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The global catch of octopus and squid shows annual variability and demand is likely to increase for both locally-supplied and imported products. However, the vulnerability of seafood resources is now well known, the reliability of fisheries catch data is still unclear, management of cephalopod stocks is mostly rudimentary, and there is uncertainty and concern about their sustainability among fisheries managers, the fishing industry, retailers, researchers and consumers. Here, a new project is presented which aims to address and resolve ways to enhance the effectiveness of seafood sustainability in general, with the aid of a freely accessible identification and traceability tool linked to sophisticated databases, and using artificial intelligence, machine learning and blockchain technology, to provide an easy and reliable way to trace seafood using octopus as a model. This project is a contribution to UN Sustainable Development Goals 2, 9, 14 and 17.

1. Introduction

The impetus for the present project stems from a recent review of the world's octopus fisheries (Sauer *et al*., 2019) where some anomalies were apparent in the information available on octopus catches. For example, the common octopus (a major source for the Japanese market) caught off the Northwest African coast in FAO Major Fishing Area 34. This area is by far the largest octopus fishery in the world, with reported annual catches off Morocco alone exceeding 100,000 t during the 1970s. Since then, there has been a decline in reported catches. Catch Per Unit Effort (CPUE), too, has shown a drastic decline, from 11.6 t per boat per year in 1981 to 6.8 t per boat per year in 2010. Total catches of octopus off neighbouring Mauritania, Senegal and Gambia are estimated to have been around 184,000 t in the 1970s, declining to around 152,000 t in 2010 (Sauer *et al*., 2019). However, the annual peak for FAO Major Fishing Area 34 is esti-

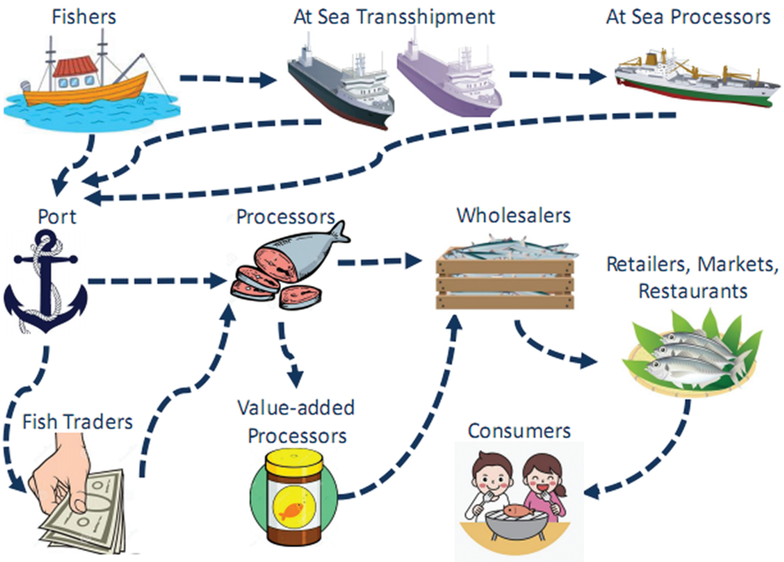

Fig. 1. Simple illustration of some of the routes taken by seafood on its way from capture by fishers through to consumption by the human population. *At-sea transshipment* involves transfer of catches from fishing vessels to a large refrigerated ship ('reefer') for subsequent transportation away from the place of capture. This saves fuel by allowing fishing vessels to remain in the vicinity of targeted fish stocks. The large reefers can receive fish from many fishing vessels and many catches from the same fishing vessel, which over a number of days may transship catches several times to the reefer before the reefer makes the return trip back to port to offload the fish in one go. *At-sea processors* convert freshly caught animals into seafood products such as surimi, fish oils and fish meal. The products are then packed and frozen onboard, ready for offloading at port. *Fish traders* sort, grade and resell whole, unprocessed seafood. *Value-added processors* enhance seafood value in ways such as preparing seafood-based recipes preserved in cans, ready for consumption. *Wholesalers* and *retailers* are involved in distribution of seafood products to shops and supermarkets for final purchase by restaurants or directly by consumers. (Figure constructed by DAW).

mated to have been more than 300,000 t in the mid-1970s. Management of the octopus fishery off Northwest Africa is challenging because of the short life cycle of octopus (1 to 2 years) and environmental variability, but also illegal fishing practices and a lack of coordinated enforcement.

The apparent anomalies in octopus catch data led IGG and WHHS to attempt to further investigate the true status of global octopus fisheries. HM identified the NSF Convergence Accelerator programme as a possible way forward. As the project application process began, eDNA specialists DAW and CLA joined the team. CLA worked up the app concept and DAW took on coordination of the grant proposal which was prepared in June, 2021, awarded in September, 2021, and the project began in October, 2021. The final products will be made freely available to all interested parties. The present paper provides an outline of this project by the Co-Principal Investigators (NSF, 2021). At the time of writing, the full team of contributors numbers 17 people and more will join as the project hopefully progresses into its second, globalizing phase. We gratefully acknowledge the current and future contributions of all team members and look forward to seeing this project through to a successful conclusion. We also thank Kevin M. Bailey for incisive comments on an earlier draft of the manuscript.

2. Seafood routes from fisher to fork

In managing and monitoring seafood resources, it is important to recognize that there are many of species and their routes through the capture and distribution network are complex. It is therefore useful to be able to monitor the total amounts of each seafood item on the market (*output* to the consumer) in order to confirm how much is being caught and distributed (*input*), and to use apparent discrepancies between *input* and *output* to inform ways to resolve problems of sustainability.

Fig. 1 presents a simple scheme of the routes taken by seafood items from their catch location until they arrive on the plate of the consumer. Much of this scheme is straightforward, as outlined in the legend of Fig. 1. Transshipment requires a little further explanation. In the past, fishing boats would simply put out to sea, catch fish and then return to port to land the catch and sell it into the seafood network (as most near-shore vessels still do). In the recovery years after the second world war, Japan resolved employment and food shortages partly by rebuilding and expanding its fishing fleet, which soon moved into distant waters around the Pacific, particularly the Bering Sea (Bailey, 2011). As the fleet expanded to operate globally, Japan built a transshipment system whereby fishing vessels at sea can sell and transfer their catches to a large, special-purpose refrigerator ship ('reefer'), thus saving time and fuel on the journey between the fishing ground and the port. Once full, the reefer takes the combined catches to port for offloading: originally, all far-seas fish were offloaded in Japan and sold through Tokyo Tsukiji Market (Sloan, 2003). However, transshipment at sea (and, to some extent, at-sea processing) removes the direct connections among fishing vessels, the fishing locality and the catch. When controls for sustainability were first attempted, the reefers would become part of a number of ways around such controls, and transshipment is still today a source of problems (e.g. FAO, 2021b). Particularly regarding the tuna trade, reefers were originally owned 100% by Japan until around the turn of the century but are now operated also by several other countries (Sloan, 2003).

Not specified in this scheme is the contribution from aquaculture (e.g. Naylor *et al*., 2000). Currently there is no large-scale aquaculture of octopus although research into the techniques necessary for commercial production is under way in several countries around the world, including Australia, China, Japan, Mexico and Spain. In 2012, aquaculture production of fish exceeded 50% of all fish used for food and more than 20 million people rely on aquaculture for employment (FAO, 2021c). Although of major importance, aquaculture has its own set of problems outside the scope of the present paper, which here addresses sustainability issues mostly concerning wild-caught seafood.

3. Problems past and present: lessons from overfishing

The number of vessels of the world's fishing fleets is estimated to be about 4.6 million (Sustainable Fisheries, 2021). During the 20th Century, it became clear that the amount of seafood available is a finite resource and that a rapid increase in fishing capacity as a result of advances in ship and fishing-net technology resulted in many species being overfished (see, for example, Iudicello *et al*., 1999; Myers & Worm, 2003; Pauly & Maclean, 2003; Sloan, 2003; Bailey, 2011). That is, the annual harvest causes a year-on-year decline in the population, as opposed to sustainable fishing where a similar amount may be harvested each year without reducing the population in the long term. The consequences of overfishing have been brought home by collapses last century of fisheries for certain species which used to be regarded as 'common', such as the Pacific sardine, Atlantic cod and herring, and the near-extinct barndoor skate, *Raja laevis* (Casey & Myers, 1998; Bailey, 2011). The central Bering Sea walleye pollock fishery (once one of the richest fisheries in the world, with an annual catch exceeding 1.7 million tonnes) underwent a catastrophic collapse in the 1980s from which it has not recovered

(Bailey, 2011), although the eastern Bering Sea fishery is still healthy at about 1.4 million tonnes per year (K.M. Bailey, personal communication to IGG).

The reasons for the collapse of a fishery have in common that so many fish are harvested that the remaining population cannot generate replacement fish to be harvested in subsequent years. The exact reasons for failure to recover are probably species- and locality-specific but include changes to the ecosystem (e.g. Jackson *et al*., 2001) and failure of the remaining target-fish population to produce sufficient eggs and larvae to overcome the massive natural mortality from predation which occurs at these stages of the life cycle (see, for example, Bailey & Houde, 1989; Moustahfid *et al*., 2009a, b). Alterations to either or both consumers (predators) and resources (prey) can have wide-ranging effects on both biodiversity and the ecosystem which supports the resource; that is, effects on other organisms in the food web (e.g., Worm *et al*., 2002; Moustahfid *et al*., 2010).

Currently, Japanese flying squid (*Todarodes pacificus*) populations migrating through the international waters of the Japan Sea are subjected to rampant overfishing by hundreds of vessels from China (Park *et al*., 2020): a situation worryingly similar to that in which mainly Japanese, Korean and Russian fishing fleets brought about the collapse of the central Bering Sea walleye pollock fishery (Bailey, 2011). Such situations bring home the need for stringent mechanisms to control fishing and systematically monitor seafood populations to ensure they are sustainable.

4. Sustainability basics

To avoid overfishing and achieve sustainability, it is first important to recognize that the term ‘*fisheries*‘ includes “the fish in the sea, . . . people interacting with fish and with fish markets, fishing technology, government policy and marine ecosystems. Fishery management is the attempt to accommodate these interactions in a way that sustains fish populations” (HCSEE, 2000). However, the fishing industry and regulatory bodies have displayed amazing conflicts of interest in the past. For example, HCSEE is a so-called non-profit institution funded by the Heinz fortune, much of which was obtained from world-wide purse-seine fishing of tuna on a massive scale, but in the past has also received substantial government grants (Sloan, 2003). During the last 20 years or so, such conflicts of interest have been recognized and progress has been made in clarifying the problems and bringing together industrial, governmental, fisher and other stakeholder interests to work in harmony towards a common goal of sustainability.

The concept of the ‘Blue Economy’ has helped greatly to tackle the problems by couching marine resources in accounting terms easily understood by all parties interested in seafood organisms and the seafood business (Spalding, 2016; Keen *et al*., 2018; Wenhai *et al*., 2019). Sustainability of seafood production, harvesting, trading and consumption is the key to successful exploitation of the riches of the ocean; that is, a thriving blue economy. When a fishery collapses everyone loses, including the fish and their associated food web and ecosystem, as well as fishers, vessel owners, the fish processing industry and hungry consumers. Efficient, responsible management of the basic resource is essential, otherwise there will be nothing to exploit.

Management of a fishery requires both qualitative and quantitative knowledge of the target resource in order to decide the appropriate level of harvesting. Qualitative knowledge involves accurate identification of a resource: knowing what the target species is by recognizing its morphological characteristics and the scientific name it has been given. This requires expert knowledge to connect morphology and name, which can be represented by correctly identified images and corresponding genomic identification of the species. Quantitative knowledge entails estimating the number of individuals in the population (the biomass) of the target species (Wenhai *et al*., 2019), which can be achieved with the help of accurate catch statistics, regular sampling and tracing the movement of seafood through the distribution network to the consumer.

Controlling and monitoring of the harvested biomass require transparent traceability of the resource from capture to consumption, ensuring in particular that harvesting has not exceeded sustainable limits through problems such as illegal, unreported and unregulated (IUU) fishing, which has been and still is a pervasive problem worldwide (FAO, 2021a; GIZ, 2021; NOAA, 2021).

5. Sustainability undermined: the role of IUU fishing

In addition to overfishing *per se*, IUU fishing was a factor contributing to the collapse of the central Bering Sea walleye pollock fishery. There are reports that many catches were routinely underreported by at least 50% (Bailey, 2011). The catch estimates for octopus caught off West Africa (section 1, above) are reconstructed catches which make allowance for massive under-reporting, lack of records and illegal activities (= IUU fishing) along the West African coast: octopus fisheries are known to have been under-reported on a massive scale (Belhabib *et al*. 2012).

When IUU fishing occurs, it jeopardizes sustainability and is, in fact, theft of fish from the international community by removing quantities above the amount that the community collectively has decided can be removed at a sustainable level. Unchecked, such theft can have devastating consequences for the future of the particular seafood items concerned and, through the food web and ecosystem effects, has the potential to affect the sustainability of all seafood (Macfadyen *et al*., 2019; Donlan *et al*., 2020).

The sad fact that IUU problems had reached a massive, systematic scale, particularly in the lucrative tuna trade, was brought to notice by Japan at the turn of this century when it was revealed that the cargoes landed by reefer ships were mixed legitimate and IUU catches, and stated to be, in effect, 'fish laundering' (analogous to 'money laundering'), whereby IUU fish are able to enter the officially approved seafood sales chain (Sloan, 2003). The Japanese representatives asked that something be done about this problem (for details, see Sloan, 2003) and the international community has since introduced a number of mechanisms to combat IUU fishing. However, still today, IUU fishing is responsible for fishing over and above agreed sustainable catches by (in monetary terms) some US$10 to US$23 billion annually (Agnew *et al*., 2009; Ocean Panel, 2021). Losses to IUU fishing are basically a measure of invisible overfishing and as long as it exists sustainability will not be achieved.

IUU fishing involves a broad range of problems (FAO, 2021a; GIZ, 2021; NOAA, 2021). Species misidentification is frequent (both deliberate and accidental) and seafood source is often unclear, although the seafood industry, retailers and consumers are becoming more aware of the problems leading to failure to attain sustainability. People now demand more information about the origin of seafood at shops and restaurants. At all levels there is increasing pressure to source sustainable seafood at prices ensuring reliable profitability. The advantages conveyed by sustainability and profitability encourage improved stock management to try to safeguard sustainability, and thereby profitability.

6. Sustainability undermining addressed: ways to eliminate theft

Since the enactment of the United Nations Convention on the Law of the Sea (UNCLOS, which came into force officially in 1994), major steps have been taken to prevent IUU fishing practitioners from conducting their activities profitably, and thereby hopefully eliminating IUU fishing, eventually (Nodzenski *et al*., 2019; FAO, 2021a; GIZ, 2021; NOAA, 2021; USCG, 2021). The Port State Measures Agreement

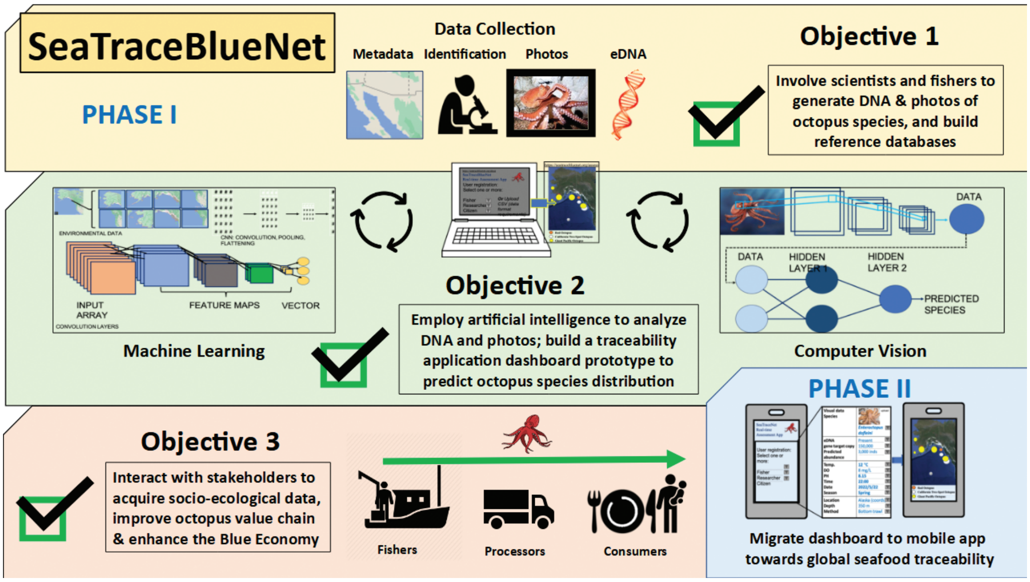

Fig. 2. Overview of the project to develop the computer and cell-phone traceability application (app), called *SeaTraceBlueNet* (STBN). STBN is the key to establishing our proposed system to help achieve seafood sustainability. During *Phase 1* of the project, scientists and fishers co-operate to build reference databases (*Objective 1*). These are: (1) a database of DNA sequences for various seafood species and the prey organisms consumed by the target seafood species; and (2) a database of images of seafood species. Artificial intelligence (computer image recognition) will be used to analyze and match images and DNA sequences to enable accurate identification of seafood species. Machine learning will be used to enable computer or mobile phone recognition of each species accurately, and this will form the basis for building the prototype traceability app STBN (*Objective 2*). Sampling of seawater in the vicinity of target species will provide eDNA signals which will be used to help quantify the presence of the target species, both spatially and temporally. *Phase II* will involve piloting STBN and obtaining feedback from stakeholders to improve it and put it into service to monitor the progress of octopus seafood products through the path from fisher to consumer (*Objective 3*). Ultimately, the information acquired is expected to inform a more transparent value chain for octopus products, protected by blockchain technology. Once successful, this system can then be applied to ensuring sustainability for any seafood product. (Figure constructed by CLA).

(PSMA) requires seaports worldwide to record all seafood transactions and to exclude IUU fishers from offloading their catches (Stop Illegal Fishing, 2019, 2021). The UN has instigated a registration system (the Ship Identification Number Scheme) where each vessel is required to have a Unique Vessel Identifier (UVI), provided by the International Maritime Organization (IMO). The UVI never changes throughout the life of the vessel, regardless of any modifications, changes in ownership or national flag under which it sails. All ships at or above 100 tonnes gross and all fishing vessels greater than 12 m length overall must have a UVI. This enables a record to be compiled of the activities and voyages of each registered vessel. The Global Record of UVIs (FAO, 2021b) includes more than 23,000 fishing vessels worldwide. Fishing vessels without a UVI (as an IMO number displayed prominently on the ship; Pew Charitable Trusts, 2019) are in violation of the PSMA.

As well as ship registration in the Global Record, a number of electronic vessel tracking measures have been mandated, including the Automatic Identification System (AIS) and Vessel Monitoring System (VMS), which are used also for safety to prevent collisions at sea. In addition, the satellite-based Visible Infrared Imaging Radiometer Suite (VIIRS) can monitor the position and routes of 85% of the boats which do not broadcast AIS or VMS signals: these are mostly IUU squid jigging and purse-seine vessels, which are detected by the bright lights required for these fishing methods (Park *et al*., 2020; Global Fishing Watch, 2021). These various tracking systems and reliable, verified and permanent identification of vessels have enabled a huge reduction in losses to IUU fishing but the losses are still very large so there are still problems requiring urgent resolution before seafood stocks will finally be rendered sustainable.

Reduction of IUU fishing to achieve sustainability can be greatly enhanced by improving traceability: identifying and tracking the exact source of seafood at each step in the commercial network from fishery to fork. Reliable traceability and sustainability can then enable new criteria for commercial enhancement of products, such as the use of ecolabels.

7. Sustainability tightened: SeaTraceBlueNet

The main aim of the SeaTraceBlueNet (STBN) project (Fig. 2) is to contribute to sustainability through major advances in accurate seafood identification and traceability, using octopus as a model resource during research and development. There are two problems when trying to manage the catch of octopuses, problems that are common to all seafood species: (i) identification (recognizing the morphological features of each seafood item and giving it its correct species name); and (ii) traceability (tracking the fate of each item). Identification is important in recognizing the range of a species and regulations for its successful management. Traceability is important in helping to regulate legitimate sales of seafood items from those fishermen and organizations who cooperate with the regulations and identifying any possible contributions from IUU fishing.

Accurate identification of seafood images will be achieved through a combination of traditional morphological characteristics aided by artificial intelligence (AI) supported by genomic data and eDNA monitoring. Traceability will be achieved with the aid of DNA sequence identification of the resource at each step from capture to consumption, using blockchain technology to ensure an accurate and immutable record of all transactions throughout the trading chain, linking *output* with *input* (see section 2). The essentials of identification and traceability will be combined in the form of a freely accessible software application (the STBN ‘app’) to inform all stakeholders and the general public of the means by which resource sustainability is being achieved.

As an example of the importance of correct identification, until recently the ‘common octopus’ consumed in Japan was regarded as a single, cosmopolitan species. However, it was shown that the species caught in the coastal waters of Japan is different from the European and West African species (Gleadall, 2016a), so in Japan there is a large annual consumption of two different species of common octopus, which are now identified as *Octopus sinensis* d’Orbigny, 1841, and *Octopus vulgaris* Cuvier, 1797. The Japanese names of these two species are madako (マダコ) and chichūkai madako (地中海マダコ), respectively (Gleadall, 2016b). However, distinguishing between these two species is very difficult, and resolving such difficulties of identification is one of the objectives of the STBN project.

Japanese populations of *O. sinensis* fluctuate widely from year-to-year and place-to-place, with little apparent correlation among different regions; and the amount of imported *O. vulgaris* has declined during the last 15 y from more than 100,000 t to around 40,000 t. In Japan at present these two species, as well as related species from other parts of the world, are still classified broadly as ‘madako.’ However, especially since these two species are from different oceans, it is clear that each species requires its own separate monitoring and management in the context of the ecosystem in which it exists (see, for example, Botsford *et al*., 1997; Jackson *et al*., 2001; Pauly & Maclean, 2003). STBN will facilitate such monitoring and management, and therefore sustainability, although other methods (e.g., Martino *et al*., 2022) are still necessary to fully appreciate the significance of broader ecosystem contributions to sustainability, since some seafood species have undergone long migrations before the time and location of their capture (see, for example, Yamaguchi *et al*., 2019).

These aims (identification, traceability and sustainability) are simultaneously becoming feasible because of a number of recent innovations and advances in techniques of identification, artificial intelligence, machine learning and blockchain validation (the latter is the technology which secures electronic money transactions). A blockchain is a decentralized, distributed digital ledger which takes the form of a growing list of transaction records, called blocks, linked together using cryptography. Each block contains information about the block previous to it, so the blocks form a chain, with each additional block reinforcing those before it. Once a transaction has been recorded, that record cannot be changed, and anyone can audit the blockchain (e.g., Leong *et al*., 2018), providing the required link between *output* (seafood at the consumer) and the original *input* (source population and locality).

8. Summary of the SeaTraceBlueNet project

The main aim of the project is to produce a traceability tool (the STBN app; Fig. 2) that will allow stakeholders (including consumers) to know the species caught, its source, and confirmation of its legitimate path from fishery to fork. This tool and its data will be made available for open use by all, including fishers, fisheries managers, industrial partners and consumers. Another aim is to use the traceability tool to devise innovative ways of assessing seafood stock status, to both ensure sustainability and maintain the value of the product.

The methods used are mostly cutting-edge, newly-developed by members of the STBN team. Octopuses in the fishery will be detected using eDNA sampling. In Phase 1, species will be identified by DNA barcoding, validated by correlation with species morphology. In Phase 2, it is planned to experiment with ways to detect the relative biomass of target species within a given area by using eDNA technology to measure the presence of certain key proteins. While collecting and analyzing eDNA samples, draft whole genome assemblies of different octopus species are being generated and made available in the public domain. To enable machine recognition of octopus species, a series of images for each species is being analyzed using data processing methods based on artificial intelligence (AI) and machine learning (ML). It is planned eventually to port the STBN interface for use as a mobile phone app, which will have full access to all the information generated. Once STBN is in action, it is planned that octopus seafood transactions can be recorded using blockchain technology and that this tool will contribute to improvements in fisheries management.

In designing and testing STBN, fishers and consumers will be included, as also will industrial partners, whose specialist input and periodic feedback will contribute to best develop the app and methods to ensure they are relevant to industry needs and requirements. Industrial partners will also benefit directly by being able to explore unique marketing opportunities to increase their market share through this venture, as well as being among the first to test tools already designed and adapted for industry needs.

9. Relevance to the UN Sustainable Development Goals (SDGs)

To conclude, it is noted that the STBN project, with its aims and objectives focused on seafood sustainability, is a potential contributor to the UN Decade of Ocean Science for Sustainable Development (from 2021 to 2030). It also contributes to the SDGs outlined by the United Nations (2015), to be realized by 2030. Four of these SDGs in particular are addressed by this project.

Goal 2: End hunger, achieve and promote food security, improved nutrition and sustainable culture, doubling productivity (including that of fishers) by 2030.

Goal 9: Build resilient infrastructure, promote inclusive and sustainable industrialization, and foster innovation and access to information.

Goal 14: Conserve and sustainably use the oceans, seas and marine resources for sustainable development, and eliminate IUU fishing.

Goal 17: Strengthen the means of implementation and revitalize the Global Partnership for Sustainable Development (GPSD: an organization established at the United Nations International Conference on Financing for Development which took place in Monterrey, Mexico, in 2002). Enhance regional and international cooperation on and access to science, technology and innovation. Enhance knowledge through global technology facilitation, particularly with regard to information and communications technology.

References

[1] Agnew, D.J., Pearce, J., Pramod, G., Peatman, T., Watson, R., Beddington, J.R. & Pitcher, T.J. (2009). Estimating the worldwide extent of illegal fishing. PLOS ONE 4 (2; e4570), 1-8.

[2] Bailey, K.M. (2011). An empty donut hole: the great collapse of a North American fishery. Ecology and Society 16 (2; 28), 1-16.

[3] Bailey, K.M. & Houde, E.D. (1989). Predation on eggs and larvae of marine fishes and the recruitment problem. In Advances in Marine Biology, 25, pp. 1-83.

[4]Belhabib, D., Zeller, D., Harper, S., & Pauly, D. (eds.). (2012). Marine fisheries catches in West Africa, 1950–2010, Part I. Fisheries Centre Research Reports Canada 20 (3), 1-104.

[5] Botsford, L.W., Castilla, J.C. & Peterson, C.H. (1997). The management of fisheries and marine ecosystems. Science 277 (5325), 509-515.

[6] Casey, J.M. & Myers, R.A. (1998). Near extinction of a large, widely distributed fish. Science 281 (5377), 690-692.

[7] Donlan, C.J., Wilcox, C., Luque, G.M. & Gelcich, S. (2020). Estimating illegal fishing from enforcement officers. Nature Scientific Reports 10 (1; 12478), 1-9.

[8] FAO (2021a). Illegal, Unreported and Unregulated (IUU) fishing. Food and Agricultural Organization (FAO). https://www.fao.org/iuu-fishing/background/what-is-iuu-fishing/en/ (last viewed 28 Nov., 2021).

[9] FAO (2021b). Global record of fishing vessels, refrigerated transport vessels and supply vessels https://www.fao.org/global-record/en/ (last viewed 28 Nov., 2021).

[10] FAO (2021c). The state of world fisheries and aquaculture 2020. https://www.fao.org/state-of-fisheries-aquaculture (last viewed 28 Nov., 2021)

[11] GIZ (2021). More fish and income from sustainable fisheries and aquaculture. Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ). https://www.giz.de/en/worldwide/78737.html (last viewed 28 Nov., 2021).

[12] Gleadall, I.G. (2016a). *Octopus sinensis* d'Orbigny, 1841 (Cephalopoda: Octopodidae): valid species name for the commercially valuable East Asian common octopus. Species Diversity 21, 31-42.

[13] Gleadall, I.G. (2016b). 東アジアに分布する商品が高いマダコの学名は *Octopus sinensis* d'Orbigny, 1841 (頭足綱: マダコ科) が妥当である [*Octopus sinensis* d'Orbigny, 1841 (Class Cephalopoda: Family Octopodidae) is the appropriate scientific name for 'madako', the highly priced consumer product endemic to East Asia]. Taxa 41, 55-56 (Japanese summary of Gleadall, 2016a).

[14] Global Fishing Watch (2021). Revolutionizing ocean monitoring and analysis. https://globalfishingwatch.org (last viewed 30 Nov., 2021)

[15] The H. John Heinz III Center for Science, Economics and the Environment (HCSEE). (2000). Fishing grounds: defining a new era for American fisheries management. Washington D.C. & Covelo, California: Island Press.

[16] Iudicello, S., Weber, M. & Wieland, R. (1999). Fish, markets, and fishermen: the economics of overfishing. Washington D.C. & Covelo, California: Center for Marine Conservation. Island Press.

[17] Jackson, J.B.C., Kirby, M.X., Berger, W.H., Bjorndal, K.A., Botsford, L.W., Bourque, B.J., Bradbury, R.H., Cooke, R., Erlandson, J., Estes, J.A. *et al*. (2001). Historical overfishing and the recent collapse of coastal ecosystems. Science 293 (5530), 629-637.

[18] Keen, M.R., Schwarz, A.-M. & Wini-Simeon, L. (2018). Towards defining the blue economy: practical lessons from Pacific Ocean governance. Marine Policy 88, 333-341.

[19] Leong, C., Viskin, T. & Stewart, R. (2018). Tracing the supply chain. How blockchain can enable traceability in the food industry. Palo Alto, California: Accenture & the Moore Foundation. https://www.accenture.com/_acnmedia/PDF-93/Accenture-Tracing-Supply-Chain-Blockchain-Study-PoV.pdf (Retrieved 30 Nov., 2021).

[20] Macfadyen, G., Hosch, G., Kaysser, N. & Tagzirla, L. (2019). The IUU Fishing Index: Poseidon Aquatic Resource Management Limited and the Global Initiative Against Transnational Organized Crime. pp. 1-116. https://iuufishingindex.net/include/IUU-Report.pdf (Retrieved 28 Nov., 2021)

[21] Martino, J.C., Mazumder, D., Gadd, P. & Doubleday, Z.A. (2022). Tracking the provenance of octopus using isotopic and multi-elemental analysis. Food Chemistry 371 (131133), 1-6. https://doi.org/10.1016/j.foodchem. 2021. 131133 (Last viewed 25 Nov., 2021).

[22] Moustahfid, H., Tyrrell, M.C. & Link, J.S. (2009a). Accounting explicitly for predation mortality in surplus production models: an approach to longfin inshore squid (*Loligo pealeii*). North American Journal of Fisheries Management 29 (6), 1555-1566.

[23] Moustahfid, H., Link, J.S., Overholtz, W.J., & Tyrrell, M.C. (2009b). The advantage of explicitly incorporating predation mortality into age structured stock assessment models: an application for Atlantic Mackerel. ICES Journal of Marine Science 66 (3): 445-454.

[24] Moustahfid H., Tyrrell, M.C., Link, J.S., Nye, J.A., Smith, B.E. & Gamble, R.J. (2010). Functional feeding responses of piscivorous fishes from the northeast US continental shelf. Oecologia 163, 1059-1067.

[25] Myers, R.A. & Worm, B. (2003). Rapid worldwide depletion of predatory fish communities. Nature 423 (6937), 280-283.

[26] Naylor, R.L., Goldburg, R.J., Primavera, J.H., Kautsky, N., Beveridge, M.C.M., Clay, J., Folke, C., Lubchenco, J., Mooney, H. & Troell, M. (2000). Effect of aquaculture on world fish supplies. Nature 405 (6790), 1017-1024.

[27] NOAA (2021). Understanding Illegal, Unreported, and Unregulated Fishing. Fishing & Seafood: Sustainable Fisheries Topics. National Oceanic and Atmospheric Administration (NOAA). https://www.fisheries.noaa.gov/insight/understanding-illegal-unreported-and-unregulated-fishing (last viewed 28 Nov., 2021).

[28] National Science Foundation (NSF) (2021). Award Abstract #2137582: NSF Convergence Accelerator Track E: Innovative seafood traceability network for sustainable use, improved market access, and enhanced blue economy. https://www.nsf.gov/awardsearch/showAward?AWD_ID=2137582 (last viewed 2 Nov., 2021)

[29] Nodzenski, S., Miller, D., Vulperhorst, V., Langley, E., Evangelides, N. & Leroy, A. (2019). Ending illegal, unreported and unregulated fishing: essential criteria for improving transparency and achieving good governance in fisheries. (published on line): Environmental Justice Foundation, Oceana, The Nature Conservancy, The Pew Charitable Trusts & WWF. http://www.iuuwatch.eu/wp-content/uploads/2019/10/Transparency-good-governance-criteria_EU-IUU-Coalition.pdf (Retrieved 26 Nov., 2021)

[30] Ocean Panel (2021). Illegal, unreported and unregulated fishing and associated drivers. Blue Paper Summary. Ocean Panel (High Level Panel for a Sustainable Ocean Economy). pp. 1-4. https://oceanpanel.org/sites/default/files/2020-09/Summary_Illegal%2C%20Unreported%20and%20Unregulated%20Fishing%20and%20Associated%20Drivers.pdf (Retrieved 30 Nov., 2021)

[31] Park, J., Lee, J., Seto, K., Hochberg, T., Wong, B.A., Miller, N.A., Takasaki, K., Kubota, H., Oozeki, Y., Doshi, S., Midzik, M., Hanich, Q., Sullivan, B., Woods, P., & Kroodsma, D.A. (2020). Illuminating dark fishing fleets in North Korea. Science Advances 6 (30; eabb1197), 1-7. https://doi.org/10.1126/sciadv.abb1197

[32] Pauly, D. & Maclean, J.L. (2003). In a perfect ocean: the state of fisheries and ecosystems in the North Atlantic Ocean. Washington DC, Covelo, California, and London: Center for Resource Economics. Island Press.

[33] The Pew Charitable Trusts (2019). The IMO number explained. pp. 1-8. https://www.pewtrusts.org/-/media/assets/2019/09/imo_number_explained.pdf

[34] Sauer, W.H.H., Gleadall, I.G., Downey-Breedt, N., Doubleday, Z., Gillespie, G., Haimovici, M., Ibáñez, C.M., Katugin, O.N., Leporati, S., Lipinski, M. *et al*. (2019). World octopus fisheries. Reviews in Fisheries Science and Aquaculture 29 (3), 279-429.

[35] Sloan, S. (2003). Ocean bankruptcy: world fisheries on the brink of disaster. Guilford, Connecticut: Lyons Press.

[36] Spalding, M.J. (2016). 8. The new blue economy: the future of sustainability. Journal of Ocean and Coastal Economics 2 (2), 1-21.

[37] Stop Illegal Fishing (2019). Keeping illegally caught fish out of African ports. pp. 1-15, PSM-SIF01/11-2019-EN. Botswana: Stop Illegal Fishing (Nordenfjeldske Development Services (NFDS), Africa).

[38] Stop Illegal Fishing (2021). Port state measures to stop illegal fishing. Stop Illegal Fishing (Nordenfjeldske Development Services (NFDS), Africa). https://stopillegalfishing.com/initiatives/implementing-port-state-measures/ (last viewed 28 Nov., 2021).

[39] Sustainable Fisheries (2021). Illegal, Unreported, and Unregulated Fishing. https://sustainablefisheries-uw.org/seafood-101/iuu-fishing/ (University of Washington; last viewed 30 Nov., 2021)

[40] United Nations (2015). Transforming our world: the 2030 agenda for sustainable development (UN Resolution A/RES/70/1). Seventieth Session Agenda Items 15 and 116: Resolution adopted by the General Assembly on 25 September 2015, 1-35. https://sdgs.un.org/2030agenda

[41] United States Coast Guard (USCG) (2021) Illegal, Unreported, and Unregulated Fishing. https://www.uscg.mil/iuufishing/ (last viewed 30 Nov., 2021).

[42] Wenhai, L., Cusack, C., Baker, M., Tao, W., Mingbao, C., Paige, K., Xiaofan, Z., Levin, L., Escobar, E., Amon, D. *et al*. (2019). Successful blue economy examples with an emphasis on international perspectives. Frontiers in Marine Science 6 (261), 1-14.

[43] Worm, B., Lotze, H.K., Hillebrand, H., & Sommer, U. (2002) Consumer versus resource control of species diversity and ecosystem functioning. Nature 417, 848-851.

[44] Yamaguchi, T., Aketagawa, T., Takayama, K., Hirose, N. & Matsuyama, M. (2019). Migratory routes of different sized swordtip squid (*Uroteuthis edulis*) caught in the Tsushima Strait. Fisheries Research 209, 24-31.