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ORIGINAL RESEARCH

Innovation to limit seafood fraud post-COVID-19

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Abstract Seafood is an important source of protein and micronutrients, but fishery stocks are increasingly under pressure from both legitimate and illegitimate fishing practices. Sustainable management of our oceans is a global responsibility, aligning with United Nations Sustainable Development Goal 14, *Life Below Water*. In a post-COVID-19 world, there is an opportunity to build back better, where locally sourced food via transparent supply chains are evermore important. This article summarises emerging research of two innovative case studies in detecting and validating seafood provenance; and using alternative supply chains to minimise the opportunity for seafood fraud in a post-COVID-19 world.

Keywords Traceability · Provenance · Sustainability · COVID-19 pandemic · Fish and seafood fraud

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Introduction

The world over, there is increasing reliance on seafood for food security. The most recent assessments by the Food and Agriculture Organization of the United Nations (FAO) revealed 35.5 percent of fish stocks are classified as overfished with increasing trends in overfished stocks and declining trends in sustainably fished stocks, now resulting in very few underfished stocks remaining (Food and Agricultural Organization of the United Nations 2022a). Illegal fishing is considered a key driver of overfishing, further threatened by climate change (Food and Agriculture Organization of the United Nations 2016: 5–7). Further, in 2020 the FAO's assessment concluded that fishing supply chains are long and complex, and many points of opportunity along the supply chain are opaque, making them vulnerable to fraudulent activity (Food and Agriculture Organization of the United Nations 2020). Worsened by the COVID-19 pandemic, supply chains lacking in transparency may become even more fractured and vulnerable to fraud affecting fishers, industry and consumers (Onyeaka et al. 2022; Love et al. 2021; Mausch et al. 2020). As such, this global crisis provided an opportunity to review and adapt supply chains (Amos et al. 2022).

At the local level, every country is charged with the responsibility to control its borders and supply chains entering through them. Law and border enforcement is tasked to control points of supply chain entry, extending to seafood, in collaboration with customs, agricultural, and food administration and regulatory bodies. Seafood products may cross several borders before becoming available for consumer purchase, muddying the supply chain and challenging authorities and regulatory controls in validating true provenance. This systemic problem existed before COVID-19 and therefore justifies the need for greater innovations in this space. Industry also has an important role to play in establishing and maintaining transparent supply chains and fill a gap where traditional government-led regulators are unwilling or unable to do so. However, domestic policies are often predicated on international.

At the international level, there exists strong commitment to build resilient seafood stocks. The United Nations (UN), through its various bodies, is committed to build sustainable fishing industries by tackling issues such as overfishing and environmentally damaging practices. Building sustainable fishing industries necessitates transparent supply chains and the use of innovative testing regimes to verify catches. Efforts to bring attention to unsustainable fishing, namely illegal, unreported and unregulated (IUU) fishing (Food and Agricultural Organization of the United Nations 2001) have been effective. However, the problem of seafood supply chain fraud could be more widespread than IUU fishing and thus challenging to quantify the full extent of the problem. Seafood fraud involves activities to intentionally deceive the consumer for criminal profit. This may include food mislabelling; adulterating; misrepresenting the country of origin, species, and/or gear and equipment used to fish; and repackaging (Lindley 2021). Problematically though, international responses to IUU fishing are recommendary rather than obligatory on relevant signatory states (Food and Agricultural Organization of the United Nations 2000). As such, while there is a strong commitment at the international level, it relies on adequate domestic uptake.

The UN's Sustainable Development Goals (SDGs) enhance the resilient fisheries agenda. Most relevant, Goal 14 is the overarching Goal that sets out to resolve global challenges related to life below water (United Nations 2015). Within it, Goal 14.4 set out to effectively regulate in pursuance of ending IUU fishing, and Goal 14.6 set out to prohibit incentives that essentially amount to corrupt licencing and that provide opportunity for overfishing that contributes to IUU fishing, both by 2020 (United Nations 2015). These goals were unmet by 2020, and with a view to extend and expand these goals (among others), in 2021, the UN hosted its inaugural global Food Systems Summit during the UN General Assembly. The Summit builds on the SDGs bringing issues such as nutrition; access to food; sustainable food production; building resilient food supply chains; and limiting food waste sharply into focus to strengthen food systems, together (United Nations 2021). These goals are particularly important amidst the COVID-19 pandemic where the pre-existing opportunity for fraud is exacerbated (Love et al. 2021; Onyeaka et al. 2022). Disappointingly, the Summit did not broaden out to "food fraud" in its remit, thus, the role of industry is even more central to building sustainable, traceable, resilient fisheries supply chains.

Despite positive steps forward, presently, no such international overarching law exists that addresses seafood fraud. The reason for this is that there is no binding universal definition of (sea)food fraud, despite some international progress to address this definitional gap. Without an agreed, binding definition, harmonised regulatory responses are challenging. The FAO and UNODC are cooperatively developing a model law to guide states on combatting crimes in the fisheries sector (Food and Agriculture Organization of the United Nations 2022b). This model law suggests including seafood fraud, however without a universally agreed definition this will not resolve the issue. The fisheries domain is already very well regulated to the point of "treaty congestion" (Lindley and Techera 2017), therefore instead of looking to further regulate fisheries, consideration should be given to broadening a public and private mix of fisheries regulators.

The important role of industry in securing supply chains in cooperation with international and domestic regulators cannot be overstated. Such organisations work alongside primary industry and regulators to target and 'clean' vulnerable loopholes disabling opportunities for fraudulent activity. For example, verifying provenance through innovative scientific traceability and testing tools establishes supply chain reliability (Leal et al. 2015; Gopi et al. 2019a; Reis-Santos et al. 2022). Not only can this important verification prevent fraud, and boost consumer confidence in the industry, but potentially provide a scientific evidence base to prosecute fraudulent offenders.

Research confirms that establishing and maintaining a secure and transparent supply chain of all foods, including seafood supply is essential (Kodana et al 2022). More broadly, research suggests that resulting from COVID-19, consumers are even more concerned about their food traceability (Quevedo-Silva et al. 2022). Indeed, as we emerge from COVID-19, we must take opportunities to rebuild and "build back better" (Michie 2020). As such, in this paper, we showcase emerging innovations to enhance seafood sustainability. Specifically, drawing on the combined research of experts who presented within the "Sustainability" stream at the *2021 World Fisheries Congress*, we discuss and provide our perspective on the benefits of emerging scientific methods used to test and validate seafood catches drawing on practical, real-world uses. We then explore the shift from global to local supply seafood chains in response to the COVID-19 pandemic and the viability of sustaining local supply going forward. Collectively, these innovative approaches encourage sustainable and resilient fisheries supply chains globally and locally, and potentially, safeguard against future pandemics.

Global: test and validate

As food labelling and traceability systems are being increasingly implemented by both governments and seafood businesses, there is a concurrent need to validate the accuracy of these systems to identify fraud, support fisheries control and uphold compliance schemes, independently of the producer's or retailer's information. As noted previously, seafood fraud occurs in two key forms, whereby retailers and consumers are intentionally deceived about (1) the authenticity of the traded species of seafood; or (2) the provenance of the seafood (e.g. location of capture, wild or farmed). DNA and other molecular-based techniques have been a mainstay for validating seafood species authenticity, with numerous studies and reviews discussing the advantages of established and emerging approaches (e.g. Bernatchez et al. 2017; Cusa et al. 2021; Martinsohn et al. 2019; Silva & Hellberg 2021). Advances are also being made in terms of using DNA to determine species' provenance to specific stocks and locations of origin spurred by increased spatial resolution on population structure assessments (Ogden et al. 2008; Bernatchez et al. 2017; Cusa et al. 2021; Del Rio-Lavin et al. 2022). As costs of DNA analyses continue to drop, we anticipate their broadscale application to increase, particularly as the monetary returns from compliance and enforcement penalties can outweigh the costs of DNA-based monitoring (Martinsohn et al. 2019). Here we focus on a much more nascent field of seafood provenance and how we can draw on key innovations in other research fields to develop effective methods to validate the provenance claims, i.e. the geographical origin, of seafood products.

Practical use

Ecologists and fishery scientists have long used geochemical markers in biomineralised tissue to track the movements and habitat use of marine animals, as well as delineate the stock structure of commercially harvested populations (Elsdon et al. 2008; Reis-Santos et al. 2022; Tanner et al. 2016). Geochemical markers are based on the underpinning theory that certain trace elements and isotopes incorporated within biominerals, such as shells and earbones (otoliths), reflect the biological and physical environment of an organism, such as diet, seawater chemistry, temperature and underlying geology. Biomineralised tissues are particularly useful for tracing the geographic origins of seafood as they are metabolically inert and the chemical information is permanently locked in the carbonate matrix. Individual isotope tracers such as $\delta^{18}O$ or $^{87}Sr/^{86}Sr$ (the latter useful in freshwater organisms only) are incorporated with little or no physiological constraints and can be applied universally; further, multi-elemental tracers can be readily optimised for individual species across different spatial resolutions (Doubleday et al. 2022; Reis-Santos et al. 2022). This contrasts with chemical markers bound within soft tissue, such as muscle, which are subject to tissue turnover (i.e. chemical markers are constantly reworked via physiological processes) and can be highly variable through time and among individuals and life history stages. Yet, soft tissue markers, based on stable isotopes, multi-element profiles, or fatty acids, remain the backbone of emerging chemical methods for seafood provenance (Cusa et al. 2021; Fonseca et al. 2022; Gopi et al. 2019a; Li et al. 2016), and there are a surprisingly small number of published studies focussed on biomineralised structures, which are largely constrained to molluscs (e.g. Daryanani et al. 2021; Mamede et al. 2021; Ricardo et al. 2015), with the exception of one study which focussed on multiple marine taxa (Martino et al. 2022b).

To date, multi element profiling via solution based inductively coupled plasma mass spectrometry (ICP-MS), whereby whole or bulk samples are digested in acid before analysis, has been the key technology adopted to analyse geochemical markers in biominerals for seafood provenance applications. However, laser ablation ICP-MS (LA-ICP-MS), whereby specific biomineral regions are targeted for analysis using a laser, could be a more cost and time effective approach for high throughput analyses. LA-ICP-MS is becoming a routine analytical technique in forensic laboratories, is based on well-established methods and standards that are readily available, requires minimal to no sample preparation, effectively removes contamination risk, and only requires a small amount of sample material (Orellana et al. 2013). To date, the use of LA-ICP-MS to investigate the provenance and movement of marine animals has been largely spearheaded by ecologists, with only two known studies capitalising on this technology with seafood provenance applications in mind (Daryanani et al. 2021; Pereira et al. 2019). Overall, whilst the ease of preparation and high throughput of LA-ICP-MS analyses in biomaterials are being harnessed to support fisheries management, their application to inform seafood provenance, compliance and policy options is still scarce (Reis-Santos et al. 2022). Potential barriers to the uptake of LA-ICP-MS may include misguided assumptions and lack of awareness of the ease of preparation, low cost per sample, and the efficiencies of using this approach for large sample sizes. However, accessibility to LA-ICPMS varies regionally, which is likely to influence uptake. Similarly, standard analytical methods used to analyse stable isotopic tracers in biominerals (e.g. isotope ratio mass spectrometry or IRMS), may face similar barriers to uptake. While methods like IRMS are not high-throughput like LA-ICPMS, sample preparation can be minimal for biominerals, as well as backed by well-established methods.

Regardless of the tracer or analytical technology used, a major advantage of biominerals is that they can be easily removed from the animal (including, with little to no loss of value to traded seafood) and stored dry with minimal maintenance and cost. Biomineral collections are also widely available for many taxa (particularly fish earbones in fisheries research and management agencies), and they provide a cost-effective means to repurpose existing samples to create global reference databases of origin of known samples from major fishery areas that are of key interest to evaluation seafood fraud. These sample stockpiles are an untapped opportunity to bypass the logistic and financial challenges of developing global geographic baseline databases or spatial reference models to verify origin claims and to underpin fisheries management and compliance throughout the supply chain. Moreover, these broad spatiotemporal archives allow researchers to determine how much isotopic and elemental signatures vary over time, which is an important consideration when using chemical markers, and is often pointed out as a drawback preventing industry uptake of chemical marker approaches (Camin et al. 2016; Martino et al. 2022b; Reis-Santos et al. 2022).

The main limitation of any natural tracer is that its accuracy is mediated by the natural variation of the tracer of interest in the environment. Thus, the power to discriminate among organisms that are collected or produced in constrained environments [e.g. lakes, rivers or estuaries—where elemental profiles of hard tissues can discriminate among sites as close as 1 km apart (Ricardo et al. 2015)] are likely to be larger than the spatial resolution at which we can determine the origin of species living in oceanic habitats. This is due to the lack of physical boundaries or the broader scale at which physico-chemical variations take place in marine environments. Ideally, in oceanic environments, we should aim to develop spatial models of chemical variation that ultimately provide maps of tracer variation and thresholds for organism assignment on a global to regional scale (Cusa et al. 2021). This was recently achieved using oxygen isotopes in biominerals, whereby global patterns were mapped in the ocean and subsequently used to track the origins of seafood (Martino et al. 2022b). While the approach worked well across latitudinal gradients, the method needs to be combined with additional tracers to improve spatial resolution.

Whilst there is no silver bullet or one method that fits all, we can take advantage of the knowledge and technology used by ecologists to trace the provenance of seafood and identify markers that work best for different products and across the entire supply chain (e.g. Gopi et al. 2019b; Cusa et al. 2021; Duarte et al. 2022; Fonseca et al. 2022; Reis-Santos et al. 2022), and speed up response times for authorities aiming to safeguard compliance and claims on geographic origin. Building on lessons learnt with otolith chemistry research (Tanner et al. 2016; Reis-Santos et al. 2018; Brophy et al. 2020), one key approach to refine provenance analyses can be the integration of different markers and tissues defined by distinct environmental and biological constraints. In doing so, we are combining independent but complementary information that can increase the spatial resolution and accuracy of provenance verification (Busetto et al. 2008; Gopi et al. 2019a; Cusa et al. 2021; Martino et al. 2022a). Further, by fusing data from multiple bio-markers, such as DNA and biomineral chemistry, we could create an even more powerful method to validate food provenance (Cazelles et al. 2021). Though it is important to evaluate the cost and time benefits of using multiple methods.

The implementation of provenance regulations is deficient globally, largely inconsistent across jurisdictions, and faces many challenges, including regarding labelling standards, regulations and incentives to apply provenance tools (Lindley 2021, 2022). Therefore, all stakeholders and players across the supply chain will play a key role in developing a coordinated effort for method development and driving the momentum for widespread implementation (Martino et al. 2022b). Innovative approaches using tamper-proof, high throughput analyses in hard tissues, together with other approaches such as DNA and biochemical analyses (e.g. Cazelles et al. 2021; Fonseca et al. 2022), will play a key role in validating seafood provenance and, therefore, supporting managers and regulatory agents in taking action on compliance, enforcement and traceability of seafood products along the supply chain. A key developmental step is to evaluate the effectiveness of different markers together with the costs-benefits of their combined use to boost and operationalise their widespread implementation. Secondly, we need to strengthen communication between researchers, industry and regulators, as well as demonstrate the tangible benefits of analysing chemical markers in biominerals, translating these benefits to the sphere of seafood provenance, and building a platform for widespread implementation. With COVID-19 changing what and how we eat, as well as the sources of our food, we now have a window of opportunity to build back better and sharpen our focus on developing frameworks to validate the provenance of seafood. Geochemical markers are already well-developed in the fields of ecology and fisheries science, and with time, these markers could be a mainstream tool for seafood provenance applications, reducing their costs and increasing their accessibility to seafood businesses.

Local: alternative supply chains

The globalisation of the seafood industry has resulted in a range of socioeconomic benefits, including increased food security and employment opportunities (Asche et al. 2015). However, the long, convoluted global supply chains often carry large environmental footprints and can easily mask undesired or illegal behaviours such as fraud, mislabeling and human rights abuses (Kumar 2019; Kummu et al. 2020). As the distance from the end consumer grows, it becomes much more challenging to ensure traceability and visibility of these social impacts (Short et al. 2021). These long supply chains also make the global seafood economy more vulnerable to systemic shocks that disrupt the flow of products (such as COVID-19) (Gephart et al. 2017; Cottrell et al. 2019).

The COVID-19 pandemic increased the vulnerability of global seafood supply chains and likely exacerbated fraud and other illegal activities that were already occurring (Love et al. 2021; Onyeaka et al. 2022). In response, many small-scale operators have been prompted to seek out new ways of doing business to promote social and environmental values related to transparency and traceability throughout the supply chain (Witter and Stoll 2017). This has come in the form of adopting alternative supply chains, which generally seek to shorten or restructure seafood value chains. While alternative supply chains are not new, they have become more prevalent particularly in North America over the last two decades (Witter and Stoll 2017; Campbell et al 2014).

These alternative supply chains take many forms such as off the dock sales, farmer's market sales, *a la carte* ordering, online and on demand ordering, and seafood buying clubs. Different business models are often used in combination with one another as well (Bolton 2015; Bolton et al. 2016; Witter and Stoll 2017). Regardless of what form they take, those participating in alternative supply chains are primarily focused on shortening and restructuring supply chains to keep consumers and fishers as connected as possible (Campbell et al. 2014; Witter 2020).

At the outset, the transition of many seafood operators away from the dominant system and toward alternative supply chains happened not as a matter of innovation or desire to be different, per se, but out of economic necessity (Knutson 2017). Increasing globalisation has also largely marginalised small-scale operators, namely in the form of privatisation and consolidation. Alternative supply chains have been a way for small-scale operators to remain viable in a seafood economy dominated by industrial fishing consolidation (Carothers and Chambers 2012; Carothers 2015). However, more recently, the documented success of these operations has resulted in more of a conscious shift towards alternative supply chains as seafood operators become more interested in promoting a unique set of social and environmental values along their supply chains (De Sousa 2021).

The benefits of alternative supply chains have already been widely documented in the literature. They include environmental, sociocultural, and economic benefits both for harvesters and consumers (McClenachan et al. 2014; Bolton 2015; Stoll et al. 2015; Bolton et al. 2016; Witter and Stoll 2017; Cumming et al. 2020; Witter 2020).

One of the most common benefits cited for moving to alternative supply chains is the increase in economic benefits and financial stability they provide fishers (De Sousa et al. *forthcoming*). By shortening supply chains, fishers do not have to split profits with processors or distributors, allowing them to capture the profits associated with these tasks while reducing their operating costs. In addition to reducing costs, alternative supply chains can improve the economic viability of small-scale fisheries by selling fish at a price premium over wholesale prices, and insulating fishers from price volatility (Brinson et al. 2011; Bush and Oosterveer 2019). When alternative supply chains involved prearranged orders, subscriptions, or buying clubs, fishers can also enjoy more stable revenue (Bolton 2015; Bolton et al. 2016; Witter and Stoll 2017; De Sousa 2021).

Alternative supply chains also tend to have less of an environmental impact. Instead of amassing significant carbon footprints by flying or shipping seafood around the world and simultaneously creating more tenuous supply chains, alternative supply chains promote local seafood consumption, minimising the distance fish travels from boat to plate. The literature also highlights how alternative supply chains are able to create new markets for locally abundant, low-value species that would not traditionally be available on wholesale markets (McClenachan et al. 2014). For a lot of these species, the costs of catching, processing, and distributing them outweigh the profits that would be made by selling them on the wholesale market. As a result, they often end up thrown back or "discarded" (Salladarré et al. 2018). Due to the nature of alternative supply chains, which are rooted in environmental and socioeconomic responsibility, they provide fishers exclusive access to a market for these fish perceived as "low-value", providing them with additional income and further supporting their livelihoods (Olson et al. 2014; Stoll et al. 2015). Given the restructured and shortened supply chains within these alternative models, there is less opportunity for fraud and mislabelling to occur, as seafood is moving between fewer hands than in traditional supply chains. Early evidence from a study done with a Canadian direct-marketing business, suggests that direct marketers have lower rates of mislabelling compared to seafood found in traditional markets, such as grocery stores and restaurants (Arness and De Sousa 2021).

The direct-to-consumer model ensures a higher level of transparency and traceability. With no "middlepersons" to give fish to before it goes to the consumer, fishers can provide consumers a guarantee as to where their fish was caught, how it was caught, and who caught it. Traceability is becoming more of a concern for consumers who are now aware of the destructive behaviours that convoluted seafood supply chains can hide and consumer trust in the food supply is low (Durham et al. 2009). Consumers want to know that they are getting what they paid for, that their fish is not being fraudulently mislabelled, and that their seafood is not coming to them as a result of slave labour (McClenachan et al. 2016). Purchasing seafood directly from seafood harvesters reassures consumers about their seafood purchases, which helps to restore trust in the food supply.

Many involved in alternative supply chains also make an extra effort to educate consumers about the true cost of their fish, so they have a better understanding of the process of harvesting, processing, and distributing fish and why seafood costs what it does (McClenachan et al. 2014; Cumming et al. 2020). Consumer education is a key component of many alternative supply chain businesses; it is most prominent in community supported fisheries (CSFs) (Campbell et al. 2014; McClenachan et al. 2014; Bolton 2015; Stoll et al. 2015; Cumming et al. 2020). The cultivation of personal relationships with consumers and emphasis on community values also allows alternative supply chains to promote the social dimensions of sustainability through consumer awareness and education, which research suggests can lead to greater stewardship over food resources (McClenachan et al. 2014; Bush and Oosterveer 2019).

Alternative supply chains are not only better for traceability and transparency, but they make the broader seafood economy more resilient. The COVID-19 pandemic highlighted the need for diversity in global seafood supply chains. The case study outlined below provides evidence of the opportunities that alternative supply chains present to increase resilience in global seafood systems.

Case study: alternative supply chains to reduce fraud and increase resilience

Throughout the COVID-19 pandemic, the success and growth of alternative supply chains was noteworthy (Stoll et al. 2021). While traditional supply chains such as export markets and restaurants faltered due to pandemic-related restrictions, alternative supply chains remained resilient to shocks and provided a lifeline to fishers with no other outlets to sell to (Bennett et al. 2020; Bassett et al. 2021; Love et al. 2021; Stoll et al. 2021).

Consumers quickly realised the instability of global food supply chains and began seeking out alternative means of accessing food products, including seafood (Stoll et al. 2021). In the spring of 2020, when pandemic-related restrictions first appeared in North America, Google Search traffic for “local seafood”, “local fish”, and “seafood delivery” saw a rapid spike in comparison to data from the previous five years (White et al. 2020; Stoll et al. 2021).

Recognising these shifts that were happening early in the pandemic, beginning in April 2020, it was important to start tracking the impacts of the COVID-19 pandemic on seafood supply chains, specifically focussing on alternative seafood businesses such as those who were selling direct to consumer through various channels, including community supported fisheries. This investigation was documented through a bi-weekly podcast series called *Social FISHtancing*,[1] and later resulted in a scientific, peer-reviewed paper (Stoll et al. 2021).

In North America specifically, most seafood is exported or sold to restaurants. Take for example, the British Columbia halibut fishery *(Hippoglossus stenolepis)*, which services almost entirely fine dining establishments along the west coast of North America. While some restaurants transitioned to offering takeout while pandemic-related restrictions required them to shut their doors, most fine dining establishments did not. For those restaurants that offered takeout, seafood often did not make it on to takeout menus as it is more susceptible to spoilage (Bennett et al. 2020; White et al. 2020; Love et al. 2021; Stoll et al. 2021).

This loss of traditional supply chain outlets led many small-scale fishers to explore alternative supply chains, rooted in getting as close to direct to consumer as possible. With fewer people involved in the supply chain, fishers selling through alternative supply chains are less reliant on outside actors and therefore less susceptible to traditional supply chain interruptions. When seafood passes between fewer people to get to the consumer, there is also less opportunity for fraud and mislabelling to occur. With seafood fraud and mislabelling occurring all over the world, shorter supply chains and more localised seafood markets could lower that number, helping to rebuild consumer trust in the seafood system and supporting the sustainability of local fisheries (Gephart et al. 2016; Love et al. 2021; Stoll et al. 2021).

Fishers and seafood stakeholders interviewed cited multiple benefits from participating in alternative supply chains during the pandemic, including

[1] Social FISHtancing Podcast. www.coastalroutes.org/podcasts.

economic stability, improved sustainability of the marine ecosystem, increased transparency, and a greater connection between food harvester and consumer (De Sousa et al. *forthcoming*). Those who were involved in alternative supply chains prior to the pandemic, cited few or no negative impacts as a result of pandemic-related restrictions (De Sousa 2021; Stoll et al. 2021; De Sousa et al. *forthcoming*). Those who engaged in community supported fisheries or other types of subscription-based supply chains, were especially insulated from the economic consequences of the COVID-19 pandemic as they had already secured pre-payment from customers.

While alternative supply chains have demonstrated benefits for both the harvesters and consumers who participate in them, some were unable to adopt alternative supply chains due to local constraints such as a lack of infrastructure, consumer knowledge limitations, and regulatory limitations. As part of this work related to the impacts of COVID-19 on global seafood supply chains, we also examined the challenges small-scale fishers in North America faced when trying to transition to alternative supply chains (De Sousa et al. *forthcoming*). Based on responses from interviewees across North America, we produced policy opportunities and recommendations that will help to support and strengthen alternative supply chains, including increased investment in waterfront infrastructure, financial incentives for direct marketing programs, and streamlining regulatory requirements for alternative supply chains (De Sousa et al. *forthcoming*).

This research on alternative supply chains during the COVID-19 pandemic provided evidence that alternative supply chains can provide additional resilience to globalised supply chains and support transparency as well as greater stewardship over marine food resources. In order to support the continued success of alternative supply chains and as a result, a more transparent and resilient seafood economy, barriers to adopting alternative supply chains should be addressed through policy, regulation, and investment. Alternative seafood supply chains can be the key to reducing problems like seafood fraud, supporting the global seafood economy by providing opportunities for small-scale fishers, strengthening local food systems and re-connecting consumers to their food and building relationships with those who harvest it. These recommendations provide opportunities to embrace alternative supply chains based on 'boat to fork' principles that reduce the environmental impacts associated with seafood production, distribution, and consumption, while simultaneously creating a more transparent and traceable seafood industry (McClenachan et al. 2014; Haas et al. 2016; Bennett et al. 2020; White et al. 2020; Love et al. 2021; Short et al. 2021).

Conclusion

Drawing on two cast study innovations presented at the *2021 World Fisheries Congress* "Sustainability" stream, we show how they can be used, either coupled or adopted alone, to improve the sustainability, traceability and resilience of global and local fisheries supply chains. This is particularly pertinent under the landscape of COVID-19, which can exacerbate the risk of food fraud (Onyeaka et al. 2022) and increase the need for food traceability (Quevedo-Silva et al. 2022). For example, emerging scientific technologies to test and validate seafood catches based on genetic or biochemical tags play pivotal role to ground-truth the origins of many seafood commodities. Shifting to local supply seafood chains, harnessing the community supported fisheries concept can be the key to eliminating problems like seafood fraud, supporting the global seafood economy by providing opportunities for small-scale fishers.

Seafood fraud extends often beyond the remit of domestic and international control (see for example Lindley 2022) and as such may make fisheries supply chains more vulnerable to fraud or other undesirable (illegal) practices. Regulatory control may be unable to adequately qualify fisheries supply chains and therefore, investing in innovations and opportunities that transcend national boundaries may be the most viable avenue. Led by industry and guided by domestic and international regulations, such as those described in the 2021 UN Food Systems Summit enhances the sustainability, traceability and resilience of food, going forward.

Given that supply chain fractures previously existed, strengthening and safeguarding against systemic shocks, like COVID-19 as well as future pandemics, is central to this research, acknowledging that the security of our food has never been so critical. While we acknowledge that there may be sound financial, practical, social, geographical and regulatory limitations impeding the uptake of these innovations, this article provided an overview of opportunities that may be adopted within the fisheries supply chains to enable local, regional and international policy- and decision-makers to develop practical and viable fisheries solutions for a post-COVID-19 world.

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Declarations

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.

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