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Indirect Impacts of COVID-19 on a Tropical Lobster Fishery's Harvest Strategy and Supply Chain

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The Torres Strait tropical rock lobster *Panulirus ornatus* (TRL) fishery is of immense social, cultural and economic importance to the region's Indigenous fishers from both Australia and Papua New Guinea (PNG). During 2020, the COVID-19 pandemic indirectly impacted this fishery as well as a number of other fisheries reliant on international export markets. The TRL fishery is managed using an empirical (data-based) Harvest Control Rule (eHCR) to rapidly provide a recommended biological catch (RBC), based on catch, fishery-independent survey indices and catch-per-unit-effort (CPUE). Here, we summarize the impacts of COVID-19 on each of these critical data inputs and discuss whether the eHCR was considered adequately resilient to this unprecedented disruption to the system. Next, we use a quantitative supply chain index to analyze the impact of disruptions to the supply chain, and inform on potential adaptation strategies. The catch and CPUE data were impacted to varying degrees by external constraints influencing fishing effort, but the fishery-independent survey wasn't affected and hence there remains an unbroken survey time-series for the fishery extending back to 1989. The eHCR was shown to be reasonably robust because it incorporates longer-term trends over a 5-year period, and accords substantially more weighting (80%) to the fishery-independent survey rather than CPUE data which can be affected by trade and other disruptions. Despite the eHCR not having been tested for scenarios such as a global pandemic, this robustness is a positive given the types of disruptions we will likely face in future climate. The weak links identified in the supply chain were the same as those previously highlighted as sensitive to climate change disruptions. Our supply chain analysis quantifies the impact on system resilience of alternative paths connecting producers to consumers and reinforces that supply chains may be particularly vulnerable to external disruptions if they are not sufficiently diverse.

Keywords: decision rules, fishery markets, fishery-independent survey, pandemic, MSE, fishery export

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INTRODUCTION

The COVID-19 pandemic (Hui et al., 2020) has indirectly led to severe economic impacts on global and Australian seafood industries (Bennett et al., 2020). This has included disruptions in shipping activity (Huveneers et al., 2021; Notteboom et al., 2021), global markets (Knight et al., 2020), food security (Steenbergen et al., 2020) and negatively impacted on commercial fisher's health and wellbeing as well as added to the challenges of protecting workers on fishing vessels (Sorensen et al., 2020). A recent review highlighted widespread heterogenous ramifications on United States fisheries (White et al., 2021). The risk of crowding and inadequate physical distancing during fishery operations has been identified as a key challenge impacting fisheries during COVID-19 (Okyere et al., 2020).

There has also been a major impact on scientific data collection in some areas of the world, such as in the United States where scientists were forced to cancel most of their major research cruises and surveys in 2020 (Link et al., 2021). Link et al. (2021) reported that the United States alone had to cancel over 50 fisheries surveys resulting in a loss of over 1,500 on-the-water days-at-sea. Although Australia was also impacted by the COVID-19 pandemic, localized outbreaks were contained relatively quickly, resulting in only a brief core "lockdown" (Huveneers et al., 2021) and hence activities such as fishing and surveys were impacted less than was the case for many other countries.

The focus of this study is the disruption caused by COVID-19 to the main export market for Australian seafood producers, and subsequent impacts on the fisheries supplying these markets. The Chinese market accounts for almost 70 per cent of Australia's $1.2 billion total seafood exports (FRDC, 2020). Three quarters of the seafood export market to China is live rock lobster, with most of the eight major lobster fisheries (**Figure 1**) reliant on exports. These exports were severely impacted during 2020, along with other high-value species including abalone, coral trout *Plectropomus* spp. and live eel (Catizone, 2020). As a result, there were short-term declines in catches around Australia of these species (Huveneers et al., 2021). Even before the World Health Organization (WHO) declared COVID-19 a world-wide public emergency, the global market for spiny lobsters, valued at United States $912 million in China alone, was halted because 90% of these high value lobsters are exported to China (Knight et al., 2020).

Primary industries such as fisheries are vulnerable not only to environmentally-induced shocks to their production phases but also to risks across the entire supply chain from supplier to consumer. This is also because in our highly globalized modern society, products such as lobsters are rarely consumed at the point where they are caught, but require being moved along progressively longer and more complex supply chains, to be consumed in distant domestic and international markets. A holistic approach to managing risk is therefore valuable as supply chain components are interrelated and mutually dependent (Lim-Camacho et al., 2015; Rosales et al., 2017; Ghadge et al., 2020; Farmery et al., 2021). An improved understanding of supply chain design on the degree of resilience or vulnerability to disruptions may shed light on improved risk management and ways to reconfigure more resilience and competitive supply chains (Lim-Camacho et al., 2017).

The science needed to support major shocks to fisheries and markets remains a challenge (FAO, 2020a,b; Link et al., 2021). In this article we use the Torres Strait tropical rock lobster *Panulirus ornatus* (TRL) fishery as a case study and summarize impacts of COVID-19 and subsequent outcomes. We also evaluate how well the harvest control rule, management system and supply chain were able to respond to the challenges that resulted due to the pandemic. To analyze the supply chain, we use a modeling approach that accounts for the relative movement of product through nodes and links in a supply chain, to theoretically identify vulnerable elements in the supply chain (Plagányi et al., 2014) and evaluate how this concurs with what actually eventuated in response to COVID-19 disruptions, as well as analyzing ways to improve the resilience of supply chains.

The Torres Strait Tropical Rock Lobster Fishery

The TRL fishery provides an important source of income for more than 400 Torres Strait Islander license holders and many island communities, as well as supporting a non-Islander sector. Fishing in the Torres Strait is governed by the *Torres Strait Fisheries* Torres Strait Fisheries Act (1984), which protects the way of life and livelihood of traditional inhabitants.

The TRL stock is shared with adjacent fisheries in Papua New Guinea (PNG) and on the northern Queensland coast (**Figure 1**). The Australian and PNG Torres Strait catch has averaged 673 t live weight since 1989. The Australian Torres Strait catch is important economically to all sectors, and contributes to a lucrative export market for live lobsters to China (**Figure 2**).

Fishery-independent monitoring of the TRL population has been carried out annually from 1989 to 2020. These surveys provide long-term information on the relative abundance of recruiting (1+) lobsters. Prior to the introduction of mandatory logbooks in the largely non-Indigenous transferable vessel holder (TVH) sector and subsequently the docket book system in the Indigenous traditional inhabitant boat (TIB) sector in 2003, these surveys also provided the only long-term information on the relative abundance of fished (age class 2+) lobsters (Dennis et al., 2015).

The TRL fishery transitioned to an output control system on 1 December 2018, which requires the setting of a total allowable catch (TAC). The harvest strategy uses a conservative biomass target reference point that takes into account that the resource is shared and important for the traditional way of life and livelihood of traditional inhabitants and is biologically and economically acceptable. Other management measures include a ban on trawlers taking lobsters, a minimum size limit (90 mm carapace length), periodic closure of the fishery to the use of hookah (surface air supply) gear around specified new and full moon periods, prohibition of use of hookah during December to January, as well as a full closure during October to November each year.

The stock is naturally highly variable due to variability in the numbers of recruits (1+ lobsters) each year, and the fishers catch mostly a single age-class (2+) only (Plagányi et al., 2019). The unfished 2+ lobsters leave the Torres Strait at the end of August-September to breed (Skewes et al., 1994). Hence, a TAC needs to be set annually in such a way as to ensure biological and economic sustainability consistent with the principles of the Australian Commonwealth Harvest Strategy Policy

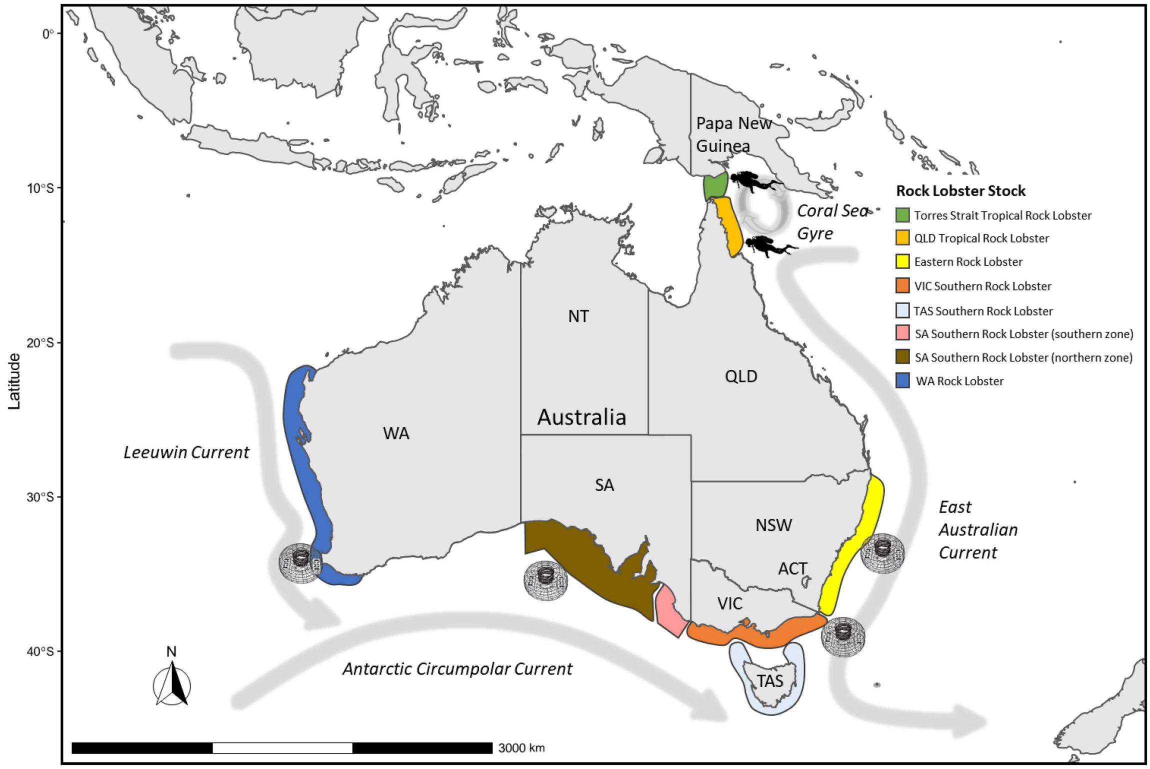

FIGURE 1 | Map of Australia and Papua New Guinea showing location of the Torres Strait tropical rock lobster dive fishery and linked Queensland (QLD) tropical lobster fishery as well as the six other major lobster trap-based fisheries as summarized in Plagányi et al. (2018), namely Eastern rock lobster *Sagmariasus verreauxi*, southern rock lobster *Jasus edwardsii* from Victorian (Vic), Tasmania (Tas), South Australia (SA) southern and northern zones and West Australia rock lobster *P. cygnus*.

(Australian Government Department of Agriculture and Water Resources, 2018) as well as the TRL fishery and Protected Zone Joint Authority (PZJA) objectives. For this reason, the annual fishery-independent survey of 1+ recruits is now conducted as close to the start of the fishing season as possible (during the November neap tides) to allow estimation of the likely size of the fishable stock the next year (Dennis et al., 2015). Previously, this information together with all other sources of information and data for the fishery were input to an integrated stock assessment model that was used to set the TAC (Plagányi et al., 2020b).

In December 2019, new harvest strategies were implemented for important Torres Strait fisheries including the lobster and bêche-de-mer fisheries (Plagányi et al., 2018, 2020c; PZJA, 2019). The strategies included some major changes to data collection methods and scientific assessments to ensure ongoing fishery and ecological sustainability and economic growth; important for the welfare of hundreds of fishers, regional-based processors and local and national sellers that depend on these resources.

For TRL, the harvest strategy outlines the objectives, monitoring requirements, stock assessment model, empirical (data-based) Harvest Control Rule (eHCR) and reference points (PZJA, 2019). The eHCR is used to rapidly provide a recommended biological catch (RBC) once the catch, survey indices and other data inputs (CPUE or catch-per-unit-effort) become available (Plagányi et al., 2018). The eHCR is a central component of the Harvest Strategy. It was simulation tested to be robust to a number of uncertainties and shocks, but not to the ramifications of a global pandemic.

MATERIALS AND METHODS

External Drivers Influencing the TRL Fishery

During the 2020 fishing season, there were a number of unprecedented external drivers that influenced fishing effort. We collated information on these through informal conversations with fishers, managers and processors. We verified information as to the impacts of changes in border regulations, charter flight availability and export demand by cross-checking with formal government announcements, such as from the Ministry of Agriculture and Rural Affairs as well as through more formal reporting of disruptions at several Tropical Rock Lobster Resource Assessment Group (TRLRAG) meetings held *via* teleconference through the year (TRLRAG, 2020). The TRLRAG forum includes Indigenous fishers and their representative bodies, non-Indigenous fisher representatives and flow-on business stakeholders, federal and state fisheries managers, and scientists. In addition to information on changes in beach prices shared by processors, we verified these decreases from

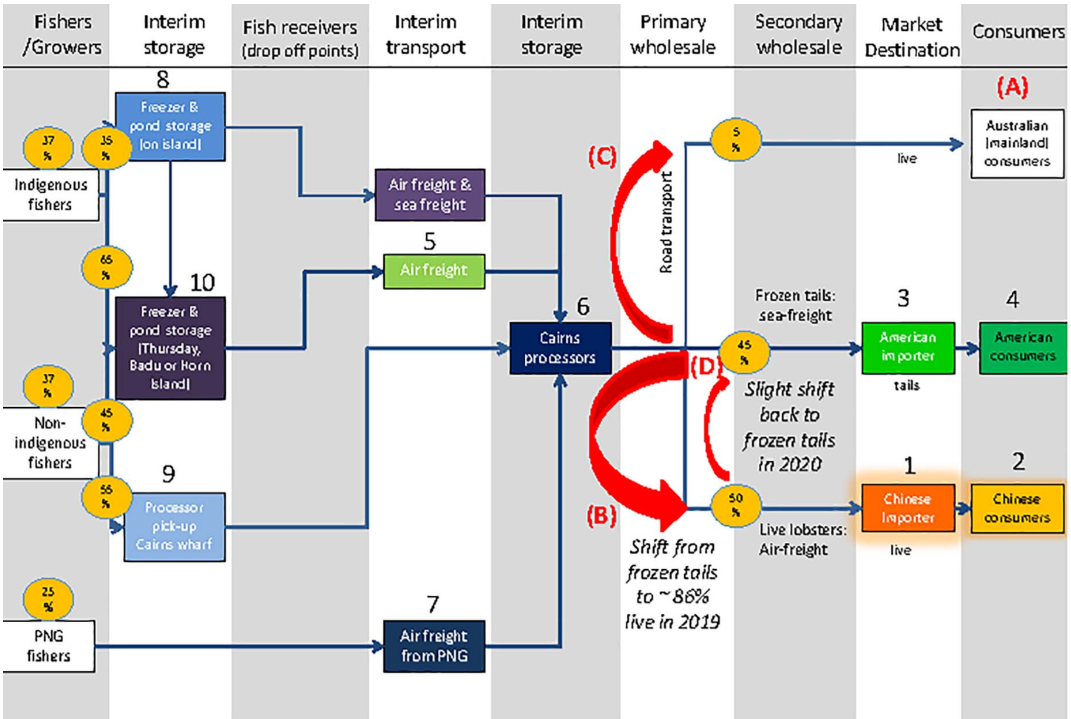

FIGURE 2 | Torres Strait tropical lobster 2012 supply chain schematic modified from Plagányi et al. (2014), highlighting with a red arrow the post-2012 shift to exporting almost all live lobsters, and a small reversal of that market shift during 2020. The large numbers next to nodes show the ranking of the top ten critical elements in the supply chain (orange highlights the most critical node) based on applying the Supply Chain Index method of Plagányi et al. (2014). The figure shows the 2012 base configuration **(A)** as well as variants **(B)** shift to more live; **(C)** increase domestic market and **(D)** greater domestic market and product split between live and tails, as discussed in the text.

restaurant advertisements. We extracted information on total seafood exports and value from the Australian Fisheries Research and Development Corporation (FRDC) Seafood Production and Trade Database.

Impacts on the Scientific Process and Survey

The indirect impacts of COVID-19 on the scientific process and data collection were also considered. A number of contingency plans were reviewed, and COVID-safe measures implemented to ensure the highest probability of the survey being conducted in a consistent and safe manner not only to the survey and boat crew but also to communities in Torres Strait.

Fishery Data

As in previous years, the fishery catch and effort data for the Australian share of the fishery were provided by the Australian Fisheries Management Authority (AFMA), and the totals and monthly distribution compared with that of previous years. The monthly catch totals from the PNG sector for the months January to September were provided by the PNG National Fisheries Authority. As agreed previously by the TRLRAG, these values were linearly extrapolated to obtain an annual total catch for use as an input to the eHCR. The CPUE data were standardized using the same methods as applied previously (Deng et al., 2020b,c; Plagányi et al., 2020b).

eHCR and Final Management Advice

The eHCR formula outputs a RBC in December for the following year. This calculation is the multiple of the average catch over the last 5 years and a statistic which measures the relative performance of the fishery based on the following five data inputs: (1) Fishery-independent recruiting lobster (1+) standardized relative numbers; (2) Fishery-independent recently-settled lobster (0+) standardized relative numbers; (3) standardized CPUE for TIB sector; and (4) standardized CPUE for TVH sector; and (5) total catch (TIB, TVH, and PNG) (using data available up until end of October). Different weightings are applied to the four abundance indices included in the relative performance statistic used in the eHCR, based on extensive testing to compare performance of alternative weightings and also considering the information content and reliability of each series, as well as a preference expressed by the stakeholders to use a portfolio approach in determining the RBC (Plagányi et al., 2018). The Preseason 1+ index is the primary index and is most reliable and direct in terms of indexing the biomass of lobsters that will be available to be caught in the next fishing season. Hence, this index is assigned the highest weighting of 70%. The Preseason 0+ index provides an early indication of the following year's recruitment, whereas the CPUE indices aim to index the relative abundance of the large 2+ lobsters, the survivors of which will migrate out of the Torres Strait to spawning grounds to the East. Each of these three secondary indices [Survey 0+ and CPUE (TIB and TVH)] is assigned a weighting of 10% (30% total) in the eHCR formula.

Simulation testing (Plagányi et al., 2016) showed that the best approach is to use the slope of the trends in the secondary indices over the last 5 years' data (after first taking the natural logarithm of the data) for each of the abundance indices. This allows the RBC to be based on medium term trends in abundance, rather than on just the current abundance.

Hence the HCR rule is as follows:

$$RBC_{y+1} = \left[0.7 \cdot \left(1 + s_y^{presurv,1}\right) + 0.1 \cdot \left(\left(1 + s_y^{presurv,0}\right) + \left(1 + s_y^{CPUE,TVH}\right) + \left(1 + s_y^{CPUE,TIB}\right)\right)\right] \cdot \bar{C}_{y-4,y} \quad (1)$$

where

$\bar{C}_{y-4,y}$ is the average achieved catch during the past 5 years, including the current year; i.e., from year y-4 to year y,

$s_y^{presurv,1}$ is the slope of the (logarithms of the) fishery-independent survey 1 year abundance index, based on the five most recent values;

$s_y^{presurv,0}$ is the slope of the (logarithms of the) fishery-independent survey 0 year abundance index, based on the five most recent values;

$s_y^{CPUE,TVH}$, $s_y^{CPUE,TIB}$ is the slope of the (logarithms of the) TVH and TIB CPUE abundance index, based on the five most recent values.

Supply Chain Resilience

To inform analyses around the impacts of COVID-19 on the TRL supply chain, we used as a base example the simplified structure of Plagányi et al. (2014), which captures the key processes and activities describing the system connections from the point at which lobsters are first landed to the point at which they are consumed (**Figure 2**). The simplified representation enables structured analysis, even though we acknowledge that behind these models are complex business structures and industry relationships.

The base example from Plagányi et al. (2014) was developed for TRL using data describing fishery operations around 2012. There have since been a number of important changes to the TRL fishery, including changes in allocations per sector, management controls and market shifts. However, the focus here is on the market outlets for lobsters, and over the past decade there has been a substantial transition from frozen tail to live product: the Australian sector's overall proportion of tailed product has decreased from around 58% down to 14% (Deng et al., 2020a). This added significant value to the fishery given that the tail represents only ~40% of the lobster by weight and live product fetches ~30% higher $/kg at market (Hutton et al., 2016; Plagányi et al., 2017). However, when COVID-19 brought fishery exports to a standstill in February 2020, fishers (particularly the PNG and TIB sectors) were forced to again convert some lobsters to frozen tail product. There were also efforts to increase sales of lobster on the domestic market and hence we also investigate the impacts of greater diversification of the supply chain.

We also acknowledge that since 2012 there have been other positive increases in diversification of the supply chain in the form of additional processors. This increased supply chain complexity would increase the resilience score, but is beyond the scope of this paper which focuses on changes in the final market destinations.

To analyze the resilience of alternative supply chain configurations to external disruptions, we used the Supply Chain Index (SCI) from Plagányi et al. (2014) (see **Supplementary Material**).

In this study, we compare the critical elements and supply chain resilience score under the 2012 base configuration [scenario (A)] with three alternative scenarios (**Figure 2**):

(B) A pre-COVID-19 (2019) scenario with almost all live exports, few tails (14%) and small (5%) domestic market;
(C) An illustrative scenario with increased domestic market (25%) and rest mostly exported overseas as live product; and
(D) An optimized scenario (manipulated to increase the resilience score), with a large (50%) domestic share, and the rest split evenly between the international markets for frozen tails and live lobsters.

The simplified representation shown in **Figure 2** has 15 elements and 16 links which are assumed constant in the scenario analysis—here we test only the implications of altering the magnitude of flows in the network.

RESULTS

External Drivers Influencing the Fishery

In response to COVID-19, the last regular live tropical lobster shipment to China left on 26 January 2020, just before the ban on live markets took effect and there was a considerable pause in international exports of lobster from both Australia and PNG. This was revoked by the 6th February indirectly as live seafood was allowed into China as an exception. This period is usually a time of high demand with peak prices for lobster and other Australian seafood due to the Chinese New Year (Plagányi et al., 2017). Following the declaration by WHO of a pandemic, the Australian Government closed its international air and sea borders on 20 March, negatively impacting freight availability.

Operators around Australia were left with live catches of several species waiting for export. Average prices for exported TRL lobster reportedly dropped 75–80 per cent (Plagányi et al., 2020a). In some cases there were large backlogs of seafood in holding tanks and a switch to exporting less-valuable frozen product (Plagányi et al., 2020a). This was also the case for all other major Australian lobster fisheries, live fish exports such as coral trout and shellfish such as abalone, all of which are subject to Australia's strict export laws. In response to the inability to freight produce overseas, short-term declines in catches were observed for some fisheries (Huveneers et al., 2021).

In April 2020, the Australian Government introduced an International Freight Assistance Mechanism whereby funding was provided to recommence shipments to China and other countries in an effort to assist Australia's stalled seafood and agriculture export trade (Ogier et al., 2021). Given that many countries closed their borders to overseas visitors, these special freight flights meant that seafood shipments could recommence despite the otherwise restricted environment. Chinese demand for lobster remained low initially due to bans on large gatherings and festivals, but exports started again from Australia, while the PNG fishery remained closed.

Toward the end of the 2020 fishing season, there were few constraints affecting the export of TRL from Australia. As a result, there were reports of some diversification of the TRL supply chain, such as more frozen tails being exported. However, it was not viable to target local consumers, with the domestic market price being less than the harvest and marketing costs in the fishery. The domestic lobster price was further reduced as a result of reduced exports of lobsters from other fisheries nationally.

Following directly after the COVID-19 disruptions, in October 2020 (when the TRL fishing season had ended) there was a second major disruption to lobster exports following reports that unacceptable levels of cadmium were found in a shipment of western rock lobsters (*P. cygnus*) to Shanghai, which resulted in delays to live lobster shipments to China at the ports of entry[1]. This resulted in cessation of fishing in response to the associated uncertainty and concerns around the potential for delays in border clearance to potentially affect all seafood and several other food products exported from Australia.

Impacts on the Scientific Process and Survey

An indirect impact of COVID-19 was that TRLRAG meetings were changed from an in-person format to teleconferences. This involved considerable preparation by the fisheries management authority given the challenges of limited suitable facilities in some of the remote island locations. However, these meetings proceeded smoothly and hence this aspect is not considered further. One ongoing aspect is that some non-critical analyses that require longer, more in-depth discussions were delayed.

There were impacts of COVID-19 on the planning and operation of the 2020 fishery-independent survey, however, this did not compromise the process of data collection once the survey commenced. Survey staff were required to liaise with government agencies, such as the State health department, and Torres Strait community stakeholders to determine requirements to enter and work within vulnerable communities. Management Plans were developed to manage the changing level of risk posed by COVID-19 for staff to travel and complete the survey. The Plans considered COVID-19 testing for survey and vessel charter operator staff, alternative travel such as chartering planes rather than commercial flights, the use of Personal Protective Equipment, Safe Operating Procedures on board the charter vessel such as daily temperature checks, strict hygiene practices, limiting contact with communities and appropriate emergency response to address possible development of COVID-19 symptoms during the survey.

Fortunately, there were no outbreaks in Queensland during the months leading up to the survey, and hence the scientific survey was successfully conducted in 2020, ensuring continuity of the 32-year data series.

Fishery Data

The total reported catch for the Australian TRL fishery (1 December 2019 to 30 September 2020) was 361.3 tons, with 216.2 tons caught by the TIB sector and 145.1 tons caught by the TVH sector (**Table 1**). The total reported catch from PNG was 90.4 tons (January–August 2020) which was extrapolated to a full year using a pre-agreed approach, yielding 126.4 tons. The 2020 catch was 84% of the TAC with a proportion of the shortfall attributable to impacts of COVID-19 in 2020 (based on discussions in TRL RAG meeting in May 2020).

During the initial period when live lobsters could not be exported, some product was converted to tails which could be frozen and stored. It was therefore anticipated that there would be an increase in the proportion of tailed product, but this effect was barely noticeable when evaluated using the entire year's data for the Australian sector (Deng et al., 2020a).

There were clear differences in the pattern of fishing through the year by the different sectors (**Figure 3**), as well as changes in economic drivers which would have likely influenced when fishing took place as well as the product type targeted. It was noted that these factors could potentially all bias the catch and effort data in terms of their representativeness as an index of stock abundance.

A comparison of the relative proportions of the total annual catch that is taken by the TIB and TVH sectors in different months shows a particularly marked difference for the TVH sector in 2020 (**Figure 3**). There is a particularly strong signal during February, and extends slightly into March. February is usually a peak catch month but the impact on catch patterns, presumably due to the disruption to the export market, is clearly seen for the TVH sector in particular which ceased fishing entirely over this period. Both sectors then seemingly compensated for lost catches during the middle of the season with a substantial increase in catches during April. For the TVH sector, the data shows an extended increase in effort up until July, and then a drop as the TVH TAC allocation is approached (98.7% of TVH quota allocation achieved). For the TIB sector, increased effort appears to be sustained until August and drops to average levels in September leading up to the fishery closure, with the final TIB sector catch being less (75.1%) of the TAC allocation.

Both the TVH and TIB sectors recorded significant effort decreases coinciding with initial COVID-19 outbreaks in early 2020. However, catch rates for both sectors increased substantially later in the 2019–2020 fishing season, and the annual CPUE point estimates were the highest values recorded in the past five seasons.

Both the TIB and TVH standardized CPUE series showed some differences from the nominal (unstandardized) series,

[1] https://www.afr.com/politics/china-widens-trade-sanction-net-to-cover-all-fishermen-20201108-p56cig

TABLE 1 | Summary of recent catch (t) per Torres Strait (TS) sector shown as a percentage of the Total Allowable Catch (TAC).

Season	TIB	TVH	AUS-TOTAL	PNG-TOTAL	TS_TOTAL	TAC	Catch/ TAC
2013	142.5	361.7	504.2	108.3	612.5	871	70.3%
2014	198.8	273.2	472.0	261.2	733.2	616	119.0%
2015	202.6	152.7	355.3	235.7	591.0	769	76.9%
2016	267.1	243.0	510.1	248.0	758.2	796	95.2%
2017	111.5	166.3	277.8	113.0	390.8	495	79.0%
2018	127.4	128.3	255.7	156.4	412.1	320	128.8%
2019	260.6	155.9	416.5	167.0	583.5	641	95.1%
2020	216.2	145.1	361.3	126.4	487.7	582	83.8%

Australian (Aus) fishery sectors are Traditional Inhabitant Boat (TIB) and Transferable Vessel Holder (TVH) sector, and third sector is Papua New Guinea (PNG).

whereas there were minor differences only between alternative standardized series (Deng et al., 2020b,c). Two of the GLM variants that accounted for "year-by-month" effects indicated large deviations in monthly fishing patterns in the 2019–2020 fishing season, in particular for March, April, and May.

For the TIB sector, the 2020 nominal and standardized CPUE index point estimate is the highest since 2004 (Deng et al., 2020b), noting that no data were available for 2013. For the TVH sector, the 2020 CPUE index is also higher than average, although similar to the 2013 point estimate (Deng et al., 2020c). A higher than average CPUE was anticipated given the lobster stock was predicted from the survey and stock assessment to be at a high abundance level. For the TIB sector, the extremely high CPUE for the month of February and overall higher than average CPUE for all months (**Figure 4**) may be partly attributable to the change in lobster spatial distribution (more lobster along the western side) relative to the previous few years. It is also plausible that the delay in the start of intensive fishing had a positive influence on the CPUE because the lobsters had more time to grow larger (noting their rapid growth rate) during the "break" from fishing and may also have aggregated during this time. If so, there is potential for a positive bias (relative to previous years) that is not accounted for in the GLMs. It would be difficult to account for this in the GLM also because we would need an understanding of the underlying factors driving the catch rates (if not abundance).

The CPUE indices provide an index of the 2+ lobsters, which are not reliably counted during the Fishery-independent survey because most will have migrated out the survey area by this time of year. The two standardized indices can be compared to see whether they show similar trends in overall biomass, and this can also be compared with the model-estimated trend in the biomass of 2+ lobsters [in this case from 2019 stock assessment (Plagányi et al., 2020b)]. These three indices have been normalized by dividing by their mean value and the two CPUE indices show similar trends, plus are also consistent with the stock assessment model projections from the previous year (**Supplementary Figure 1**).

eHCR and Final Management Advice

In the case of total catch, the eHCR uses the average catch over the past 5 years as a multiplier to inform the RBC. This dampens the influence of the most recent catch value, but if the recent value is negatively biased (as is a possibility in this case), then it can have a reasonably substantial effect on the calculation of the RBC. In the absence of COVID-19, it was predicted that the total catch would be close to the TAC, hence the total average catch was considered to be slightly negatively biased. On the other hand, it was acknowledged that the TIB CPUE data could be considered positively biased. All stakeholders at the TRLRAG management meeting agreed that the 2019–2020 season was an anomalous year and that COVID-19 indirectly impacted the eHCR indicators in different ways (TRLRAG, 2020). The management forum considered a range of alternative scenarios and sensitivity tests pertaining to implementation of the eHCR, before deciding whether to recommend the default implementation of the eHCR, or to undertake an *ad hoc* adjustment.

As there was insufficient information to fully quantify the impacts of COVID-19 on the fishery-dependent data, the TRLRAG felt they could not reasonably justify stepping outside the bounds of the agreed harvest strategy and hence there was agreement to accept the default application of the eHCR without any *ad hoc* adjustments. The global TAC for the Torres Strait Protected Zone (TSPZ) for the 2020–2021 season was thus of 623.5 tons, which is only slightly lower than the long-term average (**Figure 5**).

The influences of COVID-19 on the fishery-dependent data highlighted the valuable role that fishery-independent surveys play in terms of providing reliable information to ensure sustainable management. Ongoing work is focused on improving understanding of potential improvements to the standardization of CPUE data, and in particular, how to account for inter-sector interactions.

Supply Chain Resilience

The TRL fishery is exploited by both non-Indigenous and Indigenous Islanders, for whom it has cultural significance (Plagányi et al., 2013; Van Putten et al., 2013). TRL are passed down the supply chain either as live lobsters, which are mostly exported to China or frozen tails that are exported to the United States, predominantly *via* a holding facility in Cairns (**Figure 2**). Future analyses could be extended to include more complex aspects of the associated cross-jurisdictional regulations and management with PNG, as well as the closely-related East Coast tropical lobster fishery (**Figure 1**).

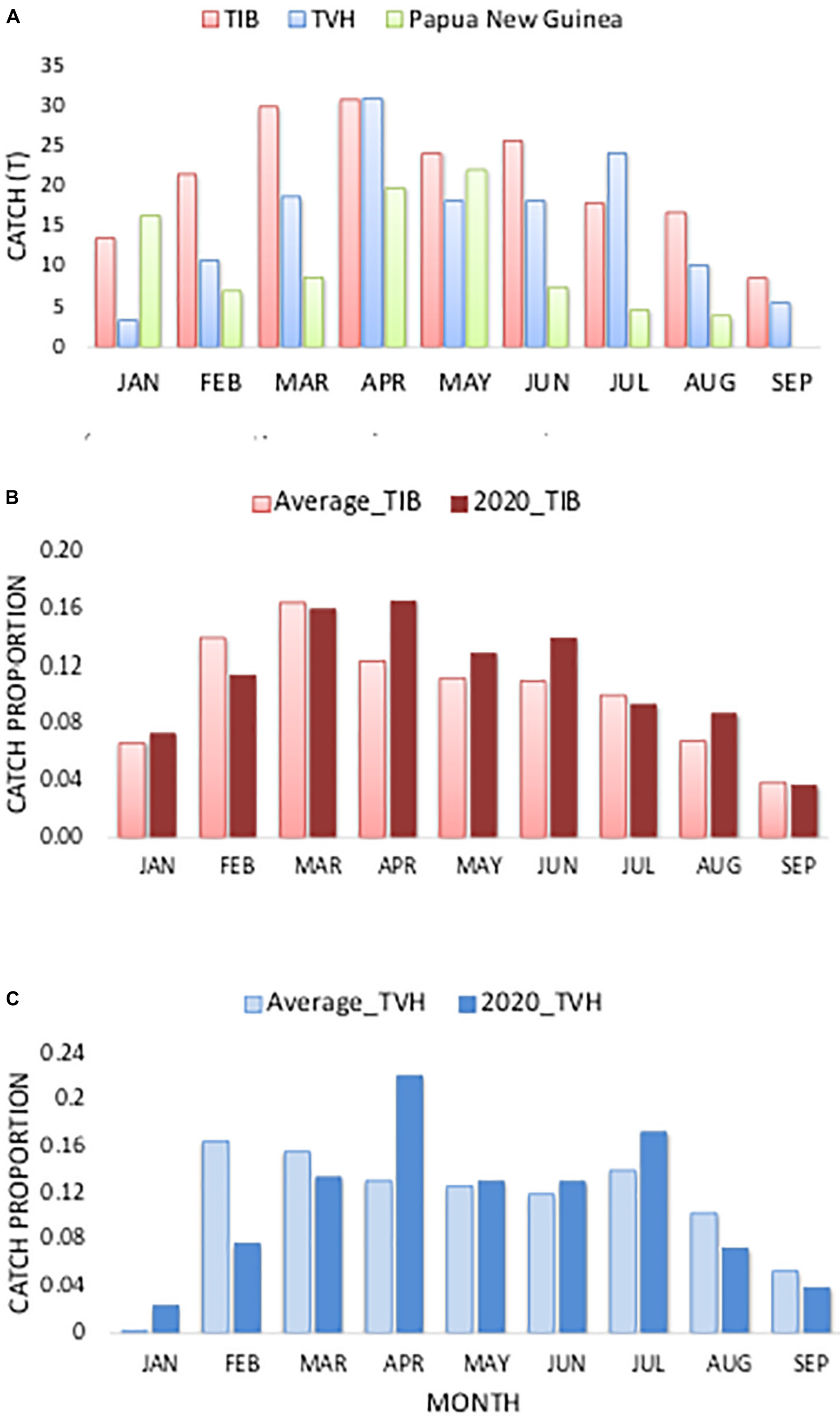

FIGURE 3 | Comparison of the relative proportion of fishing by **(A)** all sectors compared and **(B)** TIB sector and **(C)** TVH sector for months as indicated compared with the average pattern (average over 2004–2019). Data for Papua New Guinea (PNG) available until end of September only.

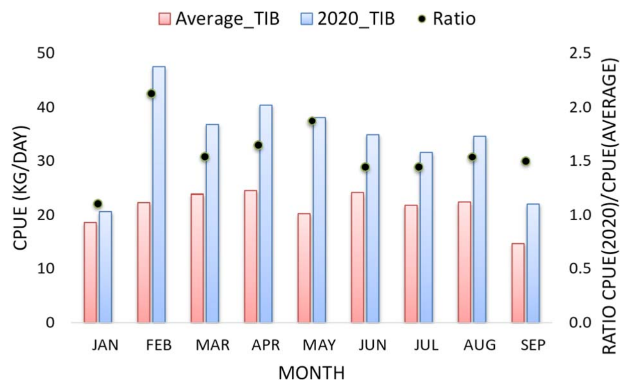

FIGURE 4 | Comparison of nominal 2020 monthly CPUE for the TIB sector with the average computed over the preceding period 2004–2019. The second vertical axis shows the ratio of the 2020 monthly CPUE relative to the average pattern to highlight the anomalous pattern observed at the start of 2020.

Over the past decade, live lobsters from PNG and the related East Coast tropical lobster fishery are also predominantly channeled *via* facilities in Cairns (Plagányi et al., 2017). In addition, there has been an increase in alternative TRL processors, which is not represented in **Figure 2**.

Under Scenario (A), the Resilience Score was 0.92 and the SCI identified the Chinese and United States markets as key elements (**Table 2**). However, under Scenario (B) which more closely reflects the pre-COVID-19 supply chain, the Resilience Score is reduced to 0.89 and the criticality of United States markets declines and is replaced by air freight being identified as a critical element. This suggests that the key mechanism for stabilizing this supply chain is to reduce uncertainty in supplying these markets. The supply chain analyses of Plagányi et al. (2014) therefore stressed that maintaining and strengthening relationships with international markets is key to underpinning the success of this supply chain. Since that time, and as illustrated by this analysis, the criticality of these elements has increased further and as they were the supply chain elements impacted by COVID-19, it is not surprising that the fishery took a huge knock.

One potential adaptation strategy that has been suggested is to increase the domestic market. Scenario (C) suggests that shifting one-quarter of product to the domestic market would increase the supply chain resilience to 0.93 (**Table 2**). The resilience of the supply chain can be strengthened further through even greater diversification of the supply chain—for example, if the domestic market absorbs half the product and the rest is split between frozen tail and live exports, then the resilience score increases to 0.94. Under optimized Scenario (D), domestic consumers are identified as the most critical node, followed by air freight handling and the Cairns processor (**Table 2**). Scenario (D) is the most diversified of the supply chain configurations analyzed and the high resilience score of 0.94 is further contrasted with an extreme streamlined scenario whereby only 5% of product is frozen and tailed, with corresponding resilience score of 0.87 (**Table 2**).

The distribution of key elements along the chain under alternative scenarios (**Figure 6**) is a useful way for highlighting the relative spread of risk across the nodes. For example, the relative distribution of SCI scores under Scenario (B) suggest a less resilient overall structure than the more evenly distributed pattern that is estimated under Scenario (D) (**Figure 6**). One important factor to consider is that the supply chain analyses have been considered as insular and independent of other changes in substitute products and products that compete on the local and international markets; and therefore future improvements in these analyses could incorporate the cross price elasticities of substitutes.

DISCUSSION

COVID-19 exposed large differences in the resilience of different seafood systems as well as shedding light on broader inequalities across societies (Love et al., 2020). Different countries were affected by different levels and responses to COVID-19, whereas different industries fared differently depending on factors such as whether they relied on fresh or frozen produce, local or overseas export markets, as well as the diversity of networks connecting fishers to buyers and consumers. In remote fishing communities such as Torres Strait, the livelihood of many small businesses and communities depend on the TRL fishery. During the initial stages of the COVID19 pandemic, fishers were not able to work and for Indigenous Torres Strait Islanders, there were limited alternatives given their geographical setting. The effect was compounded due to their efforts over the past few years to maximize the value from their fishery by transitioning to exporting live product rather than relying on domestic markets. Torres Strait lobster fishers were not alone in absorbing the financial consequences of this risk, as much of the country's high-valued product is exported. For 2018–2019, it's estimated that lobsters, abalone, prawns and bêche-de-mer contributed nearly 60 per cent of the $2.1 billion total value of wild caught seafood.

Fortunately for TRL, the disruptions occurred for only a relatively short period early in the season and once fishing resumed, both the TIB CPUE and TVH CPUE indices suggested that fishers were able to make up some lost catches because catch rates were high. The 2020 fishery-independent survey was conducted successfully and hence the survey data were unaffected by COVID-19. The fishery-independent 1+ and 0+ survey indices that are used to inform on likely abundance in the following fishing season both exhibited positive trends. Although the 0+ index is less reliable, the positive trend provides an indication of what is to be expected in future seasons. The TRLRAG considered that the eHCR was reasonably robust to this single anomalous event. The eHCR captures longer-term trends over a 5-year period, it places substantially more weighting (80%) on the fishery-independent survey which is not affected by trade and other disruptions. Also, using a 5-year average (including average catch) helps to dampen the influence of a single anomalous year. However, using a 5-year average also means that the abnormal 2020 catch will have a dampening impact on TACs for the following years.

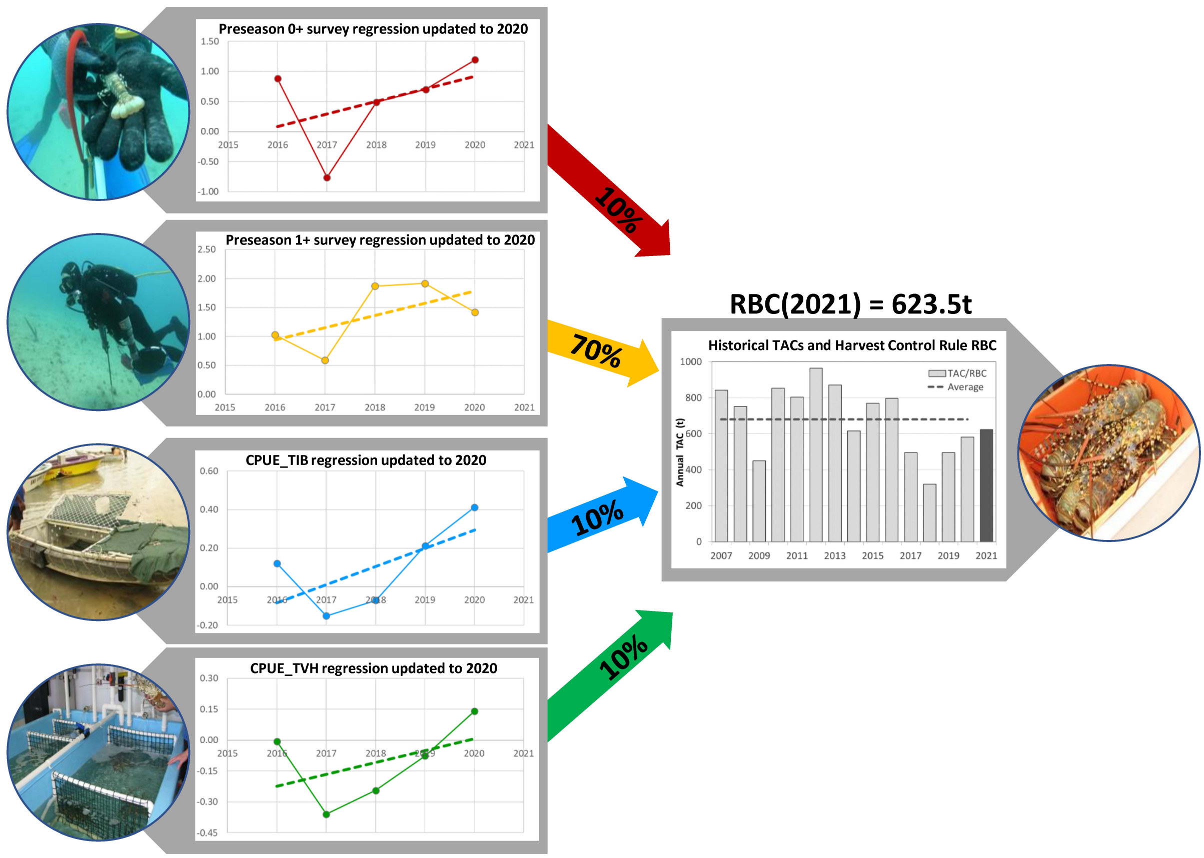

FIGURE 5 | Schematic summary of the empirical harvest control rule (eHCR) used to calculate the TRL (Tropical Rock Lobster) RBC (Recommended Biological Catch) based on the CPUE (Catch Per Unit Effort) data from two fishery sectors, the scientific survey indices of two age classes, and the total average catch over the past 5 years.

TABLE 2 | Examples of alternative supply chain scenarios showing the standardized SCI (Supply Chain Index) and Resilience Scores, together with the top three key elements identified using the method of Plagányi et al. (2014).

Supply chain scenario	SCI (standardized)	Resilience score	Top 3 key elements		
Base (2012) (frozen tails and live; few domestic)	0.084	0.92	Chinese importer	Chinese consumers	United States importer
Mostly live exports (14% tails, 5% domestic)	0.112	0.89	Chinese importer	Chinese consumers	Air freight
Increased domestic (25%) and similar tails and live	0.067	0.93	Air freight	Chinese importer	Chinese consumers
Optimized design with bigger domestic share	0.059	0.94	Australian consumers	Air freight	Cairns processor
Almost all live exports (5% tails, 5% domestic)	0.129	0.87	Chinese importer	Chinese consumers	Air freight

Although there were some concerns around the representativeness of some data during 2020, the eHCR was applied without any *ad hoc* adjustments because it was designed to be robust to uncertainty and variability in inputs. However, it was also recognized that a more formal process was needed to support decision making should similar anomalous events occur in the future. It is recognized that it isn't possible to design a harvest control rule that accounts for all possible contingencies (Butterworth, 2008). This highlights the need for further development of pre-agreed "exceptional circumstances" rules to handle events that are outside the bounds considered in the testing phase, or that provide new information that underscores the need to review the original performance of the HCR (Hillary et al., 2016).

The full economic impact of the coronavirus on the Australian seafood industry will not be known for some time, as markets and exporters are attempting to adapt to the situation.

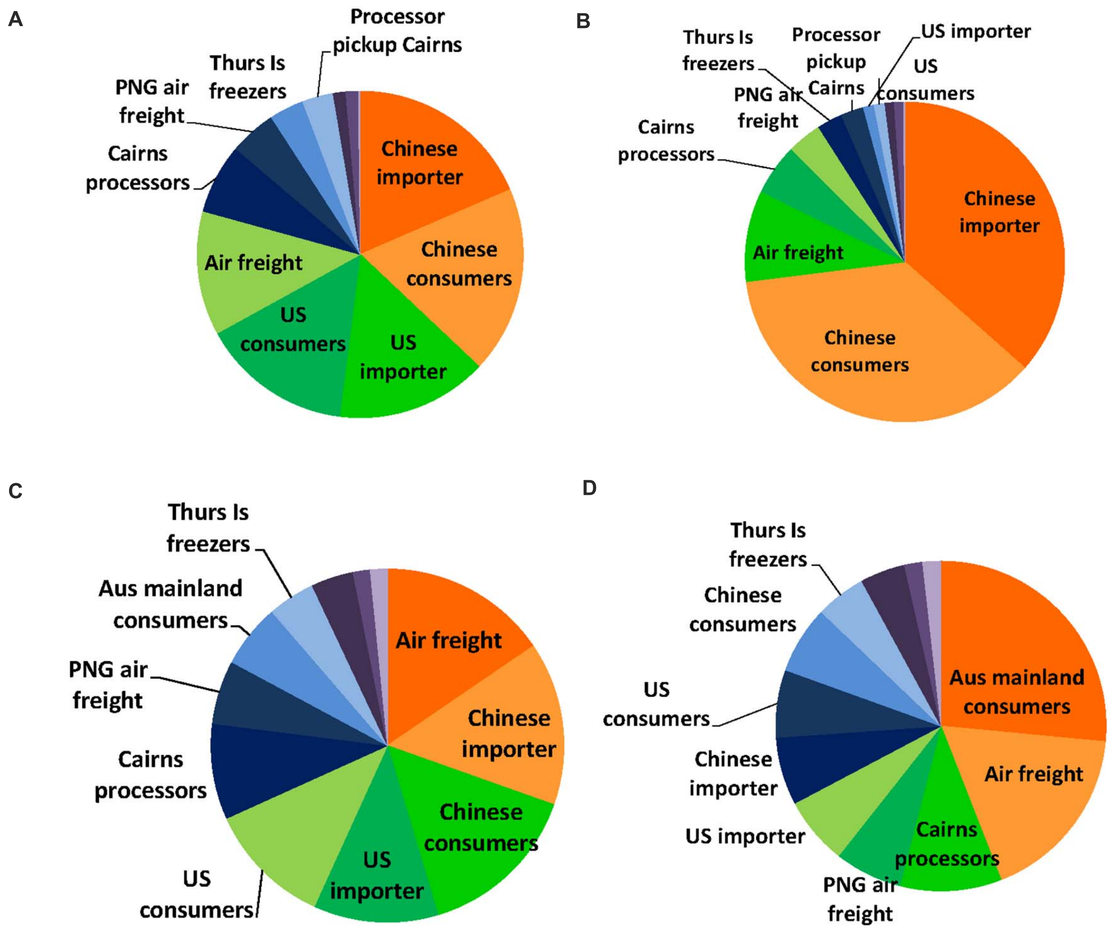

FIGURE 6 | Pie diagrams summarizing the criticality (based on individual Supply Chain Index score of each node) of elements in Tropical Rock Lobster supply chain scenarios: **(A)** 2012 base-scenario with substantial proportion of product sold as frozen tails, **(B)** 2019 scenario with very small proportions of tails and few domestic sales, **(C)** illustrative scenario with larger proportion of product sold on the domestic market, **(D)** optimized scenario with substantially more product going to domestic market and even split between frozen and live. The size of pie segments represents how critical a node is, and the overall distribution of segments provides an indication of the spread or evenness of the scores attached to different nodes. From highest to lowest scores, the color coding used is roughly red (>20%)-orange-green-blue-purple.

However, it is expected to be significant in terms of short-term revenue and employment.

For some fisheries that are regulated by a quota system, if they catch less this year, then it is possible they will be able to take slightly more next year without negatively affecting the resource. Depending on how management responds, they could partially (but not fully) offset economic losses longer term. This, however, will not be the case for the Torres Strait lobster fishery.

The Torres Strait lobster fishery is fairly unique in relying on short-lived, fast-growing lobster stocks, unlike many other lobster fisheries across the world which harvest the cold-water, long-lived, slower-growing species (Phillips, 2008). Catch and revenue each year depends on how many lobsters are available. This makes it different to fisheries that rely on longer-lived animals for which short-term declines in revenue and employment can be partially offset as fish not already landed may contribute to future yields once the current crisis subsides. For example, government in South Australia, Victoria and Tasmania are allowing uncaught Southern rock lobster and abalone (Victoria only) quotas in the 2019–2020 season to be rolled over to the 2020–2021 season. In Western Australia, the rock lobster fishing season was extended, and the TAC has been increased[2].

The economic market linkages and global connectedness of our trade systems may increasingly be subject to unforeseen social-ecological vulnerabilities (Adger et al., 2009) and transformative changes to develop more resilient supply chains (Lim-Camacho et al., 2017) may be needed to ensure ongoing sustainability of global production ecosystems (Nyström et al., 2019). Many small-scale fisheries lack the capacity to mitigate global market forces and more international solutions are needed, such as development of insurance opportunities by international financial institutions (Knight et al., 2020). There has been an increase in the appreciation of the need to adopt triple bottom line approaches to fisheries management (Plagányi et al., 2013;

[2]https://www.frdc.com.au/media-publications/fish/FISH-COVID19-Special-Issue-1/Management-moves-to-help-commercial-fishers

Dichmont et al., 2020) but much more work is needed to ensure that supply chains are adaptable enough to ensure that the outlets for seafood products are maintained in the future. This is vital not only for economic stability, but also the livelihood and mental health of fishers, their socio-cultural wellbeing, and food and nutrition security globally (Hicks et al., 2019).

Previous studies have identified the need to build resilience to changing climate as an increasingly important challenge to supply chains (Levermann, 2014; van Putten et al., 2016; Lim-Camacho et al., 2017). COVID-19 has confronted supply chains with similar disruptions to transport and markets as climate change is predicted to do, and hence we have applied the same method to analyze the connectivity of supply chains and to identify the key agents in these chains which may be fragile and hence in need of focused attention. Our analyses highlight the changes which can result from lessening the dependence on a single key element and strengthening or adding alternative complementary pathways and connections. We provide an example also of using the approach as a tool for supply chain design and redesign strategies. As with many other fisheries, economic rationalism has tended to favor a more streamlined, efficient and linear supply chain for lobster fisheries. Our analyses add to the growing recognition that market diversification is essential to fisheries sustainability (Plagányi et al., 2014; Lim-Camacho et al., 2017; Knight et al., 2020).

In the illustrative optimization scenario we developed (**Table 2**), we assumed that Australian mainland consumers would be able to absorb additional product (and pay a reasonable price), but in reality the resilience of any such redesigned supply chain strongly depends on the extent to which this assumption holds.

While transport costs would be significantly reduced, COVID-19 highlighted that increased supplies to the domestic market may also result in a substantial decrease in prices received. Additional contingency plans that were implemented during COVID-19 were to introduce mechanisms that helped increase efficiency in selling catches locally, International Freight Adjustment Mechanism, waiver boat license and quota fees, allow for alternative access options (i.e., permits for other fisheries) (see text footnote 2) and diversify product types that are more versatile in terms of "storability" [for example, converting fresh product to frozen tails (lobster) or canned product (abalone)], but there are significant costs to this adaptation strategy which also need to be considered. Fishery businesses should ideally pay more attention to supply chain risks and business continuity planning (Ogier et al., 2021). We recommend therefore that the SCI be used in combination with market demand (Hobday et al., 2014; Pascoe et al., 2021) and supply analysis and supplemented by qualitative assessment of each supply chain phase.

The pandemic brings to the forefront the fragility of the current economic market linkages and global connectedness of our trade systems. Some of our earlier research analyzed fishery supply chains and found that the key components of lobster supply chains that were most vulnerable to external shocks were the Chinese consumers, processors and airports (Plagányi et al., 2014). Our scientific scenarios have played out in real life and highlight the need for transformative changes to develop more resilient supply chains to ensure the ongoing sustainability and security of seafood and other natural resources production (Lim-Camacho et al., 2017).

DATA AVAILABILITY STATEMENT

The data analyzed in this study are subject to the following licenses/restrictions: Data include details of fishing by Indigenous fishers and only available on request in an aggregated form. Requests to access these datasets should be directed to ÉP, eva.plaganyi-lloyd@csiro.au.

AUTHOR CONTRIBUTIONS

ÉP conceived and wrote the manuscript, assisted also by SP, LB, and MT. ÉP and RD implemented the harvest strategy. ÉP did the supply chain analyses. NM, MT, SE, KS, and LD collected the field data. SP and TH collected economic information. ÉP, RD, SE, and NM analyzed the data. All authors contributed to the article and approved the submitted version.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2021.686065/full#supplementary-material

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Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.