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# Complex resource supply chains display higher resilience to simulated climate shocks

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ABSTRACT

Global resource supply chains deliver products such as fish, rice and minerals from producers to consumers around the world, linking disparate regions and economies. These supply chains are increasingly exposed to the impacts of a changing climate, yet receive little attention relative to the study of the production phase. Too often, business learns from experience if and how their supply chains can withstand and recover from climate shocks with little insight on proactively developing climate resilient supply chains. We use a network-based simulation approach to estimate the resilience of supply chains, particularly to disruption experienced during climate-related extreme events. We consider supply chain examples from three Australian resource industries – fisheries, agriculture and mining – that have experienced climate shocks in recent years. We derive four supply chain indices – evenness, resilience, continuity of supply and climate resilience – to estimate the performance of simple and complex supply chains in each industry. As with ecological systems, we show that complex supply chains with a large number of nodes and links are more resilient to disruption. Critically, all chains, regardless of their complexity, will have diminished resilience as climate disruptions become more frequent. This highlights the importance of considering the broader economic benefits of diversified chains, leading to risk reduction and improved design post-disruption. It also reinforces the importance of a systems approach to risk management in supply chains, particularly in considering adaptation options for addressing direct and indirect impacts on the chain as well as the global challenge of reducing greenhouse gas emissions.

## 1. Introduction

Societal development and globalisation relies on access to a wide range of natural resource-based products, including minerals, agricultural products, and wild seafood. These primary industries, with considerable climate sensitivity, are particularly vulnerable to shocks to their production phases (Hodgkinson et al., 2014; IPCC, 2014). However, climate sensitivity is not limited to production alone, as many other links in supply chains are at risk from direct and indirect impacts of climate shocks (Lim-Camacho et al., 2017; van Putten et al., 2016). Climate extremes and shocks, as well as slow changes, will be increasingly pervasive in primary industries globally, requiring increased attention to response and adaptation along the supply chain (IPCC, 2012, 2013, 2014). In Australia, for example, these industries contribute substantially to economic prosperity and growth through regional employment and value of gross production (mining AU$118bn, agriculture AU$30bn, fisheries AU$2.8bn (ABARES, 2015; ABS, 2016)) and climate related disruption is on the rise (Hodgkinson et al., 2014; Reisinger et al., 2014 Reisinger et al., 2014).

In Australia, as elsewhere, these commodities are rarely used where they are produced, requiring the movement of goods along progressively longer and more complex supply chains, to be consumed in distant domestic and international markets. Such supply chains may present disadvantages such as upward pressure on prices in domestic

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**Table 1**
Summary of supply metrics, including simple measures (links per node) and the standardised Supply Chain Index (SCI), Evenness and Resilience scores, and top three key nodes identified based on individual SCIj scores, for the case studies as shown for supply chain model configurations mapped in Fig. 1.

| Supply chain | No. nodes $n$ | No. links $L$ | Links/node $L/n$ | *SCI Connectance Measure* (standardised) | *Evenness (ED)* | *Resilience score (1-SCI)* | Key Element 1 | Key Element 2 | Key Element 3 |
|---|---|---|---|---|---|---|---|---|---|
| Fisheries simple – lobster | 22 | 33 | 1.5 | 0.048 | 0.26 | 0.952 | Chinese consumer | Chinese importer | Processors (Geraldton) |
| Fisheries complex – prawn | 15 | 28 | 1.87 | 0.023 | 0.35 | 0.977 | Super markets | Domestic consumers | Mother ship |
| Agriculture simple – rice pre-drought | 12 | 15 | 1.25 | 0.145 | 0.34 | 0.855 | AGS | SunRice | Overseas importers |
| Agriculture complex – rice post-drought | 20 | 25 | 1.25 | 0.071 | 0.20 | 0.929 | AGS | SunRice | Overseas importers |
| Mining simple – diamonds | 13 | 15 | 1.15 | 0.209 | 0.34 | 0.791 | Conveyors | Onsite process | Industrial sort |
| Mining complex – iron ore | 16 | 23 | 1.43 | 0.044 | 0.52 | 0.944 | Rail2 | Road/Conveyor | Sole use rail |

markets and increased logistical costs. This has led to development of 'lean' and efficient supply chains that also achieve the goals of reduced resource-use and improved timeliness as a way of achieving cost competitiveness (Gligor et al., 2015; Mason-Jones et al., 2000). As a result, some global companies seek to consolidate their supply chains, reduce lead times and distances between raw material production and retail, and ultimately develop streamlined chains with lower carbon emissions and reduced overall risk exposure (Bandaly et al., 2012; Cabral et al., 2012). Such consolidation may increase reliance on particular production regions, where any disruptions, such as extreme weather events, experienced in one location will have immediate impacts on the chain. Similarly, disruptions within a supply chain can lead to system-wide shocks, as demonstrated by the 2011 Thailand floods, which crippled multiple industries globally (Wai and Wongsurawat, 2012). Given the risks evident across the supply chain from supplier to consumer, an holistic approach to managing risk is valuable as supply chain components are interrelated and mutually dependent (Altay and Ramirez, 2010; Fleming et al., 2014; Ghadge et al., 2012; Manuj and Mentzer, 2008). Furthermore, an improved understanding of supply chain design on the degree of resilience or vulnerability to climate-related disruptions may provide supply chain managers with insights that enable improved risk management pre-disruption and reconstruction of more climate-adapted and competitive supply chains post-disruption.

Existing research about supply chain responses to climate change focuses heavily on mitigation, rather than adaptation, specifically energy efficiency and monitoring, and the reduction of greenhouse gas (GHG) emissions (Davis et al., 2011; Kagawa et al., 2015; Soosay et al., 2012). A smaller effort is focused on potential and current adaptation options for specific industries and their components (see Becker et al., 2011; Fleming et al., 2014; Lim-Camacho et al., 2015; Ng et al., 2013), exploring climate impacts in terms of emerging threats (James and James, 2010; Stewart and Elliott, 2015) and risk management options available for coping with extreme events (Andreoni and Miola, 2015; Smith et al., 2016; Wai and Wongsurawat, 2012). A limitation in this existing research is a focus on single components of the supply chain, particularly at the level of primary production, rather than the supply chain as a whole (Benedikter et al., 2013). Equally, there is typically a lack of focus on the implications of adaptation on interdependencies across the chain (Ridoutt et al., 2016), alongside a general failure to examine the strategic, tactical and operational effects of climate change across supply chains (Faruk et al., 2001; Ivanov and Sokolov, 2012; Linnenluecke et al., 2013).

For industries and their supply chains to cope with climate-related shocks, analysis and adaptation can be approached through broader, systems perspectives. While ecological theory predicts that more connected and linked systems adapt more effectively to perturbations (Holling, 2001; Pimm, 1984), economic rationalism has favoured more streamlined and linear chains, with a focus on efficiency, optimization and 'lean' functions. Outside of the impacts of specific supply chain disruptions, the relative performance of supply chains under the influence of climate change has not been examined and it is unclear what type of chain will be best placed to adapt. Here we test how the structure of resource-based supply chains might influence their ability to withstand climate shocks. We use a modelling approach that accounts for the relative movement of product through nodes and links in a supply chain, exploring the value of complex and simple supply chains in situations where shocks are frequent and unexpected, as has been projected under climate change.

## 2. Methods

We developed a comparative case study approach to exploring the influence of climate disruptions on resource supply chains. First, we evaluated the overall exposure of three Australian primary resource sectors – fisheries, agriculture and mining – identified as vulnerable to the impacts of climate change (IPCC, 2012, 2013). We selected two examples within each sector that had known exposure to climate and weather disruptions and that have contrasting supply chain types – relatively simple and relatively complex. In this paper, we distinguish 'simple' from 'complex', in an empirical sense based on the number of links and nodes in each supply chain, drawing from Plagányi et al. (2014). A first order definition of complexity is to consider the number of links per node, with more links per node implying higher complexity as the actors are more connected (Hwarng et al., 2015). But as explained in Plagányi et al. (2014), complexity is also about the degree of connectance and we use the Supply Chain Index (SCI) from that study as our measure of connectance and complexity (Eq. (1)). Lower SCI values reflect higher connectance and hence more complex supply chains (Table 1). This approach builds on research on ecological networks demonstrating that robustness increases with connectance (Dunne et al., 2002), which is aligned with our focus on analysing the resilience to climate shocks.

We also include a range of products with degrees of perishability to provide another layer of consideration in evaluating the implications of the results of this paper. We, however, do not include perishability as a variable in analysis. Here we define how we mapped the supply chains, and explain the modelling approach to estimate resilience to shocks.

### 2.1. Mapping supply chains

To generate the framework for our analysis, the first step was to map the stages in the supply chain, the main actors (nodes) and critical links between the nodes, consistent with other network analysis (see for example, Rubinov and Sporns, 2010). We created the supply chains for the selected examples based on a consistent structure used in previous work (Lim-Camacho et al., 2015; Plagányi et al., 2014; van Putten et al.,