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Critical Review

Sustainable seafood: advances in traceability, assessment, monitoring and resource management

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This review presents a synopsis of advances in some techniques and technologies that support seafood traceability while addressing some of the complexities currently challenging the integration necessary to coordinate commercial, national and international efforts in achieving seafood sustainability. These advances rely on tools such as blockchain data handling, eDNA or eRNA (together 'eNA') sampling, DNA metabarcoding, artificial intelligence and mobile applications. The microbiota associated with seafood organisms can also be monitored using eNA, to enable detection and management of any potential pathogenic developments in wild or aquaculture stocks. For successful and efficient traceability, it is necessary to guarantee data reliability and to support regulatory auditing. To ensure sustainability, however, also requires sampling, monitoring and assessments of the resource status as well as appropriate management. Effective traceability of seafood-related products will also help to resolve other problems, such as endangered species entering supply chains for aquaculture feed. Considering the still large proportion of seafood that is currently obtained and processed illegally, there is a pressing need for coherent local, national and international policies rooted in shared goals among stakeholders and supported by even-handed enforcement. This has been recently facilitated through a trend to shift liability from fishers to importers, and onwards throughout the value chain. In hand with these regulatory changes, the technologies described here will play a central role in achieving the vision for sustainable seafood supplies by the end of this decade.

Keywords: aquaculture feed, artificial intelligence, blockchain, enforcement, eNA detection, environmental DNA, metabarcoding, microbiota

Introduction

Achieving sustainable exploitation of seafood resources is complex and fraught with difficulties at many levels. For example, seafood resources are of many kinds (various protists, plants and animals; taken directly from the wild or through aquaculture production), each of which has its own quirks and problems (Dipper 2022). On the path to achieving sustainability aims, traceability is well recognised as a central concept (Thompson et al. 2005; Sterling et al. 2015; Bailey et al. 2016; Lewis and Boyle 2017; Willette et al. 2017; Borit and Olsen 2020; SALT 2021; Hoque et al. 2022; NOAA Fisheries et al. 2022; U.S. FDA 2022; Gleadall et al. 2024; Hopkins et al. 2024) and some of the recent advances towards effective traceability are here outlined. Traceability helps to ensure that seafood is safe, legally caught, accurately labelled and, ultimately, sustainable (Thomson et al. 2005). It ensures that information (such as how and where seafood is caught or farmed) is accessible throughout the global seafood supply chain, from harvest to consumer. To facilitate broad adoption, seafood traceability solutions must be easily replicable and affordable to strengthen sustainable fisheries management, and to deter illegal practices and fraud. They must also be able to fulfil the present and future expectations of conscientious producers, consumers,

and authorities, and, finally, to inform decisions enabling sustainability to be achieved. Inclusive transdisciplinary approaches are thus required to improve seafood traceability whilst building a sustainability system for fisheries and fed aquaculture (Dipper 2022; Alexander and Kelling 2024; Hopkins et al. 2024). The recent forcing of compliance deadlines for new regulations is greatly accelerating the pace of change required at a global level (SALT 2021; NOAA Fisheries et al. 2022; U.S. FDA 2022). For example, from January 2026, the United States Food and Drug Administration (FDA) will require additional traceability records for certain foods, including seafood (U.S. FDA 2022), as part of upgrading requirements for high-risk foods, augmenting the FDA Food Safety Modernisation Act (FSMA) (U.S. FDA 2011).

New technology and various tools have been successfully developed to tackle some of the illegal practices and traceability issues in the seafood supply chain (Lewis and Boyle 2017; Gopi et al. 2019). Included are blockchain data handling, environmental nucleic acid (eNA) sampling, DNA metabarcoding, artificial intelligence and mobile applications. However, while transparent practices in traceability are improving rapidly, ultimately achieving sustainability in the seafood industry remains challenging (Bailey et al. 2016; Conservation Alliance for Seafood Solutions 2017; Gleadall et al. 2024). For example, how can blockchain technology be applied to defeat illegal, unreported and unregulated (IUU) fishing issues? Can metabarcoding be used to prevent mislabelling in seafood processing? Moreover, it is not enough to aim for sustainability through technology only. It is important to communicate well with stakeholders involved in the seafood supply chain, including fishers, processors and consumers, and educate them about the importance of traceability and its role in supporting sustainability (Sterling et al. 2015; Hoque et al. 2022).

This review highlights some notable recent concepts and methods, either in use or in development, that are contributing to achieving sustainable seafood resources through the construction, maintenance and use of a robust system of traceability. However, improved traceability will not improve the sustainability of seafood production for a particular fishery unless exploitation of the resource stock is managed effectively. Appropriate resource monitoring, assessment and management are essential, and these are more challenging to achieve in some fisheries than others. We also highlight some of the outstanding issues in the assessment and management of fisheries that exploit short-lived species, such as cephalopods, whereas other fisheries pose different challenges.

Traceability defined and the potential of blockchain technology

Reviewing the surprisingly wide number of definitions available, Olsen and Borit (2013, p 148) concluded that the best definition of traceability is: “The ability to access any or all information relating to that which is under consideration, throughout its entire life cycle, by means of recorded identifications.” Applied to seafood, this definition grasps the key points of being able to reliably document the exploitation of a seafood resource by tracking the transactions occurring from its harvesting to its arrival at the point of consumption. The traceability of seafood is therefore: the ability to access any and all information relating to the transfer of each seafood item through each step in the sales chain by means of recorded identifications (adapted from Olsen and Borit [2013]). A major point is that the seafood item can be traced back reliably to its harvest source (using critical tracking events: U.S. FDA 2022), enabling the exploitation of that resource to be monitored and assessed.

Traditionally, electronic traceability systems are based on relational databases, where data are arranged in rows and columns. Blockchain technology is a promising alternative, currently being explored by many seafood companies. The blockchain database structure has two main advantages over relational databases. First, data in a blockchain database are inherently immutable—that is, they cannot be altered. This is useful because it provides a clear link to where, when, and by whom a data element was entered. Second, it becomes easier to merge data from different sources, because blockchain databases are inherently more similar (and thus easier to integrate) than relational databases. This does not mean that blockchain technology is the perfect solution for a seafood traceability system. All traceability systems are vulnerable to error in the data entered, and this is not a problem that blockchain resolves. Also, while there are different blockchain models (public, federated, private) and different consensus mechanisms (proof-of-work and proof-of-stake), they each have associated benefits and weaknesses when used as the basis for a traceability system. One significant weakness is that blockchain technology was designed to work in anonymous environments with no trust between actors, which is not a good model for a food traceability system.

Factors affecting the detection of illegal fishing activities: examples from Chile

Illegal activities associated with the seafood sales chain are common (e.g. Fox et al. 2018; Oyanedel et al. 2022). In Chile, fisheries are well regulated, yet ~60% of them are either overexploited or have already collapsed. To detect infractions of regulations requires two events: (i) the occurrence of an infraction, and (ii) detection of that infraction. When enforcement officers are in the field, it was found that the probability of an infraction occurring was 34%, the probability of detecting an infraction was 18%, and around 7% of enforcement visits dealt with an infraction (Oyanedel et al. in press). It was concluded that enforcement should target the entire supply chain, including processors and restaurants, not just fishers; and the potential of other enforcement effort strategies should be explored.

Using eNA technology to pinpoint fraud within the seafood sales chain: an example from the Gulf of Mexico of eDNA use, with comments on the use of eRNA

DNA technology has been applied to monitoring the accuracy of seafood identification through techniques such as barcoding to confirm the identity of the species of interest by testing random tissue samples

(Willette et al. 2017; Silva and Hellberg 2021). However, environmental DNA (eDNA) analysis requires only a small water sample associated with the target species and can be used to detect fraud within the food chain (Willette et al. 2021). One example is a project associated with the harvesting of *Octopus maya* from off the Yucatán Peninsula in the Gulf of Mexico (LQ and DAW, unpublished data). Tissue sampling can ensure that the species of octopus has been accurately identified (there are two other very similar species in the region which are present in small numbers but should not be identified as *O. maya*).

Even so, of more interest in this fishery is a species of crab apparently used often as bait by local fishers to catch *O. maya*: the American horseshoe crab *Limulus polyphemus* (Sandoval-Gio et al. 2020). Sampling for eDNA often revealed the presence of this threatened species in small amounts of water from the containers in which the octopuses are packed (i.e. large, dock-side stand-alone bait containers that do not contain added circulating or refrigerated seawater: LQ pers. obs.; cf. Willette et al. 2021). The horseshoe crab is also in high demand for its haemocyanin blood pigment, which is used in the pharmaceutical industry to detect the presence of endotoxins in intravenous drugs and associated with implantable medical devices (Maloney et al. 2018). Although it is possible that the eDNA detected from fished octopus was due to natural occurrences of octopuses feeding on *L. polyphemus*, illegal poaching of this species for octopus bait has long been known. Along with habitat deterioration and overexploitation for biomedical purposes, poaching for bait threatens the survival of the Yucatán population of *L. polyphemus*. Regular eDNA sampling and education of local fishers can help to minimise this problem. Techniques using the technology of eDNA sampling can contribute also to the detection of invasive species and rare species, as well as to confirm identifications of target species for the purposes of aiding fisheries monitoring efforts and combating illegal fishing (Brito and Willette 2023).

In terms of traceability for detecting IUU-related infringements and the presence of substitute seafood species, it would be useful to have some standardisation of eRNA techniques (as for eDNA: Handy et al. 2011). Currently, no standards for eRNA have been reported although several have been tested (Jo et al. 2023), but eRNA is not as extensively used as eDNA, and eRNA is generally believed to be short-lived. A recent review by Bunholi et al. (2023) considered about 300 eNA (eDNA and eRNA) studies, but only four were on eRNA, and a few more were on both eDNA and eRNA. These techniques are an emerging set of tools with the potential to facilitate traceability, but development still has some way to go.

Tracing of the globalised aquaculture feed supply using DNA metabarcoding

A major sustainability challenge for the feed-based aquaculture industry is reliance on wild-caught seafood as ingredients in the feed used to grow cultured species. Part of the total global harvest of marine fishes is reduced into fish meal and fish oil for this purpose, although much less than in previous years, estimated at ~22% of fish captures, with most of this supplied as low-value by-products (scraps and offal) remaining after processing more valuable tissues (34% of fish meal and 53% of fish oil: FAO 2024). Most of this material (>87%) is currently used for aquaculture feeds because pig and poultry feed formulations use lower-cost alternatives. Global fish meal and fish oil production has stabilised at around 5 million tonnes and 1 million tonnes, respectively, since the mid-2000s (FAO 2024).

Fragments of mitochondrial DNA can endure the transformation of raw fish into fish meal and fish oil, providing a conserved tracer of the species embodied within aquaculture feeds. Metabarcoding refers to the process of copying regions of mitochondrial genes where the DNA nucleotide sequence varies consistently among species (i.e. barcodes), and then matching species names to as many of those sequences as possible using barcode databases (e.g. Baetscher et al. 2023). Moreover, the geographic distributions of these species can reveal which regions were harvested to produce the wild fish ingredients used in aquaculture feeds. DNA metabarcoding could also allow detection of any endangered species included in feed ingredients. Thus, by elucidating both the geographical sources and species composition of feed constituents, DNA metabarcoding could provide a new tool for detecting violations of international laws or voluntary sustainability standards. There is ample opportunity to embrace DNA metabarcoding methods in the next generation of feed-supply sustainability standards, including harnessing third-party certification of results. Such DNA-based certification of wild-sourced feed ingredients complements efforts to derive novel ingredients from insects and plants (e.g. Spranghers et al. 2017; Hossain et al. 2024). The ongoing global expansion of aquaculture makes it imperative that efforts continue towards ensuring sustainable sources for all feed ingredients.

Using eNA sampling to trace pathogens potentially affecting cultured and wild aquatic organisms

Aquaculture typically involves monoculture or oligoculture, so the arrival of pathogens can and does cause massive problems from time to time (Lafferty et al. 2015). The potential for pathogenic developments in the microbiota is obviously present in the wild, but such developments are easier to detect and control in culture conditions, especially on a small scale (Sieber et al. 2024). Having a way to monitor and quantify the occurrence of pathogens is therefore an important preventative measure and also facilitates research on disease control and the development of pathogenic conditions (Wright et al. 2023). Once an organism with pathogenic potential has been detected in unusually large amounts, appropriate methods can be devised to prevent, treat and control any associated disease conditions (Bass et al. 2023). eNA sampling and subsequent comparison of the inlet to and outlet from a culture tank (or an aquaculture facility, depending on its scale) can provide qualitative and quantitative information about any pathogenic events developing within the system. This pilot monitoring strategy has been used successfully

in the maintenance of healthy cultures of squid of the genus *Sepioteuthis* and other cephalopods (Zoral et al. 2024a, 2024b), and hence clearly has applications for ensuring sustainable healthy seafood sources in the aquaculture industry.

Apps aimed at combating overfishing and other illegal practices

There are now well over 80 different seafood-related mobile apps available worldwide, providing functions dealing with many different kinds of data collection (Lewis and Boyle 2017; Calderwood 2022; Gleadall et al. 2024). An example of one app developed recently is 'SharkTrace' (TRAFFIC 2024), designed to address the challenges associated with the decline of shark populations due to overfishing and unsustainable illegal practices, such as the illicit trade in shark products. This app is designed to track shark products throughout the entire seafood supply chain, from fishing vessels to processing and wholesale distribution. Accurate and reliable tracking procedures have been ensured by development of the SharkTrace app through close collaboration with shark fishing vessels and processing companies in southern Australia and South Africa. Stakeholders can record and monitor information related to shark products at every stage of the supply chain. Technology such as radio-frequency identification (RFID) and QR tags, along with robust data validation systems, ensure that the data collected are reliable and authentic with a high degree of integrity.

Artificial intelligence and machine learning

Artificial intelligence (AI) and machine learning (ML) are increasingly pivotal in advancing seafood traceability, addressing both authenticity and sustainability challenges in the global seafood supply chain. AI technologies, such as computer vision and natural language processing, are used to streamline identification and verification processes. For instance, image recognition algorithms can analyse photographs of seafood products to determine species, size and quality, with remarkable accuracy. One notable example is the use of convolutional neural networks (CNNs) to classify fish species from images, which has been demonstrated to achieve high levels of accuracy in real-world applications (Rubbens et al. 2023). Such technologies not only expedite the verification process but also reduce human error and bias.

ML models further enhance traceability by integrating and analysing complex datasets. For example, ML algorithms can process and correlate data from various sources, such as satellite tracking, supply-chain records and genetic information, to trace seafood back to its source. An illustrative case is the application of ML in analysing genetic barcoding data, which has been employed to detect mislabelling and fraud in seafood markets (Fernandes et al. 2021). By making use of these advanced techniques, stakeholders can improve transparency, ensure compliance with sustainable practices, and combat illegal fishing activities. Overall, AI and ML are crucial in creating robust, transparent and efficient traceability systems that support both industry integrity and environmental stewardship.

Resource stocks and their assessment, management and sustainability

As noted above, traceability alone is not a complete solution to achieving sustainable seafood products. There must be evidence that the source is a sustainable fishery. This is obvious but cannot be assumed. In the seas of the European Union, both the Common Fisheries Policy and conservation legislation such as the Marine Strategy Framework Directive (MSFD) aim to ensure sustainable fishing. However, the proportion of stocks for which both fishing mortality and spawning stock biomass are consistent with the Good Environmental Status (GES) concept of the MSFD is below 50% in all of the component regions, and in the Mediterranean Sea only ~3% of stocks meet both GES criteria (European Environment Agency 2024).

Certain species groups present particular challenges, notably short-lived species. Included among these are many invertebrates and small pelagic fishes, such as sardine and anchovy, which have intrinsically volatile stock dynamics, unpredictable recruitment and high environmental sensitivity. Cephalopod molluscs (octopus, cuttlefish and squid) are the third-largest group of organisms targeted for fishing after finfish and crustaceans (such as crab and shrimp). They have been referred to as "short-lived, ecological opportunists [which] respond rapidly to environmental variability on annual time-scales" (Rodhouse 2010). Perhaps counterintuitively, such characteristics may make them as vulnerable (or perhaps more vulnerable) to stock collapse than large, long-lived fish species (Malin et al. 2011).

Fisheries for many cephalopods are apparently in decline after reaching an all-time high in 2014, with catches decreasing by ~2% annually between 2014 and 2020, although generally they show a high level of year-to-year fluctuation (FAO 2022). This is due in part to the very short lifespan of cephalopods and their exploitation as a high-potential bioresource, given their nutritional value and culinary attractiveness. Challenges facing cephalopod fisheries, as with many other harvested species, include a lack of infrastructure within the fishery and a dearth of data on recruitment, which is hard to measure owing to phenological variability: recruitment peaks tend to be both variable in timing and spread out.

To determine whether the status of a given seafood resource stock is sustainable, assessment extends well beyond merely attempting to count the number of animals constituting the resource and the numbers harvested. Most stock-assessment information and methods to date have been focused on fishes (so-called finfish), and even for those resources further research is needed to provide reasonable estimates of the stock available from year to year. Stocks are affected by numerous variables, including the quantity of prey and predators with which they interact, and the amount of the stock that is harvested. Additionally, climate-change parameters such as warming and acidification are having an impact

Seafood resources such as squid have additional complications, which recent research is now beginning to highlight (Pierce et al. in press, but cf. Caddy 1983). Stock assessment methods work poorly with cephalopods because the model assumptions (on which these methods are based) are typically not met, and those approaches that do work well may provide results that are of little or no utility for managers, because they provide a retrospective assessment, which is of poor predictive value as a result of a weak stock-recruitment relationship. A combination of catch statistics and stock modelling reveals a number of these complications. For instance, variations in squid size (as expressed by the length of the mantle) have long been known but the causes of these variations are unclear; often, two or three groups differing in size (and sometimes at a given age) can be distinguished at any given time, yet the phenological factors causing these size differences are poorly understood. Populations of the veined squid *Loligo forbesii*, for example, recruit young throughout the year but with at least two seasonal peaks (autumn and spring), presumably reflecting different spawning and hatching periods (Boyle et al. 1995; Pierce et al. 2005). Recent data show that those hatching during the summer are shorter-lived (i.e. they show higher mortality but probably also breed younger and at a smaller size), while those hatching during autumn and winter can live longer (GJP unpublished data). Although incomplete and requiring a better understanding, such information can help inform management policy for this resource by directing managers to choose which periods of the year to minimise fishing to avoid targeting new recruits or spawning cohorts.

Further research is still required, and regular and careful sampling and monitoring of squid populations is necessary to enable meaningful stock assessment and management of stability in the resource from year to year. In addition, both forecasting based on environmental predictors (Moustahfid et al. 2021) and real-time (in-season) assessment (see Arkhipkin et al. 2021) are potentially promising options, with the latter well-known from its application in the Falkland Islands squid fisheries (such as for Argentine shortfin squid *Illex argentinus*). At first sight the latter approach seems to be problematic because of the costs of collecting real-time data on catches and high fishing effort; however, self-reporting (e.g. via mobile phone apps) could avoid the need for costly observer programmes.

Nevertheless, all assessment solutions depend on effective fishery management to achieve sustainability; for example, if catches exceed safe limits in poor years and towards the end of a fishing season, then managers must limit fishing effort in key habitats at key life-cycle stages. Also, as exemplified by problems with the *I. argentinus* fishery which suffered a collapse in 2016 (FAO 2021; Arkhipkin et al. 2023), finding a way to limit currently unregulated fishing on migratory cephalopod stocks in the high seas will be important.

Conclusions: traceability innovations and fundamental resource assessment and management

Traceability is a concept that embraces under a common banner various aspects, aims and issues of sustainability. By considering this synopsis of some of the latest actions and innovations involving traceability, along with monitoring, assessment and management of the resources being exploited, it is possible to grasp the state of current progress towards achieving and maintaining sustainability. Here, the following eight points have been highlighted.

(1) Defining traceability itself has not been straightforward, but here an attempt has been made with regard to seafood in particular, noting that a critical requirement is for the input of accurate data, implying that the authorities and other stakeholders involved must find ways and means to guarantee data accuracy. (2) If reliable data can be stored using blockchain technology, traceability will be robust. (3) A major problem in the seafood industry is the presence of an unacceptable level of illegal activity at various locations in the chain of transport from harvest to consumption. The focus on rectification has tended to be on fishers and illegal fishing activity, especially small-scale fishers. However, it is becoming well understood that it is important to develop deliberate policies (a) to widen regulatory focus; (b) not to target fishers disproportionately; and (c) to include fishers in decisions on management and maintenance of fair and sustainable resource exploitation. (4) Accurate and reliable species identification is essential in monitoring at all steps in the seafood sales chain and is being facilitated through the use of DNA metabarcoding and eNA sampling methods, which are undergoing rapid development and improvement. (5) These technologies are also proving helpful in (a) monitoring the health of animals held in aquaculture facilities, as well as in (b) monitoring and stamping out trade in rare and overexploited species, (i) in their use as bait to catch more-lucrative species, and (ii) in the manufacture of feed for aquaculture. (6) A great deal is being achieved through the development and use of traceability software apps that enable monitoring of seafood resources by many stakeholders—from capture to consumption—and thereby countering and preventing illegal practices and contributing to resource assessment and sustainability. (7) AI and ML technologies can bolster many aspects of traceability by improving its efficiency, enhancing authenticity (e.g. through improved species identification and verification) and, accordingly, sustainability in the global seafood supply chain. (8) To assess a seafood resource as sustainable or otherwise requires investment in regular sampling and monitoring, as well as understanding the phenological variables of each resource to inform appropriate management strategies. Regular investment here will be necessary into the foreseeable future, since resource sustainability is the bottom line for successful seafood exploitation.

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Competing interests — Ian G. Gleadall is the Executive Director of AiCeph LLC, and a consultant to HotLand Co., Ltd, Tokyo (a fast-food franchise company specialising in octopus products).

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References

Alexander KA, Kelling I. 2024. Social sustainability in seafood systems: a rapid review. *Cambridge Prisms: Coastal Futures* 2: e1.

Arkhipkin AI, Hendrickson LC, Payá I, Pierce GJ, Roa-Ureta R, Robin JP, Winter A. 2021. Stock assessment and management of cephalopods: advances and challenges for short-lived fishery resources. *ICES Journal of Marine Science* 78: 714–730.

Arkhipkin AI, Nigmatullin CM, Parkyn DC, Winter A, Csirke J. 2023. High seas fisheries: the Achilles' heel of major straddling squid resources. *Reviews in Fish Biology and Fisheries* 33: 453–474.

Baetscher DS, Locatelli NS, Won E, Fitzgerald T, McIntyre PB, Therkildsen NO. 2023. Optimising a metabarcoding marker portfolio for species detection from complex mixtures of globally diverse fishes. *Environmental DNA* 5: 1589–1607.

Bailey M, Bush SR, Miller A, Kochen M. 2016. The role of traceability in transforming seafood governance in the Global South. *Current Opinion in Environmental Sustainability* 18: 25–32.

Bass D, Christison KW, Stentiford GD, Cook LS, Hartikainen H. 2023. Environmental DNA/RNA for pathogen and parasite detection, surveillance, and ecology. *Trends in Parasitology* 39: 285–304.

Borit M, Olsen P. 2020. *Beyond regulatory compliance: seafood traceability benefits and success cases*. FAO Fisheries and Aquaculture Circular FIAM/C1197. Rome: Food and Agriculture Organization of the United Nations. Available at http://www.fao.org/3/ ca9550en/ca9550en.pdf [accessed 3 June 2024].

Boyle PR, Pierce GJ, Hastie LC. 1995. Flexible reproductive strategies in the squid *Loligo forbesi*. *Marine Biology* 121: 501–508.

Brito A, Willette DA. 2023. eDNA detection to help combat illegal fishing and modern slavery. *The Philippine Journal of Fisheries* 30: 1–9.

Bunholi IV, Foster NR, Casey JM. 2023. Environmental DNA and RNA in aquatic community ecology: toward methodological standardisation. *Environmental DNA* 5: 1133–1147.

Caddy JF. 1983. The cephalopods: factors relevant to their population dynamics and to the assessment and management of stocks. In: Caddy JF (ed.), *Advances in cephalopod stock assessment. FAO Fisheries Technical Paper* 231: 416–452.

Calderwood J. 2022. Smartphone application use in commercial wild capture fisheries. *Reviews in Fish Biology and Fisheries* 32: 1063–1083.

Conservation Alliance for Seafood Solutions. 2017. *A common vision for sustainable seafood*. Available at https://solutionsforseafood.org/wp-content/uploads/2021/10/Conservation-Alliance-for-Seafood-Solutions-Common-Vision-for-Sustainable-Seafood-Jan-2021-1.pdf [accessed 30 October 2024].

Dipper F. 2022. Human impacts 1: Sea fisheries and aquaculture. In: Dipper F (ed.), *Elements of marine ecology* (5th edn). Oxford, UK: Butterworth-Heinemann. pp 389–458.

European Environment Agency. 2024. *Status of marine fish and shellfish stocks in European seas*. Available at https://www.eea.europa.eu/en/analysis/indicators/status-of-marine-fish-and [accessed 24 October 2024].

FAO (Food and Agriculture Organization of the United Nations). 2021. *FAO yearbook. Fishery and aquaculture statistics 2019*. Rome: FAO. Available at https://openknowledge.fao.org/items/a030854a-07fd-4ba6-b1a1-e6ebaf052585.

FAO (Food and Agriculture Organization of the United Nations). 2022. *The state of world fisheries and aquaculture 2022*. *Towards blue transformation*. Rome: FAO. Available at https://doi.org/10.4060/cc0461en.

FAO (Food and Agriculture Organization of the United Nations). 2024. *The state of world fisheries and aquaculture 2024. Blue transformation in action*. Rome: FAO. Available at https://doi.org/10.4060/cd0683en.

Fernandes TJR, Amaral JS, Mafra I. 2021. DNA barcode markers applied to seafood authentication: an updated review. *Critical Reviews in Food Science and Nutrition* 61: 3904–3935.

Fox M, Mitchell M, Dean M, Elliott C, Campbell K. 2018. The seafood supply chain from a fraudulent perspective. *Food Security* 10: 939–963.

Gleadall IG, Moustahfid H, Sauer WHH, Ababouch L, Arkhipkin AI, Bensbai J et al. 2024. Towards global traceability for sustainable cephalopod seafood. *Marine Biology* 171: article 44.

Gopi K, Mazumder D, Sammut J, Saintilan N. 2019. Determining the provenance and authenticity of seafood: a review of current methodologies. *Trends in Food Science and Technology* 91: 294–304.

Handy SM, Deeds JR, Ivanova NV, Hebert PDN, Hanner RH, Ormos A et al. 2011. A single-laboratory validated method for the generation of DNA barcodes for the identification of fish for regulatory compliance. *Journal of AOAC International* 94: 201–210.

Hopkins CR, Roberts SI, Caveen AJ, Graham C, Burns NM. 2024. Improved traceability in seafood supply chains is achievable by minimising vulnerable nodes in processing and distribution networks. *Marine Policy* 159: article 105910.

Hoque MZ, Akhter N, Chowdhury MSR. 2022. Consumers' preferences for the traceability information of seafood safety. *Foods* 11: article 1675.

Hossain MS, Small BC, Kumar V, Hardy R. 2024. Utilisation of functional feed additives to produce cost-effective, ecofriendly aquafeeds high in plant-based ingredients. *Reviews in Aquaculture* 16: 121–153.

Jo T, Tsuri K, Hirohara T, Yamanaka H. 2023. Warm temperature and alkaline conditions accelerate environmental RNA degradation. *Environmental DNA* 5: 836–848.

Lafferty KD, Harvell CD, Conrad JM, Friedman CS, Kent ML, Kuris AM et al. 2015. Infectious diseases affect marine fisheries and aquaculture economics. *Annual Review of Marine Science* 7: 471–496.

Lewis SG, Boyle M. 2017. The expanding role of traceability in seafood: tools and key initiatives. *Journal of Food Science* 82: A13–A21.

Malin L, Pinsky ML, Jensen OP, Ricard D, Palumbi SR. 2011. Unexpected patterns of fisheries collapse in the world's oceans. *Proceedings of the National Academy of Sciences of the United States of America* 108: 8317–8322.

Maloney T, Phelan R, Simmons N. 2018. Saving the horseshoe crab: a synthetic alternative to horseshoe crab blood for endotoxin detection. *PLoS Biology* 16: e2006607.

Moustahfid H, Hendrickson L, Arkhipkin A, Pierce GJ,

Gangopadhyay A, Kidokoro H et al. 2021. Ecological fishery forecasting of squid stock dynamics under climate variability and change: review, challenges and recommendations. *Reviews in Fisheries Science and Aquaculture* 29: 682–705.

NOAA Fisheries, Stimson Center and World Wildlife Fund. 2022. Seafood Traceability Practitioner's Workshop: exploring programs from design to implementation. Summary report. Available at https://media.fisheries.noaa.gov/202203/NOAAStimsonWWFWorkshopReportMarch2022.pdf [accessed 14 May 2024].

Olsen P, Borit M. 2013. How to define traceability. *Trends in Food Science and Technology* 29: 142–150.

Oyanedel R, Gelcich S, Mathieu E, Milner-Gulland EJ. 2022. A dynamic simulation model to support reduction in illegal trade within legal wildlife markets. *Conservation Biology* 36: article 13814.

Oyanedel R, Gelcich S, Milner-Gulland EJ, Wilcox C. In press. Improving detectability of illegal fishing activities across supply chains. *Scientific Reports*.

Pierce GJ, Zuur AF, Smith JM, Santos MB, Bailey N, Chen CS, Boyle PR. 2005. Interannual variation in life-cycle characteristics of the veined squid (*Loligo forbesi*) in Scottish (UK) waters. *Aquatic Living Resources* 18: 327–340.

Pierce GJ, Roumbedakis K, Pita C, Mendes R, Moreno A, Villasante S et al. In press. Problems and solutions in European cephalopod fisheries. *Oceanography and Marine Biology: An Annual Review*.

Rodhouse PG. 2010. Effects of environmental variability and change on cephalopod populations: an introduction to the CIAC '09 Symposium special issue. *ICES Journal of Marine Science* 67: 1311–1313.

Rubbens P, Brodie S, Cordier T, Destro Barcellos D, Devos P, Fernandes-Salvador JA et al. 2023. Machine learning in marine ecology: an overview of techniques and applications. *ICES Journal of Marine Science* 80: 1829–1853.

SALT (Seafood Alliance for Legality and Traceability). 2021. Seafood import regulation guide (EU, Japan, and the U.S.). Available at https://media.salttraceability.org/wp-content/uploads/2021/09/29163608/Import-Control-Report-FINAL-compressed.pdf [accessed 14 May 2024].

Sandoval-Gío JJ, Avilés-Ramírez G, Ortiz-León HJ, Zamora-Bustillos R, Rosas-Correa CO, Castro-Pérez JM. 2020. Effects of the octopus fishery on the American horseshoe crab population in the Ría Lagartos Biosphere Reserve, Mexico. *Ciencias Marinas* 46: 77–88.

Sieber N, King A, Krieg R, Zenker A, Vorburger C, Hartikainen H. 2024. Large-scale eDNA monitoring of multiple aquatic pathogens as a tool to provide risk maps for wildlife diseases. *Environmental DNA* 6: e427.

Silva AJ, Hellberg RS. 2021. DNA-based techniques for seafood species authentication. *Advances in Food and Nutrition Research* 95: 207–255.

Spranghers T, Ottoboni M, Klootwijk C, Ovyn A, Deboosere S, De Meulenaer B et al. 2017. Nutritional composition of black soldier fly (*Hermetia illucens*) prepupae reared on different organic waste substrates. *Journal of the Science of Food and Agriculture* 97: 2594–2600.

Sterling B, Gooch M, Dent B, Marenick N, Miller A, Sylvia G. 2015. Assessing the value and role of seafood traceability from an entire value-chain perspective. *Comprehensive Reviews in Food Science and Food Safety* 14: 205–268.

Thompson M, Sylvia G, Morrissey MT. 2005. Seafood traceability in the United States: current trends, system design, and potential applications. *Comprehensive Reviews in Food Science and Food Safety* 4: 1–7.

TRAFFIC. 2024. SharkTrace. Pioneering approaches to shark product traceability. Available at https://www.traffic.org/sharktrace [accessed 14 May 2024].

U.S. FDA (United States Food and Drug Administration). 2011. FDA Food Safety Modernisation Act (FSMA). Public Law 111-353 124 Stat: 3885–3973. Available at https://www.fda.gov/food/food-safety-modernisation-act-fsma/full-text-food-safety-modernisation-act-fsma.

U.S. FDA (United States Food and Drug Administration). 2022. Requirements for additional tracing records for certain foods. *Federal Register* 87: 70910–71088.

Willette DA, Simmonds SE, Cheng SH, Esteves S, Kane TL, Nuetzel H et al. 2017. Using DNA barcoding to track seafood mislabeling in Los Angeles restaurants. *Conservation Biology* 31: 1076–1085.

Willette DA, Navarrete-Forero G, Gold Z, Lizano AMD, Gonzalez-Smith L, Sotil G. 2021. Characterising industrial and artisanal fishing vessel catch composition using environmental DNA and satellite-based tracking data. *Foods* 10: article 1425.

Wright A, Li X, Yang X, Soto E, Gross J. 2023. Disease prevention and mitigation in US finfish aquaculture: a review of current approaches and new strategies. *Reviews in Aquaculture* 15: 1638–1653.

Zoral MA, Lajbner Z, Zifcakova L, Miller J. 2024a. Peracetic acid treatment of squid eggs infected with parasitic copepod (*Ikanecator primus* gen. et sp. nov.). *Nature Scientific Reports* 14: article 14513.

Zoral MA, Lajbner Z, Zifcakova L, Nakamura S, Miller J. 2024b. Co-infection of *Liburna oophaga* sp. nov. and *Ikanecator primus* on cuttlefish (*Sepia pharaonis*) eggs and the effectiveness of peracetic acid as a treatment. *Veterinary Parasitology* 332*:* article 110302.

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