathbf{L} = \mathbf{I} + \mathbf{A} + \mathbf{A}^2 + \mathbf{A}^3 + \ldots \quad (2)$$

with the impact per layer calculated as:

$$F_{PLD} = (\mathbf{q})(\mathbf{I} + \mathbf{A} + \mathbf{A}^2 + \mathbf{A}^3 + \ldots)\mathbf{y} = \mathbf{qy} + \mathbf{qAy} + \mathbf{qA}^2\mathbf{y} + \mathbf{qA}^3\mathbf{y} + \ldots \quad (3)$$

Layer 1 Layer 2 Layer 3 Layer 4

In equation (3), the aggregated impact per node can be disaggregated into its constituent parts from consumption or production perspectives by replacing matrix- with element-wise multiplication, as shown below in equations (5) and (6).

In SPA, the supply chain can be scanned and the top paths ranked according to:

$$F_{SPA} = \sum_{i,j=1}^{n} q_i(I_{ij} + A_{ij} + A^2_{ij} + A^3_{ij} + \ldots)y_j \quad (4)$$

(Lenzen, 2007) where i represents rows and j represents columns, with the demand-pull flow beginning at the impacting sector q_i and ending in final consumption at y_j.

In this study we analyse the disaggregated impact variously from the perspectives of consumption or production:

$$\mathbf{F}_c = (\mathbf{qL})' \circ \mathbf{y} \quad (5)$$

where the impact is disaggregated according to the requirements of satisfying final demand; the Hadamard ($\circ$) represents element-wise multiplication and the prime ($'$) represents transposition; or

$$\mathbf{F}_p = \mathbf{q}' \circ \mathbf{Ly} \quad (6)$$

where the impact is disaggregated according to the requirements of satisfying impacting industries.

Similar to (1a) but for downstream, enabled impact, which may be called a footprint ($\bar{F}$) can be described as:

$$\bar{F} = \mathbf{v}(\mathbf{I} - \hat{\mathbf{x}}^{-1}\mathbf{T})^{-1}(\mathbf{Q}\hat{\mathbf{x}}^{-1})' \quad (7)$$

which can be summarised as the total-intensity forward multiplier $(\mathbf{I} - \hat{\mathbf{x}}^{-1}\mathbf{T})^{-1}(\mathbf{Q}\hat{\mathbf{x}}^{-1})'$ denoted by $\bar{\mathbf{m}}$, enabled by the vector of primary inputs/value-added ($\mathbf{v}$) in monetary units. Here, $(\mathbf{I} - \hat{\mathbf{x}}^{-1}\mathbf{T})^{-1}$ is the Ghosh inverse ($\bar{\mathbf{L}}$), with the pre-multiplication of $\mathbf{T}$ by $\hat{\mathbf{x}}^{-1}$ resulting in transposition of columns to rows such that the allocation matrix ($\hat{\mathbf{x}}^{-1}\mathbf{T}$), denoted by $\bar{\mathbf{A}}$, comprises direct sales/allocation coefficients that enable others' production.

Further details are in Section 5.8.2.1.

5.3. Data and calculations

Although much of the data and IO discussion is generic to up- and downstream, in this paper unless stated, our focus is upstream analysis, e.g., scope-3 GHG Protocol categories 1-7, since the downstream IO analysis and emissions reporting is the focus of Reiner (*under review*). In analysing the results it should be noted that for the inter-industry IO calculations for the University case study, most of the general-ledger data included is expenditure (linked to upstream emissions) rather than income (downstream). In addition to relying on IO analysis for inter-industry calculations, impact calculated using non-IO methods is included in areas material for the case study.

Two separate value-chain calculations are made for upstream and downstream calculations variously in using the footprint equations (1a) for upstream and (7) for downstream. In such hybrid IO-LCA calculations, the local activity, rather than global final consumption or primary inputs, is used as the stressor for the impact analysis. In other words, (a) following a spend-based approach upstream, the organisation's expenditure is used as a proxy for final demand ($\mathbf{y}$) for the supply-chain calculations in the usual way; and (b) following an income-based approach downstream, the organisation's income is used as a proxy for primary inputs ($\mathbf{v}$) for the sales-chain calculations. The latter is in line with the case study by Lenzen et al. (2010), which focused on financial considerations,[11] conceptual work by Lenzen & Murray (2010) and the generalised downstream IO enterprise framework by Reiner (*under review*).

This University of Sydney study uses the GLORIA database, an environmentally extended database that was initially built for the UN (Lenzen et al., 2022) constructed in the Global MRIO Lab (Lenzen et al., 2017) and is also available via the cloud-based IELab (Industrial Ecology Virtual Laboratory, n.d.-b). GLORIA is the result of a collaborative effort led by the University of Sydney (monetary tables, GHG and employment satellites) and including the Vienna University of Economics and Business (remaining satellites) (Lenzen & Li, 2024, p. 2). The latest release at the time the study commenced was used, being Release 059, rebalanced MRIO tables (Lenzen

[11] Lenzen et al. (2010, p. 160) also noted that the Ghosh (downstream) model could be used for analysis beyond the price impacts that were the subject of that study: "while the supply-push scenario can – at least ex-ante – only be interpreted as a price model (price/wage changes, see Dietzenbacher, 1989; 1997)… The supply-push model can however be interpreted as an ex-post quantity model (Gallego and Lenzen, 2005)". Lenzen & Murray (2010) expand on the *ex-post* interpretation by establishing a terminology and framework for quantifying downstream carbon footprints.

& Li, 2024)). The choice of the *global,* GLORIA database rather than the Australian IELab national IO database (Lenzen et al., 2014) was based on several of the University's requirements, to: assess potential spillover impacts overseas; initially consider a diverse range of biodiversity-related indicators; and be benchmarkable through the use of a globally recognised database, with low levels of uncertainty; information on GLORIA uncertainty is in Section 5.8.1.2.

Although under Australian Accounting Standards, universities as not-for-profit entities are required to make specific accounting adjustments to expenditure and income, the basis of the case-study calculations is the *actual* expenditure and income, *not the adjusted data*, so we use the pre-"ADJUST" general-ledger data. Generally, accounting adjustments are excluded; in this vein, the [GST] goods and services tax component of the University's expenditure and income is not included, thereby being consistent with MRIO valuations selected in basic prices. We adhere to the GHG Protocol's Accounting and Reporting Principles, in particular by aiming for completeness, including by using IO for a comprehensive assessment of our value-chain to assist decision-making, with a view to increasing accuracy of emissions in the identified hotspot areas over time (World Resources Institute & World Business Council for Sustainable Development, 2011, pp. 24-25).

5.3.1. Selecting the MRIO base year

The year 2021 is used as the MRIO base year for the value-chain analysis of the University's activities in 2022, in part because GLORIA Release 059 includes UN Main Aggregates data up to the year 2021, with forecasts of all tables from 2022 onwards. Further detail is in Section 5.8.2.2. For future refreshes of the University value-chain analysis beyond 2022, it was intended that the underlying MRIO would be updated to use new GLORIA Releases and later base-year MRIO tables, with the 2022 University calculation (and any future refreshes as relevant) updated for any resultant significant differences, as advised by the GHG Protocol (World Business Council for Sustainable Development & World Resources Institute, 2001, p. 46). This would correct for errors due to the use of aged MRIO base-year data, for example to reflect economic developments in later years post-COVID-19.

5.3.2. Inclusion of process-based data

Taking a hybrid IO-LCA approach, IO data can be replaced by process-based data at various nodes/layers up the inter-industry supply chain where bottom-up data is available, and IO calculations retained for the remainder of the supply chain. Sections 5.3.2.1-5.3.2.2 provide examples from the case study, but in general, a straightforward substitution can be made by including process-based data from *direct* suppliers (Layer 1 in equation (3)) and replacing the

IO-direct impact calculated as $\mathbf{qy}$. With the total inter-industry impact calculated from equation (1b) as $\mathbf{my}$, the remainder of the supply chain from Layer 2 onwards is therefore $\mathbf{my} - \mathbf{qy}$, with the relevant direct- and total intensities in $\mathbf{q}$ and $\mathbf{m}$ variously multiplied by the amount spent on that sector, in ($\mathbf{y}$), by the reporting entity. Similarly, higher-order impacts calculated using IO analysis can be replaced, but this would require an IO expert because of the large calculations including the $\mathbf{A}$ matrix. An example in Section 5.3.6.2 is provided regarding the calculation of scope-3 electricity emissions. In a similar manner, for example, process-based emissions may be available for staff air transport (scope-1 emissions of air transport from the reporting entity's purchases), which can replace the IO-estimated staff air transport at Layer 1 using the approach described above.

5.3.2.1. Nature indicators

In addition to the combined GHG indicator (CO2-e) selected for carbon dioxide or equivalent emissions (Section 5.3.2.2), general sustainability-related indicators were chosen that were linked to biodiversity, in line with the focus at the time on the TNFD ([TNFD] Taskforce on Nature-related Financial Disclosures, 2023) and which were also additive, for straightforward comparisons. In this vein, the land-use and bluewater-consumption GLORIA indicators were selected. It should be noted that the bluewater-consumption indicator allocates global bluewater consumption across inter-industry demand only; therefore the on-site water-utilities use was analysed as part of the value-chain impact calculated using IO analysis, rather than being added to the total. Further detail regarding the Nature indicators is in Section 5.8.4.

5.3.2.2. GHG emissions

For scope-1 emissions: The GLORIA MRIO allocates global GHG emissions across intermediate and final demand; therefore the *scope-1 emissions* were *added* to the value-chain emissions, calculated using IO analysis, for holistic assessment. For scope-2 emissions: The IFRS S2 hierarchy regarding jurisdictional requirements (IFRS Foundation, 2023b, p. 14) is acknowledged by AASB S2 in terms of Australia's National Greenhouse and Energy Reporting Scheme (NGER) and scopes 1-2 emissions (Australian Accounting Standards Board, 2024, p. 51). Therefore, process-based scope-2 emissions, calculated using activity data as required under NGER(Clean Energy Regulator, 2023), replaced the IO-calculated scope-2 emissions for a hybrid IO-LCA indirect electricity emissions calculation.

5.3.3. Renewables adjustment

The use of renewable electricity via a purchasing power agreement was only noted post-calculation, in line with due-diligence requirements that scopes 1-3 emissions are set out

separately (IFRS Foundation, 2023b) and that any offsets/removals are separately quantified, using verifiable data (World Business Council for Sustainable Development & World Resources Institute, 2004, pp. 59-60).

5.3.4. Exclusions and the treatment of capital

Salaries were excluded in line with the classical IO analysis treatment of final consumers i.e., households, as exogenous to intermediate production (Lenzen et al., 2010). Similarly, we excluded moneys paid to students for general living expenses and research volunteers, as well as tax expenses (e.g., income tax, fringe-benefits tax), bad debts/losses, clearing accounts, internal expenses and impairment/depreciation/amortisation; the exception was depreciation for Right-of-Use assets because it is through depreciation of ROU assets that is how leased-asset expenditure is accounted for in Australia. We included gross capital expenditure to identify the emissions associated with our purchasing decisions; the System of National Accounts notes that either gross- or net-capital approaches can be taken (European Communities et al., 2009).

5.3.5. Country and sector harmonisation

For this pilot analysis, almost all data was harmonised with Australian sectors because of available data within the time constraints. In addition to assuming that most expenditure was local, the exception upstream was *international student agent commission*, for which non-Australian *country-specific* data was obtained, because this was a top area of expenditure in the case study, as discussed below regarding international sector harmonisation for this expenditure class.

For routine calculation of the University's impact, the University's unique class codes were harmonised with economic sectors, from GLORIA, in order to perform the value-chain analysis (Baboulet & Lenzen, 2010). Concordances with values between 0 and 1 were drawn up to harmonise to the sectors the expenditure classes for the upstream supply-chain analysis (equation (1a)). This builds in automation, with the assumption that the class-code composition remains similar temporally. For future years, it was intended that particular class codes would need to be re-evaluated; as well, it was intended that in future, the general ledger would be scanned for particularly emissions-intensive sectors, since relatively small changes could have substantial impacts and therefore the sectoral aggregation would be amended to reflect material changes.

For the non-Australian portion (*international student agent commission*, where the agents were overseas), the expenditure per regional sector was coded using the software MATLAB and added to the Australian final demand ($\mathbf{y}_{AUS}$) to arrive at the total global final demand ($\mathbf{y}$) matrix, reflecting the University's expenditure.

In the year of this pilot, 2022, the general ledger non-salary expenses for the year comprised almost one million line items across 291 unique class codes. For upstream, the sectoral harmonisation of some classes was clear, while for others, the sectoral composition was clarified by consulting the GLORIA-HSCPC concordance. The HSCPC incorporates more than 6000 sectors combined from the United Nations' Harmonised System (HS) and Central Product (CPC) classifications (Industrial Ecology Virtual Laboratory, n.d.-a); the HSCPC was developed for the Global MRIO Lab (Lenzen et al., 2017), the infrastructure of which was used to build GLORIA (Lenzen et al., 2022). For highly aggregated University classes in particular, various approaches were taken for the harmonisation, including consulting subject-matter experts, searching by keywords (such analysis may also be assisted using artificial intelligence) or project/responsibility codes and/or analysing the top-ranked expenditure by single expenditure items or group-summary amounts per unique Journal Line Description. Where the sector was undetermined, for low-priority University classes upstream e.g., regarding immaterial amounts or for activities unlikely to be high emissions-intensive such general student costs, the class was harmonised with the Education sector.

5.3.6. GHG Protocol calculations

In general, the total impact calculated using IO analysis (equation (1a) or (1b)) was disaggregated into the relevant GHG Protocol categories, using separate concordances. Upstream, the catch-all category 1 Purchased Goods and Services was calculated by deleting the other upstream GHG Protocol concordances from the concordance of all expenditure. Although the inter-industry scope-3 GHG Protocol categories were calculated in MATLAB using the matrices of size 19,680 (120 sectors x 164 regions from the GLORIA database), the carbon accountant or auditor could simply undertake the GHG Protocol category calculations using the relevant sectors' spend-based emission factor ($\mathbf{m}$) multiplied by the organisation's expenditure ($\mathbf{y}$) on that sector for upstream, from equation (1b); (a couple of exceptions are noted in the next paragraph). Spend-based emission factors are widely available commercially, while income-based emission factors have been demonstrated in previous downstream studies, e.g. (Starr et al., 2023; Xu et al., 2019), and are also calculated as part of this study in addition to total intensities for Nature indicators (the income-based multipliers are referred to generally in this

study as $\bar{\mathbf{m}}$). For some GHG Protocol categories, the allocation relied on the corporate accountant regarding particular products, for example in identifying leased assets and capital goods.

5.3.6.1. Employee commuting

For category 7 Employee Commuting: Since households were treated as exogenous to intermediate production, employee commuting was calculated separately to the upstream IO analysis.

5.3.6.2. Fuel- and Energy-Related Activities

For the calculation of scope-3 electricity emissions as part of Category 3 Fuel- and Energy-Related Activities Not Included in Scope 1 or Scope 2, an additional step was required, once the total fuel and energy-related inter-industry emissions were calculated using IO analysis. Since indirect emissions include scope-2 emissions, a separate IO calculation was made of scope-2 emissions, which was then deleted from the total IO electricity emissions upstream using $m_{elec}y_{elec} - q_{elec}y_{elec}$ for the scope-3 electricity emissions.

Further details about the GHG Protocol calculations are in Section 5.8.5, including a note on downstream categories.

5.3.6.3. Double-counting adjustment

For this first University scope-3 emissions calculation, all upstream emissions from inter-industry production were reported against upstream GHG Protocol categories, while from the downstream perspective, all emissions from inter-industry production were reported against downstream categories. This is a way of identifying hotspots regardless of any double-counting, which the GHG Protocol has noted that reporting entities may find useful (World Resources Institute & World Business Council for Sustainable Development, 2011, p. 108). Double-counting of indirect emissions may occur when upstream as well as downstream IO calculations identify emissions from the same total emissions of a given sector. The GHG Protocol does advise that additional calculations may be made to avoid double-counting (2013, p. 111). In such a case using IO analysis across the GHG Protocol scope-3 emissions categories, one could first compare sectoral emissions upstream with downstream and then make any GHG Protocol category adjustments accordingly; an example of how double-counting may be identified is in Section 5.8.5.2; the GHG Protocol does not specify how double-counting adjustments can be made but it stresses the need to highlight where the emissions remain reported, while using cross-references if necessary (2011, p. 57). As opposed to double-counting *by an organisation* between its scope-3 categories, the GHG Protocol has accepted

that double-counting *between organisations* can be "by definition" part of scope-3 analysis (2011, p. 108); alternatively, a so-called "shared responsibility" approach between producers and consumers has been proposed that enables organisations to conduct IO analysis while delineating the value chain into mutually exclusive and collectively exhaustive portions of responsibility shared by all actors in an economy, see, e.g., Lenzen et al. (2007).

5.3.7. Limitations

Data-collection issues included the fact that there could be unidentified aviation in some University class codes, for example related to scholarships. As well, assumptions were made about the sectoral composition of chemicals and consumable clinical/lab purchases that may in part explain the high emissions attributed to the chemicals/chemical products sectors; subsequently, detailed analysis was undertaken of the substantial class code comprising expenditure items classified as clinical/lab consumables that revealed that the class did not include as high a proportion of chemical products as estimated, which was corrected for future analyses for the reporting entity. It was also not possible in the time available to investigate irrigated vs non-irrigated hay purchases to incorporate this process-based information into the water footprint. As well, it was assumed that all general-ledger expenditure was in Australia, other than for international student agents. In addition to limitations regarding the methodology and data collection, it should be noted that the information presented in the next Section 5.4 has not been audited and is not an official disclosure of the University; for this reason, the results are presented in general terms, as a case study of IO analysis for environmental due diligence.

5.4. Case-study results

5.4.1. Total impact analysis

In this University of Sydney 2022 pilot study, for holistic analysis, we compare upstream and downstream Climate- and "general sustainability" impacts. Preceding this paper, downstream GHG emission results per GHG Protocol category have been analysed in detail, in the paper describing the generalised IO downstream framework for organisations (Reiner, *under review*); therefore here, we focus in detail on the upstream carbon hotspots. In addition to GHG emissions, this paper adds land-use and bluewater-consumption indicators; however, because the vast majority of sustainability hotspots in this case study are upstream, we also focus on upstream results for the Nature impact.

5.4.1.1.Climate-and-Nature direct and indirect impact

Fig. 1 compares the case study's direct use with its total upstream and downstream impact. The illustration of the results reflects the difference between Bluewater Consumption and the other indicators that is noted in the Nature-indicators methods Section 5.3.2.1.

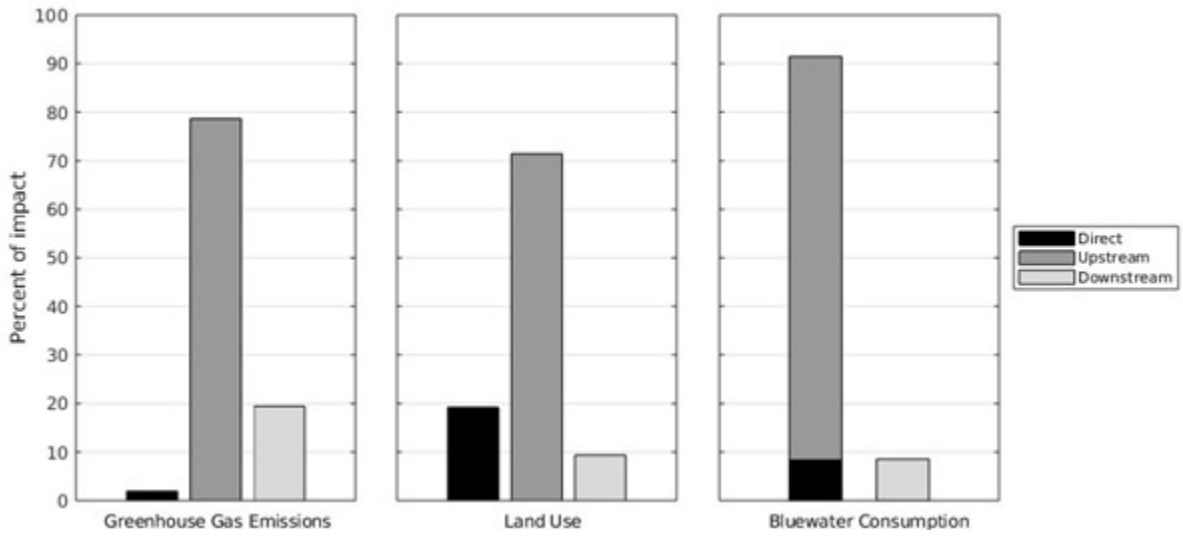


Figure. 1: The University's direct, upstream and downstream impact for Climate- and Nature in 2022; purchased water utilities is included as part of the Bluewater-Consumption indicator. *NOTE: The information in this report is not an official or endorsed disclosure of the University of Sydney and has not been internally reviewed or approved by the University or subjected to an assurance process; no reliance should be placed on the information*

The case study's direct combustion of fossil fuels (scope-1 emissions) in 2022 was found to be responsible for just 1.95% of its gross emissions. As with GHG emissions, the *on-campus impact* for the Nature indicators was a minority of the total impact; water-utilities use for Sydney campuses was equivalent to less than 1/10th of our total bluewater consumption, while University farms represented about 1/5th of our total land-use footprint. Combined, the direct impact across Climate-and-Nature indicators averaged less than 10%.

5.4.1.2. Greenhouse Gas Protocol impact per category

The University's scope-3 emissions in 2022 were responsible for the vast majority of the total emissions (more than 70%), even without accounting for renewable-energy removals. The trends in key areas of scope-3 emissions during this 2022 University of Sydney pilot, as shown in Fig. 2, are similar to those later identified in the 2024 refresh that was undertaken for the University's first scope-3 disclosure (The University of Sydney, n.d., "Climate-related Financial Disclosure"); an exception is that after 2022, activity rebounded following COVID-19, resulting in increased emissions in areas such as capital goods upstream and international students' air transport downstream. Percentages, rather than physical quantities are discussed here because the 2022 pilot results are not an official or endorsed disclosure of the University.

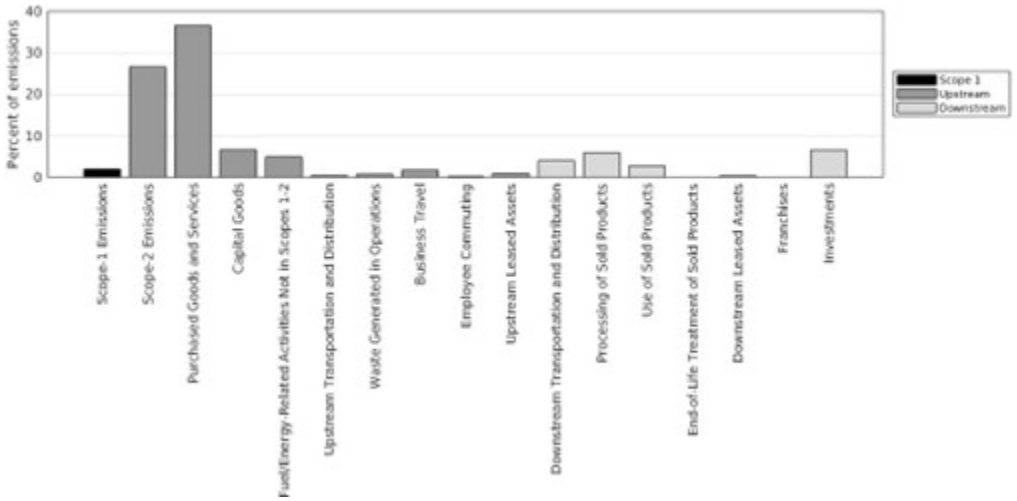


Figure 2: The University's emissions in 2022, including scopes 1-2 (1st-2nd bars on left) and Greenhouse Gas Protocol scope-3 categories 1-15 from left to right (remaining bars). *NOTE: Percentages are provided only because the information in this report is not an official or endorsed disclosure of the University of Sydney*

As can be seen from the comparative emissions in Fig. 2, the GHG Protocol categories provide a birds-eye-view in terms of direct plus indirect emissions upstream and downstream. Upstream, it can be seen that the impact of capital purchases is substantial as is energy in the supply chain; purchased goods and services is the highest spend area in addition to being the leading emissions category. Downstream the main GHG hotspots were outside of the inter-industry value chain, being from international student travel and investments, which were calculated separately and added to the emissions calculated using IO analysis. Disaggregation of scope-3 emissions, along with other indicators, can be undertaken to a high degree of resolution, using IO analytical techniques, as discussed below.

5.4.2. Upstream focus

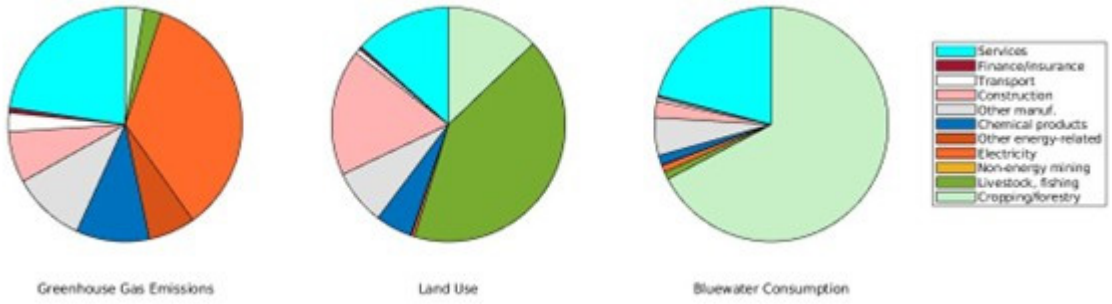
In the following, we follow the GHG Protocol approach of analysing emissions according to consumption (equation 5) rather than production (equation 6), unless otherwise stated. Similarly, we focus our analysis on sectoral, not regional results, other than in Fig 3(b); this is reflective of the fact that most impacts are calculated as being experienced domestically.

5.4.2.1.Overview

As can be seen in Fig. 3(b), most of the University's estimated geographical impact is local, based on most purchases being harmonised with Australian sectors. Alternatively, when viewed from the production rather than consumption perspective; overseas impact increased but remained unsubstantial. Looking at sectoral impact (Fig. 3(a)), although *energy* is a hotspot for GHG emissions upstream, this is not the case for the Nature indicators. Conversely, *agriculture* is not a key driver of impacts for our GHG emissions but is for the Nature indicators. Common to both the University's carbon and land footprints is *construction*, which attracted a relatively

high amount of University expenditure and which has a relatively high intensity for both the GHG and land indicators. See the previous chapter's Section 4.7.2 for the sectoral aggregator.

a. Sectors



b. Regions

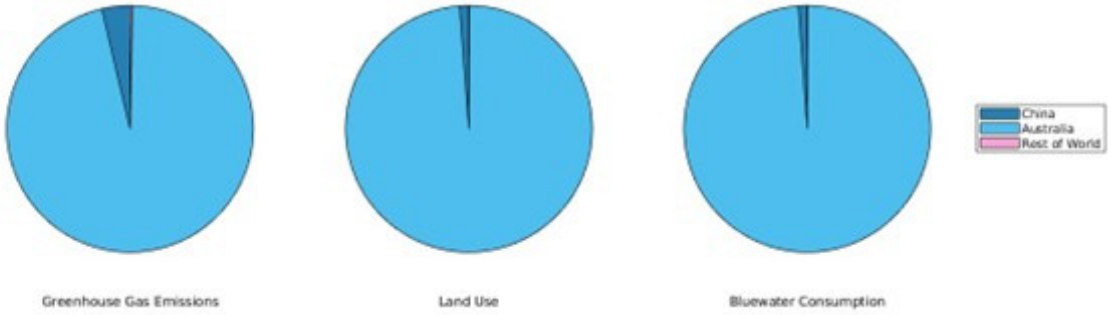


Figure 3: The University's 2022 Climate and Nature impacts by key/aggregated sectors and regions, including direct use and the upstream supply chain. *NOTE: This report is not an official or endorsed disclosure of the University of Sydney*

5.4.2.2.Greenhouse Gas Emissions

Fig. 4 disaggregates the impact by production layer decomposition (PLD) into broad sector groupings/key sectors from the 120 GLORIA sectors as shown in the previous chapters' sectoral aggregator (Section 4.7.2). Emissions at production-layer 1 only account for just over half the upstream emissions. Although scope-2 emissions (direct purchase of electricity, at production-layer 1) appears to be a hotspot, half of these annual emissions were addressed through the University's move to renewable electricity mid-year. Emissions from direct suppliers of chemical products is a hotspot, while in the left-hand panel in Fig. 4, which provides some further disaggregation of the GHG Protocol results from Fig. 2, it can be seen that emissions from services in particular increase substantially in the upstream supply chain as a result of sectoral inputs to produce services.

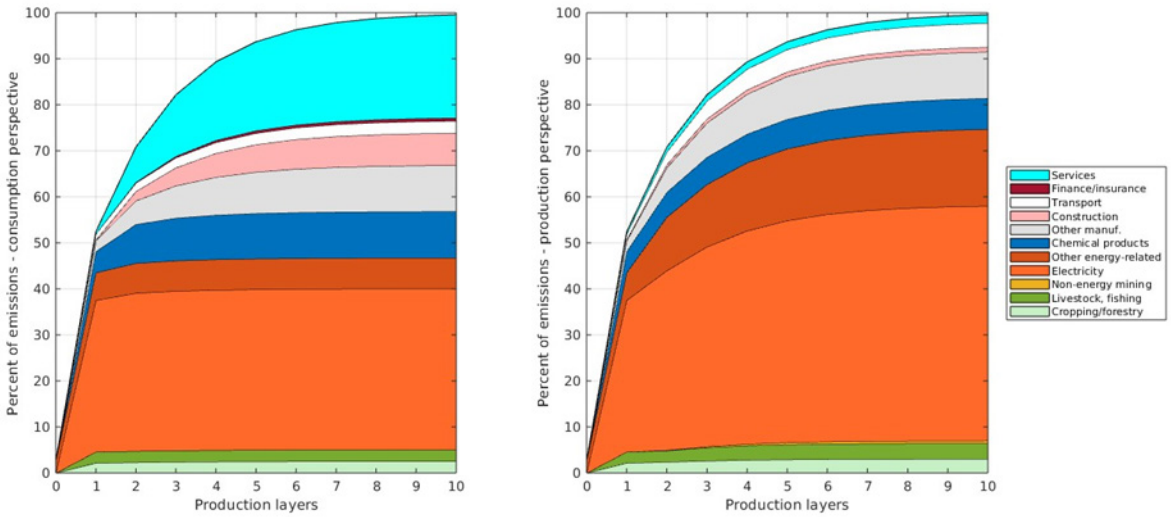


Figure 4: The University's greenhouse gas emissions in 2022 incorporating direct use and the upstreamsupply chain by production layer decomposition (PLD), from the alternative perspective of production (right) disaggregating equation (6), as well as consumption (left) disaggregating equation (5). Scope-1 emissions, resulting from purchased fossil fuels, are added at production-layer 0, while layer 1 represents direct suppliers, layer 2 represents their direct suppliers and so on. *NOTE: Percentages are provided only because the information in this report is not an official or endorsed disclosure of the University of Sydney*

When analysing upstream emissions in terms of inputs used to satisfy production ($\mathbf{q}$) (equation (6)/Fig. 4 (right)), rather than consumption/final demand ($\mathbf{y}$) (equation (5)/Fig. 4(left)), a different picture emerges. Here, the substantial emissions attributed to the services sector reduces because of their relatively low-emissions-intensity; similarly, the emissions attributed to construction from Fig. 4 (left) drops. Instead, a key source of emissions is identified as *electricity used by all the University's suppliers*. From this perspective for example, rather than observing scope-3 *emissions from electricity purchases*, we can see the *electricity emissions from all the University suppliers' purchases* that is driven by the University's total expenditure. Importantly, we see that the emissions from *electricity supplying the University's direct suppliers* (at production layer 2, orange key) is substantial, being responsible for about 1/20th of the carbon footprint.

In addition to highlighting the dominance of energy generally, a trend of electricity as an emissions-intensive supply-chain input can be seen in Table 1 (rankings that include energy are in **bold**). Table 1 shows the top supply chains using structural path analysis (SPA) in addition to scope 1 emissions, for comparative analysis. Among the top ranked are emissions-intensive activities such as aviation.

Rank	Order	Path
1	1	**Scope-2 emissions (NGER-reported)**
2	0	**Scope-1 emissions (NGER-reported)**
3	1	Australia, Basic organic chemicals
4	1	Australia, Raising of cattle
5	2	**Australia, Electric power generation, transmission and distribution > Australia, Professional, scientific and technical services**
6	2	Vietnam, Lignite and peat > Australia, Basic inorganic chemicals
7	1	Australia, Dyes, paints, glues, detergents and other chemical products
8	1	Australia, Basic inorganic chemicals
9	1	Australia, Growing crops n.e.c. [Not Elsewhere Classified]
10	1	Australia, Materials recovery
11	1	Australia, Air transport
12	1	Australia, Growing cereals n.e.c
13	2	**Australia, Electric power generation, transmission and distribution > Australia, Administrative services**
14	1	Australia, Machinery and equipment
15	2	Vietnam, Lignite and peat > Australia, Basic organic chemicals

Table 2: Structural path analysis (SPA) of the University's top GHG supply chains upstream plus direct combustion (scope-1 emissions) in 2022, with **energy in bold**. *NOTE: Rankings are provided only, but not GHG calculations, because the information in this report is not an official or endorsed disclosure of the University of Sydney*

5.4.2.3.Nature impact

As with GHG emissions, the general-sustainability indicators were also analysed from the perspective of PLD, as shown in Fig. 5, and further disaggregated according to SPA.

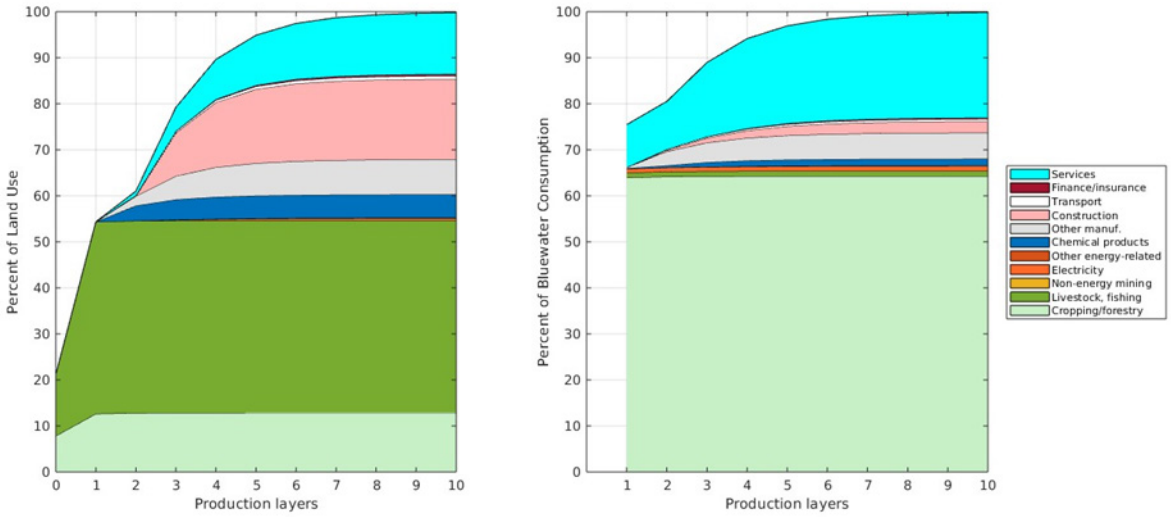


Figure 5: The University's Land Use (left) and Bluewater Consumption (right) (water used for goods and services) incorporating direct use and the upstream supply chain by production layer decomposition (PLD) in 2022, by key sectors/aggregated sectors. Production-layer 1 upstream represents the impact from direct suppliers, and includes the University's purchased water utilities, provided as part of the aggregated Services sector. *NOTE: Percentages are provided only because the information in this report is not an official or endorsed disclosure of the University of Sydney*

Bluewater Consumption: Unlike with GHG emissions, for bluewater consumption, the majority of the University's impact is from direct purchases. As shown in Fig. 5 (right-hand panel), most of the impact is from primary industry at production-layer 1. SPA revealed that about 3/5 of the

upstream bluewater consumption was calculated from just one supply chain, being direct purchases of hay comprising the University's expenditure in the sector "Growing crops n.e.c." [not elsewhere classified]. In second spot was water utilities on the main campuses, in Sydney. Another cropping sector, "Growing cereals n.e.c.", from farm purchases, was responsible for less than 4% of bluewater consumption, with all other supply chains calculated as individually contributing 1% or less to total direct and indirect upstream bluewater consumption. Because hay is identified as a hotspot, it is important to check whether this hay was purchased from irrigated areas and if a proportion was non-irrigated, a re-calculation would be undertaken; this would include amending the calculation of water used by our direct suppliers for hay production, by taking into consideration the amount of hay purchased from irrigated areas only and the water-intensity for the irrigated hay.

Land Use: In-between the results of the GHG and bluewater indicators was land use, which highlighted the impact of direct suppliers of livestock, while revealing a trend of forestry in the extended supply chain. As can be seen in Fig. 5 (left-hand panel), substantial impacts were generated by on-campus land use (illustrated at production-layer 0 upstream), as well as the University's purchase of livestock (at layer 1). Construction was particularly impactful at layer 3; this is as a result of construction using timber, which is supplied by the forestry sector, as highlighted through the SPA technique. Alternatively, when viewed from the production perspective, an increased trend of livestock in the upstream supply chain is revealed. Although less than the University's key land-use impacts from direct livestock purchases, livestock/seafood at upstream Layer 2 alone was found to be responsible for 2% of the total direct plus indirect upstream land use, while at layer 3, the additional livestock/seafood impact more than doubled. With direct suppliers representing layer 1, layer 3 includes livestock supplying meat production enjoyed by direct suppliers, e.g., at conferences and restaurants as part of hospitality.

5.5. Discussion

This research shows how new global reporting standards can be addressed in a comprehensive and integrated manner holistically, underpinned by IO analysis. We draw specifically on conceptual work (Lenzen & Murray, 2010), the finance-focused upstream-and-downstream IO enterprise study by Lenzen et al. (2010) and a new framework detailing generalised downstream "income-based" IO analysis at the enterprise level (Reiner, *under review*), and extend IO analysis to include not only GHG Protocol categories upstream and downstream, but also

biodiversity-related indicators, linking the global ISSB's climate- and general sustainability-related disclosures, and in alignment with other regional and national frameworks e.g., in the European Commission. Hybrid IO-LCA analysis for corporate reporting provides insights that are not available using process-based, bottom-up information alone or incomplete approaches, because IO can not only include the entire inter-industry value chain but it also does so to a high degree of resolution, across a range of indicators.

The ISSB's IFRS S2 Climate-related Disclosures, which points to the GHG Protocol, and the ISSB's IFRS S1General Requirements for Disclosure of Sustainability-related Financial Information, which draws on the TNFD recommendations (Taskforce on Nature-related Financial Disclosures, 2024), provide a starting point for globally aligned Climate and Nature reporting. However it is the detail where the greatest changes can be affected. For example, in the case study, the University of Sydney's relatively high GHG emissions from capital expenditure are in part because a major contributor, building construction, tends to be relatively emissions-intensive compared to other sectors but also because of the University's high expenditure in this area.

When disaggregating emissions via orders of production, a trend of electricity in the supply chain of all suppliers emerges, and it can be seen how many GHG emissions are from electricity used by our direct suppliers. The substantial building construction was not only a GHG hotspot but was also linked to forestry products/land use in the supply chain; these could be tackled through more re-use and less new materials consumption, noting that circular economy commitments involve their own emissions profile. From a procurement perspective, green-electricity requirements for example in the extended supply chain may not be politically feasible but starting the conversation with direct suppliers could fast-track a re-setting of social licence of coal-fired power. Such comprehensive analysis that includes the extensive value chain enables the comparison of on-site use, direct purchases/sales and higher-order value-chain impacts. The critical role of IO analysis is demonstrated by our findings that the value chain can account for the vast majority of the total Climate and Nature impact.

As a result of automation enabled through the model presented in this paper, once the pipeline has been set up and an organisation's general ledger mapped to sectors for value-chain calculations, subsequent analyses can be undertaken efficiently. This was demonstrated for the University of Sydney, with "refreshed" scope-3 disclosures provided for 2024 (The University of Sydney, 2025) within a matter of weeks as required for calendar-year data to be transformed within annual-reporting timeframes. It should be noted that since the commencement of this

project, the launch of artificial-intelligence models for the classification of expenditure items may assist with routine tasks such as keyword searches. However, the generally complex, detailed analysis in this project would not currently lend itself well to AI, but this could change as carbon- and sustainability accounting becomes more commonplace and items are classified by organisations using a common nomenclature.

This research takes the important step of using not only generalised upstream spend-based, backward multipliers (also referred to as emission factors for GHG calculations), but adds this to downstream enterprise calculations (Reiner, *under review)* that use income-based, forward multipliers for environmental reporting. As advocated by Rabobank recently (Kolbl et al., 2024), the inclusion of, lesser-used, downstream multipliers is important for corporate reporting because their intensities may diverge from upstream. For example upstream emissions for the beef-meat sector includes from high-intensity cattle raising; however downstream, the beef-meat sector is more likely to contribute to lower-intensity activities, such as food processing for meat pies, with the methane from livestock burps/farts, already having been emitted upstream. Academic studies have used downstream IO calculus (Ghosh, 1958) that mirrors its upstream dual (Dietzenbacher, 1997) for decades; although debate continues regarding the usefulness/interpretation of this traditional Ghosh model, "It is generally agreed that backward linkage measures should be found from the Leontief model and forward linkages from the Ghosh model" (Miller & Blair, 2022, p. 319). In our study, the starting point for downstream IO analysis is the conventional Ghosh model because of its widespread use and scalability, however our general approach to Climate-and-Nature reporting that is described in this paper could be flexible regarding other IO interpretations. Our timely completion of the pilot calculation of the University's value-chain impact was focused on facilitating the University's first scope-3 disclosure (The University of Sydney, 2025), with reference to the GHG Protocol's Accounting and Reporting Principles that stress the importance of disclosing and tracking performance in addition to continual improvement in reporting (World Resources Institute & World Business Council for Sustainable Development, 2011, p. 24). At the time of the publication of the GHG Protocol's technical guidance on scope-3 emissions, which includes the use of upstream spend-based emission factors as an option (World Resources Institute & World Business Council for Sustainable Development, 2013), downstream environmentally extended income-based IO analysis was in its infancy (Lenzen & Murray, 2010; Marques et al., 2013; Marques et al., 2012). Practically speaking, with the provision of spend-based and income-based emission factors, calculation of scope-3 emissions upstream and downstream can become relatively "pain free". Carbon accountants and auditors simply need to multiply the

spend or income per sector by the relevant emission factor to arrive at the total inter-industry value chain impact, even without the IO expertise that provides additional insights through disaggregated value-chain data that is used to calculate the multipliers.

Because IO analysis takes a full life-cycle approach to the inter-industry value chain, the question of consumer versus producer responsibility arises (Jakob et al., 2021; Lenzen et al., 2007; Wang et al., 2024). Gallego and Lenzen (2005) first addressed this from an IO perspective, noting that by consumers or producers taking responsibility beyond their areas of direct control, this could result in multiple counting along the value chain. Solutions have been proposed where value chains are split and "burdens shared between the supplying and demanding sides of every transaction in the economy (Lenzen, 2008). However, the GHG Protocol to date has focused on "shared responsibility" only from the perspective of avoiding double-counting of one's own scope-3 emissions, e.g., upstream and downstream, and has acknowledged that double-counting of scope-3 emissions *between* organisations is part of its approach to extended corporate responsibility (2011, p. 108). While taking full responsibility along the value chain may be a part of hotspot identification, however, it can lead to over-estimation from a national accounting perspective, which may be significant in an era of mandatory disclosure.

New mandatory scope-3 reporting is an important development; the question now is, not what to measure (scope-3 emissions), but the methodology to apply. Given that the Intergovernmental Panel on Climate Change has highlighted the climate emergency the world faces this decade (IPCC, 2023), the critical role of gaining oversight of our global GHG emissions in order to reduce them suggests that we should attempt to avoid "carbon leakage" that occurs through offshoring emissions-intensive industries at a national level or allowing GHG inventory to be limited to just beyond the factory gate, at the enterprise level. This could be avoided by Standards phasing in standardisation of the scope-3 method. It would remedy the fact that at one extreme organisations can use IO analysis, which is boundary-free and thereby avoids truncation errors (Lenzen, 2000), and at the other extreme, including scope-3 emissions can be as limited as, for example, measuring only up to production-layer 1. Excluding emissions beyond the first production layer (also referred to as tier 1) would cap emissions value-chain analysis at direct suppliers; in this case, the disclosed emissions could include the reporting entity's scope-1 (direct) emissions, direct emissions produced by electricity suppliers on our behalf (scope 2) and emissions from other tier-one suppliers, the latter of which may be calculated manually by asking suppliers what their emissions are. In our case-study, limiting the total upstream emissions to production-layer 1 would miss approximately half the on-site plus indirect upstream emissions, and that is not even considering the downstream inter-industry

value-chain emissions, which organisations tend not to calculate. Of course, in countries where one's scope-2 emissions are not largely from coal-fired electricity, scope-3 emissions are likely to be even more significant.

In an environment where governments may require its agencies to set net-zero targets and therefore pay for offsetting/removals, and other organisations are concerned about unfavourable comparisons from mandatory disclosures, the flexibility regarding the scope-3 method may incentivise limiting the boundaries within which a reporting entity calculates its emissions. GHG Protocol Standards, undergoing a review (Greenhouse Gas Protocol, 2024), provided flexibility because of the voluntary landscape at the time, advising that therefore scope-3 may not lend itself well to comparisons across organisations (World Business Council for Sustainable Development & World Resources Institute, 2004, p. 29). Given this lack of maturity, the advice was instead to focus on tracking emissions over time, noting that additional measures would be required for benchmarking, such as consistency in methodology (World Resources Institute & World Business Council for Sustainable Development, 2011, p. 6). It is recommended that as part of standardisation such as adopting IO analysis for identifying hotspots, the approach of "shared responsibility" be considered. This could avoid multiple-counting throughout the value chain while also not overburdening an organisation with assuming full environmental responsibility.

5.6. Conclusion

This is to our knowledge the first paper that describes the use of spend-based and income-based IO analysis to calculate scope-3 emissions for an organisation's GHG Protocol disclosures upstream and downstream, while also drawing on the same underlying data to measure biodiversity-related indicators. This novel Climate-and-Nature due diligence is aligned with ISSB's IFRS S2, IFRS S1 and includes the entire inter-industry value chain in a standardised way by drawing on IO analysis (United Nations Statistics Division, 1999), which enables analysis to a high degree of resolution with the flexibility to incorporate process-based information where available. Our research highlights the utility of upstream spend-based emission factors in concert with downstream income-based emission factors for accessible as well as robust sustainability reporting. Global Standards for scope-3 disclosures mean that organisations must consider their indirect emissions; the next crucial step is standardising the methodology. By mandating IO calculations of scope-3 emissions throughout the inter-industry value chain within a lens of continuous improvement in reporting, all organisations can take a

comprehensive view of their carbon footprint on a level playing field, fast-tracking action on the climate emergency.

5.7. References

Australian Accounting Standards Board. (2024a). *Australian Sustainability Reporting Standard: Climate-Related Disclosures* (AASB Standard No. S2). https://standards.aasb.gov.au/aasb-s2-sep-2024

Australian Accounting Standards Board. (2024b). *Australian Sustainability Reporting Standard: General Requirements for Disclosure of Sustainability-related Financial Information [voluntary]* (AASB Standard No. S1). https://standards.aasb.gov.au/aasb-s1-sep-2024

Baboulet, O., & Lenzen, M. (2010). Evaluating the environmental performance of a university. *Journal of Cleaner Production*, *18*(12), 1134-1141. https://doi.org/10.1016/j.jclepro.2010.04.006

Blanco, C., Caro, F., & Corbett, C. J. (2016). The state of supply chain carbon footprinting: analysis of CDP disclosures by US firms. *Journal of Cleaner Production*, *135*, 1189-1197. https://doi.org/10.1016/j.jclepro.2016.06.132

Bull, J. W., Taylor, I., Biggs, E., Grub, H. M. J., Yearley, T., Waters, H., & Milner-Gulland, E. J. (2022). Analysis: the biodiversity footprint of the University of Oxford: Every large organization should plot a path to net gain in biodiversity — here's how. *Nature*, *604*, 420-424. https://doi.org/10.1038/d41586-022-01034-1

Chen, G., Hadjikakou, M., & Wiedmann, T. (2017). Urban carbon transformations: unravelling spatial and inter-sectoral linkages for key city industries based on multi-region input–output analysis. *Journal of Cleaner Production*, *163*, 224-240. https://doi.org/10.1016/j.jclepro.2016.04.046

Clean Energy Regulator. (2023). *Greenhouse and energy information by registered corporation 2021-22*. National Greenhouse and Energy Reporting Scheme, Australian Government. https://cer.gov.au/document/greenhouse-and-energy-information-registered-corporation-2021-22

Commission of the European Communities - Eurostat, International Monetary Fund, Organization for Economic Co-operation and Development, United Nations, & World Bank. (1993). *System of National Accounts*. https://unstats.un.org/unsd/nationalaccount/docs/1993sna.pdf

Cooper, J., Balcombe, P., & Hawkes, A. (2021). The quantification of methane emissions and assessment of emissions data for the largest natural gas supply chains. *Journal of Cleaner Production*, *320*, 128856. https://doi.org/10.1016/j.jclepro.2021.128856

Dietzenbacher, E. (1997). In Vindication of the Ghosh Model: A Reinterpretation as a Price Model. *Journal of Regional Science*, *37*(4), 629-651. https://doi.org/10.1111/0022-4146.00073

Downie, J., & Stubbs, W. (2012). Corporate Carbon Strategies and Greenhouse Gas Emission Assessments: The Implications of Scope 3 Emission Factor Selection. *Business Strategy and the Environment*, *21*(6), 412-422. https://doi.org/10.1002/bse.1734

European Communities, International Monetary Fund, Organisation for Economic Co-operation and Development, United Nations, & World Bank. (2009). System of National Accounts 2008. https://unstats.un.org/unsd/nationalaccount/docs/sna2008.pdf

Gallego, B., & Lenzen, M. (2005). A consistent input–output formulation of shared producer and consumer responsibility. *Economic Systems Research*, *17*(4), 365-391. https://doi.org/10.1080/09535310500283492

García-Alaminos, Á., Gilles, E., Monsalve, F., & Zafrilla, J. (2022). Measuring a university's environmental performance: A standardized proposal for carbon footprint assessment. *Journal of Cleaner Production*, *357*, 131783. https://doi.org/10.1016/j.jclepro.2022.131783

Ghosh, A. (1958). Input-Output Approach in an Allocation System. *Economica*, *25*(97), 58-64. https://doi.org/10.2307/2550694

Greenhouse Gas Protocol. (2022, June). *Scope 3 Frequently Asked Questions* https://ghgprotocol.org/sites/default/files/2022-12/Scope%203%20Detailed%20FAQ.pdf

Greenhouse Gas Protocol. (2024, 16 January). *2024 Reflections and Looking Ahead: Letter from GHG Protocol Steering Committee Chair and Vice Chair* https://ghgprotocol.org/blog/2024-reflections-and-looking-ahead-letter-ghg-protocol-steering-committee-chair-and-vice-chair

Guan, Y., Huang, G., Liu, L., Zhai, M., & Xu, X. (2019). Measurement of air-pollution inequality through a three-perspective accounting model. *Science of The Total Environment*, *696*, 133937. https://doi.org/10.1016/j.scitotenv.2019.133937

Guannan Miao, Luis Villanueva, Xiao Jiang, & Marca, M. L. (2024). *A Brief Review of Input-Output Approaches to Employment Impact Assessment*. https://www.ilo.org/sites/default/files/2024-04/Brief%20Review%20of%20Input-Output%20Approaches%20to%20EmpIA.pdfHelmers, E., Chang, C. C., & Dauwels, J. (2021). Carbon footprinting of universities worldwide: Part I—objective comparison by standardized metrics. *Environmental Sciences Europe*, *33*(1), 30. https://doi.org/10.1186/s12302-021-00454-6

Huang, Y. A., Lenzen, M., Weber, C. L., Murray, J., & Matthews, H. S. (2009). THE ROLE OF INPUT–OUTPUT ANALYSIS FOR THE SCREENING OF CORPORATE CARBON FOOTPRINTS. *Economic Systems Research*, *21*(3), 217-242. https://doi.org/10.1080/09535310903541348

IFRS. (2024, May 2). *IFRS Foundation and EFRAG publish interoperability guidance*. https://www.ifrs.org/news-and-events/news/2024/05/ifrs-foundation-and-efrag-publish-interoperability-guidance/

IFRS. (2025, April 28). *ISSB publishes Exposure Draft proposing targeted amendments to IFRS S2 to ease application for companies.* https://www.ifrs.org/news-and-events/news/2025/04/issb-publishes-exposure-draft-targeted-amendments-s2/

IFRS. (n.d.-a). *ISSB and TCFD.* Retrieved August 25, 2025, from https://www.ifrs.org/sustainability/tcfd/

IFRS. (n.d.-b). *Jurisdictional sustainability consultations*. Retrieved October 20, 2024, from https://www.ifrs.org/ifrs-sustainability-disclosure-standards-around-the-world/jurisdiction-consultations-on-sustainability-related-disclosures/

IFRS. (n.d.-c). Use of IFRS Sustainability Disclosure Standards by jurisdiction. Retrieved August 25, 2025, from https://www.ifrs.org/ifrs-sustainability-disclosure-standards-around-the-world/use-by-jurisdiction/

International Sustainability Standards Board. (2023a). *IFRS Sustainability Disclosure Standard: Climate-related Disclosures* (ISSB Standard No. IFRS S2). https://www.ifrs.org/issued-standards/ifrs-sustainability-standards-navigator/ifrs-s2-climate-related-disclosures.html/content/dam/ifrs/publications/html-standards-issb/english/2023/issued/issbs2/

International Sustainability Standards Board. (2023b). *IFRS Sustainability Disclosure Standard: General Requirements for Disclosure of Sustainability-related Financial Information* (ISSB Standard No. IFRS S1). https://www.ifrs.org/issued-standards/ifrs-sustainability-standards-navigator/ifrs-s1-general-requirements.html/content/dam/ifrs/publications/html-standards-issb/english/2023/issued/issbs1/

Industrial Ecology Virtual Laboratory. (n.d.-a). *Global MRIO Lab*. Retrieved May 8, 2025, from https://ielab.info/labs/ielab-global

Industrial Ecology Virtual Laboratory. (n.d.-b). *GLORIA* Retrieved July 20, 2025, from https://ielab.info/labs/ielab-gloria

IPCC. (2023). *Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Core Writing Team, H. Lee and J. Romero (eds.)]. doi: 10.59327/IPCC/AR6-9789291691647

Irwin, A., Geschke, A., Brooks, T. M., Siikamaki, J., Mair, L., & Strassburg, B. B. N. (2022). Quantifying and categorising national extinction-risk footprints. *Scientific Reports*, *12*(1), 5861. https://doi.org/10.1038/s41598-022-09827-0

Jakob, M., Ward, H., & Steckel, J. C. (2021). Sharing responsibility for trade-related emissions based on economic benefits. *Global Environmental Change*, *66*, 102207. https://doi.org/10.1016/j.gloenvcha.2020.102207

Lu, Y., Nakicenovic, N., Visbeck, M., & Stevance, A.-S. (2015). Policy: Five priorities for the UN Sustainable Development Goals. *Nature*, *520*(7548), 432-433. https://doi.org/10.1038/520432a

Mackay, S., Hales, R., Hewson, J., Addis, R., & Mackey, B. (2025). Addressing climate inaction as our greatest threat to sustainable development. *Global Environmental Change*, *91*, 102969. https://doi.org/10.1016/j.gloenvcha.2025.102969

Kanemoto, K., Moran, D., Lenzen, M., & Geschke, A. (2014). International trade undermines national emission reduction targets: New evidence from air pollution. *Global Environmental Change*, *24*, 52-59. https://doi.org/10.1016/j.gloenvcha.2013.09.008

Kolbl, B., Beckebanze, F., Vita, G., & Wegman, J. (2024, June). *Estimating upstream and downstream supply chain emissions with input-output data: A two-way street*. Rabobank. https://media.rabobank.com/m/6a2f645745f794dc/original/Rabobank_Estimating_upstream_and_downstream_supply_chain_emissions_Kolbl_Beckebanze_202406.pdf

Larsen, H. N., & Hertwich, E. G. (2010). Implementing Carbon-Footprint-Based Calculation Tools in Municipal Greenhouse Gas Inventories. *Journal of Industrial Ecology*, *14*(6), 965-977. https://doi.org/10.1111/j.1530-9290.2010.00295.x

Lenzen, M. (2000). Errors in Conventional and Input-Output—based Life—Cycle Inventories. *Journal of Industrial Ecology*, *4*(4), 127-148. https://doi.org/10.1162/10881980052541981

Lenzen, M., Benrimoj, C., & Kotic, B. (2010). INPUT–OUTPUT ANALYSIS FOR BUSINESS PLANNING: A CASE STUDY OF THE UNIVERSITY OF SYDNEY. *Economic Systems Research*, *22*(2), 155-179. https://doi.org/10.1080/09535314.2010.484012

Lenzen, M., Moran, D., Kanemoto, K., Foran, B., Lobefaro, L., & Geschke, A. (2012). International trade drives biodiversity threats in developing nations. *Nature*, *486*(7401), 109-112. https://doi.org/10.1038/nature11145

Lenzen, M., Geschke, A., Abd Rahman, M. D., Xiao, Y., Fry, J., Reyes, R., Dietzenbacher, E., Inomata, S., Kanemoto, K., Los, B., Moran, D., Schulte In Den Bäumen, H., Tukker, A., Walmsley, T., Wiedmann, T., Wood, R., & Yamano, N. (2017). The Global MRIO Lab – charting the world economy. *Economic Systems Research*, *29*(2), 158-186. https://doi.org/10.1080/09535314.2017.1301887

Lenzen, M., Geschke, A., West, J., Fry, J., Malik, A., Giljum, S., Milà I Canals, L., Piñero, P., Lutter, S., Wiedmann, T., Li, M., Sevenster, M., Potočnik, J., Teixeira, I., Van Voore, M., Nansai, K., & Schandl, H. (2022). Implementing the material footprint to measure progress towards Sustainable Development Goals 8 and 12. *Nature Sustainability*, *5*(2), 157-166. https://doi.org/10.1038/s41893-021-00811-6

Lenzen, M., & Li, M. (2024). *GLORIA MRIO database Release 059* [Release notes]. Industrial Ecology Virtual Laboratory.

Lenzen, M., & Murray, J. (2010). Conceptualising environmental responsibility. *Ecological Economics*, *70*(2), 261-270. https://doi.org/10.1016/j.ecolecon.2010.04.005

Lenzen, M., Murray, J., Sack, F., & Wiedmann, T. (2007). Shared producer and consumer responsibility — Theory and practice. *Ecological Economics*, *61*(1), 27-42. https://doi.org/10.1016/j.ecolecon.2006.05.018

Lu, Y., Nakicenovic, N., Visbeck, M., & Stevance, A.-S. (2015). Policy: Five priorities for the UN Sustainable Development Goals. *Nature*, *520*(7548), 432-433. https://doi.org/10.1038/520432a

Mackay, S., Hales, R., Hewson, J., Addis, R., & Mackey, B. (2025). Addressing climate inaction as our greatest threat to sustainable development. *Global Environmental Change*, *91*, 102969. https://doi.org/https://doi.org/10.1016/j.gloenvcha.2025.102969

Leontief, W. (1936). Quantitative input and output relations in the economic systems of the United States. *The Review of Economics and Statistics*, *18*(3), 105-125. https://doi.org/10.2307/1927837

Leontief, W. (1970). Environmental Repercussions and the Economic Structure: An Input-Output Approach. *The Review of Economics and Statistics*, *52*(3), 262-271. https://doi.org/10.2307/1926294

Leontief, W. (1974). Sructure of the World Economy: Outline of a Simple Input-Output Formulation. *The American Economic Review*, *64*(6), 823-834. http://www.jstor.org/stable/1815236

Malik, A., Goodlet, J., Li, M., Mora, C. J., Fry, J., Munro, A., Mill, S., Noonan, A., & Lenzen, M. (2024). Assessing waste and carbon impacts of health system at a regional level. *Resources, Conservation and Recycling*, *209*, 107750. https://doi.org/https://doi.org/10.1016/j.resconrec.2024.107750

Malik, A., Lenzen, M., Lane, J., Lam, K. L., Harding, O. M., & Geschke, A. (2022). Carbon footprint and voting preferences of a council. *Resources, Conservation and Recycling*, *186*, 106535. https://doi.org/10.1016/j.resconrec.2022.106535

Marques, A., Rodrigues, J., Lenzen, M., & Domingos, T. (2012). Income-based environmental responsibility. *Ecological Economics*, *84*, 57-65. https://doi.org/10.1016/j.ecolecon.2012.09.010 Marques, A., Rodrigues, J., & Domingos, T. (2013). International trade and the geographical separation between income and enabled carbon emissions. *Ecological Economics*, *89*, 162-169. https://doi.org/10.1016/j.ecolecon.2013.02.020

Miller, R. E., & Blair, P. D. (2009). *Input-Output Analysis: Foundations and Extensions* (2nd ed.). Cambridge University Press. https://doi.org/10.1017/CBO9780511626982

Reiner, V. (*under review*). Income-based responsibility for organisations: A framework and demonstration of corporate sales-chain analysis. *Economic Systems Research*.

Robinson, O. J., Tewkesbury, A., Kemp, S., & Williams, I. D. (2018). Towards a universal carbon footprint standard: A case study of carbon management at universities. *Journal of Cleaner Production*, *172*, 4435-4455. https://doi.org/10.1016/j.jclepro.2017.02.147

Schandl, H., Marcos-Martinez, R., West, J., Miatto, A., Lutter, S., Lieber, M., Giljum, S., Lenzen, M., Li, M., Wang, H., Tanikawa, H., Krausmann, F., Eisenmenger, N., & Fischer-Kowalski, M. (2024). Global material flows and resource productivity: The 2024 update. *Journal of Industrial Ecology*, *28*(6), 2012-2031. https://doi.org/10.1111/jiec.13593

Simnett, R., Tan, H., You, J., & Zhou, S. (2025, in press). Australian listed entities' preparedness for mandatory reporting and assurance of climate-related disclosures. *Abacus*. https://dx.doi.org/10.2139/ssrn.4782398

Starr, J., Nicolson, C., Ash, M., Markowitz, E. M., & Moran, D. (2023). Income-based U.S. household carbon footprints (1990–2019) offer new insights on emissions inequality and climate finance. *PLOS Climate*, *2*(8), e0000190. https://doi.org/10.1371/journal.pclm.0000190

State of New South Wales (NSW Treasury). (2024). *NSW Treasury Policy and Guidelines – Annual Reporting Requirements: TPG23-10* (NSW Treasury Publication No. TPG23-10). NSW

Government. https://www.treasury.nsw.gov.au/sites/default/files/2024-07/tpg23-10_annual_reporting_requirements.pdf
State of New South Wales (NSW Treasury). (2025). *Reporting framework for climate-related financial disclosures* (NSW Treasury Publication No. TPG24-33). NSW Government. https://www.nsw.gov.au/sites/default/files/noindex/2025-06/tpg24-33-reporting-framework-for-climate-related-financial-disclosures.pdf
Stridsland, T., Boeve, T. M., Løkke, S., & Sanderson, H. (2024). Collaborative approaches to greenhouse gas inventory in higher education: Insights from the Universities Denmark Group. *Heliyon*, *10*(10), e30370. https://doi.org/10.1016/j.heliyon.2024.e30370
Stridsland, T., & Sanderson, H. (2023). Scope 3 Emissions of Higher Education: Review of Methods. In W. Leal Filho, M. Sima, A. Lange Salvia, M. Kovaleva, & E. Manolas (Eds.), *University Initiatives on Climate Change Education and Research* (pp. 1-22). Springer Nature Switzerland. https://doi.org/10.1007/978-3-031-25960-9_60-1
Sun, L., Kaufman, M. F., Sirk, E. A., Durga, S., Mahowald, N. M., & You, F. (2022). COVID-19 impact on an academic Institution's greenhouse gas inventory: The case of Cornell University. *Journal of Cleaner Production*, *363*, 132440. https://doi.org/10.1016/j.jclepro.2022.132440
Taskforce on Nature-related Financial Disclosures. (2024, April 24). *TNFD welcomes the ISSB's decision to commence work on nature-related issues*. https://tnfd.global/tnfd-welcomes-the-issbs-decision-to-commence-work-on-nature-related-issues/
ten Raa, T. (2017). Chapter 6: Multipliers, factor contents, and productivity. In T. ten Raa (Ed.), *Handbook of Input–Output Analysis* (pp. 223-244). Edward Elgar Publishing. https://doi.org/10.4337/9781783476329.00012
[TNFD] Taskforce on Nature-related Financial Disclosures. (2023). *Recommendations of the Taskforce on Nature-related Financial Disclosures*. https://tnfd.global/publication/recommendations-of-the-taskforce-on-nature-related-financial-disclosures/#publication-content
Troshani, I., & Rowbottom, N. (2024). Corporate sustainability reporting and information infrastructure. *Accounting, Auditing & Accountability Journal*, *37*(4), 1209-1237. https://doi.org/10.1108/AAAJ-01-2023-6244
The University of Sydney. (n.d.). *Our progress and reports*. Retrieved July 16, 2025, from https://www.sydney.edu.au/about-us/vision-and-values/sustainability/our-progress-and-reports.html
The University of Sydney. (2022). *Investment and Capital Management Investment Report 2022*. https://www.sydney.edu.au/content/dam/corporate/documents/about-us/governance-and-structure/our-portfolios/investment-and-capital-management-report-2022.pdf
The University of Sydney. (2025). *Climate-related Financial Disclosure 2024*. https://www.sydney.edu.au/content/dam/corporate/documents/news-opinions/2025/climate-related-financial-disclosure-2024.pdf
United Nations Statistics Division. (1999). *Handbook of input-output table compilation and analysis*. https://digitallibrary.un.org/record/370160?ln=en
United Nations Statistics Division. (2018). *Handbook on Supply and Use Tables and Input Output-Tables with Extensions and Applications*. https://unstats.un.org/unsd/nationalaccount/docs/SUT_IOT_HB_Final_Cover.pdf
Wang, J., Ji, C.-J., Liu, Y., Shan, Y., Hubacek, K., Wei, Y.-M., & Wang, K. (2024). Re-investigating the shared responsibility for trade-embodied carbon emissions. *Ecological Economics*, *220*, 108162. https://doi.org/10.1016/j.ecolecon.2024.108162
World Business Council for Sustainable Development & World Resources Institute. (2004). *The Greenhouse Gas Protocol: A Corporate Accounting and Reporting Standard - REVISED EDITION*. https://ghgprotocol.org/sites/default/files/standards/ghg-protocol-revised.pdf

World Resources Institute & World Business Council for Sustainable Development. (2011). *Corporate Value Chain (Scope 3) Accounting and Reporting Standard: Supplement to the GHG Protocol Corporate Accounting and Reporting Standard*. https://ghgprotocol.org/sites/default/files/standards/Corporate-Value-Chain-Accounting-Reporing-Standard_041613_2.pdf

World Resources Institute & World Business Council for Sustainable Development. (2013). *Technical guidance for calculating scope 3 emissions: Supplement to the Corporate Value Chain (Scope 3) Accounting & Reporting Standard*. https://ghgprotocol.org/sites/default/files/standards/Scope3_Calculation_Guidance_0.pdf

World Trade Organization. (n.d.). *GLOBAL VALUE CHAINS (GVC) DASHBOARD*. Retrieved June 4, 2025, from https://stats.wto.org/dashboard/gvc_en.html

Xu, L., Chen, G., Wiedmann, T., Wang, Y., Geschke, A., & Shi, L. (2019). Supply-side carbon accounting and mitigation analysis for Beijing-Tianjin-Hebei urban agglomeration in China. *Journal of Environmental Management*, *248*, 109243. https://doi.org/10.1016/j.jenvman.2019.07.014

5.8. *Supplementary Information*

5.8.1. IO background

5.8.1.1 Hybrid approaches

Using bottom-up data alone, it may be impracticable that investigations into impact could go far beyond on-site, direct suppliers and suppliers of direct suppliers. The importance of considering the extended supply chain was highlighted by Lenzen and Treloar (2002), who used the example of wooden and steel building frames to illustrate that two products that look to use similar energy use at the first couple of production layers, could prove to be significantly different when including emissions further along their supply chains. Because of the errors built into LCA, which introduces a system boundary within which to focus impact assessment, such process analysis can have truncation errors in the order of 50%, depending on the product or activity (Lenzen, 2000). Further, a case study of Australia and the US demonstrated that manually including hundreds or even thousands of one's supply-chain paths within a scope-3 materiality threshold of 0.01%, it is likely that most organisations could still only capture 70-90% of their total emissions (Huang et al., 2009, p. 235). However, path exchange is one way of incorporating important process-based data within IO calculations, which do not involve any truncation errors. The GHG Protocol recognises that because of the comprehensiveness of IO analysis, as well as its relative simplicity and efficiency, it is particularly useful for screening i.e. for identifying hotspots (World Resources Institute & World Business Council for Sustainable Development, 2013, p. 17). This may be followed up with more detailed investigations, for example targeted hybrid IO-LCA studies or process-based analysis or prioritising particular areas e.g., aviation, if relevant. Hybrid approaches enable the advantages of other methodologies to be included with IO analysis. For example, IOTs have been incorporated into computable general equilibrium (CGE) modelling. As well, although IO analysis is linear and therefore is more standardised than CGE, this rigidity means for example that there is an assumption of fixed prices but again, this can be accounted for taking a hybrid IO-LCA approach, factoring in the bottom-up information into the IO data being used. Rose & Miernyck summarised refinements and extensions of IO analysis in the first 50 years (1989), with further developments discussed by Miller & Blair (2009) and Dietzenbacher et al. (2020).

5.8.1.2. Global, multi-region input-output (MRIO) analysis

The United Nations' System of Environmental Economic Accounting (SEEA), which is aligned with the System of National Accounts (SNA), acknowledges the usefulness of IO analysis in such global holistic, quantitative analysis (United Nations et al., 2017, p. 45). For example, the Global Resource Input-Output Assessment (GLORIA) database was built for the UN, with a focus on measuring worldwide impacts against the SDGs (Lenzen et al., 2022), and underpins the publicly accessible Sustainable Consumption and Production Hotspot Analysis Tool (https://scp-hat.org/). The construction of national IO databases as well as global, multi-region input-output (MRIO) databases, also referred to as GMRIO, includes estimates and incorporates uncertainties; Lenzen et al. (2022) explain that there exists no "true" MRIO database, with trade-offs being made between selection of primary data (which are published with varying degrees of reliability) and constraints imposed on the MRIO database, which may vary depending on the priorities of the particular MRIO (Lenzen et al., 2022, Supplementary Information, p. 27). As well, there exist more MRIO data points than primary data, with primary data increasingly incorporated into a database over time; typically from the year a database is released (year N), the most recent primary data would be the UN Main Aggregates for the year $N - 2$ (Lenzen & Li, 2024a, pp. 17-18). Nevertheless, IO analysis boasts a low degree of uncertainty: a 2014 study of key MRIO databases EORA, WIOD, EXIOBASE and the GTAP-based OpenEU found that the carbon footprint results for most major economies disagreed by less than 10% between MRIO databases (Moran & Wood, p. 245); further, it was reported regarding one of the newer databases, GLORIA, that for fossil fuels, biomass and metal ores, uncertainties range from 1-3% for wealthy and/or large economies/large extractors; and up to ~10% for small and/or low-income countries. For non-metallic minerals: ~2-7% for wealthy and/or large economies or large extractors and/or users. No national material footprints were found to be more uncertain than 15% (Lenzen et al., 2022, Supplementary Information, p. 62). A paper reporting on GLORIA 2024 updates notes that, like the move to universal economic accounts in the 1950s, there is now an increasing effort to focus more on integrating material-flow physical/"satellite" accounts at for all countries and sub-nationally, incorporating available data into an increasingly robust disaggregated multipurpose data infrastructure (Schandl et al., 2024). With the move towards sustainability reporting beyond GHG emissions, a focus on improvements in environmental data collection and availability should assist crucial policy-making (Giljum et al., 2019).

5.8.2. IO calculus upstream and downstream

5.8.2.1. Basic equations

A schematic of a MIO table is provided by the OECD (n.d.). In the following equations, italics denote scalars and lower-case letters denote vectors. We denote the matrix of intermediate transactions as $\mathbf{T}$ of size $N \times N$; the final demand/expenditure/consumption column vector as $\mathbf{y}$, and the value-added/primary inputs/income row vector as $\mathbf{v}$. Then:

$$\mathbf{x} = \mathbf{T}\mathbf{1}^{\mathrm{T}} + \mathbf{y} \tag{1}$$

where $\mathbf{x}$ is total output, and $\mathbf{1}^{\mathrm{T}} = \{1,1, \ldots ,1\}$ is a suitable summation operator of N elements.

$$\mathbf{x}' = \mathbf{1}'^{\mathrm{T}}\mathbf{T} + \mathbf{v} \tag{2}$$

where $\mathbf{x}'$ is total input, with the prime denoting the transposition.

Next, a technical-coefficients $N \times N$ matrix ($\mathbf{A}$) is calculated, which shows the sectoral input requirements, referred to as a "production recipe", per monetary unit of output for each sector. Denoting the rows as *i* and the columns as *j*:

$$\mathrm{A}_{ij} = \mathrm{T}_{ij} / \mathrm{x}_j \tag{3}$$

and the entire matrix is calculated as:

$$\mathbf{A} = \mathbf{T}\hat{\mathbf{x}}^{-1} \tag{4}$$

where $\hat{\mathbf{x}}$ denotes the $\mathbf{x}$ values placed on the diagonal of a matrix and the $(^{-1})$ represents the inverse.

Ghosh, who formulated the downstream equivalent of the Leontief upstream model, conceptualised that the difference between calculating the important technical coefficients matrix ($\mathbf{A}$) and its "allocation" matrix counterpart ($\bar{\mathbf{A}}$) is that $\bar{\mathbf{A}}$ is the inverse of $\mathbf{A}$ (1958, p. 62).[12] As Dietzenbacher went on to reason, the Leontief and Ghosh models could be viewed as each other's mirror image (1997, p. 639). Also referred to as a direct *sales* matrix, its coefficients are calculated as:

$$\bar{A}_{ij} = T_{ij} / x_i \tag{5}$$

(Gallego & Lenzen, 2005, p. 368)

[12] We use the Ghosh quantity model as a descriptive tool, strictly *ex-post* (Gallego & Lenzen, 2005, p. 368): "*Ex post*… the Ghosh model can be used *descriptively* for re-tracing embodiments of primary inputs in downstream sales."

and the entire matrix is calculated as:

$$\bar{\mathbf{A}} = \hat{\mathbf{x}}^{-1}\mathbf{T} \quad (6)$$

(Dietzenbacher, 1997, p. 633; Miller & Blair, 2009)

where the transposition from "production recipe'" columns in $\mathbf{A}$ to allocation/sales rows in $\bar{\mathbf{A}}$ is achieved by *pre-multiplication* of $\mathbf{T}$.

This alternative calculation of $\mathbf{A}$ as $\bar{\mathbf{A}}$ is the main difference between the Leontief upstream and Ghosh downstream calculus. Thereafter, downstream calculations reflect the upstream calculations, with the transposition or mirror-image carried throughout, and with primary inputs ($\mathbf{v}$) rather than final demand ($\mathbf{y}$) being the stressor.

In the Leontief inverse that follows, the columns of the inverse table show the input requirements, both direct and indirect, on all other producers generated by one unit of output (Commission of the European Communities - Eurostat et al, 1993, p. 473):

$$\mathbf{L} = (\mathbf{I} - \mathbf{A})^{-1} \quad (7)$$

where $\mathbf{I}$ is an $N \times N$ identity matrix (with 1's on the diagonal and 0's elsewhere). Where, as described by Gallego & Lenzen (2005, p. 368): An element L_{ij} of the total-requirements matrix $\mathbf{L} = (\mathbf{I} - \mathbf{A})^{-1}$ represents the amount of gross output $\mathbf{x} = (\mathbf{I} - \mathbf{A})^{-1}\mathbf{y}$ from sector *i* that was produced to satisfy a unit of final demand y from sector *j* .

Downstream, the Ghosh inverse is:

$$\bar{\mathbf{L}} = (\mathbf{I} - \bar{\mathbf{A}})^{-1} \quad (8)$$

(Miller & Blair, 2009; Gallego & Lenzen, 2005)

Where, to paraphrase Gallego & Lenzen (2005, p. 368): "An element $\bar{L}_{ij}$ of the total-sales matrix $\bar{\mathbf{L}} = (\mathbf{I} - \bar{\mathbf{A}})^{-1}$, represents the amount of gross input $\mathbf{x}' = \mathbf{v}(\mathbf{I} - \bar{\mathbf{A}})^{-1}$ into industry *j* that absorbed, or utilised a unit of primary inputs $\mathbf{v}$ into industry *i*."

It has been shown that just as total output can be calculated as the supply-chain multiplier times amount spent:

$$\mathbf{x} = \mathbf{L}\mathbf{y} \quad (9)$$

alternatively, in the Ghosh model, the corollary is:

$$\mathbf{x}' = \mathbf{v}\bar{\mathbf{L}} \quad (10)$$

(Dietzenbacher, 1997)

For environmentally extended IO analysis (EEIO), we link physical indicators, from the satellite block, denoted as $\mathbf{Q}$, to economic activity.

$$\mathbf{q} = \mathbf{Q}\hat{\mathbf{x}}^{-1} \tag{11}$$

where $\mathbf{q}$ is a row vector of the relevant indicator's direct intensities in terms of the production factor (in its own physical units) per unit of sectoral output. For example, see descriptions by Gallego & Lenzen (2005) and Chen et al. (2017).

The upstream inter-industry impact is then driven in a demand-pull manner by the vector of final demand (expenditure):

$$F = \mathbf{qLy} \tag{12}$$

Note that although this as well as equation (13) below yields a scalar, the impact can be decomposed through element-wise multiplication (e.g., as shown in some later equations).
The downstream equivalent inter-industry impact, enabled by primary inputs (income) has been described as:

$$\bar{F} = \mathbf{v}\bar{\mathbf{L}}\mathbf{q}' \tag{13}$$

The upstream impact (12) can also be expressed in terms of *total* intensity (rather than *direct* intensity times the Leontief multiplier), driven by final demand:

$$F = \mathbf{my} \tag{14}$$

where $\mathbf{m}$ is a row vector of upstream total intensities, which is calculated as:

$$\mathbf{m} = \mathbf{qL} \tag{15}$$

The downstream equivalent to (15) is:

$$\bar{F} = \mathbf{v}\bar{\mathbf{m}} \tag{16}$$

where $\bar{\mathbf{m}}$ is a row vector of downstream total intensities, which is calculated as:

$$\bar{\mathbf{m}} = \bar{\mathbf{L}}\mathbf{q}' \tag{17}$$

(Chen et al., 2017)

Upstream, substituting the Leontief inverse (equation (7)) into equation (12), the impact is re-written as
$F = \mathbf{q}(\mathbf{I} - \mathbf{A})^{-1}\mathbf{y}$, which can be decomposed through a power series (Waugh, 1950) into a

production layer decomposition (PLD); in theory there can be an infinite number of supply-chain interactions:

$$F = \underset{\text{Layer 1}}{\mathbf{qy}} + \underset{\text{Layer 2}}{\mathbf{qAy}} + \underset{\text{Layer 3}}{\mathbf{qA}^2\mathbf{y}} + \underset{\text{Layer 4}}{\mathbf{qA}^3\mathbf{y}} + \ldots \quad (18)$$

In the same way, the downstream impact equation (13) can be re-written as $\bar{F} = \mathbf{v}(\mathbf{I} - \bar{\mathbf{A}})^{-1}\mathbf{q}'$ and expanded as highlighted by Li et al. (2021) into:

$$\bar{F} = \underset{\text{Layer 1}}{\mathbf{vq}'} + \underset{\text{Layer 2}}{\mathbf{v}\bar{\mathbf{A}}\mathbf{q}'} + \underset{\text{Layer 3}}{\mathbf{v}\bar{\mathbf{A}}^2\mathbf{q}'} + \underset{\text{Layer 4}}{\mathbf{v}\bar{\mathbf{A}}^3\mathbf{q}'} + \ldots \quad (19)$$

The entire inter-industry supply chain can be scanned, enabling the top paths to be ranked. In this study, structural path analysis (SPA) was carried out according to the pruning technique described by Lenzen (2002, 2007). Decomposing the upstream supply chain is:

$$F = \underset{i\ (N\text{ items})}{\sum^{N} q_i y_i} + \underset{ij\ (N^2\text{ items})}{\sum^{N} q_i A_{ij} y_j} + \underset{ijk\ (N^3\text{ items})}{\sum^{N} q_i A_{ij} A_{jk} y_k} + \underset{ijkl\ (N^4\text{ items})}{\sum^{N} q_i A_{ij} A_{jk} A_{kl} y_l} + \ldots \quad (20)$$

The downstream equivalent, paraphrasing the nomenclature by Lenzen & Murray (2010), is:

$$\bar{F} = \underset{i\ (N\text{ items})}{\sum^{N} v_i q_i'} + \underset{ij\ (N^2\text{ items})}{\sum^{N} v_i \bar{A}_{ij} q_j'} + \underset{ijk\ (N^3\text{ items})}{\sum^{N} v_i \bar{A}_{ij} \bar{A}_{jk} q_k'} + \underset{ijkl\ (N^4\text{ items})}{\sum^{N} v_i \bar{A}_{ij} \bar{A}_{jk} \bar{A}_{kl} q_l'} + \ldots \quad (21)$$

Element-wise multiplication results in the impact being decomposed per regional sector. Although the gross impact is the same, the disaggregated results vary (Miller & Blair, 2009, p. 621). Paraphrasing Malik et al. (2022) regarding upstream, the total impact may be analysed variously as:

$$\mathbf{F} = (\mathbf{qL})' \circ \mathbf{y} = \mathbf{m}' \circ \mathbf{y} \quad (22)$$

where the impact is attributed to final demand ($\mathbf{y}$), or

$$\mathbf{F} = \mathbf{q}' \circ \mathbf{Ly} \quad (23)$$

where the impact is attributed to emitting industries ($\mathbf{q}$). The Hadamard symbol represents element-wise multiplication. Note that the prime symbol for the matrix transposition is included for correct dimensions.

Similarly to upstream, so too for downstream analysis, the impact can be analysed according to different perspectives by using element-wise multiplication.

5.8.2.2. MRIO base-year testing

It was tested that the world's global flows upstream for the indicators used in this study were equivalent to downstream. Sustainability impact from the global economic system can be apportioned from the perspective of consumer responsibility, tracing the full supply-chain impact upstream back to final demand (of a product), or it can be apportioned to the producers, who enable the sales-chain impact downstream from their income for providing the product (Gallego & Lenzen, 2005; Lenzen et al., 2007). Since an underlying assumption of IO is that total output ($\mathbf{x}$) must equal total input ($\mathbf{x}'$), from *SI* equations (9-10) therefore calculated total output: $\mathbf{Ly} = \mathbf{v}\bar{\mathbf{L}}$ (calculated total input) and by multiplying both sides of the equation by $\mathbf{q}$:

$\mathbf{qLy}_{\text{global}}$ (upstream impact, from equation (12)) = $\mathbf{v}\bar{\mathbf{L}}\mathbf{q}'_{\text{global}}$ (downstream impact, from (13)).

Looking at total global emissions (rather than an individual company), whether calculating the hotspots from a consumer- or producer-responsibility perspective, it is the same global emissions ($\mathbf{Q}$) that are being apportioned for the analysis. (Recall that $\mathbf{q}$ is calculated in equation (11) by dividing the physical impact ($\mathbf{Q}$) by total output ($\mathbf{x}$), in order to obtain the direct-impact intensity per monetary unit of total output, or in other words, $q_j = Q_j/x_j$ (Lenzen & Murray, 2010, p. 264)).[13] In considering which base year to use in the GLORIA MRIO, we compared the global upstream and downstream footprints of the GHG emissions, land use and bluewater consumption indicators selected for this study. Testing the 2021 MRIO, these were broadly the same, to two significant digits for global GHG emissions at 45.68 Gt CO2e;[14] therefore the 2021 MRIO was selected as the base year for the 2022 value-chain analysis.

5.8.3. Inflation adjustment

For non-comparative studies, calculations may be made taking the year under analysis as the point in time, rather than adjusting the stressor income/expenditure to the MRIO base year. This is the approach that was generally taken for this pilot study. An exception was made for expenditure on gas utilities, because of the record gas price increases experienced globally in

[13] Lenzen & Murray (2010, p. 264) explain it thus: "The *emissions intensity* q_j of an emitting intermediate producer j is the ratio of its total emissions Q_j and its total output x_j". Lenzen & Gallego (2005, p. 369) put it this way: "A vector of coefficients $\mathbf{f}$ is defined, where each element f_j represents the impact (use, release, quantity) in terms of the production factor (in its own physical units) associated with one unit of gross output x_j of sector j."

[14] These GHG emissions for all sectors, in addition to emissions for all final demand, add together to 53 Gt CO2e; this is the same rounded number as in the 7.0 version of EDGAR for 2021, "Total GHG by country AR5" tab (European Commission, n.d.).
Note: there is usually a slight discrepancy between the source GHG emissions and GLORIA satellite due to conversion between classifications (Lenzen, M., & Li, M. (2024a). *GLORIA MRIO database Release 059* [Release notes]).

2022 following on from COVID-19 and the Russia-Ukrainian war; in order to reflect more accurately the University's emissions from gas, the expenditure on gas utilities was reduced by the estimated amount that the price of the University's gas utilities had increased during the year.

5.8.4. General Sustainability indicators used

In the case study process-based data regarding *on-site* land- and water use were obtained.

5.8.4.1. Land use

The land-use GLORIA indicators include data for agricultural but not urban use (Lutter et al., 2021, p. 14) and the GLORIA land-use indicators allocate some subsistence farming to final demand. Therefore *on-site agricultural land use* was added to the inter-industry value-chain impact, calculated using IO analysis, for consistency.

5.8.4.2. Bluewater consumption

For bluewater consumption, a different approach was required. The bluewater-consumption indicator measures water consumed as part of production (Lutter et al., 2021, p. 18), meaning that the *water utilities* for business use as part of this global use is by definition included in the IO results. Nonetheless, the bottom-up data of purchased water was used in the case study for comparative purposes in relation to the bluewater consumption in the extended value chain.

5.8.5. Greenhouse Gas Protocol categories

Below is an edited excerpt from documentation that had been prepared in anticipation of future assurance, and extended for this paper

5.8.5.1. GHG Protocol categories upstream

Concordance matrices were developed in order to disaggregate the contribution of each Greenhouse Gas Protocol category to the University's total GHG emissions throughout the supply chain (except Employee Commuting, which was added to the upstream IO calculations). The concordance matrices mapped the University's class codes to relevant sectors within each Greenhouse Gas Protocol category. Some were straightforward, such as the 2nd category, "Capital goods", which is represented by a handful of class codes classified by the University as "Capital expenditure". For these class codes, a "1" was placed against the relevant GLORIA sector; other class codes not relevant to capital goods had a zero to each sector, since expenditure from other class codes were not relevant for capital goods.

In addition to referring to the scope-3 technical guidelines for Greenhouse Gas Protocol reporting (World Resources Institute & World Business Council for Sustainable Development,

2013), harmonisation of the University class codes to GLORIA sectors has followed the sector classification of a GLORIA-HSCPC concordance obtained and used for this analysis, as discussed in the Main Text.

For this study, the concordances were read into matrices software MATLAB and the GHG emissions per category were calculated according to IO calculus in Section 5.8.2. However, the GHG emissions per category can alternatively be calculated using emission factors rather than involving supply-chain information that requires a high-performance computing environment, e.g., by using equation (14) rather than (12). As an example, Category 5 Waste Generated in Operations was comprised of the University classes: 5424 Services Decontamination, 5425 Services Waste Removal Anatomi, 5426 Services Waste Removal Chemica and 5406 Services Waste Removal. Calculating this using equation (14), for the first three classes, the GHG emissions are calculated by multiplying the spend-based emission factor for the sector "Waste collection, treatment, and disposal" (0.000156 kt CO2e per USD'000) by the University's 2022 expenditure in USD'000 for these classes. For 5406 Services Waste Removal, it was advised by University operations staff that 19% of this cost was for recycling, so this proportion of the spend in this class was multiplied by the emission factor for "Materials recovery", with the remaining 81% multiplied by the emission factor for "Waste collection, treatment, and disposal". The GHG emissions for all four classes were added together to arrive at the total emissions for the University's category 5 Waste Generated in Operations.

The Greenhouse Gas Protocol's technical guidance on calculating scope-3 emissions (World Resources Institute & World Business Council for Sustainable Development, 2013) allows some flexibility regarding inclusion of particular goods or services in the various categories and says the reporting entity's decision on the approach can be guided by what will help decision-makers understand the drivers of key emissions in order to take action.

Some decision-making and details include:

5.8.5.1.1. Category 3 Fuel and Energy-Related Activities Not Included in Scope 1 or Scope 2
The GHG Protocol category 3, "Fuel- and energy-related activities not included in scope 1 or scope 2" is calculated by deducting the *IO scope-2 emissions* (from direct suppliers of electricity) from the total supply-chain energy-related emissions to arrive at the scope-3 component of supply-chain energy emissions. Because our IO indirect emissions do not include scope-1 emissions, only scope-2 emissions calculated using IO need to be deducted to arrive at the energy-related emissions excluding scopes 1-2.

GLORIA Release 059 used in this study has 120 sectors and 164 regions so there are 19,680 regional sectors; the sector numbering in Section 4.7.2 shows that the "Electric power generation, transmission and distribution" sector is number 93 and Australia is region 11; this makes the sector numbers in Australia, where the money is spent, 120 x 10 (before the start of Australian sectors) + 93 = 1293. *The scope-3 component of electricity emissions,* derived from equation (14) less Layer 1 of equation (18) is: $\mathrm{Scope3}_{elec} = m_{1293} * y_{1293} - q_{1293} * y_{1293}$, where the "*" symbol denotes multiplication.

5.8.5.1.2. Category 4 Upstream transportation and distribution

- Transportation of goods and services was harmonised with this category, including classes 5231 CIS Decanting & Relocation and 5423 Services Dock Management.

- By comparison, expenditure on services to transport as part of business travel (parking fees/tolls) were excluded, instead being mapped to "Business travel" (see below).

5.8.5.1.3. Category 6 Business Travel

- The cost of renting cars for business travel was harmonised with this category, as recommended by the Greenhouse Gas Protocol guidance (World Resources Institute & World Business Council for Sustainable Development, 2013, p. 8). As well, related services to transport such as tolls and parking were included.

- Accommodation was excluded: although the Greenhouse Gas Protocol allows this to be included or excluded as desired, it was decided to use this category to highlight transport for business, rather than adding this to accommodation during travel.

5.8.5.1.4. Category 8 Upstream Leased Assets

Included:

Only rentals/leases that were included on the balance sheet as defined and required by accounting standards; included 7590 Depn Right of Use Asset – Lease, although this is a depreciation expense, because that is how ROU expenses are recorded, and the related 6954 Interest on ROU Asset-Leasing.

Excluded from this category:

Rental accommodation of students (comprising most of 7306 Student Travel&Accom Domestic) on the basis that the University does not operate these leases, and 5603 Hire External Venues, which is for short-term hires.

5.8.5.1.5. .Category 7 Employee Commuting

Below are the steps taken to calculate employees' upstream impact from driving to/from work; note that employees' scope-1 (direct) emissions from petrol combustion while commuting can be added to the emissions calculated using the steps below of supply-chain (indirect) commuting calculations.

Assumptions/background:

- Only emissions from employees *driving* to work were calculated, the reason being that the University enables employee driving through offering parking.
- Emissions from public transport were not calculated because these were deemed to be immaterial, since in addition to about 1/3 of commuters driving to work, another 1/3 caught the train, which are renewable-powered (Transport for NSW, 2024), and the other main type of transport, bus, was only taken by less than 1/5 of staff surveyed, and NSW busses are converting to renewables (ARENA, 2021).
- The basis of most calculations was the University Travel Choices Survey of students and staff members of the University of Sydney who lived in Sydney at the time (Balbontin et al., 2024), with additional source data extracted by one of the co-authors on request.
- There were 3 time periods in the University Travel Choices Survey (Balbontin et al., 2024), with Wave 2 chosen for our calculations. Wave 1 data was collected in May-June 2022 and the second one October-November 2022; a period where there existed no restrictions on movement; however it should be noted that the University still offered education within the hybrid format.
- Employee numbers were taken from the Annual Report and the number of weeks working annually was assumed to be 48.
- Telecommuting emissions were not optionally included (World Resources Institute & World Business Council for Sustainable Development, 2013) because results from a work-from-home calculator (Energetics, 2023) indicated that, when combined with savings from commuting, this would result in negative emissions. This is in line with research in the United States; that research also suggested that group-specific considerations were important (Wu et al., 2024).

The following calculation steps were taken:

Parking – using income from the relevant parking class code

1. Identify class code 3211 Parking (Class Definition: "Income from parking permits" [for staff and students]) as including employee parking.

2. Assume that half the parking income is from staff, based on the survey ("Wave 2"), which showed the amount paid by staff and students was similar, based on a small number of respondents.

3. Convert the result in step 2 to USD'000 as per GLORIA unit.

4. Use this Parking permits income in step 3 as the stressor, multiplied by the upstream total intensity for the "Services to transport" sector, which is No. 1306 in the matrix as per region/sector in GLORIA (Lenzen & Li, 2024b) i.e., regional sector 1200+106.

Tolls – using survey data

1. Use the AUD weekly toll paid by employee drivers identified in the survey.

2. Convert to annual amount.

3. Multiply the result in step 2 by (No. FTE[15] employees *0.2912), the latter being the proportion who said they drove.

4. Convert the result in step 3 to USD'000 as per GLORIA unit.

5. Multiply the result in step 4 by the upstream total intensity of Australia's "Services to transport" sector.

Fuel – using survey data

1. Use the AUD weekly fuel expenditure by employees identified in the survey.

2. Repeat steps 2-4 above.

3. Multiply the converted amount from the previous step (2) by the upstream total emissions intensity of the "Refined petroleum products" sector, which is No. 1263 in the matrix as per region/sector in GLORIA (Lenzen & Li, 2024b) i.e. sector 1200+63.

5.8.5.2. Double-counting example

In a hypothetical situation, if 10 ktCO2-e are calculated using IO analysis from the upstream perspective, from the Air Transport sector, relevant to category 6 Business Travel, and then 2 ktCO2-e emissions are calculated using IO analysis from the downstream perspective from the same sector, relevant to category 9 Downstream Transportation and Distribution, then there is 2 ktCO2-e that is double-counted. We may decide to delete the 2 ktCO2-e *downstream* since it is

[15] FTE rather than total number of staff was used, because in the commuting survey upon which this was based, the number of responses from casuals/affiliates was immaterial.

not substantial, to focus on the upstream hotspot; or alternatively, perhaps it is decided to share the 2 ktCO2-e removal so that 9 ktCO2-e are attributed to Air Transport upstream (Business Travel) and 1 ktCO2-e is recorded downstream (Downstream Transportation and Distribution). The screenshot below, from the University of Sydney's 2024 scope-3 emissions calculation carried out subsequent to the pilot study detailed in this paper, provides a straightforward example of how double-counting may be identified, and an adjustment made, by comparing sector emissions calculated upstream and downstream.

Alternatively, for details about a "shared responsibility" solution, where burdens are shared in a non-arbitrary manner between supplying and demanding sides of every transaction in the economy, see for example Lenzen et al. (2007) and Lenzen (2008).

	A	B	C	D	E	F
1	Lfd_Nr	Sector_names	Upstream	Downstream	Double-counted (ktCO2e)	
2	1	Growing wheat	0	3.4119		
3	2	Growing maize	0	0		
4	3	Growing cereals n.e.c	1.0331	0		
5	4	Growing leguminous crops and oil seeds	0.019679	0		
6	5	Growing rice	0	0		
7	6	Growing vegetables, roots, tubers	0.7734	0		
8	7	Growing sugar beet and cane	0	0		
9	8	Growing tobacco	0	0		
10	9	Growing fibre crops	0.39897	0		
11	10	Growing crops n.e.c.	4.895	0		
12	11	Growing grapes	0	0		
13	12	Growing fruits and nuts	0.010559	0		
14	13	Growing beverage crops (coffee, tea etc)	0	0		
15	14	Growing spices, aromatic, drug and pharmaceutical crops	0	0		
16	15	Seeds and plant propagation	0	0.2594		
17	16	Raising of cattle	7.3869	0		
18	17	Raising of sheep and goats	0.3733	0		
19	18	Raising of swine/pigs	0.12116	0		
20	**19**	**Raising of poultry**	**0.009443**	**0.0027874**	**0.0027874**	

In the example above, the emissions for Australia's sector 19 "Raising of poultry" may be reduced by the double-counted portion, for a *net* result of: upstream (0.009443) less double-counted downstream (0.0027874) = 0.006656 ktCO2e.

5.8.5.3. A note on GHG Protocol categories downstream

Similar logic used upstream may be used for GHG Protocol downstream categories, for example, in applying IO analysis to category 11 Use of Sold Products, which the GHG Protocol says can account for "indirect use-phase emissions" (World Resources Institute & World Business Council for Sustainable Development, 2013, p. 113). Non-IO methods were used in Reiner (*under review*) to calculate emissions from the following areas that are treated as exogenous to intermediate production in traditional IO analysis: investments (Miller & Blair, 2009), which was provided by an external consultant (The University of Sydney, 2022) and households, with emissions from international students' air transport optionally added (World Resources Institute & World Business Council for Sustainable Development, 2013), broadly calculated according to Heller et al. (2022).

5.8.6. *SI* References

ARENA. 2021. “New electric buses roll out on Sydney streets”, 10 November, available at: https://arena.gov.au/blog/new-electric-buses-roll-out-on-sydney-streets/ (accessed 14 October 2024).

Balbontin, C., Nelson, J. D., Hensher, D. A., & Beck, M. J. (2024). *Identifying main drivers for students and staff members' mode choice or to work/study from home or attend University campus: A case study in Australia*. https://hdl.handle.net/2123/32561

Chen, G., Hadjikakou, M., & Wiedmann, T. (2017). Urban carbon transformations: unravelling spatial and inter-sectoral linkages for key city industries based on multi-region input–output analysis. *Journal of Cleaner Production*, *163*, 224-240. https://doi.org/10.1016/j.jclepro.2016.04.046

Dietzenbacher, E. (1997). In Vindication of the Ghosh Model: A Reinterpretation as a Price Model. *Journal of Regional Science*, *37*(4), 629-651. https://doi.org/10.1111/0022-4146.00073

European Commission. (n.d.). Global greenhouse gas emissions: EDGAR v 7.0. https://edgar.jrc.ec.europa.eu/dataset_ghg70

Gallego, B., & Lenzen, M. (2005). A consistent input–output formulation of shared producer and consumer responsibility. *Economic Systems Research*, *17*(4), 365-391. https://doi.org/10.1080/09535310500283492

Ghosh, A. (1958). Input-Output Approach in an Allocation System. *Economica*, *25*(97), 58-64. https://doi.org/10.2307/2550694

Giljum, S., Wieland, H., Lutter, S., Eisenmenger, N., Schandl, H., & Owen, A. (2019). The impacts of data deviations between MRIO models on material footprints: A comparison of EXIOBASE, Eora, and ICIO. *Journal of Industrial Ecology*, *23*(4), 946-958. https://doi.org/10.1111/jiec.12833

Heller, R. F., Ya-Yen, S., Guo, Z., & Malik, A. (2022). Impact on carbon emissions of online study for a cohort of overseas students: A retrospective cohort study [version 5; peer review: 2 approved, 1 approved with reservations]. *F1000Research, 10:849*. https://doi.org/10.12688/f1000research.55156.5

Huang, Y. A., Lenzen, M., Weber, C. L., Murray, J., & Matthews, H. S. (2009). THE ROLE OF INPUT–OUTPUT ANALYSIS FOR THE SCREENING OF CORPORATE CARBON FOOTPRINTS. *Economic Systems Research*, *21*(3), 217-242. https://doi.org/10.1080/09535310903541348

Industrial Ecology Virtual Laboratory. (n.d.). *Global MRIO Lab*. Retrieved 8 May from https://ielab.info/labs/ielab-global

Lenzen, M. (2000). Errors in Conventional and Input-Output—based Life—Cycle Inventories. *Journal of Industrial Ecology*, *4*(4), 127-148. https://doi.org/10.1162/10881980052541981

Lenzen, M. (2002). A guide for compiling inventories in hybrid life-cycle assessments: some Australian results. *Journal of Cleaner Production*, *10*(6), 545-572. https://doi.org/10.1016/S0959-6526(02)00007-0

Lenzen, M. (2007). Structural path analysis of ecosystem networks. *Ecological Modelling*, *200*(3), 334-342. https://doi.org/10.1016/j.ecolmodel.2006.07.041

Lenzen, M., Murray, J., Sack, F., & Wiedmann, T. (2007). Shared producer and consumer responsibility — Theory and practice. *Ecological Economics*, *61*(1), 27-42. https://doi.org/10.1016/j.ecolecon.2006.05.018

Lenzen, M., Geschke, A., West, J., Fry, J., Malik, A., Giljum, S., Milà I Canals, L., Piñero, P., Lutter, S., Wiedmann, T., Li, M., Sevenster, M., Potočnik, J., Teixeira, I., Van Voore, M., Nansai, K., & Schandl, H. (2022). Implementing the material footprint to measure progress towards Sustainable Development Goals 8 and 12. *Nature Sustainability*, *5*(2), 157-166. https://doi.org/10.1038/s41893-021-00811-6

Lenzen, M., & Li, M. (2024a). *GLORIA MRIO database Release 059* [Release notes]. IELab.
Lenzen, M., & Li, M. (2024b). *GLORIA_ReadMe_059*. IELab.
Lenzen, M., & Murray, J. (2010). Conceptualising environmental responsibility. *Ecological Economics*, *70*(2), 261-270. https://doi.org/10.1016/j.ecolecon.2010.04.005
Lenzen, M., & Treloar, G. (2002). Embodied energy in buildings: wood versus concrete—reply to Börjesson and Gustavsson. *Energy Policy*, *30*(3), 249-255. https://doi.org/10.1016/S0301-4215(01)00142-2
Li, J., Huang, G., Li, Y., Liu, L., & Sun, C. (2021). Unveiling Carbon Emission Attributions along Sale Chains. *Environmental Science & Technology*, *55*(1), 220-229. https://doi.org/10.1021/acs.est.0c05798
Lutter, S., Sevenster, M., Piñero, P., & Giljum, S. (2021). *Technical documentation of the Sustainable Consumption and Production Hotspots Analysis Tool (SCP HAT) Version 3.0. Commissioned by UN Life Cycle Initiative, One Planet Network, and UN International Resource Panel*. https://scp-hat.org/wp-content/uploads/2021/11/Technical-Documentation_GLORIA_20210913.pdf
Malik, A., Lenzen, M., Lane, J., Lam, K. L., Harding, O. M., & Geschke, A. (2022). Carbon footprint and voting preferences of a council. *Resources, Conservation and Recycling*, *186*, 106535. https://doi.org/10.1016/j.resconrec.2022.106535
Malik, A., McBain, D., Wiedmann, T. O., Lenzen, M., & Murray, J. (2019). Advancements in Input-Output Models and Indicators for Consumption-Based Accounting. *Journal of Industrial Ecology*, *23*(2), 300-312. https://doi.org/10.1111/jiec.12771
Miller, R. E., & Blair, P. D. (2009). *Input-Output Analysis: Foundations and Extensions* (2 ed.). Cambridge University Press. https://doi.org/10.1017/CBO9780511626982
Moran, D., & Wood, R. (2014). CONVERGENCE BETWEEN THE EORA, WIOD, EXIOBASE, AND OPENEU'S CONSUMPTION-BASED CARBON ACCOUNTS. *Economic Systems Research*, *26*(3), 245-261. https://doi.org/10.1080/09535314.2014.935298
OEDC. (n.d.). *Input-Output Tables*. Retrieved 10 June from https://www.oecd.org/en/data/datasets/input-output-tables.html
Schandl, H., Marcos-Martinez, R., West, J., Miatto, A., Lutter, S., Lieber, M., Giljum, S., Lenzen, M., Li, M., Wang, H., Tanikawa, H., Krausmann, F., Eisenmenger, N., & Fischer-Kowalski, M. (2024). Global material flows and resource productivity: The 2024 update. *Journal of Industrial Ecology*, *28*(6), 2012-2031. https:doi.org/10.1111/jiec.13593
The University of Sydney. (2024). *Investment and Capital Management Investment Report 2024*. University of Sydney. https://www.sydney.edu.au/content/dam/corporate/documents/about-us/governance-and-structure/our-portfolios/investment-and-capital-management-report-2024.pdf
United Nations, European Union, Food and Agriculture Organization of the United Nations, Organisation for Economic Co-operation and Development, & The World Bank Group. (2017). *System of Environmental-Economic Accounting 2012—Applications and Extensions*. United Nations. https://seea.un.org/sites/seea.un.org/files/ae_final_en.pdf
Waugh, F., V. (1950). Inversion of the Leontief matrix by power series. *Econometria*. *18*(2), 142-154. https://www.jstor.org/stable/1907265
World Resources Institute & World Business Council for Sustainable Development. (2013). *Technical guidance for calculating scope 3 emissions: Supplement to the Corporate Value Chain (Scope 3) Accounting & Reporting Standard*. https://ghgprotocol.org/sites/default/files/standards/Scope3_Calculation_Guidance_0.pdf

6. CONCLUSIONS

6.1. Key findings

This thesis has taken a double-materiality approach to sustainability reporting by identifying industry-specific financial risks from a climate-change catastrophe, using IO analysis, and then describing novel research to apply the comprehensive IO methodology to Climate- and Nature due diligence in line with the ISSB and GHG Protocol and related frameworks such as the TNFD, considering *financial- and broader impact materiality*. In other words, looking beyond requirements from a financial-reporting perspective to due diligence from the perspective of impact on the environment. IO analysis is the focus of this thesis as a holistic, comprehensive and standardised (United Nations Statistics Division, 1999) method for quantifying impacts along the inter-industry value chain but it had not previously been directed at and developed for new mandatory sustainability reporting.

Thinking globally and initially assessing how IO analysis can be applied to indicators of extreme sustainability stressors, tailored research was conducted. For the globally unprecedented 2019-20 Australian bushfires, spillovers were analysed from calculated tourism direct losses of 4% and related infrastructure damage, with a finding of 7300 full-time equivalent jobs lost for the year just from the short-term tourism shock. This focus on the visitor economy is significant because Australia and other island nations are particularly reliant on Nature-based tourism, but such activities are also vulnerable to climate change. In addition to expected income losses such as in aviation and hospitality generally, employment in the accommodation sector was substantially impacted nationwide. Education was also identified as a hotspot, particularly in Victoria and New South Wales, which may be explained by the fact that education is a top export that is dependent on international aviation bringing students to Australia to study. Such research, which enables insights for local sectors far from the burn scar, can be complemented with a business's specific information to prepare for global warming and related disasters. For modern slavery, measuring supply-chain risk can be challenging because of data issues, making it unsuitable for an integrated IO-based mandatory human rights *and* environmental due diligence framework. However, IO analysis has underpinned reliable supply-chain analysis of exploitative-labour risk where there is robust data, which suggests that IO analysis could have an important role to play in tailored research and assessment of risk for human-rights due diligence. Overall in terms of the environmental reporting landscape, IO analysis has been demonstrated to be well-placed to quantify the financial impact to specific sectors from climate

disasters, as well as for crucial analysis of carbon and biodiversity-related indicators, through the development described in this dissertation of a framework for organisations to use IO analysis for Climate- and Nature reporting.

This body of work has generated knowledge through:

a. the first IO costing of any aspect of Australia's 2019-20 bushfires;
b. the most comprehensive and up-to-date critical review of global modern-slavery data, estimates and "slavery-like" indicators, for potential human-rights due diligence; and
c. the development of a downstream IO framework that draws on an organisation's sectoral income as the stressor, to complement well-established environmentally extended upstream IO analysis for corporate reporting.

6.2. Policy priorities emerging from the research

Thinking about the wicked problems of climate disasters as well as modern slavery, two priorities emerge from the first half of this thesis:

- 1a. recommendation for the inclusion of IO disaster analysis and/or other economy-wide standardised approaches in climate-related disclosures. In this regard, IO disaster analysis can provide a benchmarkable approach to disaster and risk analysis at the macroeconomic level, while process-based information can be added, for example, at a local-government level or from an industry-based perspective (IFRS Foundation, 2023) for a hybrid IO-LCA comprehensive analysis of financial business risk. Currently, IFRS S2 (International Sustainabililty Standards Board, 2023) for example discusses general concepts such as scenario analysis and climate-related metrics categories such as physical risks, but does not advise on economy-wide comparable estimates;
- 1b. recommendation for a precautionary approach to modern-slavery due diligence to be highlighted in legislative instruments. Without this, businesses may be inclined to seek a technological "quick fix", for example by undertaking a so-called modern-slavery footprint of their activities based on modern-slavery data and estimates not intended for this purpose, which could do more harm than good.

From an environmental-impact perspective regarding individual organisations, two priorities emerge from the downstream IO framework for corporate reporting and associated case study, which forms the second-half of this thesis:

- 2a. provision of downstream emission factors. Just as upstream, spend-based emission factors are readily available, for example provided by governments and by businesses on a proprietary basis, so too do downstream, income-based emission factors need to be made available for business use. This would mean that IO emission factors would be available for comprehensive scope-3 emissions calculations throughout the inter-industry value chain, in line with whole-of-value-chain reporting requirements, in a robust manner;
- 2b. mandating the scope-3 method. Standardised scope-3 emissions calculations are demonstrated in this thesis to be technically and practically feasible for organisations using IO analysis, which can complement the industry-averages of IO data with process-based information where available. Mandating IO analysis for scope-3 due diligence would support organisations in reporting comprehensively on their emissions.

6.3. Future research directions

Specific areas for research may include:

- for the mega-fires, analysis of the impact on supply chains for agriculture sectors, including forestry. As well, standard IO analysis could be applied to footprint the impact of post-disaster stimuli, such as the Rebuilding Australian Tourism package, *ceteris paribus*, noting the fluid economic situation following catastrophes and compound disasters. For potential whole-of-economy costing using IO analysis, although extreme localised annual losses may pose a challenge for the current IO disaster analysis optimisation model, the relative devastation to SA forestry (Government of South Australia, 2020, p. iii) may be smoothed through more aggregated analysis by harmonising forestry with other sectors, such as fishing/seafood, which suffered relatively small losses. In this way, a novel comprehensive costing of the 2019-20 bushfires may be undertaken, using IO analysis;
- for modern slavery, more hybrid IO-LCA analyses, in areas where there is rich data, will add to a web of global information on modern-slavery risk. To assist with this, continued and renewed data-collection efforts are of critical importance, particularly directed at the local level, regarding identified high-risk activities;
- in terms of quantifying business impact on climate and general sustainability as part of mandatory reporting, research is recommended to investigate an approach to “shared-responsibility”, methods for which are detailed in the literature review of Wang et al. (2024) and touched on in the Literature Review of this dissertation’s Chapter 4, regarding

organisations' relative contributions as consumers and producers to scope-3 emissions. Such an approach addresses double-counting from a national accounting perspective. Simultaneously, it can ease the burden of responsibility, while enabling organisations to prioritise action in their value-chain hotspots to address climate change.

6.4. Application and timeliness of this thesis

The research from this thesis has been acknowledged in public and business arenas for providing information and tools that can help organisations respond to the sustainability crises.

The first journal article, about the unprecedented 2019-20 Australian bushfires, which comprises **Chapter 2** of this thesis, received a High Attention Score (Altmetric, n.d.) including international television (Maynard, 2024) and The Guardian newspaper (Readfearn, 2024); critically, the research was cited in Australia's first National Climate Risk Assessment (Australian Climate Service, 2025a, pp. 121-122; 2025b, pp. 14 & 27) as part of the federal Government's case for raising its ambition in a 2035 target for its Nationally Determined Contribution under the Paris Agreement (Albanese et al., 2025). In response to the second journal article, about modern slavery, which forms **Chapter 3** of this thesis, the counter-factual findings resulted in the funding OAASIS project changing its research direction (The University of Sydney, n.d., "Finding suitable and reliable metrics"). The main novel contribution of this thesis has been in the development of a sustainability reporting framework using IO analysis for businesses generally, as well as specifically enabling the reporting of all inter-industry scope-3 emissions across the GHG Protocol categories (**Chapters 4-5**). In terms of immediacy and practicality, framework's upstream environmental due diligence was recognised by the 17th [ISCN] International Sustainable Campus Network Conference in Switzerland (Reiner, 2024). Additionally, the finalised framework was used as the basis for a University of Sydney scope-3 emissions downstream and upstream report as part of its first climate-related disclosures (The University of Sydney, 2025, paras. 3 & 7), with the calculated emission factors provided to auditors for transparency and efficient assurance. Subject-matter experts drew on the insights from the highly disaggregated value-chain analysis, in considering next steps for reducing the institution's environmental footprint.

With IO analysis applied to global Climate- and Nature reporting requirements for robust and comprehensive disclosures, the path towards implementation for all becomes paramount. Such a mandatory approach can facilitate ambitious due diligence to address climate change

and related sustainability crises holistically and in a way that is comparable across organisations.

6.5. References

Albanese, A., Chalmers, J., & Bowen, C. (2025, September 18). *Setting Australia's 2035 climate change target* [Press release]. https://www.pm.gov.au/media/setting-australias-2035-climate-change-target.

Altmetric. (n.d.). *Wish You Were Here? The Economic Impact of the Tourism Shutdown from Australia's 2019-20 'Black Summer' Bushfires - Overview of attention for article published in Economics of Disasters and Climate Change, January 2024*. Retrieved October 8, 2025 from https://link.altmetric.com/details/158895898

Australian Climate Service. (2025a). *Australia's National Climate Risk Assessment Report*. https://climateservice.maps.arcgis.com/sharing/rest/content/items/9d4850b2d64d47e28407c04681b0eeca/data

Australian Climate Service. (2025b). *The Real Economy Technical Report. A technical report for the National Climate Risk Assessment*. https://www.arcgis.com/sharing/rest/content/items/18a76d6bd5c4402facf5dfe3443d8c16/data

Commission of the European Communities - Eurostat, International Monetary Fund, Organization for Economic Co-operation and Development, United Nations, & World Bank. (1993). *System of National Accounts*. https://unstats.un.org/unsd/nationalaccount/docs/1993sna.pdf

Government of South Australia. (2020). *Independent Review into South Australia's 2019-20 Bushfire Season*. https://safecom-files-v8.s3.amazonaws.com/current/docs/Independent%2520Review%2520into%2520SA%2527s%25202019-20%2520Bushfire%2520Season%2520-%2520Web%2520Upload.pdf

International Sustainability Standards Board. (2023). *IFRS Sustainability Disclosure Standard: Climate-related Disclosures* (ISSB Standard No. IFRS S2). https://www.ifrs.org/issued-standards/ifrs-sustainability-standards-navigator/ifrs-s2-climate-related-disclosures.html/content/dam/ifrs/publications/html-standards-issb/english/2023/issued/issbs2/

IFRS Foundation. (2023). *IFRS S2: Industry-based Guidance on implementing Climate-related Disclosures*. https://www.ifrs.org/content/dam/ifrs/publications/pdf-standards-issb/english/2023/issued/part-b/ifrs-s2-ibg.pdf?bypass=on

Maynard, R. (2024, April 29). Global warming threatens future of Australia's tourism industry [Television report]. *Channel News Asia*. https://www.channelnewsasia.com/watch/global-warming-threatens-future-australias-tourism-industry-4299936

Readfearn, G. (2024, January 31). Australia's black summer bushfires ripped billions from the tourism industry. Is global warming making the cost of natural disasters worse? *The Guardian*. https://www.theguardian.com/australia-news/2024/jan/31/black-summer-bushfires-australia-tourism-industry-impact

Reiner, V. (2024, June 27). *Integrated Scope 3 and Nature Footprint Across the Supply Chain* [Conference presentation]. 2024 ISCN Conference, Lausanne, VD, Switzerland. https://coda.io/d/2024-ISCN-Conference-Website_dWeKRnU7np9/Program-and-Sessions_suFkdL9J#Conference-Program_tua01912/r50&view=full

United Nations Statistics Division (1999). *Handbook of input-output table compilation and analysis*. https://digitallibrary.un.org/record/370160?ln=en

The University of Sydney. (n.d.). *The OAASIS Project: Open analysis to address slavery in supply chains*. Retrieved September 8, 2025, from https://www.sydney.edu.au/science/our-research/research-areas/physics/big-data-combatting-modern-slavery.html

The University of Sydney. (2025). *University of Sydney first in Australia to release full climate-related financial disclosure* [Press release]. https://www.sydney.edu.au/news-

opinion/news/2025/07/21/sydney-releases-full-climate-related-financial-disclosure.html
Wang, J., Ji, C.-J., Liu, Y., Shan, Y., Hubacek, K., Wei, Y.-M., & Wang, K. (2024). Re-investigating the shared responsibility for trade-embodied carbon emissions. *Ecological Economics*, *220*, 108162. https://doi.org/10.1016/j.ecolecon.2024.108162