RESEARCH

Wish You Were Here? The Economic Impact of the Tourism Shutdown from Australia's 2019-20 'Black Summer' Bushfires

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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.

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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 m 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 and 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 CO_2-e (Australian Government Department of Industry & Resources 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 Rhianna 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, b), 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.

Methods

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, b, 2013; Malik et al. 2019; Tukker and 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 intercountry 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 (UN 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 Sect. 4 of Lenzen et al. (2014b).

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 and 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 and Giannopoulos 2018; Steenge and Bočkarjova 2007; Zhou and 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 and 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 and 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 and 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 losses. 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 to determining the post-disaster economy enables changes in intermediate demand ($\mathbf{A}$), final demand $\mathbf{y}$ and total output ($\mathbf{x}$) in order to meet the constraints of no negative values in final demand ($\mathbf{y}$). 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.

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, 31 August, 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, 10 & 14 June, 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 2020) was applied to the 2019-20 losses (Austrade & Tourism Research Australia 2021). 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 Resource 1 *SI 2.7* provides further details about the calculations of direct damages.

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 Resource 1 *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 (γ) of direct losses and capital damages.

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 (http://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).

Table 1 The gamma matrix (γ). The gamma (event) matrix comprises direct tourism losses from Australia's 2019-20 bushfires as a proportion of total output (**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; 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)

		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

Table 1 (continued)

		NSW	VIC	QLD	SA	WA	TAS	ACT	NT
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

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:

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

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, $\mathbf{qA^2y}$ 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.

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 (personal communication, 15 & 17 June, 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 Online Resource 1 *SI 2.7* for details about the calculation of the direct damages data).

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.

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. Figure 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 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).

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.

The "Accommodation" and "Cafes, restaurants and take-away" study sectors, which make up our aggregated hospitality grouping, together suffered the most losses in the
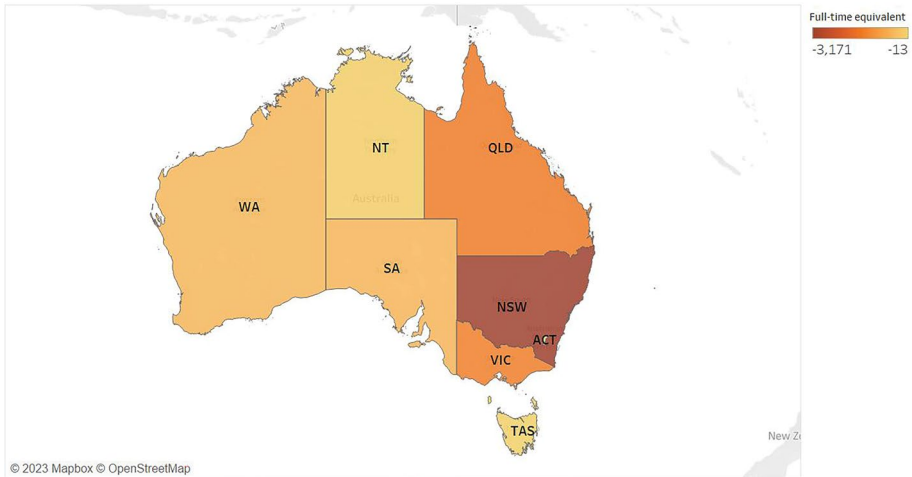
Fig. 1 Losses in full-time equivalent (FTE) jobs across Australia resulting from the tourism losses because of the 2019-20 fires. The most populous State, New South Wales (NSW), suffered about twice as many losses in employment as its neighbouring eastern States, equivalent to 3171 full-time jobs. The 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)
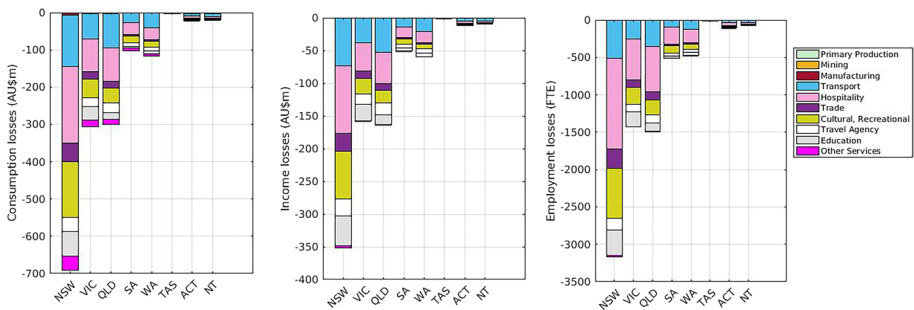
Fig. 2 Losses in consumption, income and employment, across Australia's eight States and Territories and disaggregated by broad sector groupings, because of the tourism shutdown from the 2019-20 bushfires. Hospitality and transport suffered the most losses. Regional abbreviations: New South Wales (NSW), Victoria (VIC), Queensland (QLD), South Australia (SA), Western Australia (WA), Tasmania (TAS), Australian Capital Territory (ACT), Northern Territory (NT)

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 Online Resource 1.

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.

Figure 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.

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.

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 Online Resource 1 *SI 4*.
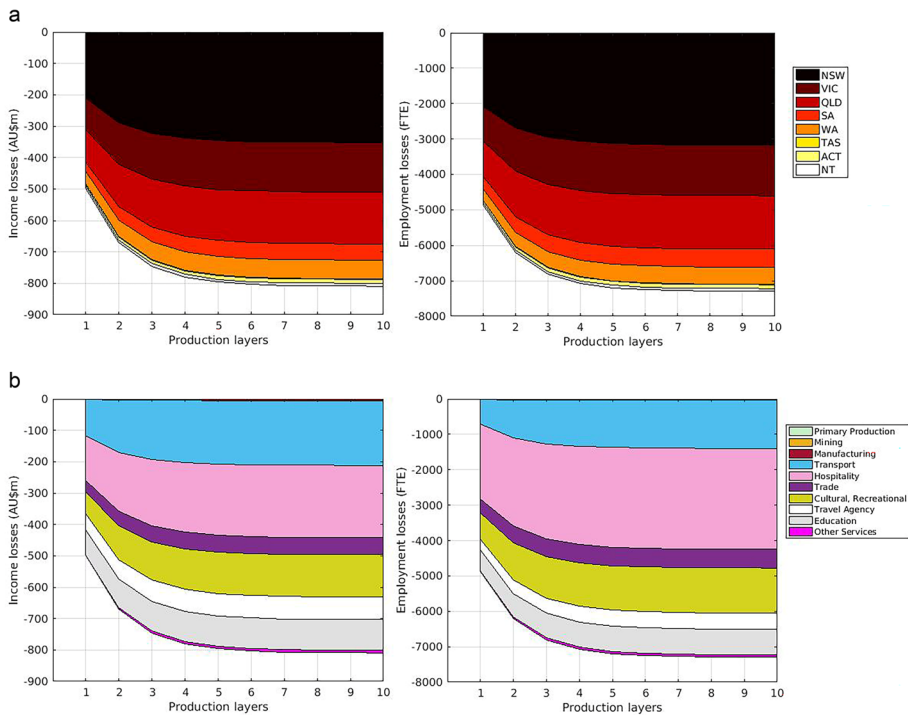
Fig. 3 Production layer decomposition (PLD) of regions (**a**) and broad sector groupings (**b**). Layer 1 represents the impact from the direct tourism losses, layer 2 represents the impact from direct suppliers and so on, with the cumulative losses up to 10 layers depicted, which represent most of 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)

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 (Fig. 4).

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.

TAS

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

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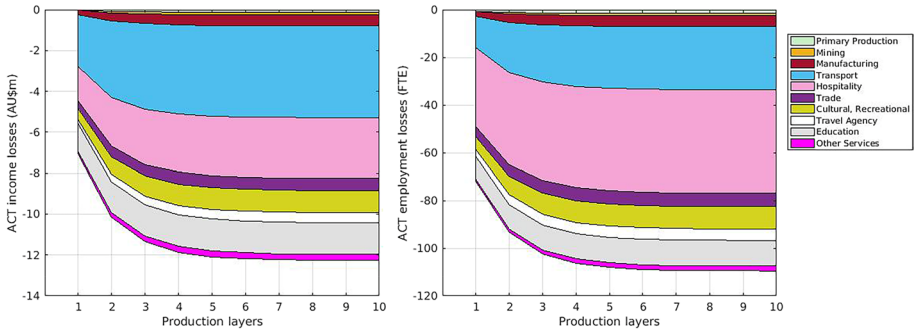
Fig. 4 Production layer decomposition of the impact of tourism losses from the 2019-20 bushfires in the Australian Capital Territory, for income and full-time equivalent (FTE) employment in broad sector groupings. Although the number of upstream supply-chain interactions is theoretically infinite, results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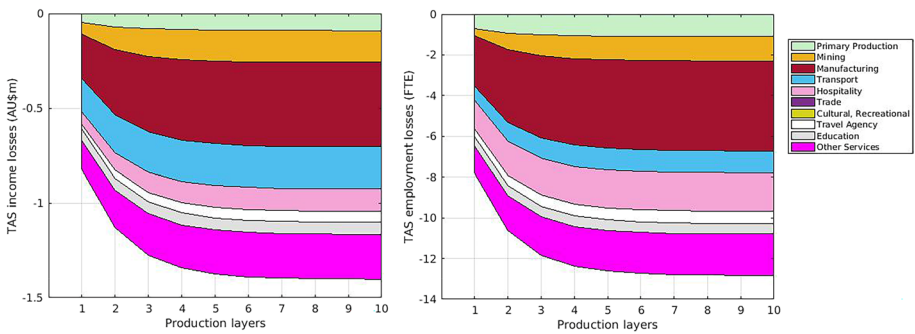

Fig. 5 Production layer decomposition, across 10 broad sector groupings, of the impact of tourism losses from the 2019-20 bushfires in Tasmania. The losses are illustrated in terms of income and full-time equivalent (FTE) employment, up to 10 orders of production

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.

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 AU$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 (Australian Government 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 2020).

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 Resource 1 SI2.6 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.

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 AU $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.

Author Contributions V.R. and A.M. conceptualised the study; V.R. performed scenario analysis and drafted the manuscript, which was initially reviewed by A.M. and M.L. Coding for the model was designed by N.L.P and A.M. Y-Y.S advised on tourism calculations and all authors edited the manuscript.

Data Availability The datasets generated and analysed during the study are available from the corresponding author on request.

Declarations

Artwork and Illustrations Tableau was used to create Fig. 1 and MATLAB was used to create all other figures.

Competing Interests The authors declare no competing interests.

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