Reviewer #1

General comment: In general the writing is okay, but there are few logical gaps in some paragraphs. Some terms are not described and explained in sufficient detail. The manuscript is not very well structured, which leads to redundancy in some parts and makes it hard to follow in other parts. From my point of view the adopted methodology to estimate the indirect damage is sound. However the description and explanations of the methods should be more extensive. Graphics and tables are only partly clear and not all of them support the understanding of main contents. Results are innovative as, to my knowledge, there are no studies dealing with indirect consequences of tropical cyclone per sector on a regional scale. Also the authors attempt to include the infrastructure damage in the estimation of the indirect consequences. However, the presentation of the results could be improved. In addition the results are not discussed sufficiently. Especially the reliability of the estimates of the direct damage should be addressed. The conclusions of the manuscript are only partly supported by the results. In general, I think the topic is appropriate for publication in NHESS, but the manuscript needs some major revisions.

General Response: We thank the reviewer for their comments. We have now revised the manuscript, as per the specific comments below. Furthermore, we provide updated figures and tables in the revised manuscript. Regarding "reliability of estimates of direct damage", we note that in section 2.4.1, and accompanying Supplementary Information 2.2 and 2.3 we acknowledge the wide range of sources we have drawn on to characterise the direct damage in both monetary and non-monetary terms. We accept the point made by reviewer 2 and have therefore added *"Nevertheless, the numbers should be treated as estimates, and ideally validated when the actual final costs are known. However, such detailed validation of disaster impacts is problematic with the rapid impact assessment which is the focus of this research."*

Specific comments:

- From my point of view the introduction could be improved by a general reorganization. At the moment two thirds of the introduction is a review/summary of the event based on newspapers and government papers followed by a paragraph describing the methods used in the study without giving an introduction to the methods.

Response: *Introduction restructure*: Currently the introduction (926 words) is structured as follows:

- 165 words event description, followed up with
- 128 words physical damage description, followed up by
- 89 words reinforcing that TC Debbie is not an isolated event
- 342 words describing significance of economic damage, followed up with
- 71 words reinforcing the importance of tools for assessing regional damage comprehensively and for future planning
- 280 words describing our aim and approach, wrapping up with
- 85 words setting the scene for the paper.

Hence, only 1/3 of the introduction describes the actual event, whereas 89+342+71 words are used for arguing that cyclones and associated floods is and will remain an important problem for Australia as a whole. We think that this information needs to be included in the introduction.

Nevertheless, we have now

- inserted some key introduction phrases to paragraphs to clarify their purpose within the introduction.

- moved the fifth paragraph into the Methods section, where – as the referee pointed out – the matching details are described.
- shifted a methods paragraph that the referee identified into the introduction as requested.

- I suggest to combine section 1 and 2. With a clearly defined review of the event and a review of input-output analysis.

Response: Conventional journal style distinguishes a non-technical introduction and a technical methods section. Given that the previous Section 2 was rather detailed, we have therefore combined Section 2 with Section 3 to form a new Section 2: Methods. This new methods section is now preceded with a short paragraph explaining to the reader what is to be expected.

- Please check how media should be cited. In the current version it is hard to check which references are cited, since the names cited in the text are not listed in the reference list.

Response: We follow the Endnote citation style of Natural Hazards and Earth Systems Sciences. We have removed the footnotes and have included references for media in the main reference list.

- Pg. 3 line 65-66: Please clarify that the cyclone names are no citations.

Response: We have edited the text as follows *"Severe tropical cyclones such as Debbie are not an isolated phenomenon. Past tropical cyclones, in Australia and elsewhere, have disrupted food supply – for example in Madagascar (Cyclone Gafilo in 2004), Vanuatu (Cyclone Pam in 2015), and Fiji (Cyclone Winston in 2016)."*

- Pg. 4 line 89: It is not clear at this point what spill-overs are. Please clarify.

Response: We have now clarified what spill-overs are. We write: "*First, we are able to examine identify the consequences of the cyclone not only for the directly affected regions and industry sectors, but for the wider Australian economy. Such indirect effects are caused by damaged businesses ceasing to supply clients, or ceasing to require inputs from suppliers. Thus, economic activity winds down elsewhere as well. Such effects are called (regional and sectoral) spill-overs*".

- Pg. 5 line 146-149: Please be a bit more specific about the novelty of your research. From my point of view the novelty is not the applied method (which was applied before in e.g. Schulte in den Bäumen 2015, as you mention as well) but rather the case-study as this method was not applied to cyclones before.

Response: We have edited the text as follows: "*One particular type of disaster IO analysis, proposed by Steenge and Bočkarjova (2007) aims at investigating post-disaster consumption possibilities as a consequence of production shortfalls resulting from a disaster. Such an assessment has been applied, for example to widespread flooding in Germany (Schulte in den Bäumen et al., 2015) and electricity blackouts from possible severe space weather events (Schulte in den Bäumen et al., 2014). Here, we apply this method for the first time to undertake an estimation of post-disaster consumption possibilities, and subsequent losses in employment and economic value added resulting from the 2017 Tropical Cyclone Debbie in Australia*."

- Pg. 6 line 156-164: This paragraph could rather be shifted to the introduction. I suggest to give a short overview of section 3 instead.

Response: Done. Thank you.

- From my point of view an explanation of the basic input-output equation and a clear naming of the symbols used in the formulas would help readers who are not so familiar with the methodology (e.g. A is named "matrix of input coefficients" in line 183 and "production recipe" in line 244).

Response: We write that "*Constraint i) in Equation (2) is the standard fundamental input-output accounting relationship stating that in every economy intermediate demand* $\boldsymbol{T}$ *and final demand* $\mathbf{y}$ *sum up to total output* $\boldsymbol{x}$. *This can be seen by writing* $\mathbf{y}_1 = (\mathbf{I} - \mathbf{A})\mathbf{x}_1 = \mathbf{x}_1 - \mathbf{T1} \Leftrightarrow \mathbf{T1} + \mathbf{y}_1 = \mathbf{x}_1$." We have also changed "production recipe" to "input coefficients matrix" to be consistent in our naming of variables.

- Pg. 6 eq. 1: Please give more information about the calculation of the Gamma-matrix.

Response: We now write "The entries of $\mathbf{\Gamma}$ are populated on the basis of primary data, in our case about cyclone Debbie (Section 2.4).".

- Pg. 6 eq. 2: For me this equation is not quite clear. Please elaborate a bit further why you max the sum of the vector of the post-disaster consumption possibil-ities y1 . Also I could not find information about this equation in Steenge and Bockarjova (2007).

Response: The problem in Steenge and Bockarjova is that final demand can become negative. Consider their pre-disaster equation 21: Change Gamma to $\begin{matrix} 0.2 & 0 \\ 0 & 0.8 \end{matrix}$ and you obtain

0.25	0.4	x	20	+	-1	=	20
0.14	0.12		40		32.4		40

Maximising y and at the same time ensuring non-negativity yields

0.25	0.4	x	20	+	0	=	20
0.14	0.12		37.5		30.2		37.5

We have now described this in the main text.

- Pg. 7 line 193: I could not find further details to the suggested input-output approach in Supplementary Information S2. Please give more information about the approach.

Response: This is simply an error. S2 should be references when describing the population of the Gamma matrix. This is now corrected.

- Pg. 8 line 229-230: "the reduction of total industry output (in 2017 compared to 2016)" How is the total industry output 2017 calculated?

Response: For this we have clarified by assuming 2017 output equal to 2016 output minus output losses attributable to the cyclone.

- Pg. 15 Fig. 1: Please include unit labels in map and the source of the satellite image

Response: We have included the units for the numbers (-2.5, -2 etc.) in the legend. We have now included the source of the satellite image.

- Please explain what superior means in this context. What makes superior eco-nomic data superior?

Response: "Superior" is a term used amongst statisticians and IO table compilers, for primary data used in reconciliation exercises where most of the information is estimated. Here, data taken from external sources is relatively superior to estimated table entries. We recognise that this detail is lost here, so we have replaced "superior" by "primary", to indicate that the data are from the primary source, or "raw".

- From my point of view this Section does not seem to be very well organized. In addition not all of the figures and tables are helpful and supporting. A discussion of the results, e.g. a comparison with results from other studies or a discussion of the reliability of the direct damage estimations is missing entirely.

Response: We have restructured this Results and Discussion section and substantially revised to clarify the content and interpretation of the primary results. This includes giving an overview of this section at the beginning, presenting on the overall results first, following by more detailed analysis of spill-overs, and discussing the implications for disaster recovery plans. In the text, we have also referring to the figures and tables more to better direct the readers to the corresponding figures and tables. In addition, a brief discussion on the reliability of the direct damage estimations is added in the Outlook section. The information on the direct damage estimations used in this study was based on the best available estimations from the government and industry agencies.

- Also it should be more emphasized that the presented results are results produced by a model (at least the indirect damage) and might not necessarily fit to the damage which really occurred in the regions.

Response: We have added in Section 3.1 "As one referee noted, our results for indirect damage are produced by a model and might not necessarily reflect damage that really occurred in the regions. However, an application of the same model to a case study where indirect effects were known (see Fig. 5 in Lenzen *et al.* 2017a) shows that measured outcomes were reproduced with reasonable accuracy."

- Pg. 14 line 3-10: From my point of view these two paragraphs do not belong here. I suggest a short overview of Section 4 at this point.

Response: We have now moved these two paragraphs into section 3.2, which presents the major results. A short overview of this Results and Discussion Section has been added.

- Pg. 14 line 3: Please indicate if these numbers are results from your models.

Response: We now write *"Our results show that"*

- Pg. 14 line 8: Please explain the term "full-time equivalent"

Response: We have included the following sentence *"Full-time equivalent means that part-time jobs are expressed as fractional full-time jobs, so that they added into a total."*

- Pg. 14 line 20-21: ". . .detailed products and supply-chains (Section 3.3)." Please be more specific about this reference.

Response: This was an error, we have now removed this reference.

- Pg. 17 line 70-71: ". . .detailed structural path analysis. . ." Please be more specific about this analysis. How did you apply it? What does the analysis exactly do? Etc. Also this should be mentioned in Section 3.

Response: We have now removed this reference and expanded on the section on production layer decomposition.

- Fig. 2: Please choose a different color for "Rest of QLD" than white. At a first look it is a bit confusing with the free space at the bottom of the plots.

Response: We have now used the colour pink for "Rest of QLD".

- Fig. 3: Please improve this figure. Currently it is very hard to get information about the damage to different industries. Hence at least for the value added this is basically the same information as shown in Fig. 1.

Response: We have used a different colour scheme to improve this figure. Instead of black and white, we now use the colour scheme 'bone' in MATLAB to highlight the bands. The underlying data for this figure is in the supplementary information section.

- Also it is not clear what the threshold theta means? Please clarify.

Response: We have deleted this as this was a left-over from the Appendix where this is listed in Section SI2.

- Table 4 and 5: How do you differentiate between the direct and indirect impacts?Since the direct effects are included in the estimation of the indirect effects

Response: The direct effects are $\mathbf{q}\Delta\mathbf{y}$ (Equation 4), and the indirect effects include all other supply chain layers. The values for indirect effects do not include the values for direct effects. Direct and indirect effects added together give total effects (last column in Table 4 and 5).

- Table 5 is not mentioned in the text.

Response: We have now mentioned Table 5 in the text.

- Pg. 21 line 148-150: ": : :Our approach can be applied to other regions, and ultimately extended to include impacts well beyond employment and value added, such as wider environmental or social consequences of disasters : : :" From my point of view this is not sufficiently supported by the results.

Response: We have moved this statement and the "Outlook" Section from the Conclusion section to the Discussion section 3.5 for a general discussion on possible future work.

- Pg.21 line 167-169: ": : :For example, about 1200 employees providing services to coal mines were affected by Cyclone Debbie, however this impact is currently not mentioned in the disaster recovery planning. : : :" This is hardly shown in the results.

Response: We have added description in section 3.4 to direct readers to Table 4 for the results. "*For instance, as shown in Table 4 for the indirect employment impacts for the "Accommodation, cafes and restaurants" sector, some 1,381 employees providing services were affected. However, this impact is currently not mentioned in disaster recovery planning documents*."

- Please be consistent with the abbreviations you introduce. E.g. in line 246 you write ". . .input-output (IO) databases." although IO was already introduced.

Response: We have now fixed this.

- Please mention and explain all figures and tables included in the manuscript also in text

Response: All figures and tables are now explained in the text.

- Pg. 11 line 245: ". . . (IELab; (Lenzen et al., 2014)." A bracket is missing

Response: We have now fixed this.

- Pg. 11 line 249: "different regions (Tukker and Dietzenbacher, 2013); see (Leon-tief, 1953) for an account of MRIO theory)." A bracket is missing

Response: We have now fixed this.

- Pg. 21 line 151: ". . .broader environemntal . . ." please correct typo.

Response: We have now fixed this.

- Pg. 22 line 176: There are two references for Koks et al. 2016. Please indicate which one is cited here.

Response: It is *Koks, E., Carrera, L., Jonkeren, O., Aerts, J. C. J. H., Husby, T. G., Thissen, M., Standardi, G., and Mysiak, J.: Regional disaster impact analysis: comparing input–output and computable general equilibrium models, Natural Hazards and Earth System Science, 16, 1911-1924, 2016.*

Reviewer #2

Comment: This is a straightforward paper with a clear structure and presentation. The highlights of this paper appear "(a) quantifying the impact of disasters in a detailed and timely manner and (b) incorporating infrastructure damages into the assessment of losses in employment and value-added", as written in the conclusion section. As for (a), it may be the first model/paper utilizing the multiregional Australian input-output table with 19 regions and 34 industries, while the process for producing such detailed input-output tables were described in other papers (page 11). So, what's new in this regard seems to be the use of the superior economic data (in sub-section 3.4.1) written in one paragraph and table 3. It seems to me if this is one of the main contributions of the paper, it should be discussed more thoroughly, if such contents are available.

Response: Regarding primary (superior) economic data we have added information in Section 2.5.1. including wider referencing of key information sources eg (Queensland Treasury and Trade, 2013, and Wilkinson, J., 2014) which contain full details of data used as constraints. We have not included these data as supplementary information as we did not want to double-up with the original authors' work, however key information could be appended if that is necessary.

Comment: In terms of (b), it is described in sub-section 3.3.2, in which they indicated that their method for this is similar to Hallegatte (2008), as written in page 8. There have been more sophisticated and/or complicated modeling frameworks to incorporate infrastructure damages with input-output analysis for disaster impact analysis, such as Tsuchiya et al. (2007) referred in this paper. So, again, this is not completely new here, either.

Moreover, their detailed multiregional input-output table is used in the rather standard way, as described in pages 6-7, with the Steenge and Bockarjova (2007) approach. There seems no new trick here, either. At the same time, the issues of input-output analysis for disaster impact analysis have been discussed and were summarized well in Oosterhaven (2017), in which he claimed six aspects of disaster impact and argued that input-output analysis covers only a subset of those six aspects. Since this paper also use the standard input-output analysis, the results of this paper should cover only the limited extent of the disaster impacts. At least, this should be discussed, and hopefully would be incorporated in the revised version.

Furthermore, since this paper focuses on the changes in consumption and value-added, the Miyazawa's enlarged input-output framework should be also discussed and would be included for the comparison of the results.

Oosterhaven, J. (2017) On the limited usability of the inoperability IO model. Economic Systems Research, 29: 452-461.

Response: We have cited the references that the reviewer lists, and we have added additional clarification to section 2.4.2, broadening our referencing to the work of others, and helping to clarify the key contribution of this work. In particular, we draw attention to recent acknowledgement of several authors that the preferred method for inclusion of infrastructure in disaster impact analysis is a continuing question.

In response to the comments, we have added the following text in the manuscript:

In compiling the gamma matrices, damages were only considered where we could find empirical monetary information. With respect to modelling the effect of capital infrastructure damages on production, we were bound by the gamma-matrix formalism of the Steenge-Bočkarjova method. We note that other more detailed and sophisticated modelling frameworks have been used, such as Tsuchiya et al. (2007).

Finally, beneficial effects can result from natural disasters. In Queensland for example, the replacement or repairs to damaged buildings and infrastructure, or any other demand for commodities required especially for post-disaster recovery, is likely to have created additional employment and value added and may have spawned technology updates. In addition, above-average rainfall may have been beneficial for pastures and water supply, and increased freshwater run-off and turbidity could have increased catches of prawn trawling. As no data were available for quantifying such repercussions, these effects are not accounted for in our study.

Steenge and Bočkarjova (2007) remarks that a preferred method for disaster impact analysis does currently not exist, due to (a) many possible research questions, and (b) many relevant items of information surrounding disasters being unknown. Steenge and Bočkarjova (2007) also clarify the strengths and weaknesses of static input-output analysis against dynamic CGE modelling. In this context, they warn against overly optimistic assumptions regarding market flexibility and substitution. Oosterhaven (2017) summarises the shortcomings of input-output-based disaster analysis approaches in their attempt to estimate real-world consequences of disasters.

Economic damage and spill-overs from a tropical cyclone

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Abstract – Tropical cyclones cause widespread damage in specific regions as a result of high winds, and flooding. Direct impacts on commercial property and infrastructure can lead to production shortfalls. Further losses can occur if business continuity is lost through disrupted supply of intermediate inputs from, or distribution to, other businesses. Given that producers in modern economies are strongly interconnected, initially localised production shortfalls can ripple through entire supply-chain networks and severely affect regional and wider national economies. In this paper, we use a comprehensive, highly disaggregated, and recent multi-region input-output framework to analyse the impacts of Tropical Cyclone Debbie which battered the north-eastern Australian coast in March 2017. In particular, we show how industries and regions that were not directly affected by storm and flood damage suffered significant job and income losses. Our results indicate that the disaster resulted in the direct loss of about 4802 full-time equivalent jobs and AU$ 1544 million of value added, and an additional indirect loss of 3685 jobs and AU$ 659 million of value added. The rapid and detailed assessment of the economic impact of disasters is made possible by the timely data provision and collaborative environment facilitated by the Australian Industrial Ecology Virtual Laboratory (IELab).

Keywords: Tropical cyclone, economic damage, spill-over, input-output analysis, hurricane, typhoon

1. Introduction

On Tuesday 28 March 2017, Severe Tropical Cyclone Debbie made landfall at Airlie Beach, in North Queensland, Australia. As a Category 4 system (equivalent to a major Hurricane or a Typhoon), it hit coastal communities with torrential rain and wind gusts up to 265 km/h, destroying or damaging homes, businesses, crops and infrastructure and, tragically, led to 12 fatalities (Queensland Government, 2017). The initial impact was felt mainly on the iconic Great Barrier Reef coral ecosystems of the Whitsunday Coast, and the surrounding communities including Bowen and Proserpine. Within 24 hours, Debbie was approximately 250 km inland, and had degenerated into a high-rainfall low-pressure system. The system progressively tracked over 1,000 km south, where it moved back out to sea around the Queensland-New South Wales Border on 31 March after significant flooding across the region. Rainfall of 150-250 mm was recorded regionally, with peaks of 400-1,000 mm, swamping remote rural, coastal and urban communities. More than a week later, widespread flooding was still being felt in the region (Queensland Government, 2017).

Dubbed the "Lazy Cyclone", Debbie moved at under 6 km/h at times, causing atypically high levels of social, economic, and environmental destruction. Over 63,000 emergency calls were made, and over 50,000 insurance claims subsequently lodged (Queensland Government, 2017). Particular impact was felt in the farming, mining and tourism industries in the northern part of the afflicted region, and by flooded businesses in the south. Annual and perennial crops and trees were destroyed, export-oriented coal mines closed, and tourism heavily impacted. Roads, rail systems and bridges were damaged or destroyed, along with community halls, airfields, tele-communications and other systems. All schools and many businesses were temporarily closed. The Australian government responded at all levels including federal military deployment of air, sea and land support, Queensland Police, Fire and Emergency, and State Emergency Systems.

Severe tropical cyclones are not an isolated phenomenon. Past tropical cyclones, in Australia and elsewhere, have disrupted food systems in Madagascar (Cyclone Gafilo in 2004), Vanuatu (Cyclone Pam in 2015), and Fiji (Cyclone Winston in 2016). The cyclone-prone area of coastal Queensland produces three quarters of Australia's perishable vegetables. In 2006, Cyclone Larry, and 2011 Cyclone Yasi (Staff, 2017) lead to shortages of bananas in Australia (Brown, 2017).

Direct economic damage caused by Debbie is significant: it has been estimated to include AU$ 1.5 billion in lost coal sales, and approximately AU$ 0.5 billion in agriculture, with major adverse impacts on sugar cane and winter horticulture supplies to southern Australia. Infrastructure damage has been estimated at over AU$1 billion (Queensland Government, 2017). Flood damage to business and trade was also significant in northern New South Wales (the state south of Queensland). Debbie also caused temporary shortages to water and energy supplies (Parnell, 2017), damaged information technology infrastructure, and led to price increases for tomatoes, capsicums, eggplants, and other vegetables (Hatch, 2017), affecting winter vegetable supply for Sydney and Melbourne. Across all sectors insurance claims of over AU$ 300 million were lodged (Underwriter, 2017).

Given that the frequency of extreme weather events such as tropical cyclones will increase due to climate change (Mendelsohn et al, 2012), developing and testing methods for assessing economic consequences of natural disasters is of growing importance. In our case study, this significance is reinforced in view of the importance of northern Australia in plans for the nation's ongoing economic development, notably in mining and agriculture (Regional Institute of Australia, 2013).

In this work, we use multi-region economic input-output (MRIO) analysis in order to investigate the economy-wide repercussions of the biophysical damage wrought by Tropical Cyclone Debbie upon the North Queensland region of Australia. Input-output (IO) analysis, as developed from Leontief's work in the 1930s, is capable of interrogating economic data on inter-industry transactions, final consumption and value added, in order to trace economic activity rippling throughout complex supply-chain networks and to unveil both immediate and indirect impacts of systemic shocks (Leontief, 1966). Over the past seventy years, IO analysis has been used extensively for a wide range of public policy and scientific research questions (Rose and Miernyk, 1989). Over the past two decades, IO analysis has experienced a surge in applications, especially in carbon footprints (Wiedmann, 2009) and global value chains (Timmer et al., 2014), and in the disciplines of life-cycle assessment (Suh and Nakamura, 2007) and industrial ecology (Suh, 2009).

This article is structured as follows: Section 2 provides a review of relevant prior work and the state of knowledge in IO-based disaster analysis, and describes the methodology underlying the disaster analysis undertaken using IO modelling. In particular, we build on prior work (Schulte in den Bäumen et al., 2015) and present an innovative approach for estimating infrastructure damages resulting from the disaster. We present the results and a discussion of key findings in Section 3, followed by conclusions in Section 4.

2. Methods

In this paper, we determine the supply-chain impacts of Tropical Cyclone Debbie, using highly disaggregated MRIO tools (Sections 2.2 and 2.3) developed within the new Australian Industrial Ecology Virtual Laboratory ("IELab") (see Section 2.5). Our approach incorporates a number of unique and powerful capabilities. First, we are able to identify the consequences of the cyclone, not only for the directly affected regions and industry sectors, but for the wider Australian economy. Such indirect effects stem from afflicted businesses being unable to supply goods and services and from their inability to acquire necessary production inputs from suppliers. As the economy is an integrated chain of production and consumption, suppliers and consumers associated with damaged business are also affected, and economic activity winds down elsewhere. Such effects are called indirect impacts or (regional and sectoral) spill-overs. Capturing spill-overs highlights the innovative strength of the Australian IELab, which offers unprecedented spatial resolution, hence allows for a comprehensive assessment of the direct as well as indirect supply-chain effects of disasters. In addition, the IELab offers sophisticated tools that, to our knowledge, have so far not been applied to disaster analysis: For example, Production Layer Decomposition is able to pinpoint the sequence of indirect impacts rippling across the regional supply-chain network. One additional advanced capability is the in-built data updating functionality in the IELab, allowing for the inclusion of recent economic and social data and enabling the timely and cost-effective analysis of disaster impacts to support expeditious decision-making. Finally, the IELab also offers data-sets and analytical tools for assessing the local/regional effects in terms of a range of physical indicators, such as carbon dioxide emissions, water use, energy use and waste, to name a few. Whilst such an assessment is beyond the scope of this study, this is surely an area of research that warrants further investigation.

In the following we will first provide a review of prior work on IO-based disaster analysis, and then explain IO theory, disaster analysis, our case study, and utilised data and updating processes.

2.1 Input-output based disaster analysis – a review

IO analysis studies feature a sub-stream dealing with disaster analysis. Okuyama (2007) provides a comprehensive review of the use of IO analysis for economic analysis of disasters. Quantitative disaster analysis is needed for understanding the impacts of a disaster, for driving effective disaster response, for informing disaster risk reduction and adaptation efforts, and for pre-emptive planning and decision-making (Cannon, 1993; Lesk et al., 2016; Prideaux, 2004; Temmerman et al., 2013). It is intuitively clear that a disaster results in direct losses in the form of infrastructure damages, and indirect higher-order effects in the form of subsequent losses in business activity (Rose, 2004). The ability of IO analysis to capture the upstream interconnected supply chains of an industry or region affected by a disaster makes it an ideal tool for assessing the full scope of impacts of a disaster event. In addition to IO analysis, computable general equilibrium (CGE) models, econometric models and social accounting matrices (SAM) are alternative modelling frameworks for estimating the indirect higher-order effects of a disaster (Cole, 1995; Guimaraes et al., 1993; Koks et al., 2016; Koks and Thissen, 2016; Okuyama, 2007; Okuyama and Santos, 2014; Rose and Guha, 2004; Rose and Liao, 2005; Tsuchiya et al., 2007). A discussion of these models is beyond the scope of this study and we focus on IO analysis, in particular the post-disaster consumption possibilities, and possible spill-overs (explained further below). IO modelling has been applied to many disasters such as earthquakes in Japan (Okuyama, 2014, 2004), floods in Germany (Schulte in den Bäumen et al., 2015) and London (Li et al., 2013), terrorism (Lian and Haimes, 2006; Rose, 2009; Santos and Haimes, 2004), hurricanes (Hallegatte, 2008) and blackouts (Anderson et al., 2007) in the USA, and diseases and epidemics (Santos et al., 2013; Santos et al., 2009), to name a few.

Prior research on disaster impact analysis, based on IO analysis, has sought ways of improving the standard IO model, for example by extending the standard framework to include temporal and spatial scales (Okuyama, 2007). For example, Donaghy et al. (2007) propose a flexible framework for incorporating short- and long-time frames using the regional econometric IO model (REIM), and Yamano et al. (2007) apply a regional disaggregation method to a MRIO model to estimate higher-order effects according to specific districts. Furthermore, a so-called “inoperability index” within the inoperability input-output model (IIOM) has been proposed as a way of assessing the effect of a disaster or initial perturbation on interconnected systems (Haimes et al., 2005). Both the static and the dynamic versions of IIOM have been applied to the case of terrorism for assessing the economic losses resulting from interdependent complex systems (Lian and Haimes, 2006; Santos and Haimes, 2004). Using the dynamic version of IIOM, it is possible to assess recovery times and also to identify and prioritise systems and sectors that are most economically critical and those crucial for guiding the recovery process (Haimes et al., 2005).

One particular type of disaster IO analysis, proposed by Steenge and Bočkarjova (2007) aims at investigating post-disaster consumption possibilities as a consequence of production shortfalls resulting from a disaster. Such an assessment has been applied, for example to widespread flooding in Germany (Schulte in den Bäumen et al., 2015) and electricity blackouts from possible severe space weather events (Schulte in den Bäumen et al., 2014). Here, we apply this method for the first time to undertake an estimation of post-disaster consumption possibilities, and subsequent losses in employment and economic value added resulting from the 2017 Tropical Cyclone Debbie in Australia. To this end, we use the Australian IELab to construct a customised sub-national MRIO table for Australia with extensive detail on regions directly affected by the cyclone. In particular, and this is the novelty of our research, we examine detailed, disaggregated *regional and sectoral spill-overs* including the consequences of this cyclone not only for directly affected regions and industry sectors, but also for the wider national economy.

2.2 Input-output disaster analysis – mathematical formulation

A specific stream of IO analysis is disaster analysis (Okuyama, 2014, 2007), focused upon IO databases employed to explore how an economy can be affected by a sudden slowdown or shutdown of individual industries. Since we are primarily interested in post-disaster consumption possibilities and ensuing employment and value-added loss, we utilise the approach by Steenge and Bočkarjova (2007). In essence, a disaster reduces total economic output $\mathbf{x}_0$ of industry sectors 1,…,*N* to levels

$$\tilde{\mathbf{x}} = (\mathbf{I} - \mathbf{\Gamma})\mathbf{x}_0, \qquad (1)$$

where $\mathbf{\Gamma}$ is a diagonal matrix of fractions describing sectoral production losses as a direct consequence of the disaster, and $\mathbf{I}$ is an identity matrix with the same dimensions as $\mathbf{\Gamma}$. The entries of $\mathbf{\Gamma}$ are populated on the basis of primary data, in our case about cyclone Debbie (Section 2.4). Post-disaster consumption possibilities $\mathbf{y}_1$ are then the solution of the linear problem

$$\max(\mathbf{1}\mathbf{y}_1) \quad \text{s.t. i)}\ \mathbf{y}_1 = (\mathbf{I} - \mathbf{A})\mathbf{x}_1 \ \ , \ \ \text{ii)}\ \mathbf{x}_1 \le \tilde{\mathbf{x}} \ \ \text{, and} \ \ \text{iii)}\ \mathbf{y}_1 \ge 0 \ \ , \qquad (2)$$

where $\mathbf{1} = \big[\underbrace{1,1,\ldots,1}_{N}\big]$ is a summation operator, $\mathbf{A} = \mathbf{T}\widehat{\tilde{\mathbf{x}}_1}^{-1}$ is a matrix of input coefficients, $\mathbf{T}$ is the intermediate transactions matrix, the '^' (hat) symbol denotes vector diagonalisation, and $\mathbf{x}_1$ is post-disaster total economic output.

Constraint i) in Eq. 2 is the standard fundamental IO accounting relationship stating that in every economy intermediate demand $\mathbf{T}$ and final demand $\mathbf{y}$ sum up to total output $\mathbf{x}$. This can be seen by writing $\mathbf{y}_1 = (\mathbf{I}-\mathbf{A})\mathbf{x}_1 = \mathbf{x}_1 - \mathbf{T1} \Leftrightarrow \mathbf{T1} + \mathbf{y}_1 = \mathbf{x}_1$. Constraint ii) states that in the short term, post-disaster total output is limited by pre-disaster total output minus disaster-induced losses. Constraint iii) ensures that final demand is strictly positive.

Condition i) is different from the approach in Steenge and Bočkarjova, because we need to ensure the positivity of final demand $\mathbf{y}$. Taking these authors' equation 23, and re-calculating for $\mathbf{I}-\mathbf{\Gamma} = \begin{bmatrix} 0.2 & 0 \\ 0 & 0.8 \end{bmatrix}$, we obtain negative post-disaster consumption possibilities $[-1 \quad 32.4]'$. Our approach would yield the post-disaster situation $\begin{bmatrix} 0.25 & 0.4 \\ 0.14 & 0.12 \end{bmatrix}\begin{bmatrix} 20 \\ 37.5 \end{bmatrix} + \begin{bmatrix} 0 \\ 30.2 \end{bmatrix} = \begin{bmatrix} 20 \\ 37.5 \end{bmatrix}$, with non-negative post-disaster final demand, and with post-disaster output $\mathbf{x}_1 = \begin{bmatrix} 20 \\ 37.5 \end{bmatrix} \leq \tilde{\mathbf{x}} = \begin{bmatrix} 20 \\ 40 \end{bmatrix}$.

2.3 Disaster impact on value added and employment

A disaster-induced transition to lower consumption levels $\mathbf{y}_1 = \mathbf{y}_0 - \Delta\mathbf{y}$ has implications for the state of regional economies, as it causes losses in value added and employment

$$\Delta Q = \mathbf{q}\Delta\mathbf{x} = \mathbf{q}(\mathbf{I}-\mathbf{A})^{-1}\Delta\mathbf{y} \ , \qquad (3)$$

where $\mathbf{q}$ holds value-added and employment coefficients. The sequence of these losses can be enumerated by carrying out a *production layer decomposition*, that is by unravelling the inverse in Eq. 3 into an infinite series (see (Waugh, 1950) as

$$\Delta Q = \mathbf{q}\Delta\mathbf{y} + \mathbf{qA}\Delta\mathbf{y} + \mathbf{qA}^2\ \Delta\mathbf{y} + +\mathbf{qA}^3\ \Delta\mathbf{y} + \cdots = \sum_{n=0}^{\infty} \mathbf{qA}^n\ \Delta\mathbf{y} \ , \qquad (4)$$

where the term $\mathbf{q}\Delta\mathbf{y}$ represent the job and value-added losses borne by producers immediately affected by the reduction of consumption possibilities due to the cyclone, $\mathbf{qA}\Delta\mathbf{y}$ describes 1st-order losses fielded by suppliers of cyclone-affected producers, $\mathbf{qA}^2\ \Delta\mathbf{y}$ 2nd-order losses for suppliers of suppliers, and so on for subsequent upstream production layers. 1st- and higher-order upstream losses can in principle occur anywhere in Australia, depending on the reach of the supply-chain network of local northern Queensland producers.

2.4 Case study: Tropical Cyclone Debbie

In order to quantify indirect economic impacts of Cyclone Debbie, we first constructed a 19-region, by 34-sector IO model of Australia, with particular regional detail for the regions close to disaster centres, that is, 10 subregions of Queensland as well as northern New South Wales (see also Figure 1). The compilation of this table and underlying data are outlined in Section 2.5.

2.4.1 Reduction in industry output, and creation of the gamma matrix

In order to estimate indirect consequences of Cyclone Debbie we further developed the method of Schulte in den Bäumen et al. (2015) and created the so-called gamma matrix, a diagonal matrix of fractions Γ_i (see Eq. 1) describing reduced post-disaster production possibilities (19×34 region-sector pairs). We determined the relative reductions in industry output by (a) sourcing public information on actual or estimated financial damages and (b) dividing these by gross output taken from our MRIO table. Information on damages included (a) the reduction of total industry output (in 2017 compared to 2016), plus (b) an annualised value of infrastructure damage, as explained below. A value of $\Gamma_i = 0.1$ indicates a 10% loss of production value (including related infrastructure costs) from 2016 to 2017. Information on the direct damages by the cyclone was sourced from a range of published government reports, informal enquiries to government offices, government and research websites, media releases, and many other media and industry reports and online sources. Table 1 provides a summary of the main impacts – further details and related data sources are provided in *SI*2.2, including a summary of infrastructure damage caused by the cyclone shown in Table *SI*2.3. The reliability of the damage estimates varies as they were sourced from different data sets. Cross-validation using multiple sources was attempted where possible. This was possible for some major sector groups (notably coal with its close monitoring by government authorities). The rapid nature of the assessment also creates some uncertainties and error potential and the values should be treated as estimates. Ideally, they should be validated or updated when the more accurate costs become known.

2.4.2 Estimation of infrastructure damage

Infrastructure damage from the cyclone in the state of Queensland was estimated at well over a billion dollars (Queensland Government, 2017). The localities of Mackay and Fitzroy had bridges, roads, airport, community infrastructure, water and wastewater treatment plants damaged or destroyed. Severe damages were also noted in Richmond-Tweed (from significant flooding), and in Brisbane (over seven bridges damaged, significant degradation of at least 350 local roads and 200 major culverts etc), as well as northern Queensland (see Supplementary Information *SI*2 for details).

As an innovation of the work of Schulte in den Bäumen et al. (2015), we estimated infrastructure damage and its attribution to sectors of the economy using an "infrastructure gamma matrix", and added this to the matrix describing production shortfalls (Section 2.4.1). In addition to the conventional current output losses, we attempted to estimate production shortfalls Δx caused by damages to capital infrastructure such as roads. In principle, gamma matrix entries describing infrastructure damages can be estimated using information on the productivity of capital π, as $\Gamma_i = \Delta x_i / x_{0,i} = \pi_i \, \Delta c_i / x_{0,i}$, where Δc_i are annual losses of fixed capital inputs. To this end, we approximated capital productivity by the ratio of gross output and gross operating surplus: $\pi_i = x_i / GOS_i$. Values for annual losses of fixed capital inputs Δc_i were obtained by annualising the total value of infrastructure damages, using a 25-year time-frame for capital depreciation. A similar, more generalised approach has been outlined by Hallegatte (2008). The total production loss coefficients (fractions in $\mathbf{\Gamma}$) were calculated by adding the current output losses and the losses induced by infrastructure damage (Table 2). The main infrastructure impacts of the cyclone were borne in sectors such as electricity, gas, water, trade, accommodation, cafes, restaurants, road transport, rail and pipeline transport, other transport, and communication services.

2.4.3 Qualifications

In compiling the gamma matrices, damages were only considered where we could find empirical monetary information. With respect to modelling the effect of capital infrastructure damages on production, we were bound by the gamma-matrix formalism of the Steenge-Bočkarjova method. We note that other more detailed and sophisticated modelling frameworks have been used, such as Tsuchiya et al. (2007).

Finally, beneficial effects can result from natural disasters. In Queensland for example, the replacement or repairs to damaged buildings and infrastructure, or any other demand for commodities required especially for post-disaster recovery, is likely to have created additional employment and value added and may have spawned technology updates. In addition, above-average rainfall may have been beneficial for pastures and water supply, and increased freshwater run-off and turbidity could have increased catches of prawn trawling. As no data were available for quantifying such repercussions, these effects are not accounted for in our study.

Steenge and Bočkarjova (2007) remark that a preferred method for disaster impact analysis does currently not exist, due to (a) many possible research questions, and (b) many relevant items of information surrounding disasters being unknown. Steenge and Bočkarjova (2007) also clarify the strengths and weaknesses of static input-output analysis against dynamic CGE modelling. In this context, they warn against overly optimistic assumptions regarding market flexibility and substitution. Oosterhaven (2017) summarises the shortcomings of input-output-based disaster analysis approaches in their attempt to estimate real-world consequences of disasters.

Table 1: Summary of major direct impacts (see Supplementary Information *SI*2 for details and sourcing).

Aspect	Region	Industries	Example impact
Coal exports	All QLD	Coal, oil and gas	Coal exports may have taken a AU$1.5 billion hit from Cyclone Debbie as more than 22 mines were forced to halt production while roads and ports were shut.
Sugar Cane	QLD- Mackay	Sugar cane growing	Damage to Queensland's sugar industry is expected to cost AU$150 million (US$114.4 million). The majority of these costs lie in Proserpine and Mackay.
Vegetables	QLD-Mackay	Other agriculture	The Queensland Farmers Federation (QFF) said early figures show actual crop damage to Bowen's vegetable industry is about AU$100 million, accounting for about 20 percent of the season's crop.
Vegetables	NSW Richmond & Tweed	Other agriculture	Lost nut production of approximately AU$ 8 million.
Agriculture, grains and sugarcane	All QLD regions and NSW Richmond & Tweed.	Grains Other agriculture Sugar cane growing	The National Farmers' Federation has cited industry groups estimating damage to crops of up to AU$ 1 billion.
Business	NSW Richmond & Tweed.	Accommodation, Cafes, and Restaurants, Trade	50 to 80 percent of these businesses will not reopen in the community of 50,000 people.
Dairy	QLD - Brisbane	Dairy cattle and pigs	It is anticipated that the cost to the farming industry in South East Queensland will be in excess of AU $6 million.
Infrastructure	All QLD	Multiple industries	The cost of recovery would 'be in the billions' of dollars, with roads, bridges, crops, homes and schools all needing serious repairs.
Insurance	All 19 regions (with most focus on QLD and Northern NSW)	Multiple Industries	Insurance losses AU$ 306 million. Over a AU$ 1Billion in insurance claims.
Fatalities	-	-	12 Fatalities.
Evacuation costs	-	-	25,000 residents evacuated in Mackay, and 55,000 in Bowen.
Schools	-	-	400 schools closed.
Airflights	-	-	Flights cancelled Townsville from March 27. Virgin Airlines losses in the 3 months to March AU$ 62.3 million was impacted by Cyclone Debbie.
Rail	-	-	QLD Rail suspended trains between Rocky and Townsville NQ Bulk Ports closed at Mackay, Abbot Point and Hay Point.
Emergency workers	-	-	1,000 emergency workers deployed, 200 Energex workers.
Defence forces	-	-	1,200 personnel deployed.

Table 2 – Entries of the Γ matrix (fractional production losses) including (a) industry output and (b) infrastructure costs annualised over 25 years. Note that a fraction of 0.1 means a 10% reduction in reduced production (between 2016 and 2017) including both lost productivity plus a share of cost relating to infrastructure damage (annualised over 25 years).

	Rest of NSW	NSW-Richmond - Tweed	VIC	QLD-Brisbane	QLD-Wide-Bay-Burnett	QLD-Darling Downs	QLD-South West	QLD-Fitzroy	QLD-Central West	QLD-Mackay	QLD-Northern	QLD-Far North	QLD-North West	SA	WA	TAS	ACT	NT
1 Sheep	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2 Grains	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3 Beef cattle	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4 Dairy cattle and pigs	0	0	0	0.110	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5 Other agriculture	0	0.070	0	0	0	0	0	0	0.186	0.530	0	0	0	0	0	0	0	0
6 Sugar cane growing	0	0	0	0	0	0	0	0.035	0	0.263	0.112	0	0	0	0	0	0	0
7 Forestry and fishing	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8 Coal, oil and gas	0	0	0	0	0	0	0	0.056	0	0.053	0.078	0	0	0	0	0	0	0
9 Non-ferrous metal ores	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10 Other mining	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11 Food manufacturing	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12 Textiles, clothing and footwear	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13 Wood and paper manufacturing	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
14 Chemicals, petroleum and coal products	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
15 Non-metallic mineral products	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
16 Metals, metal products	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
17 Machinery appliances and equipment	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
18 Miscellaneous manufacturing	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
19 Electricity supply, gas and water	0	0.004	0	0.001	0	0	0	0.003	0	0.020	0.001	0	0	0	0	0	0	0
20 Residential building construction	0	0.016	0	0	0	0	0	0.015	0	0.020	0.013	0	0	0	0	0	0	0
21 Other construction	0	0.000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
22 Trade	0	0.042	0	0.002	0	0	0	0.017	0	0.013	0.010	0	0	0	0	0	0	0
23 Accommodation, cafes and restaurants	0	0.220	0	0.005	0	0	0	0.005	0	0.100	0.005	0	0	0	0	0	0	0
24 Road transport	0	0.016	0	0.002	0	0	0	0.051	0	0.082	0.009	0	0	0	0	0	0	0
25 Rail and pipeline transport	0	0	0	0	0	0	0	0.014	0	0	0	0	0	0	0	0	0	0
26 Other transport	0	0	0	0	0	0	0	0.006	0	0	0	0	0	0	0	0	0	0
27 Communication services	0	0	0	0	0	0	0	0.011	0	0.032	0.001	0	0	0	0	0	0	0
28 Finance, property and business services	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
29 Ownership of dwellings	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
30 Government administration and defence	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
31 Education	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
32 Health and community services	0	0.007	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
33 Cultural and recreational services	0	0.021	0	0.002	0	0	0	0.056	0	0.097	0.006	0	0	0	0	0	0	0
34 Personal and other services	0	0	0	0	0	0	0	0.055	0	0	0	0	0	0	0	0	0	0

2.5 Data

We used the Australian Industrial Ecology Virtual Laboratory (IELab; (Lenzen et al., 2014)) to construct a customised sub-national MRIO table (including the input coefficients matrix $\mathbf{A}$ and initial total output $\mathbf{x}_0$) for Australia with extensive detail on regions directly affected by the cyclone. The IELab is a cloud-computing environment that allows for the construction of customised IO databases. IO tables document the flow of money between various industries in an economy – national IO tables present national data on intra- and inter-industry transactions between industries in a national economy, whereas MRIO tables harbour detailed data on trade between two different regions (Tukker and Dietzenbacher, 2013); see (Leontief, 1953) for an account of MRIO theory). MRIO tables can either be global or sub-national. Global tables feature more than one country, and provide detailed data on international trade between countries, whereas sub-national MRIO tables provide detailed trade data for regions within one country. These tables have been extensively used for undertaking environmental, social and economic footprint assessments (Alsamawi et al., 2014; Hertwich and Peters, 2009; Lenzen et al., 2012; Oita et al., 2016; Simas et al., 2014; Wiedmann et al., 2013). Coupling of economic MRIO data with so-called physical accounts, as conceived by Nobel Prize winner Wassily Leontief in the 1970s, allows for the enumeration of direct as well as indirect supply-chain impacts (Leontief, 1970, 1966).

The IELab is capable of generating MRIO databases, where industry sectors can be distinguished for a number of Australian regions. Users are able to choose from a set of 2214 statistical areas (Level 2; (ABS, 2016f)) to delineate MRIO regions with their specific research question in mind. The regional and sectoral flexibility of the IELab (see (Lenzen et al., 2017a) was exploited by generating a regional partition of Australia that is more detailed around the regions where the cyclone caused most of its damage (Queensland and Northern New South Wales), and less detailed elsewhere (Fig. 1). As a sectoral breakdown we used the 34-sector industry classification from the Queensland regional IO database ((OGS, 2004); see Supplementary Information *SI*1).

A number of national, state and region-specific data sources were used for constructing the MRIO database used in this work. These are the income, expenditure and product accounts (ABS, 2016c), the IO tables (ABS, 2016b, 2017b) for the national level; the state accounts (ABS, 2016a) and the Queensland IO tables (OGS, 2002) for the state level; and the household expenditure survey (ABS, 2011), Queensland regional IO tables (OGS, 2004), the business register (ABS, 2016d), the census (ABS, 2012) and the agricultural commodities survey (ABS, 2016g) for the regional level. Detailed regional employment data were taken from the labour force survey (ABS, 2016e).

2.5.1 Primary economic data

In order to be meaningful, any regional IO analysis needs to be supported by specific regional data (see an IELab-based analysis of Western Australia by Lenzen et al. (2017a)). We therefore sourced primary economic data to update the IO data for sub-regions and sectors most affected by Cyclone Debbie, with the most recent financial and economic information available. In particular, data were sought covering value of production, total output, salaries paid, gross operating values, regional export, turnover, and regional economic productivity (Table 3). Key resources identified included detailed government analyses of Gross Regional Product in the 10 Queensland regions (Queensland Treasury and Trade, 2013) and Northern NSW (Wilkinson, 2014) .

Primary data collection was also targeted to those sectors most influenced by the cyclone in order to improve the reliability of the estimate of primary damage. For example, to improve the accuracy of coal productivity data, correspondence and consultation was initiated with the Queensland Department of Natural Resources and Mines. This yielded high-resolution information on production value data at SA4 level (Statistical Area Level 4) across Queensland. Importantly this also identified which of the study regions produced negligible coal and this information was also included as constraints in the MRIO balancing process.

Key sources of information included accounts published by the Australian Bureau of Statistics (ABS), e.g. covering the gross value of agriculture and manufacturing sales and wages. Grey literature including regional economic studies, value of production accounts kept by State agencies, and Treasury investigations also provided important data within which to constrain the reconciliation of our MRIO base table.

Table 3 Summary of primary economic data used as constraints in compilation of the MRIO.
(All values in AU$ 2017 unless period otherwise specified)

Data aspect	**Region**	**Sector/s**	**Years**	**Example data**	**Reference**
GRP	All Queensland sub-regions.	All	2010-11	GRP Mackay 2011 = $22 billion	Queensland Treasury and Trade, 2013
GRP - Richmond Tweed	NSW - Richmond & Tweed	All	2011-12	GRP > $8.5 billion	(Wilkinson, 2014)
Coal	QLD – all regions	Coal, oil and gas	2015-16	Production value by SA4** area, eg $19.437 billion sales for 2015-16 calendar year with $12.234 billion in SA4 Mackay; and $6.170 billion in Fitzroy.	(Keir, 2017)
Import and export of horticulture products	QLD – all regions	Part of other agriculture	2014-15	$112.9 million of horticulture products import; $156.8 million of horticulture products export	(Horticulture Innovation Australia, 2016)
Gross Value and Local Value of Agricultural Commodities	SA4 region	Over 60 agricultural commodities	2007-08 to 2014-15	$1,119 million gross value of agricultural commodities produced in Mackay in 2014-15	(ABS, 2016g)
Manufacturing sales & service income, wages and salaries, employment	10 QLD regions and NSW-Richmond &Tweed	Food product manufacturing and all other manufacturing	2006-07 is latest	Food product manufacturing in Mackay = $1,051 million in 2007.	(ABS, 2008)
Manufacturing sales & service income, wages and salaries, employment	QLD – all regions	Food product manufacturing and all other manufacturing	2010-11 to 2014-15	Food product manufacturing in QLD = $20,131 million in 2015.	(ABS, 2017a)

* GRP - Gross Regional Product; ** SA4 – Statistical Area 4

3. Results and Discussion

In this section, we first present an analysis of the magnitude of the direct impacts and economic spill-overs of Cyclone Debbie (in Section 3.1). We then further explore the nature of these spill-overs by production layers and by detailed products (Section 3.2). Finally, the implications for disaster recovery plans (Section 3.3) and the outlook (Section 3.4) are discussed.

3.1 Overview of spill-overs

Not surprisingly, Tropical Cyclone Debbie wreaked the most intense havoc where it made landfall, in the regions of Mackay (QLD-M), Fitzroy (QLD-F), and Northern Queensland (QLD-N), and where heavy rains caused widespread flooding, around Brisbane (QLD-B) and in Northern New South Wales (NSW-Rm&T; see Figure 1). There is not a single region in the remainder of Australia that is unaffected by the cyclone. In the multi-region IO disaster model in Eq. 2, these spill-overs come about because businesses experiencing production losses are unable to supply their clients, and also cancel orders for their own inputs, thus leaving businesses elsewhere with reduced activity. Our results for indirect damage are obtained from a model and as such might only approximate the damage that really occurred in the regions. However, an application of the same model to a case study where indirect effects were known (see Fig. 5 in (Lenzen et al., 2017b)) shows that measured outcomes were reproduced with reasonable accuracy.

Our results show that tropical Cyclone Debbie affected about 8487 jobs (Table 4), and caused a loss in value added of about AU$ 2.2 billion (Table 5). Employment losses are expressed in terms of *full-time equivalent (FTE) employment temporarily affected*. Full-time equivalent means that part-time jobs are expressed as fractional full-time jobs, so that they are added into a total. The time span of a job disruption may range between a number of weeks (for example for coal mines that could be re-opened soon after the cyclone; (Ker, 2017; Robins, 2017) to one year (for example tree crops that will not yield until one year later).

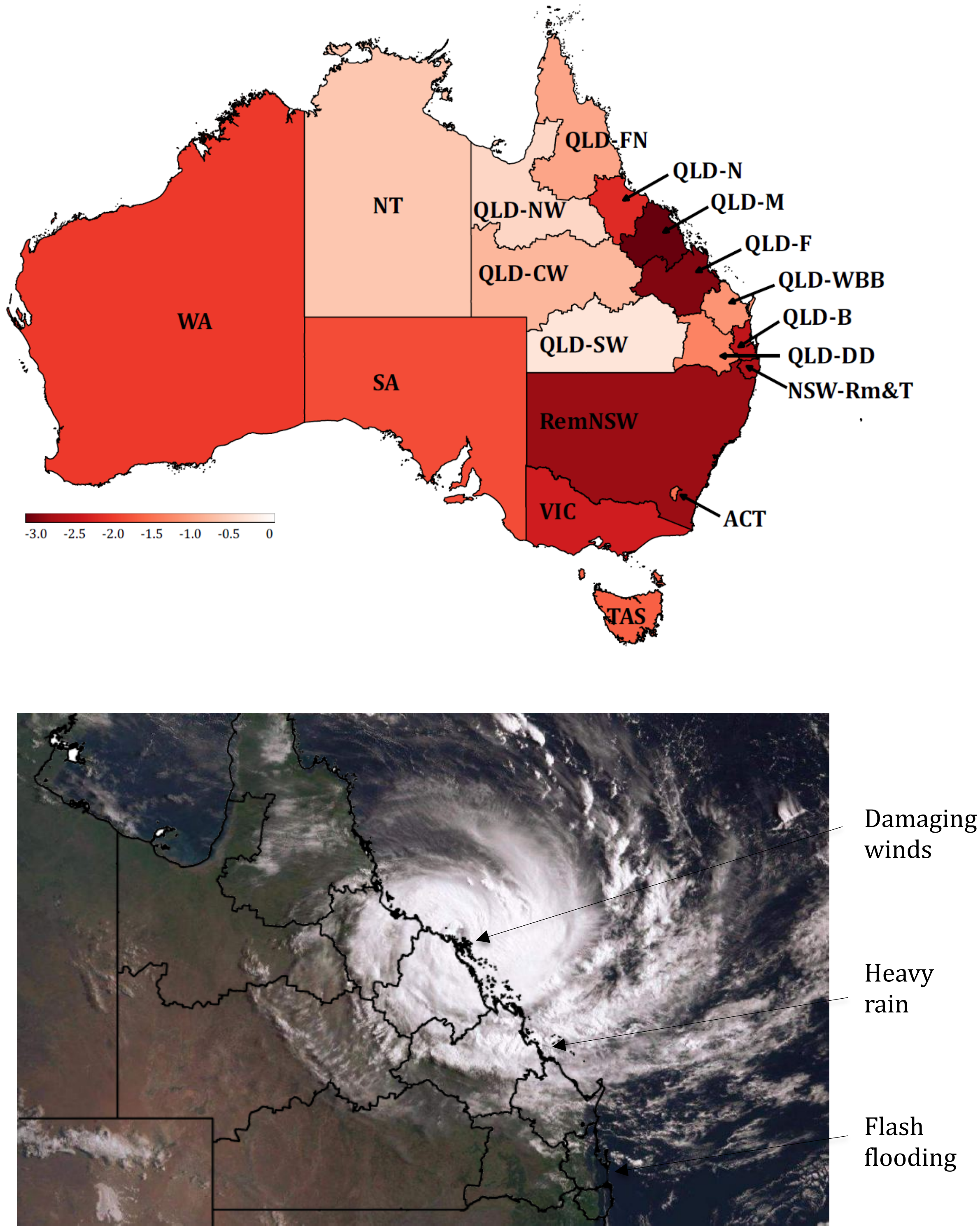

Figure. 1: Geographical distribution of Value Added loss caused by Tropical Cyclone Debbie. Value-added (*VA*) loss is expressed as $\Delta VA = \mathbf{q}_{VA}(\mathbf{I}-\mathbf{A})^{-1}\Delta\mathbf{y}$. A comparison of our results (top, $-\log_{10}(\Delta VA)$, with ΔVA in AU$m) with a satellite image of the cyclone (ABC, 2017) (bottom) shows losses in northern Queensland regions as a direct consequence of the destructive winds, and losses in southern Queensland and northern NSW as a result of heavy rain and floods occurring in the cyclone's wake. *Region acronyms:* RemNSW: *Rest of New South Wales (NSW);* NSW-Rm&T: *NSW Richmond & Tweed;* VIC: *Victoria;* QLD-B: *Queensland (QLD) – Brisbane;* QLD-WBB: *Wide Bay Burnett;* QLD-DD: *Darling Downs,* QL-SW: *South West;* QLD-F: *Fitzroy;* QLD-CW: *Central West;* QLD-M: *Mackay;* QLD-N: *Northern;* QLD-FN: *Far North;*

QLD-NW: *North West;* SA: *South Australia;* WA: *Western Australia;* TAS: *Tasmania;* ACT: *Australian Capital Territory;* NT: *Northern Territory.)*

3.2 Spatial analysis of spill-overs by production layers and by products

The production layer decomposition defined in Eq. 4 indicates how the direct and spill-over impacts of the cyclone unfolded regionally. In Fig. 2, production layers 1&2 indicate that the total value added losses in all of the regions physically affected was about AU$ 1,500 million. In addition, the cyclone caused another AU$ 660 million of value added lost across the supply-chain network of the directly affected businesses. These additional losses are shown in the production layers that follow.

As shown in Fig. 2, about 4,800 jobs were directly affected (production layers 1&2), and an additional 3,700 indirectly (from production layer 2 onward). The combined sectoral and regional spill-overs are therefore significant.

Whilst the coastal areas of Northern Queensland, Mackay, Fitzroy, Brisbane (in South Queensland) and Northern New South Wales (Richmond-Tweed area) were affected immediately by storm and flood damage, repercussions were subsequently felt in the rest of the affected regions, and later on within the rest of Australia. Losses in value added and employment cascaded throughout inter-regional supply-chains, as subsequent transactions were cancelled. Shortfalls were noticeable even by distant suppliers, removed from directly affected producers by four or more transaction nodes (Fig. 2).

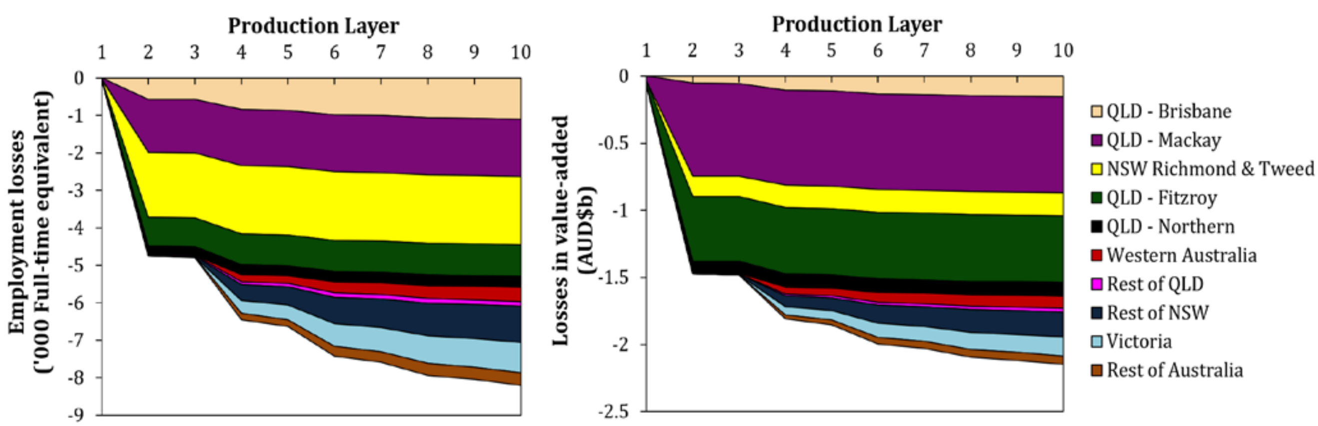

Figure. 2: Total losses in value added and employment resulting from Tropical Cyclone Debbie for various regions across a number of upstream production layers. The figure shows the first ten production layers, which are upstream layers of the supply chain (See *SI*3 for underlying data).

Our production layer assessment reveals the employment and value added losses in different layers of production. Each of these layers are comprised of a range of industries. It is important to identify the industries affected in different layers of production. Our assessment shows that whilst only a selected number of industries and regions were directly affected by the storm and flooding (coal, tourism, sugar cane, road transport, vegetable growing; black stripes in Fig. 3), these direct losses resulted in many more indirect losses in the supply chain. We further analysed the losses in different layers of production (Fig. 3) and identified top 20 sectors that experienced the greatest total (direct and indirect) employment and value added losses.

The top-ranking industries affecting employment directly and elsewhere are those connected to tourism (such as accommodation, restaurants, recreational services, and retail trade, (see Table 4 and Figure 3). In the Richmond-Tweed area of New South Wales, 1132 jobs were affected directly in accommodation, cafes and restaurants, and about 466 indirectly in other industries and regions due to supply-chain effects (spill-over). Similar effects are observed in Mackay and Brisbane in Queensland. The temporary coal mine shutdown in Mackay and Fitzroy affected as many jobs indirectly as directly. Damaged and closed roads affected road transport establishments, and almost equally the industries that depended on them. Likewise, value added losses are observed both directly and indirectly in the supply chain (Table 5).

3.3 Implications for disaster recovery plans

Analysis of the impacts of disasters, such as undertaken in this paper, can have constructive uptake by informing disaster recovery plans as well as regional plans more generally. In August 2017, the government of the Australian state of Queensland released a management review of Cyclone Debbie and recommended improved Business Continuity Planning (BCP) as a way to build: *"… business and organisational resilience […] Enhanced BCP within state agencies, businesses and communities will help all to be more resilient to the impact of events. […and..] should feature permanently in disaster management doctrine*." In addition, the report noted that "*BCP needs to consider supply chains, and the numbers and skills of frontline staff required to ensure functioning of critical services"* (IGEM, 2017).

Consideration of the large indirect impacts identified in this article, would help improve future planning. This could be achieved, for example, by considering the large number of employees indirectly affected by the disaster (as shown in Table 4), and the related services and products they provide. For instance, as shown in Table 4 for the indirect employment impacts for the "Accommodation, cafes and restaurants" sector, some 466 employees providing services were affected in the Richmond-Tweed area. However, this impact is currently not mentioned in disaster recovery planning documents.

Table 4: Direct, indirect and total employment affected by Cyclone Debbie, by state and sector.

Region	Sector	Direct employment impacts (FTE)	Indirect employment impacts (FTE)	Total employment impacts (FTE)
NSW-Rm&T	Accommodation, cafes and restaurants	-1132	-466	-1597
QLD-M	Coal, oil and gas	-466	-821	-1287
QLD-F	Coal, oil and gas	-349	-616	-964
QLD-M	Accommodation, cafes and restaurants	-421	-171	-592
NSW-Rm&T	Trade	-367	-184	-551
QLD-M	Other agriculture	-208	-260	-468
QLD-Brisbane	Accommodation, cafes and restaurants	-272	-113	-385
QLD-Brisbane	Trade	-187	-99	-286
QLD-M	Road transport	-137	-93	-231
QLD-F	Trade	-146	-68	-214
NSW-Rm&T	Other agriculture	-87	-103	-191
QLD-N	Coal, oil and gas	-57	-102	-159
QLD-F	Road transport	-93	-63	-155
QLD-N	Trade	-90	-47	-137
QLD-M	Trade	-94	-42	-137
QLD-Brisbane	Dairy cattle and pigs	-56	-53	-109
QLD-F	Personal and other services	-72	-27	-99
QLD-M	Residential building construction	-22	-76	-98
QLD-F	Residential building construction	-22	-74	-96
QLD-N	Residential building construction	-22	-70	-92
	Total	-4802	-3685	-8487

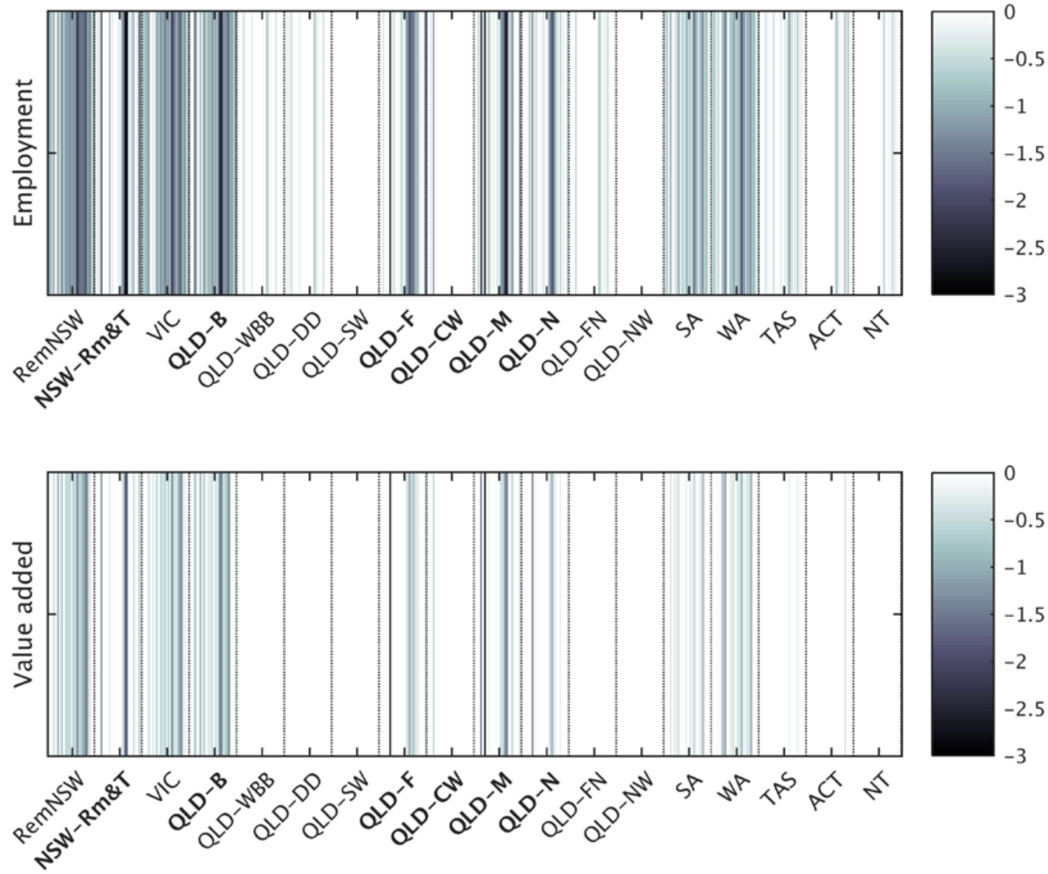

Fig. 3: Spill-over in employment and value added losses resulting from a tropical cyclone, by state and sector.
(The magnitude of employment and value-added losses is expressed as $\log_{10}|\Delta Q|$ and visualised as lines on a grey scale. Each line represents one of the 34 industries in each region, in the sequence order listed in Supplementary Information *SI*1. Region acronyms as in Fig. 1, bold regions are those directly affected. See also *SI*4)

Table 5: Direct, indirect and total value added affected by Cyclone Debbie, by state and sector.

Region	Sector	Direct value added impacts (AU$m)	Indirect value added impacts (AU$m)	Total value added impacts (AU$m)
QLD-M	Coal, oil and gas	-581	-176	-757
QLD-F	Coal, oil and gas	-435	-133	-567
NSW-Rm&T	Accommodation, cafes and restaurants	-81	-83	-164
QLD-N	Coal, oil and gas	-71	-22	-93
QLD-M	Other agriculture	-41	-47	-88
NSW-Rm&T	Trade	-39	-34	-73
QLD-M	Accommodation, cafes and restaurants	-30	-31	-61
QLD-Brisbane	Accommodation, cafes and restaurants	-19	-20	-40
QLD-Brisbane	Trade	-20	-18	-38
NSW-Rm&T	Other agriculture	-17	-19	-36
QLD-M	Road transport	-14	-16	-31
QLD-F	Trade	-16	-13	-29
QLD-F	Road transport	-10	-11	-20
QLD-N	Trade	-10	-9	-18
QLD-M	Trade	-10	-8	-18
QLD-Brisbane	Dairy cattle and pigs	-9	-10	-18
QLD-M	Residential building construction	-2	-13	-16
QLD-F	Residential building construction	-2	-13	-15
QLD-N	Residential building construction	-2	-12	-15
NSW-Rm&T	Residential building construction	-2	-12	-14
	Total	-1544	-659	-2203

3.4 Outlook

In this work, we have focused upon losses of employment and value added, because these are currently of immediate importance for governments, insurers and the media. Future work could investigate possibilities for re-structuring the geography of production and supply-chain networks with the aim of finding more "disaster-resilient" configurations. In addition, there are variants of IO-analytical methods that allow establishing optimal recovery paths (Koks et al., 2016), and these approaches could be integrated into the Australian Industrial Ecology Virtual Laboratory.

Future work could also consider the effects of cyclones beyond national borders. The disruptions of coal exports due to Tropical Cyclone Debbie, for example, caused bottlenecks in Indian and Chinese steel mills (The Barrel, 2017), and during the aftermath of the storm, steel producers were looking for alternative sources of coal such as Russia, Mongolia or Mozambique (Serapio, 2017). Such trade relationships can be taken into account using nested, multi-scale, global multi-region IO frameworks (Bachmann et al., 2015; Tukker and Dietzenbacher, 2013; Wang et al., 2015).

Our approach can be applied to other regions, and ultimately extended to include impacts well beyond employment and value added, such as wider environmental or social consequences of disasters. The IELab already has many satellite accounts (and is being expanded) to assess broader environmental and social flow-on effects. The growing number of "virtual laboratories" for IO analysis (Geschke and Hadjikakou, 2017) for countries in disaster-prone zones (Indonesia, Taiwan, China) means that the work described in this paper can be readily applied to other geographical settings.

4. Conclusions

Powerful tropical cyclones have the ability to cause severe disruptions of economic production that are felt far beyond the areas of landfall and flooding. Here, we used an IO-based analytical tool for enumerating the post-disaster consumption possibilities, and ensuing direct and indirect losses of employment and value added as a consequence of the Tropical Cyclone Debbie that hit the Queensland regions of Australia in March and April 2017. Our work contributes an innovative approach for (a) quantifying the impact of disasters in a detailed and timely manner and (b) incorporating infrastructure damages into the assessment of losses in employment and value-added.

Our results from this Australian case study suggest that Cyclone Debbie caused substantial damage to spill over into regions and sectors not directly affected: Industries directly hit by the cyclone suffered approximately 4802 job losses, but some 3685 jobs were affected in these industries' supply chains. A total of AU$ 2203 million losses in value added was observed, AU$ 1544 million of which were direct with particular impact around Mackay and Fitzroy, as well as the coastal areas of Northern Queensland, Brisbane and northern New South Wales (Richmond-Tweed area). These findings demonstrate that the full supply-chain effects of major disruptions on national economies are significant, and that this type of study will become increasingly important in a future likely to be fraught with extreme weather events, as the frequency and intensity of tropical cyclones increase as a result of climate change (Mendelsohn et al., 2012).

This work demonstrates rapid analysis of the wide indirect impacts of Cyclone Debbie. It shows how significant consequences can be felt, as spill-overs, in regions well outside the landfall and flood zones caused by the cyclone. Our work suggests improved planning could help account for these impacts, minimise them in future, and thereby help transition the affected economies towards greater resilience.

Competing interests

The authors declare that they have no conflict of interest.

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