New and Emerging Technologies for Sustainable Fisheries:

A Comprehensive Landscape Analysis

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Contents

List of Acronyms

ADB	Asian Development Bank
AFMA	Australian Fisheries Management Authority
AFSC	Alaska Fisheries Science Center
AI	Artificial Intelligence
AIS	Automatic Identification System
AWS	Amazon Web Services
BDC	Berring Data Collective
BDP	Big Data Project
BFAR	Bureau of Fisheries and Aquatic Resources (Philippines)
CI	Conservation International
CPUE	Catch Per Unit Effort
DARPA	Defense Advanced Research Projects Agency
DFI	Development Finance Institution
DL	Deep Learning
DNB	Day Night Band
DOV	Diver Operated Vehicle
EDF	Environmental Defense Fund
EEZ	Exclusive Economic Zone
EFCA	European Fisheries Control Agency
EIB	European Investment Bank
EIF	European Investment Fund
EM	Electronic Monitoring
EMR	Electronic Monitoring and Reporting
ERP	Enterprise Resource Planning
EU	European Union
FAD	Fish Aggregating Device
FAO	Food and Agriculture Organization (of the UN)
FIP	Fishery Improvement Project
GDST	Global Dialogue for Seafood Traceability
GEF	Global Environment Facility
GFW	Global Fishing Watch
GPS	Global Positioning System
GSI	Genetic Stock Identification
GSM	Global System for Mobile communications
IMO	International Maritime Organization
IUU	Illegal, Unreported and Unregulated (fishing)
JICA	Japan International Cooperation Agency
LiDAR	Light Detection and Ranging
MCS	Monitoring Control and Surveillance
MPA	Marine Protected Area
MSC	Marine Stewardship Council
MSP	Marine Spatial Planning
NFC	Near Field Communications
NFWF	National Fish and Wildlife Foundation
NGO	Non-Governmental Organization
NOAA	National Oceanic and Atmospheric Administration

OECD	Organisation for Economic Cooperation and Development
PNA	Parties to the Nauru Agreement
PSMA	Port State Measures Agreement.
RFID	Radio Frequency Identification
RFP	Request for Proposals
ROV	Remotely Operated Vehicle
RUV	Remote Underwater Vehicle
SALT	Seafood Alliance for Legality and Traceability
SAPO	Sistema de Alerta, Prediccion, y Observacion
SAR	Synthetic Aperture Radar
SBI	Smart Boat Initiative
SDG	Sustainable Development Goal
SERNAPESCA	Chile National Fisheries Agency
SK	Saltonstall-Kennedy
SLAR	Side-Looking Aperture Radar
SOF	Sustainable Oceans Fund
SSF	Small-Scale Fishery
TNC	The Nature Conservancy
TUV	Towed Underwater Vehicle
UAS	Unmanned Aerial System
UN	United Nations
USAID	United States Agency for International Development
USGS	United States Geological Survey
USV	Unmanned Surface Vehicle
VIIRS	Visual Infrared Imaging Radiometer Suite
VMS	Vessel Monitoring System
WCPFC	Western and Central Pacific Fisheries Commission
WCPO	Western and Central Pacific Ocean
WWF	World Wildlife Fund


Photo by seapics.com

1. Introduction

The oceans are at an inflection point. The excesses of the 20th century — over-exploitation of most of our accessible biological resources, over-pollution by plastics and other chemicals, over-crowding of coastal and marine space by unorganized and competing interests and over-capitalization of extractive industries — are being tempered by a rapidly growing realization that these excesses are having very real consequences, not just for marine life and ocean ecosystems, but for the food security and nutrition of the world's population, the livelihoods of the communities that depend on the ocean and the very future of humanity itself.

The huge scale of detrimental impacts to the world's oceans are a direct result of the rapid technological change that we have experienced since the first industrial revolution. This broad change is not only causing the greatest existential threat we have ever faced — a warming climate — but has driven massive increases in our ability to harvest the ocean's mineral and biological resources, new manufacturing processes on land that have resulted in huge amounts of effluent leaking into the ocean and atmosphere and rapid globalization, enabled by better communications and transportation, that has upended traditional ways of life in favor of consumption-based existences. It is ironic then, that emerging technologies are not just the reason that we have come to realize the scale of these impacts but are also essential for mitigating and reversing them. The past several decades have seen an incredible range of technological advances that are impacting everyone on Earth. Perhaps the most important category has been the proliferation of communications networks to reach all corners (and some depths) of our globe. Cellular networks that support the 3.5 billion people that now use a smartphone are becoming faster and more accessible. Tens of thousands of micro-satellites, some the size of grilled cheese sandwiches,[1] are being launched to form mesh networks over large areas of the earth's surface. New methods of communicating underwater, such as hydro-acoustic modems,[2] are being developed. This communication infrastructure is supporting and driving forward a digital revolution. The advent of cloud-based computing, which effectively gives anybody with an adequate internet connection access to a super-computer, is decentralizing access to new technologies and allowing them to be applied in more places around the world. New sensor technologies that are expanding the range of data types that can be collected — and reducing the costs of collecting that data — are expanding our horizons for what is possible to understand about the oceans and our influences on them. New analysis tools that leverage the power of artificial intelligence are increasing our ability to make use of these expanding datasets in ways that we never would have thought possible until recently. The ability of more users to create more value from more information is driving the development of integrated technologies, where single information sources are being used by multiple parties. A data management paradigm that emphasizes free use, access and sharing is taking over from one of information monoliths, where the parties that collect data are the only ones to store and use it.

The fourth industrial revolution, where integrated tech-

[1] https://swarm.space/
[2] http://www.teledynemarine.com/acoustic-modems

nologies are increasingly being used to automate production processes is happening now and at the same time as the fourth wave of environmentalism, where environmental responsibility is becoming an integral part of doing business. This nexus represents a grand opportunity to utilize new technologies to foster environmental sustainability in ways that are aligned with business operations and the result is the restructuring of most of the world's industries — a restructuring that has the emerging potential of digital technologies at its heart. And while most industries are moving towards this new paradigm quickly the world's fisheries are being left behind. There are many underlying reasons for this: fishermen are often disenfranchised, poorly organized and lack a voice in the policy process; fish are difficult to count; fishermen are often independent operators that are highly dispersed and hard to keep track of; and many fisheries are difficult to manage, which has resulted in their depletion to levels far-below their potential. All of these factors (as well as many others) complicate efforts to 'normalize' or 'rationalize' the management of not just the resource, but the entire industry, making efforts to improve fisheries difficult from both logistical and investment perspectives. However, the factors that make investment in technological progress difficult also represent the areas where technology can make the most impactful differences and drive the most progress towards a digital future for fisheries.

And while progress has been slow, a widespread mobilization of human, capital and political resources has been occurring over the past decade, with new technologies at its core, aimed at reversing the impacts of previous actions while charting a course for sustainable use of the oceans.

This global mobilization toward sustainable use is taking on a sense of increased urgency and is reflected by the establishment of United Nations (UN) Sustainable Development Goal 14 (SDG 14) in 2015, which aims to "*conserve and sustainably use the oceans, sea and marine resources for sustainable development*"[3] as well as the UN declaration of a Decade of Ocean Science for Sustainable Development[4] with an overarching goal of reversing declining ocean health and gathering stakeholders behind a common framework to ensure that all countries benefit from ocean science in their sustainable development of the oceans. Other global initiatives that have gained traction include the FAO-led Port State Measures Agreement (PSMA),[5] which aims to fight illegal, unregulated and unreported (IUU) fishing by refusing port services, including offloading capabilities, to vessels engaged in these activities, and the IUCN's call to protect at least 30% of the area of the ocean by 2030 with no extractive activities allowed (30x30).[6] Efforts such as these are a recognition that the challenges facing our sustainable use of the ocean are too big to be tackled piecemeal.

None of these initiatives would be achievable without the central role played by emerging technologies. For example, countries participating in the PSMA are able to identify which vessels to sanction because we have technology-based vessel tracking and seafood tracing systems. Understanding which areas to protect under the 30x30 initiative in order to maximize ecological protection while minimizing conflicts with other ocean users depends on our ability to understand and map the spatial distribution of marine habitats and anthropogenic activities. And the UN's Decade of Ocean Science has been declared in recognition that we now possess the technologies needed to make a giant leap forward in understanding not just the ocean's ecosystems, but how our activities impact them. Collaborative agreements such as these, which initiate national-level responses, have important roles to play in driving technological innovation. For example, the International Maritime Organization (IMO) has a mandate requiring the global shipping fleet to halve greenhouse gas emissions by 2050[7] which has contributed to the possibility of zero emission vessel propulsion systems entering the market by 2030 (Leape et al. 2020), and the IMO Cape Town Agreement on fishing vessel safety[8] should help to reduce risks to commercial fishing crews by setting achievable performance standards for vessel construction and design.

Government regulations can be important drivers of innovation, especially if regulatory agencies focus on writing regulations that are responsive to the current technological state of play but also incentivize further innovation and achievement of efficiencies.

Governments are also playing an important role in providing funding for technological development and serving as a conduits for funding, such as World Bank investments. Overall, the funding environment for fisheries and ocean technologies is strengthening with traditional sources of philanthropic, non-governmental organization (NGO), government and multi-lateral funding for technology development and fishery improvement being increasingly complemented by return-seeking investments through impact funds and the private sector. Funding technology development for fisheries and sustainable oceans uses has always been challenging as the established market for these products and services is relatively small. For example, while funding for aquaculture innovations that have a clear commercial imperative is plentiful, funding for fisheries monitoring and ocean science is relatively lacking. This is beginning to change. Increasingly, a 'blue economy' approach is being taken to investing in the oceans space for sustainability-focused investments, often framed in the context of achieving SDG 14. This approach is underpinned by the belief that there will be significant ongoing growth in the blue economy and that while most of the mechanisms for creating monetary value are currently poorly understood, they will continue to become elucidated.

[3] https://sdgs.un.org/goals/goal14
[4] https://en.unesco.org/ocean-decade
[5] http://www.fao.org/port-state-measures/en/
[6] https://www.iucn.org/resources/issues-briefs/marine-protected-areas-and-climate-change
[7] https://www.imo.org/en/MediaCentre/PressBriefings/Pages/06GHGinitialstrategy.aspx
[8] https://www.imo.org/en/MediaCentre/PressBriefings/Pages/25-Torremolinos-Conference.aspx

We don't understand how value in the oceans space will be created in the future, just that the potential is massive.

However, the path towards a strong, sustainability-focused ocean economy has a gap in it, a result of the circular notion that a strong market for ocean technologies is needed to drive technological innovation but to stimulate this market investments in technological solutions need to occur now when it is not well-defined. This is where technology accelerators, private investors and specific philanthropic funders are coming in, bridging this gap with financial and often technical support. But stimulating this market is more than just a question of funding aimed at increasing the supply of technological innovations. What is also needed is a stimulation of demand for the information that will be collected using these innovations, demand which will come from a widening array of users. One source of information demand is relatively well described: major seafood buyers are increasingly emphasizing responsible sourcing of seafood that is environmentally friendly, safe, avoids lining the pockets of nefarious supply chain actors and involves a fair distribution of benefits to all nodes in the supply chain. Consumers are willing to pay for these characteristics (e.g. Fonner and Sylvia 2015; Zander and Feucht 2018) which imparts direct value to collecting traceability data. And while securing this information has traditionally involved the use of interoperable traceability systems that have been out of reach of all but the biggest companies, these functions are increasingly becoming available to many more supply chain actors, including small-scale fishers, through smartphone and cloud-based applications.

Increasing the demand for information will depend not only on demonstrations that value — both direct monetary value and indirect conservation value — can be derived from information in geographies where technological literacy is already high, but in increasing the capacity of potential users of information in geographies where that literacy is not high.

New technologies have a critical role to play here as, increasingly, the requirements for human capital to undertake valuable tasks are being subsumed by the technology itself. Recent advances in technology have improved the cost-effectiveness of existing data collection techniques but have also expanded the suite of tools at the disposal of fishery managers looking to make informed management decisions. Advances have come in our ability to convert data to knowledge, and to use that knowledge to effect successful fisheries and oceans management. Moreover, more rapid and intensive data collection supported by technology, machine learning and artificial intelligence dramatically enhances the potential for adaptive fisheries and oceans management in response to changes in the ocean due to global warming or other drivers.

The amount of fisheries and ocean data being collected is increasing exponentially, driven both by increases in the supply of data (through improvements and cost reductions in sensors and the platforms that support these sensors), and the demand for data. And mirroring the wider move away from 'information monoliths', a new ocean data ecosystem, in which data are shared more widely, local and traditional knowledge are better integrated and the environment for data innovation is healthy, is happening now (Leape et al. 2020). This new ocean data ecosystem will usher in an age of 'radical transparency' in fisheries and oceans activities and as the tools and processes for wider — and easier — sharing of ocean data improve, more and more data users will appear, demanding more interoperability and integration of data. To ensure the sustainable use of our ocean we need to understand, in a measurable way, the impacts of our actions. Emerging technologies that are integrated into this new data ecosystem will enable a greater and more flexible understanding of marine processes and how they respond to anthropogenic influences and underpin all efforts to engage in sustainable management of any ocean industry — none more so perhaps than the fishing industry.

What are the broad technological advances that are having major implications for global fisheries and marine resource management? Who are the major players involved in driving fisheries and oceans management towards a new digital paradigm? What challenges are being effectively addressed and which are not? To answer these questions (and many more), this document provides a landscape analysis of the technological 'state of play' as well as current activity relating to the use of new and emerging technologies to help solve common fishery-related challenges at the global, regional and national levels, including the individuals, organizations, countries and technology service providers engaged in these activities. Activities range from on-the-water technical implementations of cameras or other sensors to collect data, to regional scale efforts to monitor illegal fishing using satellites, to global scale efforts to streamline and modernize data management systems. Activities are focused on solving situation-specific challenges and, although each fishery is different, we have identified a group of challenges that are common to many fisheries and that serve as focal points for this report. These challenges are: accounting for fisheries catch and effort, compliance monitoring, stock abundance and productivity estimation, ocean ecosystem monitoring, increasing the transparency of the supply chain and data integration and management. We start in section 2 by providing an overview of the technologies that are helping to transform management of the oceans space and discuss the current and likely future implications that these developments are having. In section 3 we discuss the major categories of fishery-related challenges named above and discuss specific practical initiatives aimed at addressing them. We conclude in section 4 with an overview of the funding and financing environment that these initiatives operate in and discuss current and future trends in the major types of funding categories.

Photo by Leslie Von Pless/EDF

2. Transformative Technologies

The transformative potential of the digital revolution is growing exponentially, driven by rapid improvements in functionality and reductions in cost of sensors that collect information, platforms that house sensors and in the technologies used to compile, analyze, transmit, store and access data.

While rapid improvements are being made in almost every field of study or application, technical advances that are key to improving sustainable fisheries and ocean management are occurring in several areas. These include the development of sensors that translate the wide spectrum of physical phenomena to measurable digital information, the proliferation of constellations of satellites that monitor the ocean, the advent of fully autonomous data collection platforms that can explore the extent of the marine environment without need for human control and improvements in fishing technology that are increasing operational efficiency while minimizing environmental harm. But the most important advances are those that are fueling all industries — not just ocean-based ones. These include the large-scale uptake of smartphones to all corners of the globe, the associated prodigious increases in speed and reach of wireless data networks that are making the Internet of Things (where *all* things are connected) possible, the ongoing shift from monolithic computer servers to cloud-based computing (which brings the power of a super-computer to anyone with an internet connection) and the development of the fields of machine learning and artificial intelligence which enable us to make sense of, and draw value from, the huge amounts of data that characterize this revolution. In this section we give a broad overview of some of the most important technological advances and discuss potential implications of these advances for fisheries and ocean management.

2.1 Sensors

Sensors measure physical or chemical variables such as light and sound and translate these measurements into digital information, or data. They are the foundation of ocean monitoring and scientific discovery: more and better sensors means more and better data. The evolution of sensors is being driven by miniaturization and power reduction (Leape et al. 2020). Reducing the amount of power needed to operate a sensor, often by making it smaller, means that it can operate for longer on a set amount of battery power or can reduce the amount of energy needed to be generated through solar panels or other methods. Power reductions in turn help to drive miniaturization, which enables sensors to be placed on new and smaller platforms which themselves require less energy to operate. Some sensors are so small that they are now being embedded on the systems tasked with carrying data such as fiber optic cables (Zhan, 2020), and they require so little power to operate that they can be placed onto the backs of bumblebees (Iyer et al., 2020).

Optical sensors

Cameras used in fisheries and ocean monitoring have benefited from advances driven by the market for smartphone cameras. Compared to just a few years ago, cameras are now smaller, lighter, higher resolution, capture images at a higher frame rate, have greater zoom capabilities, perform better in low light conditions and are available at a much-reduced cost. Off-the-shelf camera systems designed for the transportation industry are durable enough to withstand conditions common to the high seas and Arctic. SnapIT,[9] a New Zealand based technology company, has designed camera systems for fisheries monitoring that are submersible to 4000m. Cameras that record up to a 360º field of view are now available, meaning that monitoring everything above (or below) a plane is feasible, with software performing focus and zoom functions after image capture. These new systems have the potential to reduce the number of cameras needed for a given situation and effectively let viewers explore vessel activities in their own virtual reality experience. Hyperspectral cameras go beyond the visible light spectrum and capture inputs continuously across the entire electromagnetic spectrum. While these types of cameras are being used in the food and manufacturing sectors (to sort out rotten food from fresh, for example; (Elmasry et al., 2012; Xu & Sun, 2017)), their full potential has yet to be realized in the oceans space. Recently, however, researchers have been exploring the use of hyperspectral imaging to identify species of fish based on their electromagnetic signature (pers. comm. S. Romain).


A SnapIT solar VMS unit

Photo by SnapIT

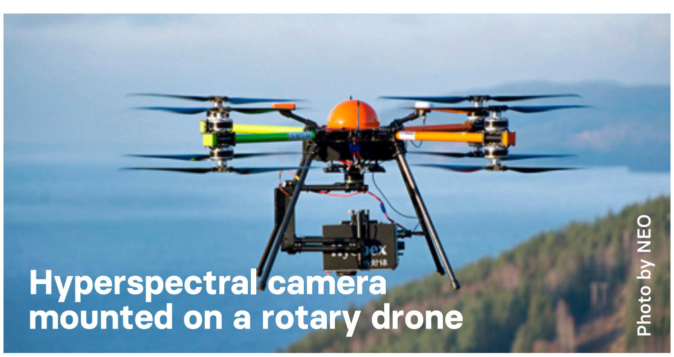

Hyperspectral camera mounted on a rotary drone

Photo by NEO

Acoustic sensors

The ocean is on average ten trillion times opaquer than the atmosphere (Leape et al. 2020) so while cameras are suited for operating above the surface, acoustics hold much greater promise for exploring the ocean's depths. An increasing number of acoustic tools are being developed for new uses and existing tools are constantly improving (Baumgartner et al., 2018). These include long-baseline positioning tools that track ships and divers, acoustic sound traps that record ocean soundscapes, echosounders that paint a picture of the ocean underneath a platform, side scan sonars that help fishermen locate fish and acoustic doppler profilers that measure the speed and direction of water currents. The ballooning world of ocean acoustics includes estimating fish population abundance, assessing behavior and distributions of fish and mammal species, acoustically tagging and tracking endangered species and using long-range low frequency acoustic thermometry to assess global warming by measuring polar pack ice thickness as well as glacier and ice-sheet stability (Howe et al., 2019).

Biochemical sensors

The increasingly wide range of biochemical sensors that have potential applications for the oceans is mainly a result of technology transfer from the medical and pharmaceutical industries. Spectral flow cytometry[10] and other spectroscopic techniques (e.g. (Cabernard et al., 2018; Schymanski et al., 2018) have huge potential to transform the ways we observe and manage the ocean. Advances in biochemical sensors and related instrumentation are the key to identifying objects like micro-plastics or harmful algae in water samples. These advances are translating to faster, more portable analyses that offer more users the ability to monitor pollution and water quality. Biochemical sensors record key metrics of climate change, such as carbon dioxide levels, the pH of water and concentrations of methane, and help scientists to study biological responses of marine life in response to climate stresses such as increasing ocean acidification (Stillman & Paganini, 2015). As these sensors become more precise, dependable, small and inexpensive, their deployment becomes more widespread (McPartlin et al., 2016). Formerly, collecting information on chlorophyll, salinity, depth, currents, turbidity, oxygen saturation and other oceanographic variables was restricted to well-funded scientific research projects. The cost and size of oceanographic sensors has now decreased to the point where hand-deployed instruments by citizen scientists or inexpensive sensor arrays attached to small-scale fishing vessels are now feasible.

Radar

While natural aperture Side Looking Airborne Radar

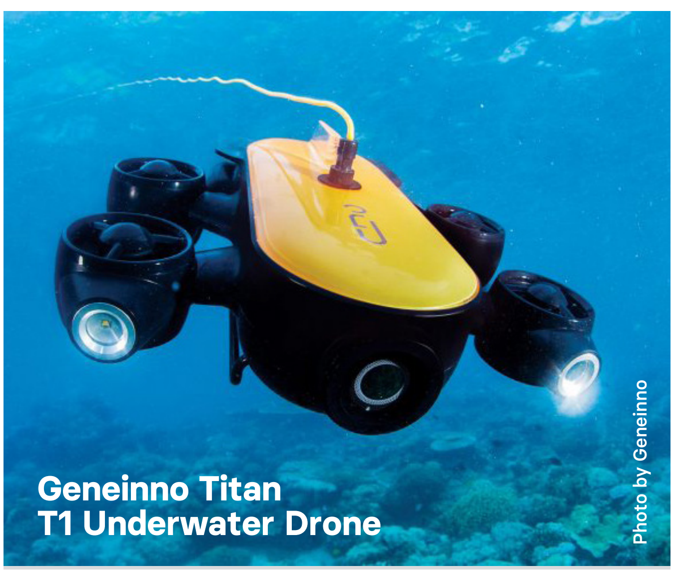
9 https://www.snapit.group/

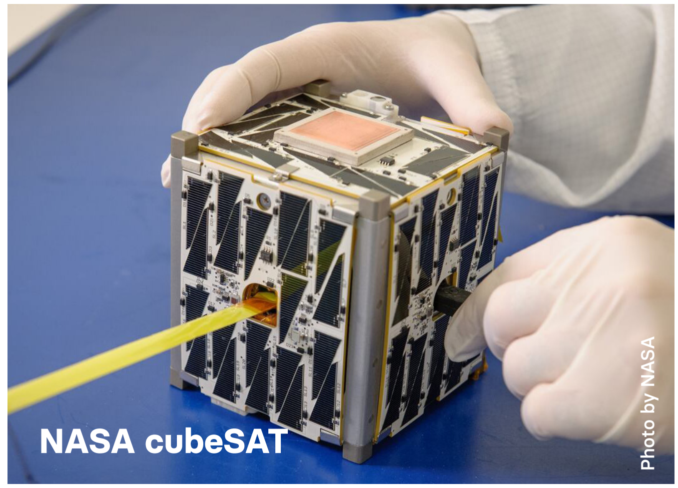
10 https://www.thermofisher.com/ca/en/home/life-science/cell-analysis/flow-cytometry/flow-cytometry-learning-center/flow-cytometry-resource-library/flow-cytometry-methods/spectral-flow-cytometry-fundamentals.html

(SLAR) has been in use for decades to observe sea ice drift and detect oil spills,[11] advances in Synthetic Aperture Radar (SAR; a subset of SLAR) technology that have occurred over the last decade are significant for many reasons. SAR involves the emission of radar pulses and the detection of the return signals when they bounce off objects (such as the ocean surface) to create two dimensional images that can then be analyzed. The resolution of SAR images has improved to the point where we can now detect schools of fish swimming at or near the surface from the wavelets that form from their wake (Klemas, 2013). SAR systems are not impacted by clouds or inclement weather, as are visible spectrum cameras, so they may hold the key to full-time fishery surveillance. They are now small and energy-efficient enough to be mounted on drones and micro-satellites, and it is clear that they have a significant role to play in future monitoring of the marine space.

LiDAR

Radar bounces radio waves off objects — Light Detection and Ranging (LiDAR) effectively does the same thing with lasers. LiDAR is now the primary source of geospatial data used by researchers for mapping of the sea floor. The simplicity, low cost, small size and low power requirements of radiometric LiDAR systems mean that they can be flown in small aircraft and drones (Santos, 2000). LiDAR provides a more cost-effective alternative to ship-based Sound Navigation and Ranging (SoNAR) for mapping and monitoring shallow water coral reef ecosystems (Costa et al., 2009). As well as SAR, LiDAR possesses significant potential for defining the geographical extent of suitable fishing grounds, particularly at a scale that is relevant to resource exploitation as instruments are small enough to be mounted on drones such as surface or autonomous underwater vehicles (AUVs).


Geneinno Titan T1 Underwater Drone
Photo by Geneinno


NASA cubeSAT
Photo by NASA

2.2 Satellite remote sensing

As sensors decrease in size, cost and power requirements, they become more suitable for wider use on a variety of platforms, including satellites where these factors are critical. Satellite technology has driven a remote sensing revolution, which has seen a shift from largely experimental missions driven by big government institutions to more nimble projects that support a wider variety of users and needs (Leape et al. 2020). Small satellites, which have benefited greatly from advances in miniaturization, are being launched with greater frequency: while less than 1,000 small satellites were launched from 2006 to 2015, some analysts predict that 7,000 will be launched between 2018 and 2027.[12] Approximately 82% of these satellites will be part of constellations built by major corporations such as SpaceX and Amazon tasked with a variety of purposes such as expanding space-based broadband internet and improving earth imaging.

Increasing satellite capacity expands the coverage area and interval of rapidly improving sensors such as SAR, optical sensors such as the Day Night Band (DNB),[13] and the Visible Infrared Imaging Radiometer Suite (VIIRS).[14] It is now possible to detect the glow from a single streetlight from 800km above the surface of the earth, and we can track small illegal fishing vessels at night and through inclement weather. Small satellites equipped with SAR systems, capabilities traditionally associated with large government agencies, are becoming more widespread and this has major implications for marine surveillance. Capella Space[15] and IceEye[16] are two companies launching constellations of SAR-equipped small satellites. Capella plans to have an operational network by 2022 and will eventually launch a total of 36 satellites, meaning that their customers will be able to order 'on demand' images of a particular target at least once per hour at a remarkable 20 inch resolution over a 5km by 5km area.[17] IceEye plans an 18 satellite constellation with similar capabilities. While Capella's

[11] https://www.iosсproceedings.org/doi/abs/10.7901/2169-3358-1983-1-349
[12] https://euroconsult-ec.com/6_August_2018
[13] https://earthdata.nasa.gov/worldview/worldview-image-archive/the-day-night-band-enhanced-near-constant-contrast-of-viirs
[14] https://viirsland.gsfc.nasa.gov/Products/NASA/BlackMarble.html
[15] https://www.capellaspace.com/
[16] https://www.iceye.com/satellite-missions
[17] https://news.mongabay.com/2019/08/no-place-to-hide-for-illegal-fishing-fleets-as-surveillance-satellites-prepare-for-lift-off/

service model is geared towards supporting defense and intelligence services,[18] IceEye is focused more towards helping find illegal fishing vessels, identify human trafficking and other rights abuses.[19]

2.3 Data Collection Platforms

Mirroring improvements in satellite technology, ocean-based data collection platforms such as semi-autonomous drones and buoys have benefited from miniaturization and power reduction and, importantly, advances in the field of power harvesting. Along with lower power use, the ability to harvest energy from the sun or waves (or even microbial fuel cells that leverage the natural oxidation of detritus on the seafloor to harvest energy; Reimers and Wolf (2018)) and then to store this energy for future use in advanced battery systems (such as aluminum based systems that use seawater; (Tian et al., 2021)) has driven a revolution in the design and capabilities of data platforms. Thanks to improvements in data transmission (including the increasing use of acoustic modems; (Sendra et al., 2015)), platforms are becoming increasingly connected. Advances in processing capabilities mean that 'swarms' of platforms with distributed intelligence are very much becoming the dominant paradigm for undersea observation and monitoring systems. And data collection platforms are increasingly eschewing the need for human control. Semi-autonomous drones are generally tasked to follow particular tracks or look for particular objects and collect various types of information by a human programmer, and then left to perform those tasks autonomously. Drones can be configured with a number of sensors, processors and data transmitters that can provide high quality real-time observations to scientists and managers (Colefax et al., 2018), including acoustic technologies such as tag telemetry receivers and passive acoustic recorders.

Aerial drones

Aerial platforms such as airplanes or balloons that help fishermen locate fish have been in use for decades (Santos, 2000), but we are now seeing a wholesale change in the way these tools are being deployed and used. The decreasing costs of aerial drones, increasing flight times and easier launch and retrieval at sea are rapidly expanding the utility of Unmanned Aerial Vehicles (UAVs; Colefax, Butcher, and Kelaher 2018). The range of compact sensors that UAVs can be equipped with has widened significantly over the last decade and now include low-light digital cameras, thermal infrared radiometers, LiDAR and SAR (Harris et al., 2019). Among many other uses, their potential for fisheries Monitoring, Control and Surveillance (MCS) has the attention of policy-makers, environmentalists and researchers alike (Toonen & Bush, 2020).

Underwater drones

Underwater drones are impacting many ocean industries, including extending the reach of scientific research. They are instrumental in exploring the seabed and inspecting undersea platforms or pipelines and also provide new opportunities to the pharmaceutical industry, allowing the study and collection of new specimens that might hold immense value to humankind (World Economic Forum, 2017). While many drones are tethered to surface vessels, Autonomous Underwater Vehicles (AUVs) operate without the continued control of human operators and are either pre-programmed to conduct set underwater missions or use Artificial Intelligence (AI) to decide on routes and activities autonomously. Most AUVs can operate to 200 m depth, with some operating beyond 5000 m. Fish-like drones, which can be self-propelled for about 8 hours are already being used alongside other drones in coral reef monitoring (Pieterkosky et al., 2017). While some AUVs such as HabCam[20] and Slocum gliders, are extremely expensive, others, such as the consumer-focused Trident drone[21] are much less costly and more accessible.


Photo by Getty

Surface drones

Surface drones (or unmanned surface vehicles; USVs) operate on the interface between the ocean and the atmosphere and are thus able to study both the environment underneath the drone, such as the seafloor and water column, as well as the atmosphere above it. Positioned on the surface they can transmit data faster and more cost effectively than underwater drones, and also have access to a constant source of solar energy. For example, Liquid Robotics Wave Glider[22] uses a combination of solar arrays to harness power for instruments and kinetic wave energy for propulsion in an innovative two part design. Surface drones such as the wave glider can be fitted with an array of sensors and other data collection in-

[18] https://www.bbc.com/news/science-environment-51296585
[19] https://www.bbc.com/news/science-environment-51296585
[20] https://habcamvm.whoi.edu/about/
[21] https://www.sofarocean.com/products/trident
[22] https://www.liquid-robotics.com

struments and can actively collect and transmit (via satellite, cell or broadband) real-time data for up to a year in ideal conditions. There is significant potential for USVs to reduce the cost of ocean data collection and to expand the spatial and temporal coverage of acoustic stock surveys (Greene et al., 2014). Other surface drones include the Datamaran[23] and the Saildrone.[24] USVs are beginning to see application to the commercial space. For example, Aker BioMarine,[25] a company that fishes for krill in Antarctic water, uses a Sailbuoy[26] to help their vessels hunt for krill aggregations.[27]

A Saildrone USV

Buoys

Buoys have been used for decades to collect and transmit oceanographic data, but recent changes in their design and the way they are deployed have huge implications for ocean management. 'Smart' buoys are now equipped with sophisticated computers, cameras, oceanographic sensors, data loggers and satellite transmission systems, and are capable of being re-tasked at a moment's notice for new data missions. Buoys are now self-powered through solar panels and can remain at sea for long periods of time (Henriques et al., 2016). Low-cost buoys are a vital tool for monitoring climate change impacts as they can be deployed extensively by a wide variety of organizations (Vitale et al., 2018). For example, Sofar Ocean's Spotter[28] buoy is solar-powered and transmits real-time wave, wind and temperature data to a cloud based portal which allows easy access to information from the global network of Spotter buoys, while the Spotter 'Dashboard' allows easy data analysis and visualization. Buoys are also being equipped with echosounders that can help fishermen determine the species composition beneath Fish Aggregating Devices (FADs).[29] Buoys are now being deployed as part of networks of interconnected devices and sensors that can solve bigger challenges, such as effectively combatting IUU fishing by detecting illegal fishing vessels (Ng et al., 2020). For example, DARPA's 'Ocean of Things (OoT) program[30] will encompass thousands of drifting buoys that collect oceanographic and other sensor information — including activity data on vessels, aircraft and even marine mammals — and then transmit data via satellite to the cloud.

Marine animals

A small but potentially significant area of innovation is the use of marine animals to collect data by outfitting them with small Conductivity-Temperature-Depth Satellite Relay Loggers (CTD-SRLs) which collect information and transmit data automatically to servers via satellite (Treasure et al., 2017). Small radar detectors have also been mounted on albatrosses, who range farther than drones ever could, to help in detecting illegal fishing.[31]

Fishing vessels and their gear

The technology used by fishermen to hunt for and catch fish has improved to the point where the wheelhouse of a modern fishing vessel more resembles that of a spaceship than of the HMS Titanic. More and more vessels are being equipped with advanced sonar devices that can be used to help map the seafloor to a high resolution, and with oceanographic sensors that could expand the existing network of ocean observing data. Several initiatives have also focused on placing sensors on fishing vessels and their gear to aid in the collection of oceanographic data. As one example, the eMOLT[32] program in the Northeast United States equips lobster traps with oceanographic sensors. The data collected are then shared between fishermen (to help them understand the relationship between bottom conditions and lobster catch) and scientists.

2.4 Smartphones

Around 3.5 billion people now use smartphones, in effect giving almost half of the world's population fingertip access to a portable personal computer. Smartphones incorporate GPS sensors and Bluetooth connectivity meaning that they can act as analysis, storage and transmission devices for a huge range of variables. For example, biochemical sensors that detect marine toxins are being integrated with smartphones (Su et al., 2017) for portable use in the field, and smartphone apps

[23] http://www.automarinesys.com/
[24] https://www.saildrone.com
[25] https://www.akerbiomarine.com/
[26] http://www.sailbuoy.no/
[27] https://thefishsite.com/articles/small-drone-set-to-deliver-big-data-on-antarctic-krill
[28] https://www.sofarocean.com/products/spotter
[29] https://satlink.es/en/
[30] https://oceanofthings.darpa.mil/
[31] https://www.bbc.com/future/article/20200708-the-albatrosses-who-catch-pirates-on-the-high-seas
[32] https://www.fisheries.noaa.gov/feature-story/low-cost-technology-helps-connect-fishermen-and-students-science

for fisheries monitoring and management are proliferating (see section 3.1.3). Perhaps the most important characteristic of smartphones for future marine fishery management is that they allow two-way data transfer, which opens up the prospect of managers having real-time influence on fishing activity, especially in small-scale fishery contexts (Bradley et al., 2019).

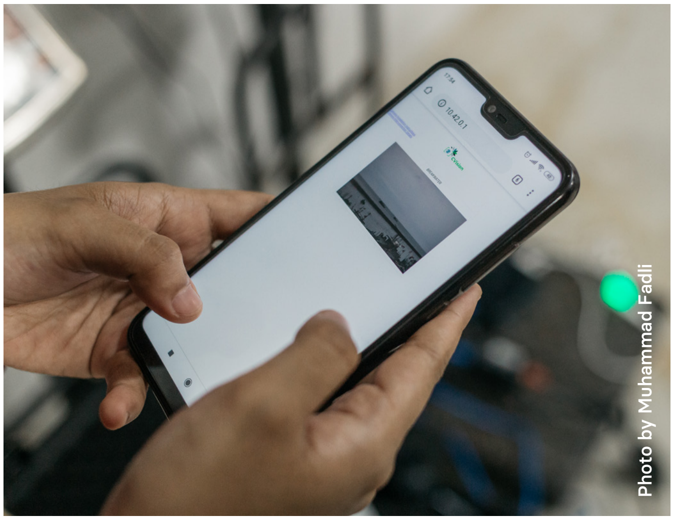


Photo by Muhammad Fadli

2.5 Citizen scientists

The digital revolution is causing wholesale societal changes. Thanks to smartphones, the internet and ready access to the cloud, ordinary citizens are now able to collect and analyze a huge array of data types. There is increasing interest in tapping this incredibly powerful source of scientific discovery and contribution, and tools are being developed to support this. For example, smartphone apps are being designed to allow members of the public to engage in science by submitting photos or other data that can be used to update species distribution maps (Silverman 2016; Leape et al. 2020). Smartphone apps have been used to help track pollution and improve flooding forecasting (Leape et al. 2020), as well as track distribution shifts of reptiles.[33] MERMAID[34] is an online-offline cloud based platform that allows scientists to share and analyze coral reef surveys, with over 570 registered users.[35]

2.6 Data connectivity

We are on the cusp of the fifth generation (5G) of telecommunications. While 4G connected people to each other and to the power of the internet with unprecedented reach and speed, 5G promises to connect *everything* to everything else, ushering in societal change on an unprecedented scale and impacting every one of earth's industries.[36] This is a future of the Internet of Things (IoT), where devices automatically transmit data between each other for the purposes of performing functions automatically and dynamically without the need for human intervention. The Ocean of Things (OoT),[37] currently being developed by DARPA and discussed above, is a harbinger of what is to come for ocean users. However, to make this future a reality, billions of new connections will be required — connections that rely on close-range device-to-device technologies such as Bluetooth and Near Field Communications (NFC), medium range connections through WiFi and cellular networks, and long-range technologies such as satellite communications. The IoT will also drive a fundamental shift in the design of our data architectures (Leape et al. 2020). Sensors will become smart and will perform computational tasks independent of the network at large, and workflows and processes will become increasingly automatic, driven by distributed intelligence.

Although lightning-fast 5G cellular networks are set to be a key component of the digital future (It has been estimated that the global economic impact of 5G will reach $12 trillion by 2035),[35] a key tradeoff for the oceans space is limited range compared to 4G networks. 4G towers have ranges of up to 10km compared to less than 1km for 5G infrastructure[38]. And although we can expect more cellular infrastructure in coastal areas for marine users and perhaps internet mesh networking to extend range seawards, the introduction of 5G networks may have limited direct impact on ocean industries. However, this does not diminish the scale of the shift in overall connectivity that are we are about to see. Nearly 750,000 miles of fiber optic cable on the ocean floor already connect the world and new cables are continually being laid.[39] Satellite communications are undergoing a step change with current movement towards small satellites which are less costly and easier to launch providing thousands of new platforms to facilitate data connectivity, and much of this capability will impact the marine space. Between 2018 and 2027 over 7000 small satellites are expected to be launched (compared to less than 1000 between 2006 and 2015), as part of a growing global space industry that is expected to generate $1.1 trillion in revenue by 2040, approximately 40% of which will be linked to internet services.[40] While much of this infrastructure will enable high bandwidth communications, increases in low-bandwidth, low-cost communications such as Swarm which might just enable transfer of text messages from anywhere on the surface of the earth also has significant potential to improve marine space connectivity, especially for small-scale fishers.

To fill in communication gaps, advances are being made in providing connectivity to the internet to remote areas through internet mesh networking, which propagates a

[33] https://www.herpmapper.org/
[34] https://datamermaid.org/
[35] https://www.newswise.com/articles/new-tech-lets-marine-scientists-track-real-time-health-of-coral-reefs-around-the-world
[36] https://www.weforum.org/agenda/2018/01/the-world-is-about-to-become-even-more-interconnected-here-s-how/
[37] https://www.darpa.mil/program/ocean-of-things
[38] https://www.businessinsider.com/5g-high-speed-internet-cellular-network-issues-switch-2019-4
[39] https://www.nytimes.com/interactive/2019/03/10/technology/internet-cables-oceans.html
[40] https://www.seattlebusinessmag.com/technology/boeing-back-race-build-space-based-internet

source signal over a wider area using additional receivers and re-transmitters. On land, companies such as Vanu[41] have been innovating new ways to connect rural communities all over the world, focusing on low power consumption and flexible connection types. On the ocean, prototypes of mesh networks[42] made up of vessels and base stations using commercially available equipment have been tested[43] and acoustic modems have massive potential to connect constellations of buoys or other platforms, perhaps enabling them to act as coordinated groups, with some systems currently being tested (Leape et al. 2020).

Importantly, there may be a (welcome) disparate impact that better mobile communications have for developing nations, as these countries seem to benefit disproportionately more from these advances than developed countries.[44] Wherever the digital revolution leads us, advances in data connectivity are one of its cornerstones and one that all other advances are required to keep pace with.

2.7 Artificial Intelligence

The development of AI has profound implications not just for the way we analyze ocean data, but also how we collect it. Machine learning techniques are in a constant state of improvement and applications continue to expand. The basic architecture of traditional machine learning algorithms is still very simple at its core, with training requiring a lot of human expertise and frequent interventions to correct mistakes,[45] but the number of new applications and the amount of specialized architectures that exist are growing exponentially. A new class of algorithm, Deep Learning (DL), learns about the task at hand through a network of neurons that organize the task into a hierarchy of concepts, starting with simple concepts and increasing in complexity. Computer vision is now powered by DL Convolutional Neural Networks (CNNs) and can identify patterns or objects more accurately than humans in many cases, for example in the analysis of CT scans[46]. Computer vision is the key to a future where machines are as intelligent as humans, and AI and machine learning are essential for processing the huge volumes of data being collected (Leape et al. 2020). In the oceans space, two major areas where AI has gained traction are in analyzing images (generally camera images but acoustic spectrograms as well) to detect and identify objects or patterns, and big data analysis tools, where relationships between variables not identified in current theoretical or statistical models are gleaned by examining large and often unorganized datasets.

Machine vision has a potentially major application in camera based electronic fisheries monitoring by enabling the efficient and large-scale generation of management and enforcement data from video data. It is just a matter of time before electronic monitoring systems on board vessels are capable of automatically producing management-ready data (not just video) on catch and effort and transmitting these data in near real-time to managers. Machine vision has a huge range of other oceans uses, including conducting no-kill stock assessments (where video of fish populations in the ocean are used instead of bringing fish populations onto a boat so they can be counted), habitat surveys and piloting surveillance drones around protected areas.

AI and machine learning make it possible to analyze complex systems and large, diverse datasets, especially in cases where theory is lacking. Better weather prediction (on the 2 week to 2 month time frame),[47] early warning for climate related impacts to marine ecosystems, identifying anthropogenic impacts in complex marine ecosystems and processing 'dark data' such as tables, figures and text from the internet to penetrate organized wildlife trafficking crime rings (WEF, 2017), are just some of the recent use examples of AI in the oceans space. Machine learning tools are already being used to reduce search time for target species in some fisheries which can save fuel, time and money and while many companies in the marine space use advanced analytics (sophisticated methods to collect, process and interpret big data), their use in fisheries is typically limited to small-scale pilots. However, some analysts estimate that if large fishing companies adopt the AI tools and techniques necessary to unlock latent value, they could potentially reduce annual operating costs by $11 billion, with some benefit passed on to consumers in the form of lower prices (Christiani et al., 2019).

AI is an important enabler of edge computing, where software lives in physical machines allowing data to be collected, processed and analyzed in place, or on 'the edge.'[48] Edge computing is the key to networks of interconnected machines that possess distributed intelligence. And when these networks are connected to other networks (such as the internet) the potential is profound. Amidst all of the shining potential, a note of caution: it is nearly impossible to understand how DL networks identify the relationships that they do and without a theoretical model to guide the analyst, existing bias, inequity and prejudice are very likely to be propagated by these models which, after all, are only as good as the data you put into them (Leape et al. 2020).

2.8 Data Systems and the Cloud

The volume of global data is expected to reach 175 zettabytes by 2025,[49] with the amount of data collected in the ocean space growing exponentially. This is largely due to a self-reinforcing big data revolution, where the techniques

41 http://www.vanu.com/solutions/rural/
42 https://www.researchgate.net/publication/283864896 _Wi-Fi_network_for_over-the-sea_communication
43 http://www.globalmarinenet.com/product/redport-halo-long-range-wifi-extender-system/
44 https://www.weforum.org/agenda/2018/01/the-world-is-about-to-become-even-more-interconnected-here-s-how/
45 https://www.weforum.org/agenda/2018/01/the-world-is-about-to-become-even-more-interconnected-here-s-how/
46 https://www.forbes.com/sites/cognitiveworld/2019/06/26/the-present-and-future-of-computer-vision/#51fa0dd3517d
47 https://cleantechnica.com/2020/01/25/birds-oceans-wildfires-oh-my-how-machine-learning-is-changing-climate-research/
48 https://www.kdnuggets.com/2018/11/trends-computer-vision-technology-applications.html
49 https://www.bernardmarr.com/default.asp?contentID=1846

needed to process, analyze and visualize copious amounts of data in a manageable fashion have in turn helped to drive an 'explosion' in data varieties and derivatives (Runting et al., 2020). Traditionally, large datasets have been collected by government agencies, companies and scientific researchers and stored by those same entities resulting in a 'monolithic' process where, even if permissions to share data are acquired, the transaction costs of accessing and using that data are non-negligible (Leape et al. 2020). The 'big data revolution' will involve a fundamental change in the way data systems are organized, towards a future where datasets of all kinds are easily accessed by more people, including scientific researchers. One characteristic of this new system are 'data lakes', essentially places in a data network where users can 'dump' large amounts of data that do not necessarily conform to accepted data 'schema' or tagging standards. They hold particular promise for situations where users do not need to exert lasting control over their data and cases where concerns over data privacy are low, such as with oceanographic data (Stein & Morrison, 2014). For example, the USGS and NOAA have recently started to use data lakes with a goal of allowing the user base to increase and with it new ways of creating value from information. Some initiatives that are trying to create this digital ocean ecosystem include UNESCO's Global Ocean Observing System,[50] and the Centre for the Fourth Industrial Revolution for the Ocean's Ocean Data Platform.[51]

Perhaps the most transformative vehicle for data management is cloud computing, which enables on-demand network access to a shared pool of computing resources including storage, analysis tools and software, including AI (Vance et al., 2019). Thanks to better data connectivity, the cloud brings the power of a supercomputer to everyone with an internet connection. The data servers that 'are' the cloud are power hungry; most large server farms are located in areas where electricity is inexpensive. These power requirements are being addressed in new ways. For example, Project Natick[52] submerged a range of servers off the coast of Scotland to see if the systems continued to operate as normal under water. The success of this experiment opens the door to further exploitation of the ocean's natural cooling properties and potential renewable energy generation capabilities.[53]

2.9 Fishing gear modifications

The tools used to capture fish and seafood have traditionally been designed with efficiency as the prime consideration — ensuring that as much of the target species ends up on the vessel as possible. More stringent bycatch and size limit regulations are increasingly incentivizing 'clean' fishing. In addition, concerns over habitat destruction caused by certain types of gear, whale entanglements in fishing gear and 'ghost' fishing (where fishing gear continues to trap animals long after it has been lost from human control) have all contributed to efforts to improve the design of all types of fishing gear.

Trawl fishing gears used to be thought of as indiscriminate tools for catching marine biomass, and bottom trawls were particularly singled out for detrimental impacts on the marine ecosystem. However, several promising areas of research designed to increase selectivity of fishing gear have gained traction recently. Einar Hreinsson of the Marine Research Institute of Iceland has proposed using lasers to guide fish into nets[54] instead of sweep lines that drag along the ocean


Photo by Carlos Aguilera

[50] http://www.unesco.org/new/en/natural-sciences/ioc-oceans/sections-and-programmes/ocean-observations-services/global-ocean-observing-system/
[51] https://www.oceandata.earth/
[52] https://natick.research.microsoft.com/
[53] https://www.bloomberg.com/news/articles/2016-02-02/microsoft-built-a-cloud-server-in-the-pacific-ocean-to-save-water-and-energy
[54] https://archimer.ifremer.fr/doc/00585/69713/67603.pdf

floor. Different species react to different wavelengths of light which may increase fishing selectivity.[55] In New Zealand, Tiaki[56] is a new fishing method that involves the use of a 'live' cod-end, where fish are kept submersed and alive inside a semi-rigid structure when first brought on board a fishing vessel, allowing high survival of discarded species and higher quality products. WWF's International Smart Gear competition formerly awarded a $30,000 grand prize to a gear design that has the greatest promise to reduce bycatch. The most recent winner (the last iteration occurred in 2014) was an air cannon-launched sampling device for purse seine fisheries which samples the quality and size composition of fish in the seine before fish are killed, ensuring greater survival of potential bycatch.[57] Pelletized bait inserts for longline fisheries that can repel sharks while attracting target species, and escape panels for trawl nets designed to release particular species have also shown promise. Fishing gear that leverages new digital technologies to become more selective and efficient and that reduces environmental impacts compared to traditional gear has a significant role to play in future fisheries management.

2.10 Biotech

Advances in biotechnology can help to reduce the environmental impacts of anthropogenic activity. For example, most aquaculture feed will be free of fish at the end of this century, with companies producing high protein feed from methanotrophs,[58] insects,[59] seaweed[60] and other ingredients (WEF, 2017). Genetically modified fish can survive better in harsh conditions than naturally occurring species, and can convert feed into muscle much more efficiently, reducing the amount of feed needed to produce product. These impacts will likely have positive impacts on our ability to produce food from the sea in the future.

In addition to advances in the way fish are grown in the ocean, wholesale changes in the way we think about food production are afoot. Cultured fish produced through the application of cellular agriculture techniques is undergoing a rapid transformation that will potentially be hugely disruptive to existing animal-based food systems. Cultured fish is produced by applying tissue engineering techniques to the production of fish muscle for consumption as food (Kadim et al., 2015; Stephens et al., 2018). One of the earliest attempts to culture fish in a lab occurred in the early 2000s when researchers in New York established the feasibility of an in vitro muscle protein production system for the purposes of nourishing space travelers on long voyages to Mars (Benjaminson et al., 2002). The authors cultivated the flesh of Carassius auratus (the common goldfish), using Fetal Bovine Serum (FBS) as part of a solution of nutrients needed for muscle growth. In 2013, Dr Mark Post demonstrated to the world that beef could be grown in the lab when he unveiled the first cultured beef burger[61]. This event marked the beginning of a wave of development in techniques to culture meat products using cellular agriculture techniques. In 2015, Modern Meadow,[62] produced cultured steak chips, although the company is now focused on producing cultured leather, and in 2016, Memphis Meats[63] created a beef meatball from cultured beef. This was followed in 2017 by cultured fried chicken and duck a l'orange. Up until 2015 there were no companies focused on lab grown seafood. Since then several have started up including Finless Foods,[64] Blue Nalu,[65] and Seafuture.[66] Soon, consumers will be able to choose between wild, farmed and cultured fish, with hugely significant, but as yet undetermined, implications for all who depend on the ocean.

BlueNalu's cell-based fish product

Photo by BlueNalu

[55] https://medium.com/datadriveninvestor/could-lasers-and-robots-save-the-oceans-f752d43ce61a/
[56] http://www.tiaki.com/
[57] https://www.worldwildlife.org/press-releases/lasers-escape-windows-and-air-cannons-among-innovative-ideas-in-competition-to-reduce-fisheries-bycatch/
[58] https://www.calysta.com/
[59] https://www.hatcheryinternational.com/partnership-brings-sustainable-insect-based-protein-to-aquaculture-feed-3556/
[60] https://www.globalgae.com/
[61] https://www.theguardian.com/lifeandstyle/2017/sep/20/lab-grown-meat-fish-feed-the-world-frankenmeat-startups
[62] http://www.modernmeadow.com/
[63] http://www.memphismeats.com/
[64] https://finlessfoods.com/
[65] https://www.bluenalu.com/
[66] http://seafuturebio.com/


Photo by Leslie Von Pless/EDF

3. On-the-Water Activities

The categories of technologies we describe in section 2 (as well as many others) are being applied by a range of individuals and organizations to a broad suite of global ocean challenges in many sectors of the economy. In this section we give an overview of these activities, focusing on those challenges that relate directly or indirectly to the management of marine fisheries. These activities range from on the water technical implementations of cameras or other sensors to collect data, to regional scale efforts to detect illegal fishing using satellites, to global scale efforts to streamline and modernize data management systems. While we have identified a large set of applications and specific projects in this section, the current ecosystem of on-the-water activities is constantly evolving and it is outside the scope of this report to account for all of them. Instead, we aim to use specific activities to illustrate the nature and scope of this ecosystem of practice. We do not endorse any commercial product listed in this report.

We have identified six groups of challenges that serve as focal points for this section and discuss how technologies are being used to address each. These challenges are: accounting for fisheries catch and effort, fishery compliance monitoring, stock abundance and productivity estimation, increasing the transparency of the supply chain, ecosystem health monitoring and deriving value through data integration and management.

3.1 Accounting for fisheries catch and effort

Most of the world's fisheries do not collect catch data that are reliable enough for accurate catch accounting or sufficiently detailed to support decision making. Catch data are the basic building blocks for fisheries management — they are an essential ingredient for stock and ecosystem assessments as well as for implementing many types of management tools, such as individual fishing quotas and total allowable catch limits. Data on catch quantities and composition are necessary for accurate catch accounting. Catch records should also include time and location data and ideally be connected to measurements of fishing effort. Catch and effort data are generally collected on the water or at the point of delivery, normally using paper reporting methods such as fishermen's logbooks or observer/monitor records. The main issues with these methods are that self-reported data such as logbooks can incentivize false reporting if management systems are not sophisticated enough, paper based data collection can result in information 'silos' where efforts to transcribe data into a digital, usable format fall short and the cost of employing humans to collect fishery catch information is often extremely limiting to monitoring efforts. Digital technologies are helping to address all of these issues.

3.1.1 Electronic Monitoring

Some fisheries around the world have implemented camera-based Electronic Monitoring (EM) systems. These systems have been in use for over 20 years, mainly in fisheries where image processing requirements are relatively simple, such as when the goal is to monitor for full catch retention (no discarding at sea) or when monitoring for protected

species interactions with the fishing gear (Fujita et al., 2018). Recently, advances in many aspects of EM technology have broadened its application to a wider range of fisheries and in programs where monitoring goals are more complex (Michelin et al., 2018). For example, cameras are becoming more robust, higher definition, and less prone to condensation and other image quality issues. Hard drives are increasing in capacity while decreasing in physical size. Equipment in general is becoming less costly. Software solutions that integrate sensor outputs with GPS data are cutting down on data processing time while increasing accuracy, and increased understanding on the part of fishermen of their responsibilities has led to more efficient interactions between fishermen and management agencies.

While improvements in EM systems have been occurring at a rapid pace, ultimately these systems will require minimal human input and provide high quality, complete data in close to real-time and that are ready to be applied in the fisheries management process. This will require automating all aspects of data collection, transmission, and processing in an integrated EM and reporting system where AI-enabled systems operate on the 'edge'. While developments are rapidly being made in integrating EM with electronic reporting there are still three main areas where human input is necessary: generating the main data record, video review and data transmission.

Main data record

The first area is related to the idea that data inputted by fishermen (such as hailed weight of catch, the amount of a species discarded, or the time and location of a haul) form the main data record, while the EM data are used to audit the fisherman's input. In the future, all EM systems will be sophisticated and reliable enough to provide the main data record, taking the onus away from fishermen to record management data.

Video review

Second, the review of camera imagery in order to estimate catch amounts, catch composition and length composition of the catch is carried out by data reviewers who manually review the camera imagery. Recent advances in the fields of AI and machine learning have led to rapid improvements in automated image recognition and processing methods that are reducing the need for human input. These technologies have applications in other sectors of the economy that are helping to fuel their rapid development, for example in the self-driving car and home monitoring sectors. Development of image recognition algorithms is also being accelerated by open source competitions (such as n+1 fish, n+2 fish[67] or Fishackathon)[68] that offer competitors significant monetary prizes to develop software. Initiatives such as The Nature Conservancy's fish.ai,[69] which provide free access to a vast tagged image library, are helping to provide the data needed for development. In the small but growing private EM sector, advances are being made to meet increased demand for EM with companies such as SnapIT developing and manufacturing bespoke camera systems for fishery monitoring, Integrated Monitoring[70] and Satlink[71] pioneering satellite transmission of monitoring data, and New England Marine Monitoring[72] working to improve the workflow of video review through the use of AI.

Government supported research and development for EM is a key fixture. In the United States, for example, external grant-making programs such as NFWF's Electronic Monitoring and Reporting Grant Program[73] complement in-house efforts like the EM Innovation project,[74] which is a collaboration between NOAA's Alaska Fishery Science Center (AFSC) and the University of Washington (UW). As part of this project AFSC researchers and fishermen have been collaborating in order to design physical infrastructure (e.g., camera chutes that funnel the catch into camera view) as well as catch handling protocols to provide a standardized stream of primary data for video review. This stream of standardized video data

[67] https://www.drivendata.org/competitions/48/identify-fish-challenge/
[68] https://fishackathon.co/
[69] http://fishnet.ai/
[70] https://integratedmonitoring.net/
[71] https://www.satlink.com.es/en
[72] https://www.nemarinemonitoring.com/
[73] https://www.nfwf.org/programs/fisheries-innovation-fund/electronic-monitoring-and-reporting-grant-program-2020-request
[74] https://www.fisheries.noaa.gov/feature-story/developing-machine-vision-collect-more-timely-fisheries-data

is then analyzed using AI-based video recognition software developed by UW's Electrical Engineering and Computer Science Department.[75] Recent advances include automating the collection of accurate (<2% absolute error) length compositions from catch, which is particularly complicated as fish are generally curved in a 2 dimensional image. This area of research has significant implications for streamlining the catch-handling protocol for future EM systems.

Generating automatically-derived length and species composition data will require significant amounts of future development in both catch handling processes and algorithm development and is still several years away from maturing. Even though automated species identification has been the subject of much research over the past decade, there is still no published example of actual deployment in a fishery by a regulatory agency (Bradley et al., 2019). However, automatically identifying different types of fishing activity such as discarding behavior from video data is currently feasible (pers. comm. Mark Hager). These advances help to increase the efficiency of the video review process (which is a key component of overall EM program cost; Sylvia, Harte, and Cusack (2016)) and hold the key to the efficient wireless transmission of video data as capture software on the 'edge' can automatically parse relevant video clips. We know of one implementation (pers. comm. Mark Hager) of an automatic activity recognition protocol for EM video review that is currently under regulation, and companies like CVision AI[76] and Chordata[77] are pushing development to other fisheries.

Data transmission

Third, the transmission of EM data currently occurs mainly through the manual removal and delivery of hard drives to fishery management agencies. As data connectivity improves, this step will eventually become redundant meaning that near real-time data will soon be available for fisheries management and for input into a digital ocean data ecosystem (see section 2.8). Wireless transmission of EM data is one of the keys to scaling EM across all of the world's industrial fisheries as many vessels remain at sea for several months at a time with little access to mailing services. Wireless data transmission also has implications for managing fisheries in the context of climate change as it enhances the potential of management to rapidly adapt to changing conditions (but relies on management structures being flexible enough to respond to new data streams). Several EM pilot projects have trialed the transmission of video data over cellular networks (e.g. Mortensen et al. 2017; Plet-Hansen, Bergsson, and Ulrich 2019), and although transmission costs are still relatively high, better video compression techniques and video parsing using machine learning algorithms promise to bring costs down to a scaleable level. The use of long-range WiFi systems in ports that see frequent vessel traffic holds promise for the efficient wireless transfer of video data; some trials are underway.[78] With exponential increases in satellite transmission capabilities through the launch of small satellite constellations, a future where satellite transmission of EM data is the norm is closer than we might think.

Camera-based EM has seen most applications in medium to large-scale commercial fisheries in developed countries with very few small-scale fishery applications. Companies such as Saltwater Inc.[79] have developed small-scale camera-based EM systems suitable for operation by solar or battery power, and The Nature Conservancy's FishFace[80] project aims to create algorithms that can automatically identify fish species from camera images, potentially allowing smartphone based EM systems for small-scale fisheries. However, EM systems make sense where management institutions function well and create a demand for EM data streams as part of the fishery monitoring process. Small-scale fisheries, especially in developing nations, often don't have the management processes in place to readily make use of EM data. Institutional capacity building which emphasizes the value of collecting fisheries information will be an essential component of a multi-pronged strategy to improve small-scale fisheries monitoring.

For small-scale fisheries that have limited resources and capacity to purchase, maintain and operate VMS or AIS systems, alternative methods to quantify and map fishing effort have been developed. Selgrath, Gergel, and Vincent (2017) show how participatory mapping, which involves using stakeholder knowledge to map fishery resources and activities, can be used to characterize spatial and temporal estimates of fishing effort. Johnson et al. (2017) present a spatial method of estimating fishing effort in small-scale fisheries based on two variables that are relatively accessible: the number of boats in a community and the local coast human population. They showed that their method can accurately predict fisheries landings in the Gulf of California, Mexico.

3.1.2 Electronic Reporting

Electronic Reporting (ER), where catch and fishing activity data are either input by fishermen or collected automatically on the vessel and transmitted in digital form to management authorities, is becoming increasingly widespread across industrialized and small-scale fisheries alike. And although paper logbooks are still the norm, ER technologies including electronic logbooks, smartphone applications, Vessel Monitoring Systems (VMS) and Automatic Identification Systems (AIS) promise to reduce transcription errors and allow more rapid data availability for managers. For example, all observer data collected by Western and Central Pacific Fisheries Commission (WCPFC) member countries are currently transmitted electronically to managers (Bradley et al., 2019). In the Gulf of Mexico, shrimp fishery electronic logbooks have

[75] https://people.ece.uw.edu/hwang/
[76] http://cvisionai.com/
[77] https://pt.chrdta.com/em/
[78] https://www.snapit.group
[79] https://www.saltwaterinc.com/
[80] https://www.natureaustralia.org.au/what-we-do/our-priorities/oceans/ocean-stories/fishface/

been used since 2007 to monitor fishing effort and generate the data needed for stock assessments, with recent advances including the use of cellular networks to transmit data from vessels to managers.[81] The Maldivian skipjack fishery employs an online tool to link license information with catch quotas and landings data. The tool, Fisheries Information System[82], was adopted to help the fishery comply with Marine Stewardship Council (MSC) certification standards.

While VMS data rely on location transmission at regular intervals from vessel to satellite, AIS messages are broadcast by vessels omni-directionally so they can be received by other ships, ground based receivers and satellites. AIS has recently been made compulsory for fishing vessels over 15 meters in length in the European Union (Holmes et al., 2020). Although AIS data consist solely of a vessel ID, their location and a time stamp, some researchers have been exploring how AIS data can be used to shine a light on fishing activity. Natale et al. (2015) showed the applicability of AIS data to the production of high-resolution maps of trawl fishing effort in Sweden and Souza et al. (2016) developed methods to identify fishing activity for three gear types: longline, purse seine and trawl, relying on machine learning techniques to develop illuminating algorithms. Several initiatives have been made to map fishing effort at a high spatial resolution using VMS data. Recently, Guillot et al. (2017) developed an improved method of discerning fishing activity from VMS data that is computationally efficient. Their new method belongs to the class of Hidden Markov Models (HMM) that accounts for autocorrelation in time between fishing events. It is clear that advances in computational methods such as these, as well as better applications of AI and machine learning, will continue to improve our ability to discern types of fishing behavior from positional data.

While there may be institutional reluctance to transition to a new system due to cost concerns, Thuesen (2016) showed that substantial costs savings from moving to new electronic systems can potentially be realized, even in small-scale fisheries. The proliferation of smartphones has enabled applications to take the place of traditional paper logbooks, increasing efficiency in the data reporting process and enabling electronic reporting to spread across the globe. Recent work by the Environmental Defense Fund in Indonesia's blue swimming crab fishery has demonstrated how a smartphone app[83] can help in the transition of small-scale fisheries data collection from paper-based collection to electronic reporting. Another example, Abalobi,[84] is an integrated small-scale fisheries information-management system that enables small-scale fishers in South Africa to drive data collection that is integrated into information and resource networks such as market and weather portals. The user interface is through a smartphone app that allows fishers to log their catch and access analytics tools to help in activity planning. Jiorle, Ahrens, and Allen (2016) evaluated the accuracy of a recreational angler app for reporting catch rates of certain species in the United States and found that when concerns surrounding self-reporting bias are corrected, apps such as these have the potential to generate reliable data in situations where traditional methods cannot. Recently a researcher in Sri Lanka developed a smartphone app that could convert a fisher's phone into a VMS by utilizing the phone's GPS receiver, mobile data access, internal storage, and Unicode compatibilities (Nyananda, 2017). In addition to the VMS capabilities, an e-logbook was incorporated into the app which facilitates the electronic reporting of catch details and is electronically linked to positional data.

These advances demonstrate that collecting data in small-scale fisheries can be achieved cost-effectively by the use of smartphone apps and other low cost electronic technologies. However, a key challenge lies in creating the systems and structures that enable the compilation, analysis and visualization of small-scale fisheries data. These systems can reduce barriers to data use, thereby increasing the demand for data, but must be low cost, easy to operate and readily accessible. A recent development is PeskAAS (Tilley et al., 2020), a flexible open source digital application that enables the management, analysis and visualization of small-scale fisheries catch and effort data. The system has been trialed in Timor-Leste and is currently being rolled out in more geographic areas.

3.1.3 Remote sensing for estimating catch and effort

Satellite imaging and sensor technologies are improving rapidly, facilitating their application to fisheries monitoring. Many fishermen fish at night and use powerful lights to attract squid and other species. These lights can then be detected from space using rapidly improving sensors such as visible infrared imaging radiometer suite (VIIRS[85]) and potentially used for estimating fishing effort. The analysis of satellite camera images also has potential to provide estimates of effort through the application of machine learning and image recognition techniques. For example, Al-Abdulrazzak and Pauly (2014) use Google Earth to count intertidal fishing weirs in six countries in the Arabian Gulf and estimate that actual catches are likely to be up to six times higher than those reported in official statistics.

3.1.4 Shore-based cameras

While the use of satellite imaging to quantify fishing effort is increasing rapidly, shore based imaging through the use of digital cameras has also been on the rise recently. For example, Keller et al. (2016) used shore-based cameras to monitor artificial reef sites in Australia to estimate temporal changes in fishing effort, and Lancaster et al. (2017) show how shore based remote camera monitoring can quantify recreational vessel compliance with coast rockfish conservation areas in the Salish sea, Canada. The Oregon Recreational Boat Survey has been using video boat count methodology to successfully

81 https://www.fisheries.noaa.gov/southeast/commercial-fishing/electronic-logbook-gulf-mexico-shrimp-permit
82 http://ipnlf.org/what-we-do/projects/fisheries-information-system
83 https://www.edf.org/oceans/these-six-pilot-projects-are-making-fishing-more-sustainable
84 http://abalobi.info/
85 https://ngdc.noaa.gov/eog/viirs/download_dnb_composites.html

quantify fishing effort in most major ports in Oregon since 2009 (Edwards & Schindler, 2017) and, recently, the Oregon Department of Fish and Wildlife have been collaborating with EDF's Smart Boat Initiative (SBI)[86] to develop machine learning algorithms to increase the efficiency of the monitoring process. The technology, called 'SmartPass' uses machine learning algorithms to automatically count and identify vessels that travel through a geographical pinch point such as a pass or harbor entrance (Haukebo et al., 2021). SmartPass systems have also been tested in small-scale and recreational fisheries in Indonesia and the Gulf of Mexico, United States.

3.2 Compliance monitoring

The ability to monitor fishing activity is essential for effective enforcement of fishery regulations. Ensuring that only legal fishing occurs increases confidence in stock assessment metrics, can increase revenues derived from legal fishing opportunities and helps to promote good stewardship practices. Slave and indentured labor in fisheries have also come increasingly into the spotlight[87] and surveillance efforts are critical to efforts to address this important issue. While licensing and registration systems along with vessel identification systems are important components of effective compliance monitoring, the major challenge to effective surveillance of the world's fisheries is the sheer vastness of the ocean which compounds a lack of capacity for implementing and enforcing vessel-based monitoring systems (such as VMS or AIS which are easily turned off). These challenges are being overcome thanks to new digital vessel-based technologies and, perhaps most importantly, by the huge constellations of small satellites that are being launched over the next decade. This planned increase in satellite coverage of the world's oceans will allow improved communication in the oceans space and will also improve the distribution, frequency and cost of providing SAR images to fishery Monitoring, Control and Surveillance (MCS) agents.

Global efforts to combat illegal fishing are becoming more coordinated. The International MCS network is a voluntary network of persons responsible for fisheries MCS, including representatives of RFMOs and fishery managers, aimed at promoting and facilitating coordination between members to improve the efficiency and effectiveness of MCS activities.[88] MCS agents are also working with port managers to automate port entry systems, allowing entry and provision of services to vessels who comply with various MCS requirements, such as a continuously operating AIS system.

3.2.1 Vessel tracking devices

As well as sophisticated AIS and VMS systems that are mainly in the purview of industrialized fisheries, a plethora of small-scale vessel tracker devices exist. Most of these devices are solar powered and installation is generally as simple as bolting them onto the hull of a vessel. Some devices use GSM cellular networks to transmit positional data while others use satellite services to transmit data. For example, Pelagic Data Systems[89] provides vessel tracking systems specifically for artisanal fisheries. Instead of relying on expensive satellite systems, the Pelagic system consists of a tiny solar powered hardware box that is easily installed on small vessels. Data, including the location and time of fishing and the gear type used, are automatically transferred to a server when the vessel comes within range of a cell phone tower. The overall system can map and measure fishing effort to assist managers, support area-based and rights-based management, and potentially provide monitoring of illegal fishing activities. A range of other companies have started to provide similar solar- or battery-powered tracking devices over the last decade. Some incorporate Bluetooth connectivity, which enables the potential to incorporate data from other vessel sensors into the system.[90] Others incorporate a range of value-added services for fishermen (such as analytical data on fishing operations) into the overall data system.[91]

Initiatives are also underway to use VMS and AIS to track fishing vessels and then to use machine learning techniques to identify incursions into prohibited areas and to detect movement patterns associated with illegal trans-shipments. OceanMind[92] provides analytical services and tools and a platform that makes use of satellite data, fishing vessel databases and AIS and VMS systems to surveil fishing vessel activity and alert fisheries agencies to suspicious activities. The platform is capable of synthesizing multiple streams of data in near real time in order to provide actionable enforcement advice. While the system can flag potential illegal behavior very effectively, it relies on close coordination with management authorities. OceanMind has partnered with some supermarket chains to help increase accountability

Pelagic Data Systems tracker

Photo by Pelagic

[86] https://www.edf.org/oceans/smart-boats
[87] http://www.ilo.org/global/topics/forced-labour/policy-areas/fisheries/lang--en/index.htm
[88] http://imcsnet.org/
[89] https://www.pelagicdata.com/
[90] https://solarvms.com/
[91] https://thoriumvms.com/
[92] https://www.oceanmind.global/

and transparency in the supply chain.[93] Another technology platform, Global Fishing Watch (GFW),[94] is a partnership between SkyTruth,[95] Oceana[96] and Google. GFW aggregates information from AIS and VMS on fishing vessels worldwide, integrates available SAR data from satellites and employs machine learning techniques to identify fishing activity. GFW provides the (mainly anonymized) information to anybody in the world with an internet connection. A global movement towards better transparency in fishing has been typified by announcements that Indonesia, Panama and Chile are making country-wide VMS data available to the Global Fishing Watch (GFW) platform.[97]

3.2.2 Remote Tracking for Monitoring, Control and Surveillance

While the applications of VMS and AIS systems to fisheries surveillance are obvious, the vast majority of illegal fishing is likely conducted by vessels that do not carry tracking devices. In these cases remote monitoring must be conducted. Examples of technologies for remotely monitoring fishing vessels include low cost radar systems (such as those provided by the Anthropocene Institute)[98] mounted strategically near fishing grounds which can be used to surveil marine protected areas (MPAs), closed areas and Territorial User Rights for Fishing (TURFs). Advances have also been made in the use of UAVs for use in conservation and other non-military applications. For example, in the Seychelles the FishGuard[99] project is being developed to utilize long range fixed wing drones that are guided by AI and require minimal human input to monitor huge swathes of the EEZ for illegal fishing.[100] Drones are also being used in Belize to monitor the Turneffe MPA.[101]

Further aloft, there has been a modest level of exploration of remote sensing techniques to shine a light on illegal fishing. For example, Longépé et al. (2017) combine the use of space-borne high resolution SAR imagery with AIS and VMS systems to ascertain the extent of illegal fishing in the Arafura Sea, Indonesia. Another example is Karagatan Patrol,[102] which is an online platform that tracks ships through VIIRS and has been applied in the Philippines, where the detection of commercial scale lights within 15km of the shore implies illegal fishing.[103] Kongsberg Satellite Services,[104] partly owned by the Norwegian Government, has launched enough satellites to make upwards of 50,000 passes per month over certain areas of the ocean. This capacity is being used to generate images that can monitor pollution, fishing vessel activity, ice movements and deforestation. Planet Labs[105] has launched "the largest constellation of Earth-imaging satellites" which are used by Skytruth and others working on detecting IUU fishing. Hawkeye 360[106] and UnseenLabs[107] are examples of an emerging effort to launch 'smallsat' constellations for radio-frequency monitoring services, at least partially for tracking fishing vessels. GFW predicts that radio-frequency monitoring data will soon become less expensive and more readily available, following trends with AIS data, SAR data, and even optical satellite data. Optical satellite data was previously too expensive to scale, but that is changing since Sentinel was launched by the EU with a free, full and open data policy.[108]

Acoustic sensors have broad potential to monitor marine areas as they are relatively inexpensive and can be deployed on a wide variety of platforms. Fishing vessels emit acoustic signals that can be used in some cases to identify classes of vessels or even individual vessels. If more than two hydrophones are part of a monitoring system, it is possible to triangulate the exact location of the vessels and identify their speed and direction. This makes them potentially suitable for coastal monitoring of MPAs or community-based TURFs where illegal fishing activity within these areas can easily be distinguished from legal activity. While several companies, such as Loggerhead Instruments[109] and Ocean Instruments,[110] manufacture passive acoustic sound traps that can be used

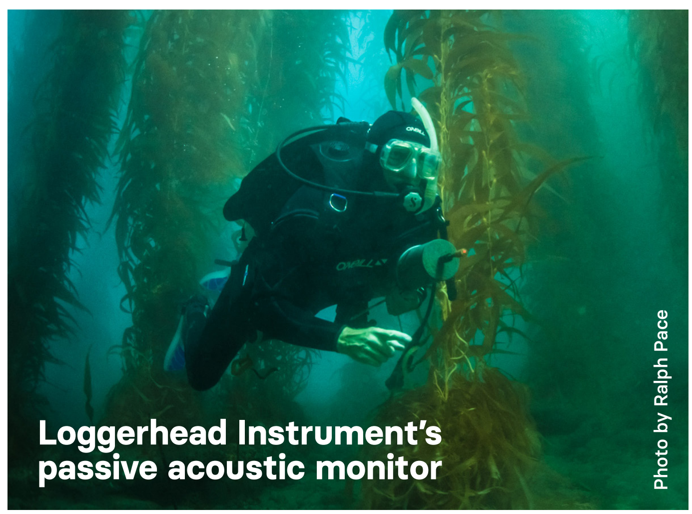

Loggerhead Instrument's passive acoustic monitor

Photo by Ralph Pace

[93] https://news.microsoft.com/on-the-issues/2019/06/06/ocean-mind-illegal-fishing/
[94] https://globalfishingwatch.org/
[95] https://skytruth.org/
[96] https://oceana.org/
[97] https://globalfishingwatch.org/programs/indonesia-vms/
[98] https://www.anthropoceneinstitute.com/oceans/overfishing/marine-monitor/
[99] https://www.grida.no/activities/275
[100] https://www.seafoodsource.com/news/environment-sustainability/drones-fisheries-enforcement-potential-remains-untapped-even-as-projects-advance
[101] https://www.suasnews.com/2019/08/water-landing-drones-routinely-fly-bvlos-missions-over-marine-reserve-against-illegal-fishing-and-pro-biodiversity/
[102] http://www.karagatanpatrol.org/
[103] https://news.mongabay.com/2020/06/lockdown-allowed-illegal-fishing-to-spike-in-philippines-satellite-data-suggest/
[104] https://www.ksat.no/
[105] https://www.planet.com/
[106] https://www.he360.com/
[107] https://unseenlabs.space/
[108] https://sentinel.esa.int/web/sentinel/sentinel-data-access
[109] https://www.loggerhead.com/
[110] http://www.oceaninstruments.co.nz/

for acoustic monitoring, efforts to monitor fishing effort, such as incursion into a protected area, are still at a nascent stage. Conservify[111] is developing open source systems for community based acoustics monitoring, and in Australia, passive acoustic sensors are being used to detect vessel activity in MPAs (Kline et al., 2020).

3.3 Stock abundance and productivity estimation

Better estimates of stock abundance and productivity improve confidence in the ability of fisheries management regulations (such as total allowable catch) to achieve management goals and may increase benefits derived from the fishery in the long run. However, many fisheries lack sufficient resources to collect fishery dependent data (data collected during the course of fishing operations) let alone those needed to carry out fishery independent surveys — these generally require a high level of scientific expertise as well as significant financial resources. Stock abundance estimates, which are the main input into fishery sustainability target points such as catch limits, are currently made using either catch per unit effort (CPUE) data or fishery independent survey data. Technological advances are improving the ways fishery dependent catch data are being collected and reducing the cost of conducting abundance surveys. Stock productivity is currently estimated with demographic models that require data on age- or length-specific survivorship, fish growth rates, recruitment as a function of stock size and other parameters. These kinds of data may be more difficult to collect than abundance data, regardless of what tools are available. However, technologies such as small ROVs and autonomous vehicles that are inexpensive to purchase and operate may facilitate the collection of much more length composition data by using lasers and automated fish recognition, measurement and counting software. These data can then be used to calculate estimates of fishing mortality and reproductive capacity.

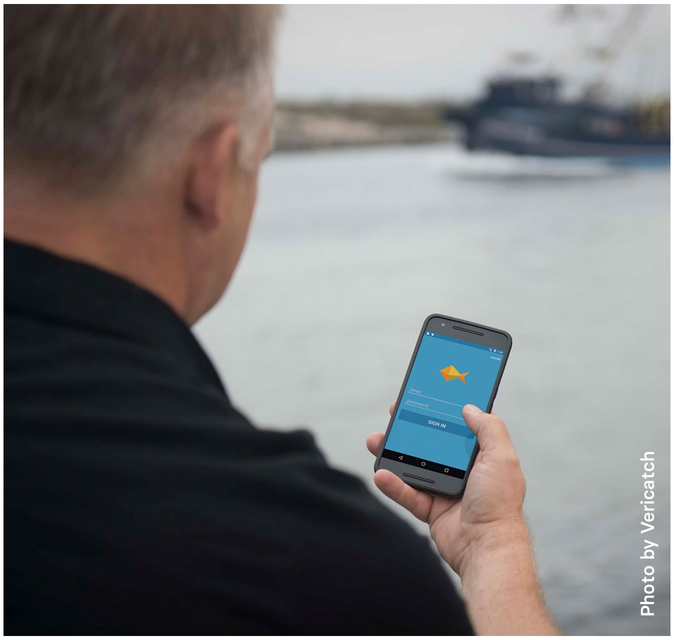


Photo by Vericatch

Advances in the collection of abundance and productivity data are complemented by advances in the tools that are necessary to collate, analyze and visualize these data. For example, dashboards for displaying fishery performance indicators such as CPUE over time and space are rapidly being developed. OLSPS,[112] Woods Hole Group[113] and Vericatch Solutions[114] all have these types of analytical tools in production. Advances in computer vision are also being leveraged to convert audio and visual data into real insights on fishery health, and citizen scientists are even getting in on the action. For example, NOAA's Pacific Islands Fisheries Science Center has been using video cameras to collect images of bottom-fish species and has launched OceanEYES,[115] an initiative to engage volunteer citizen scientists to help identify fish and annotate images so that they can be readily fed into computer vision algorithms.

3.3.1 Visual camera surveys

While conventional Remotely Operated Vehicles (ROVs) continue to be relatively expensive to purchase and operate (requiring a large vessel with significant power supply capabilities), new, smaller ROVs such as the BATFish[116] offer a more cost effective way to collect data through images and sensors from which fish density, composition and length structure can be estimated. The BATFish is a hydrodynamic towed sled that provides a cost effective broad area visual survey. It incorporates two cameras, lights, a multi-beam sonar, altimeters and recorders into a 130 pound system designed to be towed behind a small (~25 ft) vessel. In addition to Towed Underwater Video (TUV) systems, other technologies in development include Baited Remote Underwater Video systems (BRUVs), which use bait to attract fish to the camera view; Remote Underwater Video (RUV) systems, which operate autonomously; Diver Operated Video (DOV) systems, which are operated by a diver using SCUBA gear; and stereo video techniques, which generate a 3D image through the use of two cameras set at different angles. Importantly, all of these technologies are improving significantly over time. They are becoming smaller and cheaper, collecting higher resolution images, using smaller and more powerful batteries and increasing in information storage capabilities. These techniques can be used to estimate stock biomass and species composition while resulting in far lower fish mortality than traditional methods, and also provide the possibility of collecting additional information including data on fish habitat, behavior, length composition and movement.

111 http://conservify.org/
112 https://www.olsps.com/
113 http://www.whgrp.com/
114 https://vericatch.com/
115 https://www.fisheries.noaa.gov/feature-story/citizen-scientists-help-count-deep-7-bottomfish-hawaii
116 https://www.maregroup.org/batfish.html

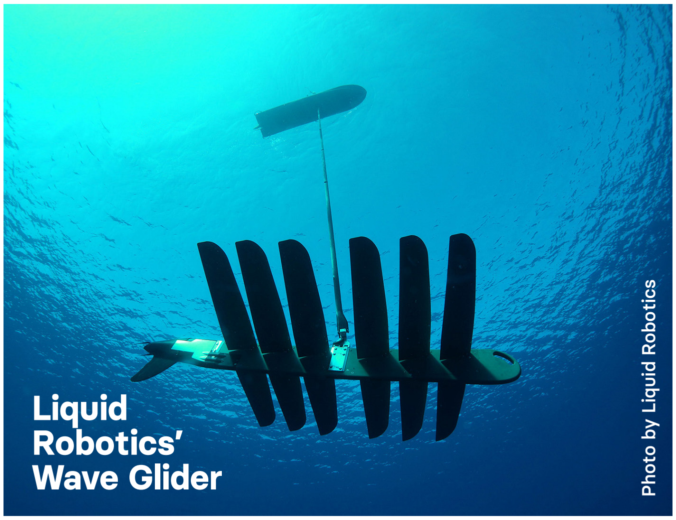
NOAA researchers have developed the CamTrawl,[117] a stereo camera system installed near the codend (the back end) of a trawl net. The trawl aggregates fish and funnels them into view of the camera where they are recorded before being released unharmed. NOAA scientists then use an algorithm to identify and estimate the size of fish to species, enabling them to run through 2-3 million still images in less than a day — something that would take human reviewers significantly longer to do.[118] Other examples include the Habcam project[119] which returns 500,000 images per day from various cameras mounted on underwater vehicles. In conjunction with the New England Fisheries Science Center, researchers from Woods Hole Oceanographic Institute have developed an algorithm to detect sea scallops that is both quick and sufficiently accurate (a detection rate of between 60-95%, which is consistent with human classification from images). On the U.S. west coast, the Oregon Department of Fish and Wildlife uses ROVs equipped with stereo cameras to measure the composition, abundance and lengths of rockfish species in habitats that are not accessible by traditional trawl assessments.[120] The C-BASS Camera-Based Assessment Survey vehicle,[121] a towed vehicle equipped with stereo cameras, is used by University of South Florida scientists to conduct habitat assessments in the Gulf of Mexico and recently to help perform visual counts of red snapper as part of assessment surveys.

Although researchers have access to large and increasing amounts of high-quality video and other imagery, these data are extremely tedious to analyze using existing manual techniques. Rapid development in technology-based platforms has enabled camera imaging to be used for habitat assessment and population estimates, although processing image data has lagged behind (Bicknell et al., 2016). The most impactful advances in improving the efficacy of image analysis lies in automation of the process through advanced algorithms. There are a few notable examples of image analysis algorithms that show promise. For example, researchers from the University of Washington's department of Electrical and Computer Engineering [122] are leading an effort to use machine learning techniques to automate image identification from ROVs. There are various problems, especially with a high false detection rate, but these problems are starting to be overcome by the use of motion extraction across frames and other advances. The Fish4Knowledge Project[123] aims to automate video image identification and annotation by collaborating with the public to develop algorithms that are effective at information abstraction from video images, as well as data storage. Project researchers used underwater live video feeds as a testbed and developed an online game to encourage users to select and identify fish in order to gather a large number of annotated images for testing the analysis techniques. This game has resulted in a large number of users producing high quality annotations. To make machine learning algorithm development more accessible to more people, Kitware[124] has been working with NOAA scientists to develop Video and Image Analytics for Marine Environments (VIAME),[125] an open source software platform to enable the development of computer vision for underwater image analysis. In the aquaculture space, Tidal[126] has developed an underwater camera system for fish farmers that can detect and interpret fish behaviors not visible to the naked eye.[127] It is likely that developments such as these that are driven by commercial imperatives will play a big part in developing technologies that will eventually be applied in the fishery science space.

3.3.2 Acoustics for assessments

In addition to video and camera imaging, active (sonar) and passive (hydrophone-based) acoustic methods are widely used in fisheries and aquaculture. For example, passive acoustic techniques have recently been applied to improve feeding efficiency in the farming of tiger prawns (Smith & Tabrett, 2013), and active techniques are used to estimate the abundance of Pacific hake during the biennial joint U.S.-Canada Integrated Ecosystem and Pacific Hake Acoustic Trawl Survey.[128] Increasing the scope of adoption of less expensive acoustic technologies seems feasible. Advances in acoustic technologies and their applications are continuing to provide benefits to fishery managers. For example, broadband backscatter techniques for imaging the water column are an improvement on narrowband echo sounders and have recently become feasible due to decreasing equipment costs (Bassett et al., 2016). While the U.S. west coast hake fishery has been assessed with the aid of acoustic surveys for several years, recently work has begun to identify protocols where acoustic and bottom trawl surveys are combined in order to assure that sampling encompasses the entire vertical range of the species being surveyed (Kotwicki et al., 2017). Fishery managers at the Quinault Indian Nation have been using an automated hydroacoustic monitoring system which allows for the detection, sizing and 3D tracking of salmon at ranges in excess of 200 m. The system monitors and conducts an autonomous fish count, operating 24 hours a day, and communicates fish status parameters to fisheries managers in real-time (Klemas, 2013).

[117] https://www.st.nmfs.noaa.gov/aiasi/afsc_camtrawl.html
[118] https://www.st.nmfs.noaa.gov/aiasi/Home.html
[119] https://habcam.whoi.edu/
[120] https://www.dfw.state.or.us/MRP/fisheries/populations.asp
[121] https://www.marine.usf.edu/scamp/about/visual-surveys-with-c-bass/
[122] https://people.ece.uw.edu/hwang/
[123] https://groups.inf.ed.ac.uk/f4k/
[124] https://blog.kitware.com/kitware-and-noaa-host-viame-software-integration-and-training-workshop/
[125] https://www.viametoolkit.org/
[126] https://x.company/projects/tidal/
[127] https://9to5google.com/2020/03/01/alphabet-x-tidal-ocean/
[128] https://www.fisheries.noaa.gov/west-coast/science-data/joint-us-canada-integrated-ecosystem-and-pacific-hake-acoustic-trawl-survey#collecting-acoustic-data-at-sea



Liquid Robotics' Wave Glider[129] can be fitted with an array of sensors and other data collection instruments and can actively collect and transmit (via satellite, cell or broadband) data for up to a year in ideal conditions. Greene et al. (2014) lay out a vision for using this relatively inexpensive technology to replace fishery research vessels to conduct acoustic stock assessment surveys, postulating that a 'fleet' of gliders could conduct the U.S. west coast hake assessment in about one eighth of the time in which it is currently conducted and at a much reduced cost. AFSC recently used another platform — the Saildrone — to conduct the 2020 Bering Sea pollock assessment.[130]

Scientists are experimenting with the use of Slocum Gliders[131] to locate populations of spawning fish. Slocum Gliders harness the energy of existing ocean currents to 'glide' through the ocean (in a manner somewhat analogous to traditional glider airplanes) and surface at regular intervals to transmit data via satellite. The gliders operate on their own power and can operate on a pre-programmed survey track for several weeks. They have been fitted with passive acoustic receivers to 'listen' for spawning aggregations of fish, some species of which have been found to make particular vocalizations when massing together to spawn.[132] This technology is currently being applied in the northwest Atlantic, and some parts of the Caribbean.[133]

Acoustic telemetry, where individual fish are tagged with an acoustic transmitter and their movements tracked, has improved our understanding of marine stocks. For example, Verhelst et al. (2016) applied acoustic telemetry to Atlantic cod (Gadus morhua) in the North Sea to shed light on seasonal migratory behavior. While this type of information is of obvious value to stock assessment scientists, it can also be potentially used to implement fishing quotas or other management tools on a spatio-temporal basis.

3.3.3 eDNA and genetics

There has been significant recent interest in the field of environmental DNA (eDNA) analysis, which identifies genetic material shed by macro-organisms into the surrounding environment whether dead or alive. A promising technique for estimating stock abundance involves the use of eDNA collected from seawater as a metric for fish species abundance and composition and researchers are just beginning to understand the possibilities of using these techniques for fisheries assessment. Until recently, eDNA efforts have been restricted to species detection (presence/absence; Kelly et al., 2014). However, recently Stoeckle, Soboleva, and Charlop-Powers (2017) drew eDNA from the Hudson River estuary, finding that eDNA detected abundant and common estuary species rather than uncommon ones, which implies a quantifiable relationship between stock abundance and eDNA abundance. Most fish in the estuary have mitochondrial sequences in GenBank,[134] enabling identification of amplified eDNA sequences. The study found that eDNA has a sort of 'Goldilocks' quality, i.e., it lasts long enough that it is able to be detected, but not so long that it can't be localized. Importantly, the researchers rarely detected freshwater species despite inflow from the Hudson River, and species detection differed by season consistent with the springtime movement of fish populations. Recently, Sigsgaard et al. (2016) provided an important proof of principle that eDNA data could be used to provide population-level information. Efforts have been underway to determine relationships between the amount and composition of eDNA in seawater samples and the species-specific density of fish in an area. Thomsen et al. (2016), in a comparison of trawl survey catch to eDNA composition in seawater, found a high proportion of eDNA belonging to the Greenland shark (Somniosus microcephalus) despite just a single specimen being caught. These advances have important implications for the detection and assessment of species that may be able to avoid fishing gear and are beginning to illustrate the possibilities of using eDNA, or the 'barcodes to biomes' approach, not just for stock assessment, but for formal integrated ecosystem evaluation, including food web assessments (Goodwin et al., 2017).

eDNA detection in marine water is challenging: a large water volume to biomass ratio, sea currents and high salinity mean that eDNA is much less concentrated, more quickly dispersed, and may not be well preserved. However, it is important to recognize that eDNA provides numerous advantages that most other sampling efforts lack. Extraction can be performed in virtually any marine environment, unlike sampling by bottom trawling. It requires little expertise or effort, reducing costs and making it easier to implement in rural areas and developing countries. DNA identification is also more objective and certain than visual samples, and there is a distinct possibility that we will be able to estimate the abundance

129 https://www.liquid-robotics.com/platform/how-it-works/
130 https://www.fisheries.noaa.gov/feature-story/ocean-going-robots-effective-surveying-pollock
131 http://www.teledynemarine.com/slocum-glider
132 https://oceanservice.noaa.gov/facts/ocean-gliders.html
133 https://oceanexplorer.noaa.gov/okeanos/explorations/ex1502/background/leg1/welcome.html
134 https://www.ncbi.nlm.nih.gov/genbank/

of a particular species in a given area simply by analyzing a sample of seawater from that same area. Sensors developed to detect and identify DNA are now readily available in easy-to-use, portable commercial products, enabling field-based analysis of eDNA (Yamahara et al., 2019).

Another area of genetics research which has increased rapidly in the last decade is the use of Genetic Stock Identification (GSI) to examine population structures and to define distinct species, sub-species, and stocks. The west coast GSI project, led by researchers at Oregon State University, is aimed at uncovering patterns in catch locations and times of 'weak' salmon stocks, mainly originating in northern California (Teel et al., 2015). While this information is yet to be used for real time management, its potential is significant: if consistent spatio-temporal patterns can be discerned, or if near real time genetic information can be generated, reactive management involving short term closed areas could generate significant benefits to west coast fishermen (Satterthwaite et al., 2015). In another example, Canadian researchers are using genetic techniques combined with traditional knowledge and social science methods to better understand northern fish populations, eventually improving remote communities' management capacities.[135]

3.4 Ocean ecosystem monitoring

Ecosystem quality is a strong determinant of fish community composition, productivity and overall system resilience. Improved knowledge of the extent and composition of habitat types in a fishery can improve the ability of managers to set regulations such as closed or protected areas or define area-specific regulations such as allowable gear types. While crucially important for the sustainable management of fisheries, both the tools used and the outputs generated from ecosystem monitoring efforts have broad application beyond the fisheries space. For example, monitoring for pollutants such as effluent from aquaculture farms or microplastics can help the allocation of mitigation resources and identify likely sources, and using better data as inputs into a coordinated Marine Spatial Planning (MSP) approach can increase benefits to all users of the ocean space (see Collie et al., (2013) for an overview). However, data are rarely collected in sufficient detail to be useful for ecosystem-based management or ecosystem health management due to limited resources.

Conventional approaches to measuring ecosystem health are extremely time-intensive and costly to implement, have sometimes led to the exclusion of fishing communities' inputs in the process and for some methods, such as bottom trawl surveys, have a significant ecological impact (NOAA Fisheries, 2020). Emerging technologies, many of which are markedly less invasive, can efficiently measure biological characteristics such as fish community composition and productivity, and enable the collation of real-time physical oceanographic data such as temperature, salinity, dissolved oxygen and sometimes carbon capture potential. New approaches are being developed that leverage AI tools to analyze the massive datasets being collected by a range of advanced sensors in order to better monitor marine ecosystems. Emerging technologies also have the capacity to collect real time data and bring us closer to near real time data analysis. This provides stakeholders (including fishermen and governments) with an opportunity to forge adaptive responses to complex climate change effects. Overall, more technologies for measuring ecosystem health are being developed that are environmentally conscious, cost-effective, transmit real-time data and adaptive to emerging challenges.

3.4.1 Mapping ocean ecosystems

Remote sensing techniques have the potential to inform habitat designation and mapping, including the design of MPAs. The science is based on the idea that key oceanographic variables, such as sea-surface temperature, salinity and chlorophyll levels, can be measured remotely and are good proxies for marine biodiversity, habitat extent and quality (Kachelriess et al., 2014). Remote sensing offers repeatable, standardized and verifiable information on long-term trends in ecosystem structure and processes at the global scale. Remote sensing data are available at much broader spatial and temporal scales than in situ measurements ever will be and, combined with emerging advances in big data analysis, hold significant potential for generating insights that inform how we plan and site anthropogenic activities in the marine space. In one recent example, scientists used big data techniques to identify good candidates for MPAs that have the highest ecological-economic tradeoff, using more than 22 billion data points on economic activity as well as ecological data.[136]

Semi-autonomous drones also hold much promise in gleaning insights regarding the distribution and scale of oceanographic processes. In 2017, NOAA scientists deployed a fleet of semi-autonomous drones, Saildrones,[137] across the Pacific Ocean for 8 months to study signs of climate-disrupting El Niño events.[138] These drones collect high resolution ocean data such as environmental and atmospheric variables and can be equipped with a specialized echo sounder for fish stock assessment and survey depth. Saildrones record sharp gradients in the distribution of oceanographic variables, which would not usually be detected by satellites or left unaccounted for by stationary or aging buoys (Voosen, 2018), providing valuable input for climate models. Other surface drones include the Datamaran,[139] which has been deployed to observe marine mammals and study seismology.

SLAR and SAR (Brown, Fingas, and Hawkins 2003) can trace backscatter patterns caused by oil slicks and fish schools. Mounted on aircrafts, these technologies have been used to detect schools of jack mackerel, skipjack tuna, southern bluefin tuna and dolphins (Klemas, 2013), and have

[135] https://newsroom.carleton.ca/story/track-fishing-boost-food-security/
[136] https://www.sciencedaily.com/releases/2020/04/200407131507.htm
[137] https://www.saildrone.com/
[138] http://www.sciencemag.org/news/2018/03/fleet-sailboat-drones-could-monitor-climate-change-s-effect-oceans/
[139] http://www.automarinesys.com/

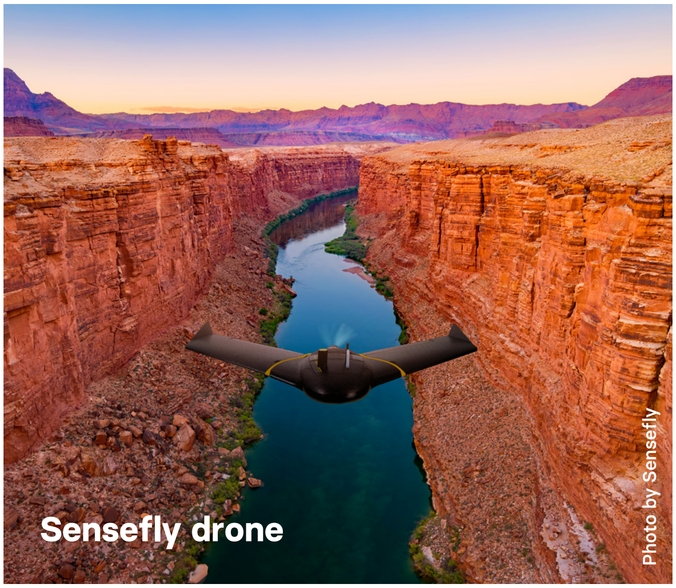
also been used to map sea ice conditions since the 1960s by the U.S. Coast Guard. In addition to observing the overall ice conditions, individual ice floes were identified on SLAR imagery by their size, shape and surface characteristics.[140] Today, tracking sea ice conditions is an important endeavor in assessing climate change impacts on fisheries.

3.4.2 Pollution monitoring

Pollutants such as microplastics pose a detrimental threat to aquatic and terrestrial life, especially as many bioaccumulate through the food chain. *"The likelihood of disease increases from 4% to 89% when corals are in contact with plastic"* (Lamb et al. 2018, pg. 460). Emerging technologies such as nanoparticle sensors, mapping techniques, hyperspectral imaging and 3D modeling can all contribute to mapping unaccounted-for plastics. Spectral flow cytometry has huge potential to identify a range of substances in situ, allowing things like plastics and harmful species of algae to be identified in water samples with portable equipment and in close to real time (Leape et al. 2020). These techniques identify objects like microplastics based on molecular vibrations and open up the prospect of portable, platform-based microplastic detectors (Araujo et al., 2018). Organizations such as Draper,[141] which place microplastic sensors on AUVs, are collaborating with the U.S. Environmental Protection Agency to create robust networks of microplastic sensors with data sharing platforms using a Plastic Particle Pollution index (PPPi).[142] Information collected by hyperspectral sensors also holds potential for improving the monitoring of plastic pollution as hyperspectral cameras can identify microplastics in seawater and are relatively straightforward to deploy (Fu et al., 2020). Although most hyperspectral cameras deployed in the oceans space are currently deployed on air-borne platforms to identify objects from afar (such as oil spills), their use for in situ sampling of a range of substances is increasing (Kachelriess et al., 2014).

In response to increasing occurrences of harmful algal blooms (HABs; McPartlin et al. (2016)), the Monterey Bay Aquarium Research Institute (MBARI) has developed an Environmental Sample Processor (ESP)[143] which aims to automate toxic algae detection at moorings. This technology has replaced the outdated technique of collecting and delivering water samples to laboratories as the ESP uses molecular probe technology to transmit real time data at a much lower cost. The Chemical Sensor Group[144] at MBARI also employs gliders fitted with sensors to measure concentrations of dissolved chemicals.

[140] https://trid.trb.org/view/3635
[141] https://www.draper.com/explore-solutions/microplastics-sensor
[142] https://www.draper.com/sites/default/files/2019-03/Infographic%20Final.pdf
[143] https://www.mbari.org/technology/emerging-current-tools/instruments/environmental-sample-processor-esp/
[144] https://www.mbari.org/science/upper-ocean-systems/chemical-sensor-group/



Sensefly drone

3.4.3 Monitoring marine animal health

A number of organizations are leveraging new technologies to monitor the health of many types of marine animals. For example, the Duke Marine Lab[145] has been testing drones in a range of ecosystem monitoring efforts. Using SenseFly fixed-wing eBee UAS[146] and their Thermomapper camera, which relies on thermal imagery to automatically detect and count marine wildlife, researchers conducted population surveys of gray seals on remote islands in eastern Canada and New England.[147] The SenseFly eBee has also been used to create a 3D surface model of penguin colonies and for thermal melt water mapping off glacier faces in Antarctica.[148] Other drones, such as Sofar's low-cost Trident ROV,[149] can be customized to include sensors, modules and add-ons in order to collect site-specific oceanographic data. The Ocean Alliance's SnotBot[150] program uses drones to noninvasively collect exhaled breath condensate from a whale's blow. Equipment attached to the drone include petri dishes, sponges, cameras and microphones used to collect blow samples containing DNA, stress and pregnancy hormones, microbiomes and possibly other indicators of the animal's health.

Using biomimicry, scientists are inventing technologies that can un-invasively collect data on complex ecosystem dynamics. For example, the Robofish[151] can cooperatively track moving targets underwater, such as groups of whales or schools of fish with minimal impact on natural fish behavior. Schools of these robots could potentially work together to track large herds of animals or map expanses of pollution that can grow and change shape.[152]

3.4.4 Acoustic ecosystem monitoring

Monitoring underwater acoustics has been a key component of conducting fishery stock assessments and can also provide a unique perspective into monitoring ecosystem health. In Boston Harbor in the northeast United States, a system of buoys equipped with passive acoustic recorders, advanced algorithms and data transmission capabilities has been used in conjunction with a variable marine speed corridor to reduce the incidence of whale strikes by the shipping industry.[153] The system alerts regulators to the presence of whales (identified by the sounds they make), and an adaptive speed limit is imposed when whales are close to shipping lanes.

Passive acoustic sound traps, such as those designed by Loggerhead Acoustic Instruments[154] and Ocean Instruments[155] have been used to monitor fish and mammal vocalizations, overall ocean soundscapes, and noise from wind turbines, pile driving and seismic surveys. Loggerhead Instruments have developed high speed motion dataloggers to study animal behavior in unprecedented detail, which could yield important insights into anthropogenic noise pollution on marine population health. The company has

Snotbot

145 https://nicholas.duke.edu/marinelab
146 https://www.sensefly.com/drone/ebee-x-fixed-wing-drone/
147 https://sites.nicholas.duke.edu/uas/
148 https://sites.nicholas.duke.edu/uas/highlights-from-antarctica-research/
149 https://www.sofarocean.com/products/trident
150 https://whale.org/snotbot/
151 https://magazine.washington.edu/uw-researchers-create-robofish-that-can-talk-to-each-other/
152 https://www.engr.washington.edu/facresearch/highlights/aa_robofish.html
153 https://www.technologyreview.com/2008/05/07/34531/stopping-ship-whale-collisions/
154 http://www.loggerhead.com/
155 http://www.oceaninstruments.co.nz/

also collaborated with scientists at the University of Miami to create the Medusa Ocean Profiler[156] to cost-effectively study the environment of larval fishes. Ocean Instruments' sound traps have been employed to develop a novel approach for automated detection of marine mammals. Their supporting software that is capable of integrating acoustic data with other types of information is potentially hugely transformative, as this allows efficient population of statistical and machine learning models for deriving insights.

Citizen scientists are being employed to help monitor ecosystem health in new ways. For example, an interdisciplinary team in the United Kingdom has designed a Sonic Kayak equipped with acoustic hydrophones and speakers that researchers and citizen scientists can use to eavesdrop on the ecosystem below and also obtain underwater sound and temperature data (Griffiths et al., 2017). As citizen scientist kayakers paddle, they hear and record sounds picked up by the hydrophones in the water, allowing them to listen in on marine animals and monitor the effects of passing ships and other man-made sounds. Sonic kayaks such as these have also been used to track fishery behavioral and migratory patterns in a shallow high-energy fringing reef habitat in a Hawaii marine reserve (Meyer & Holland, 2001).

3.4.5 Monitoring coral reef health

Monitoring coral reef health is a significant pathway in measuring climate change impacts on ecosystem health, and LiDAR techniques have been pivotal in this endeavor to better understand coral reef habitat dynamics (Klemas, 2013). The Bedrock Ocean Exploration initiative,[157] which aims to map the entirety of the world's oceans has used LiDAR to create a bathymetric, 3D map of the seafloor, such that coral reef structure, cover and diversity can be monitored across timescales. Using the U.S. Army Corps of Engineers SHOALS (Scanning Hydrographic Operational Airborne LiDAR Survey) system, researchers found that measures such as reef rugosity are strongly associated with measures of fish assemblage structure . LiDAR techniques have also been combined with commercial catch information to characterize the geographic footprint of the western Victoria abalone fishery in Australia (Jalali et al., 2015). NOAA researchers in Puerto Rico have also used LiDAR techniques to map complex mixed benthic habitats [158] and determined that morphometric patterns from LiDAR bathymetry function were good predictors of several fish and coral indicators commonly used in resource management planning (Pittman et al., 2009). Buoys such as Sofar's Spotter[159] have also been used to monitor coral reefs to better understand coastal processes in Vanuatu, South Pacific Islands.[160] To promote marine ecosystem monitoring through citizen science, Aqualink,[161] philanthropically supports communities to manage their local marine ecosystems by remotely collaborating with scientists, and provides Sofar's smart buoy, Spotter, to partner communities.

3.4.6 Oceanographic observing

As accessibility to ocean data is becoming less constrained, the ocean observing community can effectively tackle the challenge of forging standards and practices that enable integration of data from sensors across devices, manufacturers, users and domains (del Rio et al., 2017). There is huge potential for creating intelligent underwater sensor networks, using multimedia techniques for marine sensing and data visualization, improving marine disaster sensing and forecasting and providing services for ocean industries such as sea-ice monitoring for the shipping industry. Companies including CLS,[162] Smart Ocean Systems,[163] Garmin,[164] Hohonu[165] and others design and build low cost oceanographic sensors and promise to drive this revolution forward by increasing the availability of oceanographic instruments for a wider range of organizations. Networks of buoys have also been used for decades for oceanographic observing with much of the data as well as analysis tools publicly available.[166]

Aside from traditional deployments of oceanographic sensors by scientific organizations, there is increasing interest in using fishing vessels as platforms of opportunity for data collection. The Berring Data Collective (BDC)[167] supplies fish-


Berring Data Collective

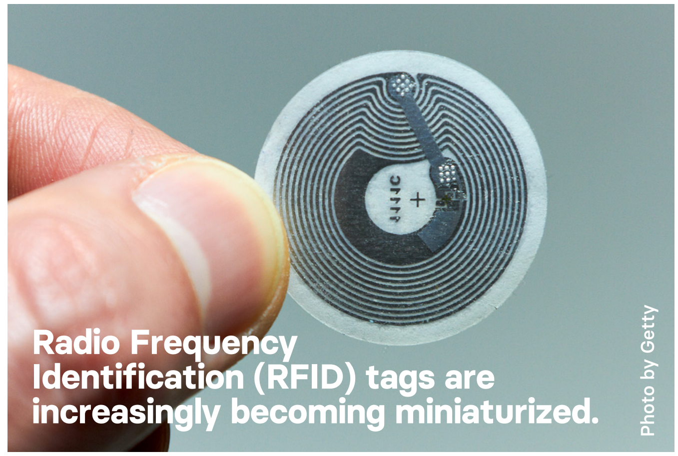
[156] https://www.loggerhead.com/past-projects
[157] https://bedrockocean.com
[158] https://www.fugro.com/about-fugro/our-expertise/innovations/laser-airborne-depth-sounder-lads
[159] https://www.sofarocean.com/products/spotter
[160] https://www.sofarocean.com/posts/coastal-risk-assessment-in-a-coral-reef-lagoon
[161] https://www.aqualink.org/
[162] https://fisheries.groupcls.com
[163] https://www.oceannetworks.ca/innovation-centre/smart-ocean-systems
[164] https://buy.garmin.com/en-US/US/shop-by-accessories/sensors/cAccessories-cSensors-p1.html
[165] https://www.hohonu.io/
[166] https://www.ndbc.noaa.gov/
[167] https://berringdatacollective.com/

ing vessels with the sensors and other equipment necessary to collect oceanographic data. Sensors are generally affixed to gear, and so collect a vertical profile of the water column. BDC are focused on ensuring that data collected are provided to as wide a variety of users as possible. Another example is New Zealand's Moana Project[168] which was initiated in 2018 in response to climate change and aims to improve understanding of coastal ocean circulation, connectivity and marine heatwaves. It also seeks to provide information that supports sustainable growth of the seafood industry. The project applies the Internet of Things concept to develop a low-cost ocean temperature profiler to be deployed by the fishing communities 'on all boats, at all times'. The goal is to develop an open-access ocean forecast system by developing new ocean circulation models using a combination of advanced modeling and data from the project's smart ocean sensors. This broad-based, multi-institutional project illustrates the potential scale and importance of these kind of cooperative fisheries research efforts.

3.5 Increasing the transparency of the supply chain

Seafood is among the most globally traded goods with supply webs radiating from key production areas such as Southeast Asia and the South Pacific to markets throughout the developed and developing world. These complex chains are naturally opaque, providing ample opportunities to misrepresent product types and characteristics, hide catch from illegal and unreported sources and mask slave- and child-labor practices. Increased supply chain traceability improves the ability of producers to differentiate their products (particularly through the designation of ecolabels such as MSC certification),[169] increases consumer confidence in product provenance, allows the realization of operational efficiencies and can increase the bargaining power, legitimization and well-being of small-scale, often disenfranchised fishers.

Enabling seafood supply chain traceability involves developing the global data architectures and supply chain processes that are suitable for complex seafood supply chains where products change form (from whole fish to a variety of value added products) at various nodes along the chain, operate in a multitude of different languages and which include firms of vastly different size and technological capacity (Bhatt et al., 2016). As such, traceability systems must be interoperable, essentially meaning that they must work seamlessly for all parties in the supply chain. Connected sensors are a game changer for traceability in the seafood industry — many of the interoperable systems being implemented rely on recent advances in various digital technologies such as Radio Frequency Identification (RFID) tags, QR and bar codes that



Radio Frequency Identification (RFID) tags are increasingly becoming miniaturized.

physically identify products as they move through the supply chain. These digital identifiers facilitate the maintenance of database systems that track a product throughout its lifecycle. Other technologies facilitate the creation of records in a database system by automatically identifying or measuring products in digital form at the point of landing. For example, MER consultants is working to develop 'smart scales' for use in Puerto Rico that automatically identify and measure species placed on the scale and integrate these data with weights and time and location metadata.[170] The Nature Conservancy's smart weighing scale[171] also helps to integrate data on where and when fish are caught with physical characteristics such as weight and length. Measurements are linked to a unique identifier encoded to a barcode and data are then stored in a database and linked with each fish as it moves through the supply chain. Another example of an integrated traceability system is Simba by Dynamic Systems,[172] which uses a barcode system to track products from the moment the fish is caught, all the way through to retailers.

Some companies such as Vericatch Solutions[173] are bypassing the requirement to affix a physical identifier to products as they move through the supply chain by relying on existing lot numbers to form the basis of the traceability system. Know your Fish[174] is a cloud supported Software as a Service (SaaS) that allows all companies in a supply chain to track products using common lot numbers. Information on catch provenance as well as other educational resources can then be transmitted to consumers at point of sale. ThisFish[175] is a seafood traceability resource that provides consumers with a portal with which to trace a seafood product's origins — where and when the product was caught, by whom, and who processed it. Although this system is only operational for a handful of fisheries in North America and Europe, further development is occurring with much focus on leveraging the platform to increase companies' operational efficiencies.

Recently, blockchain technology has been used to pio-

[168] https://www.moanaproject.org/
[169] https://www.msc.org/home
[170] https://www.seafoodandfisheriesemergingtechnology.com/session-1-resources ("Developing smart scales and data solutions for small scale fisheries").
[171] https://www.nature.org/ourinitiatives/urgentissues/oceans/future-of-fisheries/fishface-using-technology-to-change-the-way-fisheries-are-managed.pdf
[172] http://dynamic-systemsinc.com/software/seafood/
[173] https://vericatch.com/
[174] https://vericatch.com/products/knowyourfish/
[175] http://thisfish.info/

ThisFish app in action at the factory

neer a new method of tracking and tracing seafood products. Blockchain enables distributed databases that are incredibly secure, accessible to all in the network and updated in real time to all portals or users in the system. In a pilot conducted in 2016, Provenance[176] used a combination of smart fish tags and blockchain to track fish caught by fishermen in Indonesia. Some work has also occurred in the WCPFC area through WWF and in conjunction with ConsenSys[177] and TraSeable[178] to develop a traceability system that uses RFID tags to store product identification and blockchain technology to track products through the supply chain.[179] Another example is Release, a blockchain powered marketplace that brings buyers and sellers together on a platform where everyone has access to authentic information.[180] These projects demonstrate that tracking fish products securely can be carried out without the need for a centralized data management system and illustrates the potential applications for blockchain technology in the seafood industry.

The future of traceability systems lies in their continued integration with more and different types of information. Many large companies already employ extensive Enterprise Resource Planning (ERP) systems designed to increase business operational efficiencies and these systems are increasingly being employed for consumer facing traceability purposes. In general, there is a huge amount of potential to integrate regulatory information and needs such as quota allocations and licenses into data management systems that also perform traceability functions.

There are several organizations focused on improving traceability in the seafood supply chain through coordinated action. The Global Dialogue on Seafood Traceability (GDST)[181] is a global organization with the goal of advancing a unified global framework for traceability. Among other activities, the GDST is focused on developing industry standards for interoperability which they hope will enable universal application of seafood traceability across the world's complex seafood supply webs. The Seafood Alliance for Legality and Traceability (SALT)[182] provides a platform for a global community of supply chain stakeholders to collaborate on improving the legality and traceability of the global seafood supply.

3.5.1 Reducing seafood fraud

There are a number of companies that seek to increase consumer and retailer confidence in the products they sell. For example, Trufish,[183] provides DNA testing services to avoid mislabeling. Trufish is an annual subscription service that randomly and regularly selects a set number of seafood product samples for DNA testing in order to verify species identity. Verifik-8[184] offers data analysis to improve the visibility of sustainable practices in fisheries. This company connects producers and buyers to de-risk operations and attempts to build trust up and down the supply chain. Verifik-8 identifies the environmental and social risks in the supply chain, help companies comply with regulatory pressure from importing markets and helps to meet customer demand for responsible sourcing. Another product, BackTracker,[185] is an electronic seafood traceability and verification platform that checks supply chain information against official landings data collected by governments. BackTracker provides third-party verification of seafood purchased against the original fishing vessels lot or landing. As product moves through the supply chain participants using BackTracker can verify key product attributes such as species, fishing vessel, fishing area, landing port and volumes against official government landing records. All of the data in BackTracker are encrypted so users can determine which data are shared and which are kept confidential.

3.5.2 Sourcing responsible seafood

Understanding the provenance of seafood is becoming more and more important, partly because consumers are becoming more health and environmentally conscious, but also because supply chain practices are coming under increasing public scrutiny.[186] Products that adhere to sustainability and labor best practices (and that have the labels to prove it) command a premium in some markets and in some major retail

176 https://www.provenance.org
177 https://consensys.net/
178 https://www.traseable.com/tag/fisheries/
179 https://www.wwf.org.nz/what_we_do/marine/blockchain_tuna_project/
180 https://www.globenewswire.com/news-release/2020/07/12/2060937/0/en/Release-Is-Transforming-The-World-s-Agriculture-Fisheries-Logistics-Through-Its-Blockchain-Powered-Social-Commerce-Platform.html
181 https://traceability-dialogue.org/
182 https://www.salttraceability.org/
183 https://www.indiegogo.com/projects/trufish#/
184 https://www.verifik8.com/
185 http://www.backtrackerinc.com/
186 https://www.fisheries.noaa.gov/international/international-affairs/forced-labor-and-seafood-supply-chain

chains are a prerequisite for inclusion on stocking lists. In 2017 more than 60 of the largest players in the tuna industry pledged to source tuna only from socially and environmentally responsible producers by signing the Tuna 2020 Traceability Declaration,[187] which included the requirement for all product to be traceable to the individual vessel level by 2020. Companies and suppliers are gaining more access to the information needed to make responsible sourcing decisions. As one example of this, FisheryProgress[188] is a platform that encourages consistency in Fishery Improvement Project (FIP) reporting and increases users' confidence in information on the success of FIPs worldwide.

Efforts to increase public awareness of environmental and supply chain issues are increasing. Ecolabels such as MSC certification or OceanWise[189] labels provide assurance to buyers that the seafood they are purchasing has been deemed sustainable by experts in the field. Other labels such as Seafood Safe[190] assure consumers that their seafood is considered low risk for mercury and other environmental contaminants. NOAA runs the FishWatch database,[191] which provides information to consumers on the sustainability of more than 50 fish stocks commonly consumed in the United States. Other efforts include organizing small-scale producers to create public awareness of seafood supply issues — the Local Catch network[192] shows that an engaged community of practice made up of fishermen, chefs and other supply chain actors can be a powerful tool to drive sustainability and increase benefits to local small-scale fishermen. The technology is effective yet not complex, consisting of a website that houses educational resources and includes a Seafood Finder map which connects buyers with sellers, among other resources.[193] Another example is Oyster Common, an AI-powered marketplace for local seafood that enables fishermen and fish farmers to connect with restaurants and customers through a virtual fishmonger.[194]

3.5.3 Tracking small-scale seafood

One of the main concerns with ecolabels such as MSC are that the requirements for certification are often difficult to meet, especially in small-scale fisheries in developing countries. This might be because the institutional capacity that enables sustainable fisheries management is lacking or the economics of small-scale fisheries is such that monitoring costs outweigh the value of the fishery. Inexpensive small-scale trackers such as Pelagic Data Systems VTS,[195] Zunibal's vessel tracer,[196] can help to start legitimizing small-scale fishers. However, for many small-scale fisheries even an inexpensive tracker is out of reach. In these cases, smartphones are often the only possible option for helping to track seafood (Leape et al. 2020). Some apps such as Abalobi[197] are specifically designed with small-scale fishers in mind. Abalobi's traceability capability is implemented entirely through their smartphone app and an online platform and can effectively trace seafood from landing site to final consumer. A consumer-facing QR code which contains a link to more information on the products they are buying can be generated, helping to educate consumers and differentiate products. There is a key tradeoff between encouraging integration of small-scale fishers into international supply chains which can bring economic growth, and domestic markets that may improve food security and wellbeing. This tradeoff must be explicitly addressed when designing interventions such as a FIP.

In small-scale fisheries where enforcement is limited, fishermen must be incentivized to collect information that can be used for fisheries management and traceability. This is where FishCoin[198] comes in, effectively creating a mechanism that allows the sellers and the buyers of the seafood to negotiate the value of, and pay for, the catch and traceability data. FishCoin utility tokens that power the blockchain are bought on the application, transferred for the data through a supply chain and then destroyed when they are redeemed for rewards such as a mobile data top up. While this system does not verify data accuracy, it helps to build trust as there is little point in a buyer paying for inaccurate data and creating an immutable record whereby mass balance and other forms of triangulation can be used to check the veracity of the data. FishCoin is an open source blockchain based ecosystem that shares the commissions from the transfers between stakeholders with the developers who build applications around the protocol. Further, mechanisms are also in place to make the fishers and farmers shareholders in the business of traceability, generating them income in the future as well as tax revenues for the government for fisheries research, monitoring, compliance and surveillance.

3.6 Data integration and management

Improvements in our ability to analyze data, by integrating data of multiple types and from various sources and by making sense of large, previously intractable data sets, provides a huge opportunity to increase our understanding of marine ecosystems and improve the way we manage it. Shifting the data collection paradigm in fisheries towards electronic-based reporting is perhaps the most important step towards facilitating the application of new advances in data science and knowledge creation. While paper forms are

[187] https://www.weforum.org/agenda/2017/06/tuna-2020-traceability-declaration-stopping-illegal-tuna-from-coming-to-market/
[188] https://fisheryprogress.org/
[189] https://seafood.ocean.org/
[190] https://www.ecofish.com/products/seafoodsafe.htm
[191] https://www.fishwatch.gov/
[192] https://localcatch.org/
[193] https://finder.localcatch.org/
[194] https://oystercommon.com/
[195] https://www.pelagicdata.com/solutions/hardware
[196] https://zunibal.com/en/product/vessel-tracer-solar-ivms/
[197] http://abalobi.info/
[198] https://fishcoin.co/

gradually being phased out in developed fisheries, they are still the norm. In addition, vast quantities of fisheries data exist in various paper or digital archives (data 'silos') and are not used as an input into management or anything else. Moreover, a key data gap in fisheries all over the world is the lack of long term data series describing the status of the resource or the activities of the fishing fleet. Converting paper-based data into electronic records efficiently would enable the construction of time-series of catch, effort and length compositions to drive improved stock assessments and better fishery statistics.

There is also a great need to create improved data management systems capable of updating data rapidly, facilitating easy visualization of the data and displaying fishery performance indicator values relative to target and limit values for management. Providing fishery managers with insights from their data — instead of just the data — can help to close the gap to science based fishery management, especially in contexts where institutional capacity to derive those insights is limited.

Standardized data entry and management systems that streamline entry, quality assurance and visualization of the data for real-time status assessments is the golden ticket for adaptive science-based management of fisheries, which is increasingly important given the unprecedented impacts of climate change on fish (Burden & Battista, 2020). Developing a standard protocol that identifies parameters to measure, units and frequency will enable a data management system to be more efficient. Cloud-based systems allow for continual entry by multiple users and a virtual back-up of data, in addition to access to high powered statistical and analysis tools and it is clear that the cloud is the backbone of future — and many current — data management systems.

There has been an explosion in the amount and different types of ocean data collected in the last decade. And while the collection of particular data streams is generally motivated by one party, these different streams have huge potential value for many different parties. This value has not been realized in most cases, but there are signs that the digital ocean ecosystem is waking up. There are many examples of this emerging paradigm, including Sinay[199] who apply machine learning techniques to large amounts of diverse ocean data to make environmental improvements. The company uses data from over 6000 sources to prevent environmental harm and improve companies' operational efficiency. Shipping companies are also starting to realize value from better weather forecasts generated by complex algorithms based on multiple sources of data, and aquaculture farm operators benefit from better prediction models that give advance warning of sea lice infestations by synthesizing multiple types of data. Scientists have already built robust integration networks such as NeXOS,[200] available as an open source software developed by 21 partners from the government, public, private and scientific communities, which allows both real time data transmission and real time data analysis. Gybe[201] has created algorithms that combine real time data from its sensors with remote sensing imagery to adaptively improve water stewardship remotely.

For fisheries, better integration and use of multiple types of data will usher in new paradigms in both the way we manage fisheries and the ways we catch fish. While fishermen at sea have historically lacked access to oceanographic, market and other real time data that could inform their choices about where and how to fish, this is changing. And while managers generally lack the data streams as well as the decision support tools they need to make similar improvements in dynamic management, the new digital ocean ecosystem and improvements in data networks will generate a step change in how fishery managers design and implement regulations. One example of this is the Parties to the Nauru Agreement's (PNA) Fisheries Information Management System (iFIMS), which integrates multiple layers of data including license and registration, catch and activity information to allow PNA managers to track vessel activities in close to real time (Bradley et al., 2019).

3.6.1 Improving fishing operations

The integration of advanced data management systems into fisheries management is still rare (Leape et al. 2020), but this is changing. Some parties have proposed a wholesale change in the way data are managed in the fisheries space. For example, Bradley et al. (2019) propose a new model for data management that empowers fishermen and managers to collect, access and benefit from shared fisheries data. The Cape Cod Commercial Fishermen's Alliance has set a goal of changing the existing narrative around data use and designing a system that empowers fishermen to access and utilize their data to improve business decisions while also allowing scientists to access the data they need to support science based management decisions.[202]

Ecocast[203] is an online platform that uses near real time information on oceanographic variables integrated with historical catches of target and bycatch species to assign probabilities of catching different species to different areas. In a similar vein, TurtleWatch[204] is a map providing up-to-date information about the thermal habitat of loggerhead sea turtles in the Pacific Ocean north of the Hawaiian Islands. DOLFIN[205] is a business intelligence platform developed by Woods Hole Group which integrates company specific logbook and VMS data with oceanographic data. Machine learning is used to identify the most interesting correlations and these relationships are then provided as input into fishermen's decisions on where and when to fish. Higher catch rates and fuel savings from reduced search time are key benefits. In Japan, JAMSTEC[206] has developed a fishery forecasting system for the squid fishery in Aomori Prefecture, with the idea that furnishing information to fishermen on the probable location

199 https://sinay.ai/en/
200 http://www.nexosproject.eu
201 https://www.gybe.eco
202 https://em4.fish/wp-content/uploads/2020/02/2019-Digital-Public-Report-1-Fisherman-First-Data-Ecosystem.pdf
203 https://coastwatch.pfeg.noaa.gov/ecocast/
204 https://www.fisheries.noaa.gov/resource/map/turtlewatch
205 https://fisheries.groupcls.com/fishermen/fisheries-intelligence/
206 https://www.jamstec.go.jp/teams/e/kichiji/index.html

of squid on the fishing grounds can reduce fuel consumption (Leape et al. 2020). This project is so successful that it has since been transferred to private hands. A long standing company, SeaState Inc.,[207] provides quota tracking services to many fishermen in the Bering Sea pollock fishery and the west coast whiting fishery. The company maps catch and bycatch data provided by each vessel in the fleet and helps the fleet to decide where to fish in order to minimize bycatch.

Large fishing companies are also starting to grasp the value that data tools can offer to their business operations. For example, Aker BioMarine[208] uses machine learning to help predict where krill biomass is likely to be by analyzing multiple streams of data, from weather conditions and oceanographic information from satellites, to actual fish catches, and helps to eliminate a significant amount of search time. The company is also using these data to optimize factory and vessel operations, using data from onboard sensors to optimize fuel efficiency.[209] UAVs are also becoming increasingly accessible to fishers to maximize their search efficiency. For instance, the Tunadrone,[210] is a fixed wing drone that can be launched and retrieved from vessels at sea and used to detect tuna schools. TASA,[211] the largest fishing company in Peru has ordered one of Kongsberg Maritime's Sounder USV,[212] equipped with a wideband acoustic echosounder, with the goal of using it to help in searching for anchoveta aggregations and optimizing fishing operations among the company's 48 fishing vessels.

The SailBuoy in action

Photo by Aker


Tunadrone in action

Photo by Tunadrone

3.6.2 Deriving new value from an ocean data ecosystem

While new technologies are improving fishing operations, enabling dynamic ocean management, improving the link between consumers and fishermen and efficiently creating value through existing mechanisms, most of the value to fishermen that will be generated in the next 50 years will be through mechanisms that are not yet well established. The first steps towards this vision are being taken through efforts to increase sharing of ocean data. For example, a new Ocean Data Alliance brings together companies, scientists and environmentalists to create an open source platform[213] to facilitate the sharing of ocean data (WEF, 2017). In the United States, the NOAA Big Data Project (BDP), launched in 2015, aims to increase access and usability of NOAA's data resources and is essentially an experiment to determine what value can be realized from previously siloed data (Vance et al., 2019). The BDP is a collaboration between NOAA and five of the largest players in cloud computing, including AWS, Google and Microsoft. These important steps to emphasize wide sharing and utilization of data are forming the foundation for a new data paradigm.

[207] https://acct.seastateinc.com/
[208] https://www.akerbiomarine.com/
[209] https://www.seafoodsource.com/news/supply-trade/precision-fisheries-of-the-future-will-rely-on-data-and-ai-to-improve-profits
[210] https://www.marineinstruments.es/products/tunadrone/
[211] https://www.tasa.com.pe/acerca-de-tasa-acerca-de-tasa-en.html
[212] https://www.kongsberg.com/maritime/about-us/news-and-media/news-archive/2019/perus-largest-fishing-company-first-to-order-flexible-new-sounder-usv-from-kongsberg/
[213] https://www.oceandata.earth/

Climate change will continue to be a driving force for technological innovations in the ocean space. Early warning systems that alert fishery and ocean managers to potential crises are now feasible with better and cheaper sensors, real time connectivity and big data tools to identify trends (WEF, 2017). Climate change will drive our management of the ocean towards more adaptive, agile models such as dynamic fishery closures, and these changes will rely on a healthy data ecosystem. Sistema de Alerta, Prediccion, y Observacion (SAPO)[214] is a new initiative aimed at gaining better understanding of the impacts of a changing environment on the Humboldt current ecosystem. While data collection is a key part of this project, finding new ways to identify predictors of fishery change through new data tools is where the most impactful advances will be made.

As more and more ocean users compete for space, marine spatial planning and dynamic ocean management will become larger parts of the conversation. Marine aquaculture is coming under increasing scrutiny for environmental performance as operations multiply. These installations provide a natural source of demand for ocean information — to help with initial siting or effluent monitoring — but also provide a potential supply of information. Aquaculture infrastructure can easily be fitted with oceanographic and other sensors that can fit into the ocean data ecosystem. The future is clear — more types and amounts of data from more sources will be used in more ways to create value in ways that we mostly don't know about yet.

Photo by Tim Briggs/EDF

[214] http://blogs.edf.org/edfish/2020/10/06/in-south-americas-humboldt-current-this-collaboration-to-build-more-climate-resilient-fisheries-brings-together-two-great-fishing-nations/

Photo by Carlos Aguilera

4. Ocean Technologies Funding Environment

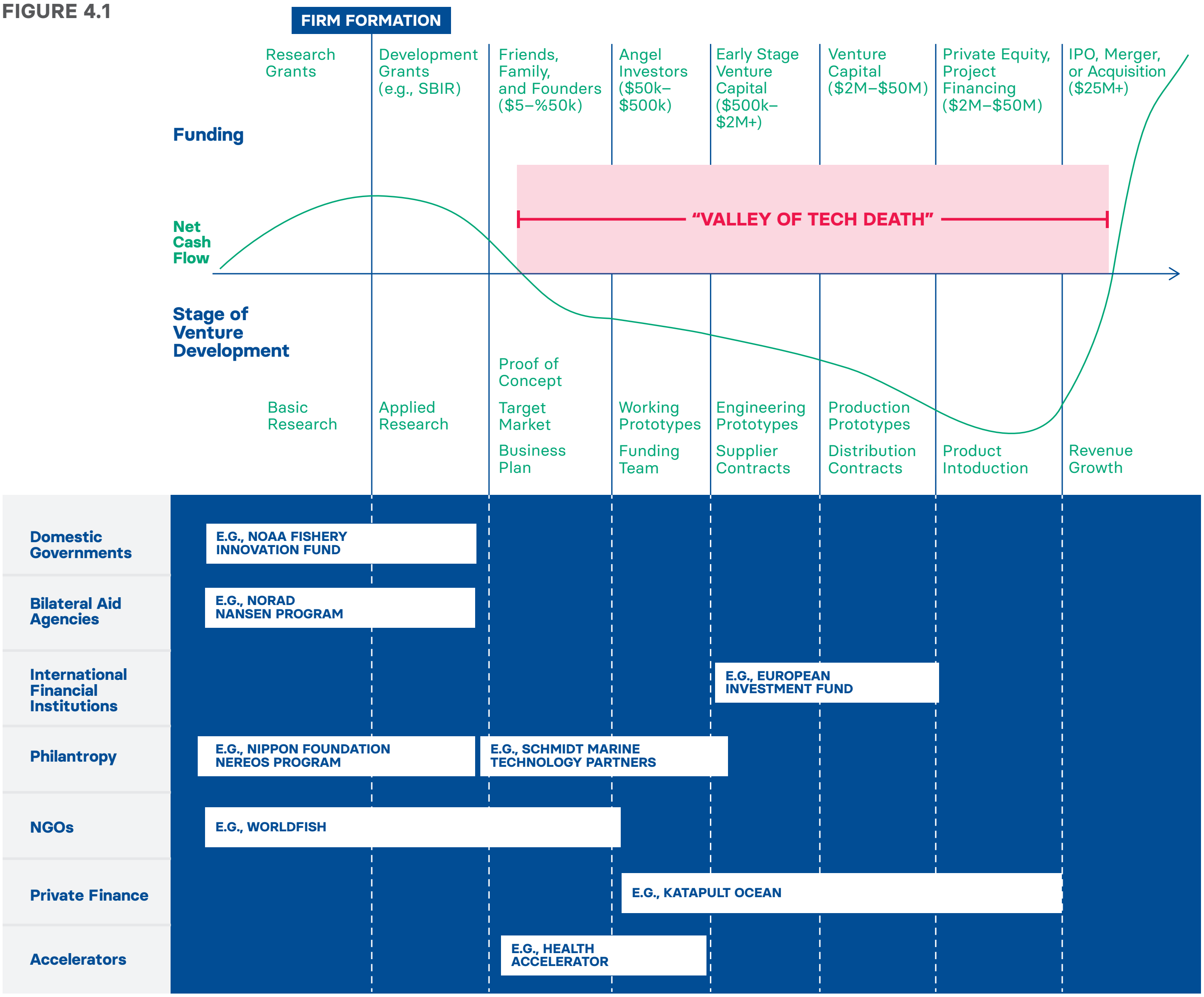
This section describes the current and future trends in the funding environment for fisheries and oceans technologies. A variety of organizations play a role in funding or financing fisheries and oceans technologies, and we have attempted to present the role of the organization *type* in general as well as the role that specific organizations play, and are likely to play, within this typology. Building on a review of the grey literature, we sent surveys to 71 practitioners from foundations, NGOs, investment funds, technology companies, research organizations, intergovernmental and multilateral institutions and technology accelerators on their impressions of and experiences with funding, or receiving funding for, fisheries and ocean technologies. We received 28 responses, a 39.4% response rate (table 4.1). After synthesizing this information we followed up with 15 expert respondents in the form of an interview. The findings outlined in this section are a high-level summary of our grey literature review, surveys, interviews and personal communications.

TABLE 4.1

Summary of survey and interview solicitations

		Responded to Survey		Interviewed	
Funder/Finance Category	**No. in Initial List**	**U.S. Based**	**Non-U.S.**	**U.S. Based**	**Non-U.S.**
NGOs	14	4	6	3	1
Investment funds	10	3	0	1	0
Foundations	17	7	0	1	0
Technology companies	15	3	2	1	1
Research organizations	4	2	0	1	0
Intergovernmental & multilateral institutions	2	0	0	1	0
Accelerators & others	10	1	0	4	1
TOTAL	**71**	**20**	**8**	**12**	**3**

FIGURE 4.1



Funding sources distributed by their financing niche along the graph depicting net cash flow from funding sources to private, for-profit companies. In the context of this report, this graph applies to emerging technology companies that are fishery or ocean focused. The original Valley of Death figure comes from the UC Davis Center for Entrepreneurship, and we have amended it with the blue box. (Source: greentechmedia)

4.1 Funding sources

Organizations playing roles in the funding landscape for fisheries and oceans technologies can be grouped into eight categories of financing and funding institutions. These are:

1. Domestic governments
2. Bilateral aid agencies
3. International financial institutions
4. Multilateral Institutions
5. Philanthropic organizations
6. Non-Governmental Organizations (NGOs)
7. Private financiers
8. Technology accelerators

In this document we refer to all organizations in these categories as *funders*. However, an important distinction between funding and financing is that funders generally do not seek a return on their investment while financiers do. Philanthropy, NGO funding and government grants are considered funding while investment from development banks, accelerators, and investment funds is considered financing. Furthermore, some organizations loan money to governments or other entities for projects related to fisheries technology but do not finance for-profit companies directly. For example, the World Bank might lend money to the government of India for a project to monitor demersal resources using remote sensing as a forecasting tool. The relevant government agency in India would likely then put out a request for proposals (RFP) to find a technology company to engage on the project. In this way, international financial institutions, bilateral aid agencies and other multilateral agencies indirectly provide funds that could be used to support technology companies at various stages of development.

Other funders support for-profit technology company development or research and development (R&D) directly. These include accelerators, philanthropic organizations, NGOs and private finance, with each category of funder tending to focus on companies at specific phases of development (figure 4.1), although there is variance within categories. And although most sources of funding for ocean technologies are interested in the end goal of promoting sustainable use of marine resources and preserving threatened ecosystems and communities, some groups of funders are inherently more focused on using technology to implement solutions while others are focused on policy- and education-focused projects. This section provides a summary of the areas of focus, models of engagement and core activities of organizations in each funding category.

4.1.1 Domestic governments

Domestic governments predominantly provide technology-focused funding through agency grants, which are a form of public non-return-seeking capital (De Vos et al., 2020). Federal governments often devolve grant-making responsibilities to specific government agencies which support specific economic sectors. For example, the Bureau of Fisheries and Aquatic Resources (BFAR)[215] in the Philippines is responsible for regulating the fisheries and aquaculture industries and is responsible for allocating government funding in the fisheries and oceans space. BFAR also works with other government agencies to secure international support for national fisheries programs. National fisheries agencies are commonly focused on stock assessments — abundance and productivity estimation, as well as data integration and accounting for fisheries catch and effort. Most government agencies restrict grant making to their nation, but some participate in projects that have global or regional implications. For example, the development of advanced fishery monitoring technologies through government grants in the United States often involve non-U.S. technology companies. Government agencies play a significant role in supporting socially and economically valuable projects that may not be immediately profitable and because government grants can lower the risk of investment, agencies commonly collaborate with the private sector to increase the scale of impact of their projects.

While government grants are the largest category of non-return seeking capital for ocean technology projects, the public funding available in the United States specifically for ocean and fisheries technology projects is relatively low compared to other areas. Current total annual expenditure on R&D in the United States is about $125 billion, with less than $2 billion of this allocated to ocean sciences (Leape et al. 2020) and, as a whole, federal funding for ocean technologies in the United States has been declining. There are, however, some notable sources of funding available which play key roles in the development of fisheries and oceans technologies. For example, the National Fish and Wildlife Foundation's Fisheries Innovation Fund,[216] which is a partnership between NOAA, Kingfisher Foundation and the Walton Family Foundation, supports projects related to fisheries innovation and electronic monitoring and reporting. Government funding tends to play a key role in early stage research and development of technologies and associated processes and this is also a common source of criticism — that developing a runway for future scaling, growth and implementation of these technologies is often lacking through government funds (OECD, 2019). Table 4.2 describes some notable government agencies active in the ocean technology space.

Photo by Jason Houston

[215] https://www.bfar.da.gov.ph/
[216] https://www.nfwf.org/programs/fisheries-innovation-fund

TABLE 4.2.

Some notable governmental agencies engaged in funding ocean technologies

National Oceanic and Atmospheric Administration (NOAA)	NOAA is responsible for all ocean and atmospheric federal funding initiatives, with the National Marine Fisheries Service (NMFS) the agency responsible for fisheries management and implementation of federal fisheries regulation.[217] • NOAA supports sustainable fisheries innovation through funds from the Saltonstall-Kennedy Grant Program (SK grants)[218] and research initiatives like the Bycatch Reduction Engineering Program (BREP).[219] • NOAA partners with the National Fish and Wildlife Foundation (NFWF)[220] to administer the Fisheries Innovation Fund, which includes the Electronic Monitoring and Reporting Grant Program.[221] The grant program serves as a platform for NOAA to actively partner with fishermen, state agencies, and other stakeholders to integrate technology into data collection and streamline data use and management. The program's goal is to *"improve quality, quantity, and timeliness of fisheries-dependent data"*.
European Fisheries Control Agency (EFCA)	EFCA[222] is a European Union (EU) agency involved in researching and developing technologies with fisheries management applications. • The EFCA works to develop information systems that will share data between EU member states. • EFCA's traceability technologies are aiding in efforts to enforce the EU's discard ban. • The agency helps to coordinate EU activities by creating systems for monitoring fisheries activities, provides training to member states. • EFCA also engages in international work through the Common Fisheries Policy, focusing mainly on fighting IUU fishing.
Ministry of Fisheries (New Zealand)	New Zealand's Ministry of Fisheries has a technologically advanced sustainable fisheries branch[223] and a new Fisheries Change Program (FCP).[224] • The FCP has three areas of focus: 1) introduce mandatory electronic catch and position reporting, 2) simplify and improve fishing policies and 3) improve monitoring and verification capabilities by using technologies such as on-board cameras. • The ministry's support of emerging technologies for fisheries has resulted in the enforcement of their quota management system through the use of electronic tools such as EM.
Australia Fisheries Monitoring Authority (AFMA)	AFMA[225] monitors and manages commercial fishing in Australian waters and also provide services to Australian fishermen. AFMA embraces the use of technologies for fishery monitoring and to help fishermen comply with regulations. Activities include: • Services for fishers: including providing logbooks and forms, their GoFish[226] quota and registration system, and other tools for quota management. • Fisheries management: including management booklet resources, information on methods and gear and other fishery- and species-specific management information. • Helping fishermen adhere to rules and regulations: including domestic as well as international fishery compliance. • Environmental research: includes science and research aimed at reducing bycatch, improving harvest strategies, designing ecological risk management strategies and improving protected species management.
Philippines Bureau of Fisheries and Aquatic Resources (BFAR)	BFAR is the government agency responsible for the development, improvement, management and conservation of the country's fisheries and aquatic resources. Responsibilities include: • Preparing and implementing a National Fisheries Industry Development Plan. • Issuing licenses for vessels and registering commercial fishermen. • Establishing and maintaining a comprehensive Fishery Information System.[227] • Providing advisory services and technical assistance to fishermen and industry. • Formulating rules and regulations for conservation and management of fish stocks.
Chile National Fisheries Agency (SERNAPESCA)	The National Fisheries Agency[228] in Chile is a public body functioning under the Ministerio de Economía, Fomento y Turismo. The purpose of this agency is to monitor compliance with fishing, aquaculture and environmental health regulations. • SERNAPESCA is responsible for executing national fisheries policy. • The agency plays an institutional capacity building role and are actively exploring the use of technologies for fisheries monitoring.

[217] https://www.fisheries.noaa.gov/
[218] https://www.fisheries.noaa.gov/grant/saltonstall-kennedy-grant-program
[219] https://www.fisheries.noaa.gov/national/bycatch/bycatch-reduction-engineering-program
[220] https://www.nfwf.org/
[221] https://www.nfwf.org/programs/fisheries-innovation-fund?activeTab=tab-3
[222] https://www.efca.europa.eu/en
[223] https://www.mpi.govt.nz/fishing-aquaculture/sustainable-fisheries/
[224] https://www.mpi.govt.nz/fishing-aquaculture/commercial-fishing/fisheries-change-programme/
[225] https://www.afma.gov.au/
[226] https://ebusiness.afma.gov.au/
[227] https://www.bfar.da.gov.ph/about_us.jsp?id=70
[228] http://www.sernapesca.cl/english

4.1.2 Bilateral aid agencies

Many countries allocate public funding to development assistance through national agencies, known as bilateral aid. Agencies act bilaterally when they predominantly have programs focused towards individual countries, although they may have a few multilateral (i.e., regional) programs as well. USAID[229] is an example of a bilateral aid agency, having several aid and development programs with specific countries, but they also administer multilateral programs, such as the Oceans and Fisheries Partnership (OFP).[230] Bilateral aid is often given through grants and generally focuses on big challenges such as improving air quality and the distribution of public goods such as education or infrastructure (De Vos et al., 2020). Bilateral development agencies, such as USAID and the Japan International Cooperation Agency (JICA)[231] are government agencies that coordinate development assistance for economic and social growth of developing countries and promote international cooperation. These agencies often have oceans programs that aim to support sustainable development of fisheries, including developing or testing marine technologies. Table 4.3 summarizes the activities of some notable bilateral aid agencies.

TABLE 4.3.

Some notable bilateral aid agencies

United States Agency for International Development (USAID)	USAID's Oceans program has taken a direct approach to supporting fisheries technologies through their Oceans and Fisheries Partnership (OFP)[232] and the Sustainable Ecosystems Advanced project (SEA).[233] • The OFP has dedicated US$25 million to date to strengthen electronic catch documentation and traceability (eCDT), promote sustainable fisheries and conserve marine biodiversity in the Asia-Pacific region. • The SEA project is a 5 year program from 2016-2021 that promotes the adoption of an electronic-based vessel registration system in Indonesia. • The strategy of USAID changes based on the priorities of the current administration. The strategy that underpinned the OFP is shifting toward a new Indo-Pacific Vision and Strategy[234] that is less focused on fisheries and more focused on democratic governance systems, trade, economic growth and security. • USAID will also be shifting focus under the New Partnerships Initiative (NPI)[235] to prioritize small start-up businesses receiving the benefits of federal funding, rather than large existing federal contractors. Within the NPI, the Small Business Applied Research (SBAR) program[236] was launched as a field-based initiative to expand USAID's access to emerging technology, products, services and scientific applications developed by U.S. small businesses.
Japan International Cooperation Agency (JICA)	JICA is responsible for administering development assistance to developing countries. • Fishery initiatives revolve around fishery resource management, aquaculture development and fishery value chain development. • Along with an interest in promoting Japan's advanced technology in the aquaculture sector, JICA's actions are focused on instituting management and policy-based sustainable fishery solutions.

Norwegian Agency for Development Cooperation (Norad)	Norad[237] is funded by the Norwegian government and functions under the Norwegian Ministry of Foreign Affairs.
	• Norad runs the Fish for Development program[238] which aims to reduce poverty through food security and sustainable management activities. The program is broken down into three components:
	  ◦ Research and development: which includes the Nansen program,[239] a bilateral program between Norway and FAO. The Nansen program employs research vessels to collect data on the state of oceans and fisheries around the world.
	  ◦ Business development: helping to develop sustainable and profitable businesses with a focus on the aquaculture industry.
	  ◦ Resource management and legislation.
	• Norad provides bilateral support to countries like Vietnam and Namibia for new regulatory frameworks and legislation, including those supporting the Convention on Biological Diversity.[240]
	• Norad supports the development of artisanal fisheries in South Africa and Namibia and have supported the International Fund for Agricultural Development in Mozambique.

4.1.3 International financial institutions

Multilateral development banks, regional development banks and bilateral development banks are all examples of financial bodies founded by multiple nations for the purpose of supporting economic growth and development (De Vos et al., 2020). Development banks tend to lend money to national governments rather than to the private sector through concessional loan facilities where they extend capital at below market interest rates in order to achieve development goals (De Vos et al., 2020). However, many of them also use grant making facilities to disburse non-return seeking capital. The World Bank is the largest example of an international financial institution and serves as a model for several regional development banks.

Development banks support projects that have a low chance

[229] https://www.usaid.gov/
[230] https://www.usaid.gov/asia-regional/fact-sheets/usaid-oceans-and-fisheries-partnership
[231] https://www.jica.go.jp/english/our_work/thematic_issues/fisheries/index.html
[232] https://www.usaid.gov/asia-regional/fact-sheets/usaid-oceans-and-fisheries-partnership
[233] https://www.sea-indonesia.org/
[234] https://www.usaid.gov/sites/default/files/documents/1861/Strategic-Approach-Indo-Pacific-Vision_Feb2020.pdf
[235] https://www.usaid.gov/npi
[236] https://www.usaid.gov/SBAR
[237] https://www.norad.no/en/front/
[238] https://www.norad.no/en/front/the-knowledge-bank/programmes-in-the-knowledge-bank/fish-for-development/
[239] http://www.fao.org/3/a-i6039e.pdf
[240] https://www.un.org/en/observances/biological-diversity-day/convention

of receiving funding from commercial investors. They tend to focus on broad economic sectors for investment and support numerous sub-projects that are diverse in approach but topically relevant. Development banks are a significant source of funding for ocean conservation as they recognize that, for many countries, marine resources are the base upon which their economies are built (World Bank and United Nations Department of Economic and Social Affairs, 2017). As development banks have become more engaged with the UN Sustainable Development Goals, they have also increased their interest in fisheries and aquaculture (especially through the lens of achieving SDG 14). However, while development banks invest heavily in the blue economy, they are considered risk averse in their investments and are therefore less likely to fund emerging technologies.

Another type of international financial institution, Development Finance Institutions (DFIs) have different capital structures to development banks and generally invest in companies in middle income countries at lower rates than commercial banks (De Vos et al., 2020). One of the arms of the World Bank is the International Finance Corporation (IFC),[241] which is a DFI. Table 4.4 summarizes the activities of some notable international financial institutions.

TABLE 4.4.

Some notable international finance institutions

World Bank — PROBLUE	The World Bank's active ocean portfolio is currently ~ US$5.6 billion.
	• The World Bank, and many of their partners, have adopted a Blue Economy approach[242] to oceans and implementing SDG14, which "supports economic growth, social inclusion and the preservation or improvement of livelihoods while at the same time ensuring the environmental sustainability of oceans and coastal areas." PROBLUE[243] was endorsed in February of 2019 and is an umbrella multi-donor trust fund housed at the World Bank that supports work in this area. PROBLUE has four pillars, two of which are most relevant to fisheries:
	  ◦ Fisheries and aquaculture: improving fisheries by tackling the underlying causes of overfishing and strengthening aquaculture sustainability.
	  ◦ Seascape management: building government capacity to manage marine resources, including nature-based solutions and mobilizing private sector finance.
	• Some examples of World Bank funded programs include:
	  ◦ The National Program for Innovation in Fisheries and Aquaculture[244] Project in Peru is one of several World Bank supported projects focused on supporting sustainable fisheries and developing knowledge on ocean health. A component of this project is to finance a competitive grant mechanism that funds innovative projects and gives between US$5-20 million annually.
	  ◦ In the Maldives, the Sustainable Fisheries Resources Development Project[245] aims to improve marine aquaculture and fisheries. The project works to enhance the government's ability to monitor the fisheries sector through the development of key fisheries management and planning instruments and other forms of capacity building.

Asian Development Bank	In 2019, the Asian Development Bank (ADB) launched its US$5 billion Healthy Oceans Plan[246] which will focus on sustainable fisheries among other areas. • The plan aims to attract more private sector investment in the blue economy by lowering the financial risk of investments through grants and support. • While the ADB does not play a direct role in investing in fisheries technologies, their institutional capacity building is important, helping to create an environment that is conducive to technology uptake.
European Investment Bank (EIB)	The EU Climate Bank,[247] a part of the EIB, has committed €2.5 billion to ocean projects (including fisheries) over the next 5 years with the intention of attracting €5 billion in public and private investment into the blue economy. The EIB will invest in the private sector and is focused on investments within the EU. • The Blue Sustainable Ocean Strategy (BlueSOS)[248] guides the distribution of a majority of ocean funding. • The EU Climate Bank is focused on supporting multiple project categories, including sustainable coastal development, sustainable seafood production, green shipping and biotechnology. • The EIB also created the Sustainable Blue Economy Finance Principles,[249] a guide for investors on the sustainable use of ocean resources. These principles were officially endorsed by the UN Environmental Program and serve as an example of how development banks can aid in institutional capacity building. Partners include the European Commission, WWF and the World Resources Institute. The European Investment Fund (EIF) is another branch of the EIB, which has partnered with the European Commission to launch the BlueInvest Fund.[250] • The aim of the EIF is to support small and medium sized businesses in Europe by increasing their access to finance. • The EIF consistently partner with other funders like venture capital funds, banks and microfinance institutions to create blended capital structures. • The fund serves as a method for the EU to foster innovation, research and development and entrepreneurship within Europe.

[241] https://www.ifc.org/wps/wcm/connect/corp_ext_content/ifc_external_corporate_site/home
[242] https://www.worldbank.org/en/topic/oceans-fisheries-and-coastal-economies#2
[243] https://www.worldbank.org/en/programs/problue
[244] https://projects.worldbank.org/en/projects-operations/project-detail/P155902
[245] https://projects.worldbank.org/en/projects-operations/project-detail/P157801
[246] https://www.adb.org/sites/default/files/am-content/484066/action-plan-flyer-20190430.pdf
[247] https://www.eib.org/en/about/priorities/climate-action/index.htm
[248] https://www.eib.org/attachments/thematic/eib_blue_sustainable_ocean_strategy_en.pdf
[249] https://ec.europa.eu/maritimeaffairs/befp_en
[250] https://ec.europa.eu/commission/presscorner/detail/en/IP_20_167

4.1.4 Multilateral Institutions

Multilateral institutions are funded and run by their member states and generally offer external non-return-seeking funding like grants, but also run internally funded programs that function as institutional sub-groups (De Vos et al., 2020). However, some multilateral institutions are exploring new ways of disbursing funds. For example, the Global Environment Facility (GEF) pioneered the Non-Grant Instrument Pilot Program,[251] which is the first of its kind for multilateral agencies. Under this program, GEF awarded the Meloy Fund (a profit-seeking impact fund) US$6.78 million in 2019.[252]

Member states make the decisions on what challenges they will prioritize and they are able to form collaborative projects in a committee-based structure. As a result of their ability to easily distribute pooled resources to various projects, a significant portion of funding for aid comes from multilateral agencies (De Vos et al., 2020). The focus of each institution is dependent on the priorities of their members, and some dedicate a significant amount of energy towards marine and fishery specific challenges. For example, institutions like the United Nations, Organisation for Economic Cooperation and Development (OECD), and various Regional Fisheries Management Organizations (RFMOs) are especially dedicated to marine conservation and promoting sustainable fisheries.

The UN is the largest example of a multilateral institution. The UN operates UN Oceans,[253] but also manages groups like FAO[254] and UNESCO.[255] Collectively, these groups are responsible for a large portion of the institutional funding for ocean technologies and support of the blue economy. These institutions are particularly interested in funding technology projects that aim to address IUU fishing and improve methods of ocean observation, although they are broadly driven to support projects that work towards achieving the UN Sustainable Development Goals.

TABLE 4.5.

Some notable multilateral agencies

The United Nations (UN), Food and Agriculture Organization (FAO), and the United Nations Educational, Scientific, and Cultural Organization (UNESCO)	Through the UN Oceans program, FAO, UNESCO, and SDG 14, the UN has a broad global impact on improving fisheries sustainability. • Many projects are technology-based, such as the use of satellite data for the Counter-Terrorism Committee Executive Directorate (CTED)[256] and the development of the Global Ocean Observing System (GOOS).[257] • FAO has been engaged with fisheries technologies and are contributing to efforts to develop vessel monitoring systems with catch documentation schemes as well as a global cloud-based collaboration platform to support fishery resource monitoring.
Organisation for Economic Cooperation and Development (OECD)	The OECD is an intergovernmental economic organization with 37 member countries. • The OECD does not financially contribute to the fisheries technology landscape in the same way as other multilateral institutions but the resources they publish, such as handbooks on making informed policy decisions[258] or their Biennial Review of Fisheries,[259] are quantitative resources useful for management and play a vital role in global fisheries institutional capacity building.

Global Environment Facility (GEF)	The GEF[260] is dedicated to addressing the largest environmental threats that the earth is currently facing. They provide funding through grants and also engage in co-financing of projects.
	• A key focus area is international waters,[261] where the GEF works to promote sustainable fishing practices and governance. This program has three parts: strengthening the national blue economy, improving management of waters outside of national jurisdiction and enhancing water security in fresh water.
	• The GEF funds the Global Sustainable Supply Chains for Marine Commodities Project (GMC Project),[262] which is a two part project that is highly focused on capacity building and run by the United Nations Development Program.
	  ◦ The first part of the project is the creation of multi-stakeholder dialogue spaces called Sustainable Marine Commodity Platforms that are used to formulate sustainable blue policies.
	  ◦ The second part of the project is to engage retailers and buyers in supporting sustainable fishery reform.

4.1.5 Philanthropic foundations

Philanthropic foundations have contributed an estimated US$8.7 billion to the fisheries and oceans landscape in the last ten years,[263] and philanthropic funding for marine conservation is increasingly coming from individual philanthropists. There are two predominant ways that foundations support projects: grants and blended finance instruments. Foundations that use the classic grant structure are typically less interested in projects directly related to new technologies and tend to be more involved in policy- and management-

[251] https://www.thegef.org/sites/default/files/council-meeting-documents/16_EN_GEF_C_47_06_GEF-6_Non-Grant_Instrument_Pilot_and_Updated_Policy_for_Non-Grant_Instruments_1.pdf
[252] https://www.thegef.org/news/innovative-finance-project-sustainable-fisheries-launched-leading-investors
[253] http://www.unoceans.org/
[254] http://www.fao.org/home/en
[255] http://www.unesco.org/
[256] https://www.un.org/sc/ctc/page/2/
[257] https://www.goosocean.org/
[258] https://www.oecd-ilibrary.org/agriculture-and-food/the-oecd-handbook-for-fisheries-managers_9789264191150-en
[259] https://www.oecd-ilibrary.org/agriculture-and-food/oecd-review-of-fisheries-policies-and-summary-statistics-2017_rev_fish_stat_en-2017-en
[260] https://www.thegef.org/
[261] https://www.thegef.org/topics/international-waters
[262] https://www.thegef.org/project/global-sustainable-supply-chains-marine-commodities
[263] https://fundingtheocean.org/funding-map/

focused solutions. Some foundations have set up an internal funding structure with a similar portfolio and investment strategy to a typical impact investing firm, with more of a focus on innovative and technology-focused projects. In these cases the foundation generally expects financial returns on their investment and sustainable growth from the company or product they have funded.

Foundations typically operate on five year cycles for prioritized programs and often adjust focus and priorities on this timeline. Several major foundations are currently focused on accounting for catch and effort and increasing supply chain transparency, and many of these projects are related to addressing IUU fishing and human rights violations. Our research exposed contradictory views on whether funding from foundations is increasing or decreasing in the fisheries technology sector. While some survey respondents feel that foundations have maintained a consistent interest in fisheries and oceans technologies, others cite foundations' competing priorities and changing preferences as possible reasons for inconsistent funding and limited interest in technology-based ocean solutions. The COVID-19 pandemic is also likely to reshape funding priorities.

TABLE 4.6

Some notable philanthropic foundations

Gordon & Betty Moore Foundation	The Moore Foundation has given US$320 million in grants since 2004 to ocean initiatives, most of which have been dedicated to the improvement of fisheries management systems. Their Oceans and Seafood Markets Initiative (OSMI)[264] supports the development and implementation of technological solutions for transparency and accountability in fisheries located in the United States and Canada. • In 2016, Moore announced the dedication of US$90 million to OSMI and two other initiatives working to decouple food production from negative environmental impacts. • The core goals of the initiative include adjusting system conditions, creating an education continuum and recruiting & engaging industry players. • OSMI is made up of 4 partners: FishWise,[265] Future of Fish,[266] the Institute of Food Technologists' Global Food Traceability Center[267] and WWF. • Each of the participating organizations have collaborated to create in-depth seafood traceability resources, with some more focused on technology. For example, the Seafood Industry Traceability Toolkit[268] by Future of Fish includes 12 tools and resources that help companies move towards improved supply chain traceability.
The David and Lucile Packard Foundation	The Packard Foundation has dedicated US$1.6 billion to date on researching and promoting ocean health. One global strategy is fighting illegal fishing, which is done through their work with Oceans5 (see below). Another strategy is centered on global seafood markets,[269] which aims to strengthen global market demand for sustainable seafood and reduce the trade of IUU seafood. • The global seafood markets strategy includes three strategic initiatives related to supporting sustainable seafood sourcing in the United States and Japan, creating sustainability programs to increase market access for some fisheries and promoting environmentally responsible fishery and aquaculture improvements. • The Packard Foundation also helps to promote increased supply chain transparency at every level, from supporting public retail sustainability commitments to developing a web-based project progress platform for public consumption. These initiatives rely on the development and adoption of full-chain seafood traceability technologies.
Walton Family Foundation (WFF)	WFF dedicated US$250 million to ocean conservation between 2016-2020. • Their Oceans Initiative[270] aimed to end overfishing and improve ocean health and coastal livelihoods in five countries: Indonesia, Peru, Chile, Mexico, and the United States. • Their Markets Strategy[271] aimed for all of these countries to have systems in place for traceability and have eliminated IUU fishing with the help of emerging technologies. • In early 2021 WFF announced a new 2025 strategy[272] with key environment-focused initiatives focused on driving innovation to solve environmental challenges as well as using markets to advance sustainability.
Oak Foundation	The Oak Foundation[273] dedicated US$100 million between 2016 and 2020 to support ocean conservation projects. Their initiatives include both Small-Scale Fisheries and Industrial Fisheries programs. • The Small-Scale Fisheries (SSF) program is focused on improving fisheries governance and increasing SSF visibility. The program supports local organizations that are working to raise the visibility of SSFs on the global development agenda and ensuring that governance reform for small-scale fisheries is adequately funded. • The Industrial Fisheries program works to reduce illegal fishing through better documentation. While technology interventions are not explicitly stated in a goal, they are valuable components in the success of the initiative's work on strengthening international fishing regulation and policy.

264 http://futureoffish.org/sites/default/files/docs/resources/OSMI-traceability-collab-one-pager_1.pdf
265 https://fishwise.org/
266 http://futureoffish.org/
267 https://www.ift.org/gftc.aspx
268 http://futureoffish.org/resources/grids/seafood-industry-traceability-toolkit
269 https://www.packard.org/wp-content/uploads/2017/02/Global-Seafood-Markets-Strategy-2017-2022-EXTERNAL.pdf
270 https://www.waltonfamilyfoundation.org/our-work/environment/oceans
271 https://www.waltonfamilyfoundation.org/about-us/newsroom/walton-family-foundation-outlines-seafood-markets-strategy
272 https://www.waltonfamilyfoundation.org/strategy2025#environment
273 https://oakfnd.org/

Bloomberg Philanthropies	Bloomberg Philanthropies[274] has dedicated US$139 million since 2014 to run their Vibrant Oceans Initiative.[275] • The initiative includes work in 10 countries. • Bloomberg Philanthropies have been very involved in the Global Fishing Watch platform and together are working on a large marine data project to aid in identification of fishery challenges.[276]
Oceans5	Oceans5[277] is "an international funders' collaborative" made up of philanthropists working to protect the world's oceans. Oceans5 prefer investing in time-bound projects and are focused on projects that either work towards ending overfishing or establishing marine reserves. Oceans5 is currently working on 13 projects related to fisheries technology, with a particular interest in the applications of remote sensing and electronic monitoring. • In Indonesia, Oceans5 is supporting the Kemitraan Partnership[278] to secure a new transparent monitoring program that will operate on about 4,000 commercial Indonesian fishing vessels. • One of the global projects of Oceans5 is to help the Stimson Center,[279] a think tank in Washington D.C., evaluate distant water fishing fleets. This project is more focused on institutional capacity building by providing a better understanding on how these fleets impact political discourse and local communities. • In Honduras and Belize, Oceans5 is active in a partnership with these countries' governments that aims to improve fisheries data collection and marine surveillance on the national level. In order to accomplish this goal, the project will implement electronic licensing, vessel tracking and catch documentation systems.
Waitt Foundation	The Waitt Foundation[280] acts as a partner for governments to help them institute sustainable ocean plans. • As well as offering support through partnerships, the foundation offers grants and technical assistance and organizes scientific expeditions. • Most of the Waitt Foundation's work is centered around marine protected areas and policy/management solutions. • Waitt administers the Rapid Ocean Conservation Grants Program[281] that provides small grants to projects working on solutions to emerging conservation issues.
Oceankind	Oceankind's mission is to: *"improve the health of global ocean ecosystems while supporting the livelihoods of people who rely on them."*[282] Oceankind's areas of focus include: fishing, climate change, habitat loss and pollution, which they believe are the most significant issues facing the world's oceans. Oceankind pursue two general approaches to addressing these challenges: Oceankind Conservation and Oceankind Innovation. • The Oceankind Conservation initiative focuses on supporting leading non-profit organizations working on marine conservation. This initiative invests in exceptional leaders and strives to scale conservation technologies by working in the policy space, among other activities. • The Oceankind Innovation initiative aims to advance promising marine conservation technology, supporting scientific and technological advances that have significant scaling potential and direct applicability to marine conservation problems.
Kingfisher Foundation	Kingfisher[283] aims to *"restore and preserve the health and resilience of marine fish populations through the reduction or elimination of illegal, destructive and economically unviable fishing practices"*. • Kingfisher offers innovative financing, risk management and policy incentives intended to support solutions that are higher risk and offer high levels of long term reward. As such, one of their core investment principles is to tolerate risk. • A core focus area includes developing sustainable models for fisheries management. • Kingfisher is a key supporter of NFWF's Electronic Monitoring and Reporting Program.


Photo by Jason Houston

[274] https://www.bloomberg.org/
[275] https://www.bloomberg.org/program/environment/vibrant-oceans/#overview
[276] https://www.bloomberg.org/press/data-on-global-fishing-activity-and-ocean-ecosystems-now-available-on-bloomberg-terminal/
[277] https://www.oceans5.org/
[278] https://www.linkedin.com/company/kemitraanpartnership/
[279] https://www.stimson.org/
[280] https://www.waittfoundation.org/
[281] https://www.waittfoundation.org/roc-grants
[282] https://oceankind.org/
[283] http://www.kingfisherfoundation.org/

4.1.6 Non-governmental organizations

Non-governmental organizations (NGOs) provide funding through grants, programs and partnerships. However, NGOs also rely heavily on grants, private donations and government funding themselves to operate. Many funders support NGOs for specific projects of interest in fields often related to technological development or political change, acting as partners by providing funding and access to experts. Although some NGOs are able to provide small grants, there is often more energy put towards internal research, innovation and product development (De Vos et al., 2020).

As a funder group, NGOs play an important role in technology-based projects, currently working on and interested in funding projects related to accounting for catch and effort, small-scale fisheries monitoring and increasing the transparency of the supply chain. Many of these projects are related to electronic monitoring and reporting and detecting IUU fishing. As a group, NGOs also tend to have high levels of interest in AI, robotics, satellite data and improved data management systems and have important roles to play in bridging the science-policy divide (Leape et al. 2020). Many NGOs are starting to prioritize human well-being, including food security and nutrition, as primary motivations for fisheries conservation (Levine et al., 2020).

TABLE 4.7.

Some notable NGOs

Environmental Defense Fund (EDF)	EDF[284] empowers fishing communities around the world to improve their own livelihoods while caring for the ocean. EDF also develops and seeds innovative technologies into the marketplace. EDF is focused on achieving sustainable and climate resilient fisheries covering more than 60% of global catch, to improve ocean health and sustain food and job, including for 500 million people whose well-being will be increased through better food security and improved livelihoods. Within the Oceans program, EDF's Ocean Technology Solutions (OTS) team is working on fisheries technology projects through its Smart Boat Initiative[285] and other efforts that aim to accelerate the exploration and adoption of new technologies to improve global sustainability in the fishing sector. EDF's work in oceans technology has resulted in the adoption of fisheries technologies in a range of countries, including Sweden, Chile, Peru, Indonesia, Philippines, Japan and the United States. Some examples of EDF's technology-based work include: • In the United States EDF is working with fishermen in the west coast groundfish trawl fishery to improve the experimental EM program through the application of machine learning tools and wireless transmission technologies. • The SmartPass project in the United States and Indonesia (Haukebo et al., 2021) is aimed at improving small-scale and recreational fisheries monitoring by leveraging AI algorithms and digital cameras to automatically generate data on fishing vessel activity. • In Sweden, fishermen collaborated with government officials and EDF to develop and adopt FishRight,[286] an online platform that allows fishermen to trade quotas in real time. FishRight reduces bycatch and helps Sweden comply with the EU's new discard ban. • In Chile, Ecuador and Peru EDF and partners are working to create an 'early warning system' for climate driven impacts to the Humboldt current ecosystem by integrating multiple data types and applying big data tools. • EDF is working with the Alaska Fisheries Science Center's Fisheries Innovation project[287] to develop computer vision technology to automatically count and identify groundfish species on trawl vessels.
Oceana	Oceana[288] advocates for science-based fisheries management and has worked very closely with Global Fishing Watch. • Oceana's initiatives include a focus on responsible fishing and their Save the Oceans, Feed the World campaign.[289] They also administer the Seafood Fraud initiative[290] which uses DNA testing for fish identification. • Their support focuses mainly on institutional capacity building through campaigning, litigation and conducting research. For example, in 2019 Oceana filed a lawsuit against NMFS for its failure to prevent the overfishing of anchovies off of the west coast of the United States.
The Nature Conservancy (TNC)	The Nature Conservancy works on marine conservation and fisheries sustainability globally and partners with fisheries managers and other stakeholders to develop new technologies and to increase the demand for sustainably sourced seafood. • TNC collaborate with the Conservation Alliance for Seafood Solutions[291] on FIPs in the Western Central Pacific Ocean (WCPO) longline tuna fisheries. Through these FIPs they are identifying ways to reduce bycatch and are pioneering new technology and data analytic solutions to collect data on fishery health, fleet compliance and to improve traceability. TNC are deploying EM systems for longline vessels as part of these efforts. • TNC also run an accelerator program in partnership with Techstars,[292] called the Techstars Sustainability Accelerator,[293] which supports a diversity of sustainability-minded startups and includes blue-tech members like Bext360[294] and Gybe.[295]

284 https://www.edf.org/
285 https://www.edf.org/oceans/smart-boats
286 https://www.edfeurope.org/swedish-fisheries
287 https://www.fisheries.noaa.gov/feature-story/developing-machine-vision-collect-more-timely-fisheries-data
288 https://oceana.org/
289 https://oceana.org/feedtheworld
290 https://oceana.org/our-campaigns/seafood_fraud/campaign
291 https://solutionsforseafood.org/collaborators/the-nature-conservancy/
292 https://www.techstars.com/
293 https://www.techstars.com/accelerators/sustainability
294 https://www.bext360.com/
295 https://www.gybe.eco/

World Wildlife Fund (WWF)	WWF[296] is deeply invested in ocean-focused projects and have historically been dedicated to implementing marine protected areas and developing policy-based solutions to the world's fishery challenges. • More recently, WWF has been engaged in technology-focused initiatives including starting the Smart Fishing Initiative[297] and co-founding OpenSC.[298] • The Smart Fishing Initiative has made progress in topics like tuna management, banning driftnets, and increasing MSC certification in countries like Russia. They are also dedicated to ending IUU fishing in the EU and the United States through their involvement in government task forces and coalitions. • WWF's 2020 fisheries goals include improving global food security, improving the management and sustainable trade of certain fish species such as tuna and whitefish and improving the livelihoods of fishery-dependent communities.
Conservation International (CI)	Conservation International's[299] involvement in ocean conservation spans three areas: Blue Nature, Blue Production, and Blue Climate. • CI works on tools, partnerships and programs for place-based integrated ocean management, sustainable fisheries and aquaculture, mitigating carbon emissions through blue carbon and increasing adaptive capacity of communities to climate change. • Their impact fund, Conservation International Ventures,[300] is not exclusively ocean-focused but has invested in fishery technologies like SafetyNet.[301]
WorldFish	WorldFish[302] is an international, non-profit research organization that aims to reduce poverty and hunger in developing countries through improved aquaculture and fisheries. • Their small-scale fisheries program[303] promotes capacity building by funding research and supporting policy initiatives for better fisheries governance. • Their aquaculture technology program[304] aims to increase resource efficiency and sustainability within the aquaculture sector. Technologies of interest include: fish breeding and genetics, disease detection and control, nutrition and feeds and enhanced production systems.

4.1.7 Private finance

This category of funders includes impact investment, venture capital and other private sources of funding which are return-seeking. Impact investment and venture capital are the two most prominent forms of private financing for sustainable and innovative ocean solutions and technologies. In contrast to foundations, impact investment funds are heavily focused on innovation and technology-based solutions. All investment funds expect some kind of return on their investment, although impact firms may be willing to receive lower rates of return in exchange for the social good that their portfolio companies are creating. Impact investment funds also tend to be more tolerant of longer investment horizons and higher risk company profiles than mainstream investors (De Vos et al., 2020). However, they are considered to be more conservative with their investments than foundations because their primary objective is to increase the size of their assets while making a positive impact. Venture capital firms are slowly joining impact investment funds by investing in the blue economy. Venture capitalists have a lower risk tolerance than impact investment funds and are generally unwilling to take a lower return in exchange for a higher positive impact, perhaps explaining why venture capital is not yet a common financier in this space.

Private capital in investment funds, including impact investment and venture capital funds, has been identified as a relatively untapped funding source (Fitzgerald et al., 2020). Many impact funds are generalists with few focused specifically on fisheries and aquaculture. However, many of these funds have an interest in marine technology companies as part of a blue economy focus. While the challenges of interest for this funder group are not clear, there are trends in the types of technologies that receive funding. For example, sensors and AI technology, as well as data sharing and compiling platforms, are recurring categories of investments. These trends are likely correlated to the risk profile and degree of market evidence for each technology type. Although the perception is that funding from investment funds has been increasing over time, survey respondents disagreed on their ability to access this capital. Some have noted that investment funds are increasingly interested in blue economy and marine technology focused companies, leading to more investments. Others feel that venture capital funding for fisheries related technologies is still very limited because fisheries are traditionally considered risky investments. The fishing industry itself is starting to contribute increasing amounts of funding, especially in ways where a direct return is probable. For example, industry is contributing increasing amounts of funding for FIPs, perhaps because markets that support FIPs are growing in the United States and Europe (Levine et al., 2020).

[296] https://www.worldwildlife.org/
[297] https://wwf.panda.org/discover/our_focus/oceans_practice/smart_fishing/
[298] https://opensc.org/
[299] https://www.conservation.org/
[300] https://www.conservation.org/projects/conservation-international-ventures-llc
[301] https://sntech.co.uk/
[302] https://www.worldfishcenter.org/
[303] https://www.worldfishcenter.org/content/worldfish-research-program-resilient-small-scale-fisheries
[304] https://www.worldfishcenter.org/content/aquaculture-technologies-and-best-management-practices-training-program-0

TABLE 4.8

Some notable investment funds

Althelia's Sustainable Ocean Fund (SOF)	The SOF[305] just finished its second round of funding and now has US$92 million to invest in areas such as sustainable seafood, the circular economy and ocean conservation. SOF supports technologies that improve supply chain efficiency. • The SOF has a unique blended strategy that takes a diversified approach to investing in both sustainable fisheries and the blue economy. • The fund was created in 2016 and portfolio companies are not yet public. • The fund's strategic partners are EDF and CI, which provide technical expertise and project oversight.
Conservation International (CI) Ventures	CI Ventures is an innovative finance mechanism that applies finance tools to support conservation. The predecessor to CI Ventures was Verde Ventures, which eventually became the eco.business Fund.[306] CI Ventures has completed eight deals to date, with US$2.7 million directly invested by CI and US$9.8 million in additional co-financing from partners. By 2028, their goal is to have made 100 deals, have 1.2 million acres managed globally, and support 60,000 livelihoods. • CI Ventures was set up as a philanthropically funded investment vehicle to offer opportunities for riskier investments or earlier stage companies in geographies and market segments that might not otherwise be accessible. The blue economy is one of their key areas of focus. • CI Ventures initially worked with strategy from the CI Center for Oceans[307] to find ideas for blue solutions such as sustainable seafood and marine pollution. • CI Ventures are most focused on global and regional issues, seafood companies and the supply chain in CI's priority geographies (e.g., Cuba, South Africa, Kenya, Peru). • Although CI's strategy revolves around supporting small-scale fisheries, CI Ventures is hesitant to invest in smallholder fishing cooperatives that supply fish to a limited local market as the scale of impact of this investment would be limited. They are interested in solutions that could be deployed to help small-scale fisheries at scale. • Fisheries and aquaculture technologies in their portfolio include SafetyNet Technologies and Jala.[308]
Schmidt Marine Technology Partners	The Schmidt Family Foundation[309] funds Schmidt Marine Technology Partners (SMTP)[310] to fill the investment gap left by other funds. They provide capital through grants. • SMTP focuses on sustaining fisheries and ocean research and has invested in technologies like Conservation X's DNA Barcode Scanner[311] and Pelagic Data Systems' vessel trackers, among many others. • SMTP also act as a valuable source of information for funders and entrepreneurs about emerging trends and companies.

Katapult Ocean	Katapult Ocean,[312] located in Oslo, Norway, recently closed their first investment fund at US$4 million, having invested in 24 ocean startups. They are currently raising a larger second fund with the intention of investing in another 40 blue-tech companies.
	• As a general ocean program, the technology-focused investments in their portfolio are not all related to fisheries.
	• Some relevant companies in their portfolio include Innomar[313] and Atlan Space.[314]
	• In addition to being an investment fund, Katapult Ocean also offers a 3-month accelerator program located in Oslo:
	  ◦ In exchange for 8% equity, all startups receive US$150,000. However, there is also a US$50-100 thousand dollar program entry fee (depending on the ticket size).
	  ◦ There are five sectors covered by the program: transportation, ocean health, harvesting, energy and new frontiers.

BlueInvest Fund	The BlueInvest Fund[315] was created by the European Commission in partnership with the European Investment Fund. Its goal is to finance underlying equity funds that support the blue economy. • BlueInvest is a new equity investment fund that was created in February 2020 and has a value of €75 million. • Because the fund is new, the portfolio is not public. However, investment topics of interest have been shared and include: fisheries and aquaculture, blue biotechnology, and wave and tidal energy. • The fund is also complemented by the European Commission's BlueInvest platform,[316] a resource center that allows for networking and promotes investment readiness for startups and early stage businesses.

4.1.8 Accelerators

Accelerator programs are often either funded and run by a series of sector-relevant partners or are a branch of an investment developer. For example, Katapult Ocean[317] is an investment firm that also runs an accelerator, while the Oceans X Labs accelerator[318] is run in partnership with an NGO (WWF) and a private technology company (Conservation X Labs).[319] Accelerator programs provide support for very early-stage companies that need funding and expertise to scale their business. They tend to have a highly-specific sector focus and

305 https://althelia.com/wp-content/uploads/2020/08/SOF-Impact-Report-2020.pdf
306 https://www.ecobusiness.fund/en/
307 https://www.conservation.org/about/center-for-oceans
308 https://jala.tech/
309 https://tsffoundation.org/
310 https://www.schmidtmarine.org/
311 https://conservationxlabs.com/dna-barcode-scanner
312 https://katapultocean.com/
313 https://www.innomar.no/
314 https://www.innomar.no/
315 https://ec.europa.eu/commission/presscorner/detail/en/IP_20_167
316 https://webgate.ec.europa.eu/maritimeforum/en/frontpage/1451
317 https://katapultocean.com/
318 https://www.worldwildlife.org/magazine/issues/spring-2017/articles/oceans-x-labs-kickstarting-conservation-tech-entrepreneurship
319 https://conservationxlabs.com/

many have a mission to focus on companies with a positive social or environmental impact. The accelerator investment model involves making relatively risky, early-stage investments in a product and typically comes in the form of cash and resources, often with equity changing hands in return. The non-financial support they provide during the accelerator program (e.g., access to a network of experts, financial and management training) is intended to lower the risk of their investment by preparing the companies for successful growth.

Accelerators are relatively new financing mechanisms for oceans and fisheries technology companies. They are almost exclusively interested in technology, allowing them to have a high degree of influence over emerging marine and fisheries-focused companies. Because being an ocean-focused company can make it more difficult for start-ups to get funding, some entrepreneurs are turning to accelerator programs as a way to lower their company's risk profile (Ritter & Cheung, 2019). Accelerators have been identified as a potential way to help ocean technologies scale, which has been the stage where most new ocean companies have difficulty obtaining funding (Leape et al. 2020).

Related resources that can increase the attractiveness of an investment are innovation hubs and networks that are designed to bring together a diverse group of actors including business, research institutions and government agencies to work on a range of innovations in a number of ocean sectors (OECD, 2019). For example, the Norwegian Centers of Expertise Maritime CleanTech cluster[320] supports the development of environmentally friendly technologies, and the Ocean Futures Innovation Hub in Victoria, B.C.[321] and the Center for Ocean Ventures and Entrepreneurship in Halifax, Nova Scotia allow marine companies to share resources, provide mentorship to smaller companies and act as growth incubators.[322]

TABLE 4.9

Some notable accelerators

Fish 2.0	Fish 2.0[323] is a well-established marine technology-focused accelerator competition that has been running since 2013. The program brings together key ocean investors and mentors, such as the Salmon Innovation Fund and Aqua-Spark and is focused on both aquaculture and fisheries topics including supply chain traceability and quality control and assurance. • Competition finalists include companies like Organic Ocean[324] which employs technology to offer sustainable seafood products to the consumer. • Many of the companies involved with Fish 2.0 are focused on aquaculture, as funders are increasingly looking towards funding technologies in that market. • Fish 2.0 also offers Fish 2.0 Connect,[325] a platform that sets up a network between funders and entrepreneurs.
OceansX Labs	OceansX Labs[326] is a joint project between WWF and Conservation X Labs. Their goal is to "solve global challenges of oceans conservation through the power of emergent technologies, open innovation, collaborative problem solving, and entrepreneurship." • OceansX labs have a solutions pipeline,[327] an open source hardware platform called the Digital Makerspace and an accelerator program. • The organization is focused on 10 Grand Challenges for Oceans Conservation,[328] including *"Transparency and Traceability from Sea to Shore: Ending Overfishing"*. • The companies in the accelerator are mainly focused on aquaculture — feed and medicine — and some are working on plant-based and lab-grown seafood.
Sustainable Ocean Alliance (SOA) Ocean Solutions Accelerator	In 2019, a US$1.5 million donation was given to SOA with the intention of boosting the accelerator program. The goal of the Ocean Solutions' accelerator is to create 100 companies by 2021 that are working to solve the ocean's biggest problems. • Each program lasts for 2 months and members have access to SOA's network of funders and mentors. • Fisheries members include Smart Catch,[329] EcoDrone[330] and ONET Global.[331]

4.2 Recent funding activities

Many practitioners in the space perceive that funding for fisheries technology projects is generally increasing, with a few exceptions. The technologies that have received the biggest increase in funding over the past few years include those focused on electronic monitoring and reporting, satellite-based communications, remote sensing, aquaculture monitoring and blockchain traceability. Here we discuss some of the major trends that were identified during the course of our research.

320 https://maritimecleantech.no/
321 https://southislandprosperity.ca/ocean-hub/
322 https://www.timescolonist.com/news/local/a-hub-for-ocean-innovation-pitched-for-victoria-1.24171925
323 https://www.fish20.org/
324 https://organicocean.com/
325 https://www.fish20.org/connect/about-connect-for-visitors
326 http://www.oceansxlabs.org/
327 http://www.oceansxlabs.org/what-is-oceans-x-labs
328 https://conservationxlabs.com/grand-challenges
329 https://www.crunchbase.com/organization/smartcatch#section-overview
330 https://oceansunmanned.org/eco-drone/
331 https://onetglobal.com/

4.2.1 Increasing amount & diversity of funding

There has been a noted increase in funding, especially from philanthropic sources. There is a widespread perception that ocean-focused philanthropic funders are increasingly interested in funding ocean technologies, which may be driven by individuals who have made money in the technology sector starting up philanthropies or family foundations. There are increasingly more diverse sources of funding available. Impact investors are broadly interested in the technology space and some, such as Aqua-spark[332] and Althelia (see table 4.8), are specifically looking to invest in technology in the seafood space. Some public sources of funding have also increased, such as the USAID Oceans and Fisheries Partnership which is testing electronic traceability technologies to combat IUU fishing in the Asia-Pacific Region.

As development banks have become more involved in advancing the Sustainable Development Goals (SDGs) for food security and livelihoods, they have been increasingly interested in fisheries and aquaculture. The World Bank's Blue Economy Program,[333] with an active portfolio of around US$5 billion, is one example of this as they support the sustainable use of ocean resources for economic growth, improved livelihoods and jobs and focus on fisheries sustainability and ocean ecosystem health. Following the World Bank's example, local and national governments are realizing the value of the blue economy and are providing resources to companies in this space. Although these resources are not always financial, government support lends legitimacy to the emerging companies working on adapting technology for fisheries which may facilitate additional funding. Over the past five years, there has been significant growth in blue economy initiatives and accelerators, such as AltaSea,[334] SeaAhead,[335] PNOC,[336] IOC,[337] and OceanHub Africa,[338] which often have a significant amount of government support. One expert interviewed has spoken with government officials in Indonesia and Ireland who have *"described their governments awakening to the importance of ocean conservation and business as a driving economic force."*

There is an increasing amount of private investment capital available for fisheries-related technologies, particularly in wealthier countries. This category of funding has tended to go mainly towards traceability technologies to help combat IUU, as well as big data initiatives. Similarly, there has been an increase in private investments and grant-making for innovative ideas supporting for-profit ventures or blue technology. As an illustration of this trend, Fish 2.0 (see table 4.9) pioneered an approach for matching start-ups and investors in the blue technology space that has since been increasingly scaled up and adopted by initiatives like BlueInvest,[339] which launched a 75 million equity investment fund for the Blue Economy in early 2020.

4.2.2 Recent trends by technology type

There has been an increase in funding for technologies focused on analyzing catch and effort, tracking vessel location and improving scientific data collection.

4.2.2.1 Electronic Monitoring & Reporting (EMR) technologies

EMR technologies have been widely supported in the R&D phase by governments, NGOs and foundations, but expectations are increasing that the fishing industry will start to pay technology costs going forward. However, there is very little private capital going into fishery applications of EMR technology, perhaps due to the risky funding environment. Technology accelerators and impact investment funds focused on ocean conservation, which are the primary vehicles for private investment in early stage technology start-ups, are a relatively new development which may explain this (Ritter & Cheung, 2019).

Practitioners observe that, in many contexts, industry seems increasingly willing to accept the technology but are more reluctant to pay for it. This is challenging, as governments generally do not want to subsidize industrial fisheries and in many EMR pilots, when monetary support runs out, the most common result is that the project ends. One exception has been on-board location sensor projects (e.g., Pelagic Data Systems)[340] which tend to be funded by government sources rather than philanthropic sources. This may be because of a relatively lower technology cost, combined with the direct and obvious utility of these technologies to fisheries managers for monitoring and enforcement.

In the United States, federal and regional funds have been made available for EMR, but this varies by region depending on congressional support. Funding seems to be more concentrated towards more advanced, automated monitoring techniques, such as on-board video monitoring. There are some grant opportunities available to support EMR development, including US$3.7 million in 2019 from the NFWF EMR Grant Program.

4.2.2.2 Satellite-based technologies

Satellite-based VMS and AIS trackers and remote sensing through electro-optical or SAR sensors are the most common satellite-based technologies used in fisheries. The growth in this area builds on ongoing government and private investments in satellite technology for defense, weather, communications, space research and other applications that are not specific to fisheries (see section 2.2 for more detail). Venture capitalists are increasingly interested in low-earth orbit (LEO) related companies, with the most interest in launch and miniature satellite startups (Besha & MacDonald, 2017). Adoption of low-cost technologies used in other industries can speed

[332] https://www.aqua-spark.nl/
[333] https://www.worldbank.org/en/topic/environment/brief/the-world-banks-blue-economy-program-and-problue-frequently-asked-questions
[334] https://altasea.org/
[335] https://sea-ahead.com/
[336] https://www.pnwoceancluster.com/
[337] http://www.sjavarklasinn.is/en/about/
[338] https://www.oceanhub.africa/
[339] https://blueinvest2020.converve.io/index.html
[340] https://www.pelagicdata.com/

development times, making this an attractive prospect for venture funding.

Reflecting investment that has led to development in this space, the cost of obtaining AIS data has decreased significantly over the past decade, in part due to increasing satellite coverage. Global Fishing Watch indicates that the cost of its license with a prominent satellite data provider decreased by 90% per volume of data between 2015 and 2019, due to increasing satellite coverage, lower satellite launch costs and increased competition between providers.

There are increasing amounts of aid funding available focused on combating IUU fishing and working with lower-income countries to track their fishing fleets. For example, a number of countries in West Africa manage their industrial vessels with inshore exclusion zones that are easy to monitor with VMS, so increasing VMS coverage is seen as a low-hanging fruit to address IUU fishing. World Bank loans to these countries for sustainable fisheries development projects often include VMS coverage targets. Foundations and NGOs are particularly interested in funding remote sensing technologies with applications in addressing illegal fishing. Oceans5 has incorporated technologies into its strategies for every region globally, while TNC is using VMS data to monitor fleet compliance with fishery regulations. Other practitioners have noticed an increase in private investment, from firms like SeaAhead[341] and Schmidt Marine Technology Partners (see table 4.8), in a combination of satellite-based systems, EMR and traceability to combat IUU in large-scale fisheries.

Remote sensing technologies can also be used by fishing fleets to help them to improve fishing operations, such as helping to find fish (Klemas, 2013). These efforts are more likely to be funded by industry and investment funds than other funder types. For example, funds like SeaAhead are investing in companies like ShipIn,[342] which provides real-time fleet monitoring services for commercial fleets. Satellite remote sensing is a useful tool for incorporating habitat considerations into marine fish population dynamics (Chassot et al., 2011), so may receive increased funding attention as more fishery managers work towards implementing an ecosystem approach to fisheries management.

4.2.2.3 Aquaculture technologies

As the aquaculture industry continues to grow there is increasing commercial interest in instrumentation and data for fish farming. The Ocean Finance Handbook (De Vos et al., 2020), identified aquaculture as an emerging blue economy sector, with marine aquaculture estimated to have the strongest growth. To meet projected aquaculture demand, it is estimated that an additional US$150-300 billion is needed in capital investment (de Vos et al., 2020). There are many technology startups in this domain, including InnovaSea,[343] eFishery[344] and Algaeba,[345] and more are entering the industry as a result of increased attention from funders. Aquaculture is projected to account for 62% of total seafood production by 2030 (WEF, 2017), and better technologies can improve the environmental and business performance of aquaculture operations through better siting, better pollution control and monitoring and better feed practices.

There has been growing investment in aquaculture farm management software, including several accelerators focused on this area (e.g., Hatch,[346] Katapult Oceans (see table 4.9), F3 Tech).[347] This has far outnumbered the amount of new companies focused on fishing vessel monitoring. A recent report found that over half of the fisheries startups included in the analysis were focused on aquaculture (Ritter & Cheung, 2019). Investment funds and accelerators are particularly interested in aquaculture technologies because they are considered to have lower risk profiles, more visible returns and are more likely to be quickly acquired by large corporations than other fisheries technology sectors.

4.2.2.4 Blockchain traceability technologies

Blockchain-enabled supply chain traceability platforms have exploded, with so many startups in the space that they are difficult to keep track of. Fishcoin,[348] which aims to incentivize small-scale fishers to collect and transmit management and supply chain data, is one notable example. In 2019, the National Fisheries Institute[349] and IBM's Food Trust[350] launched a pilot[351] to introduce blockchain technology to the seafood supply chain. This work is being funded by the Seafood Industry Research Fund (SIRF).[352] The Inter-American Development Bank[353] runs a Blue Tech Challenge[354] that provides grants to businesses working on sustainable technologies for the blue economy and has funded companies working on blockchain enhancement of seafood supply chains. Additionally, FAO has identified blockchain as a disruptive technology through an internal initiative that tracks technologies with the intention of encouraging their adoption. While blockchain technologies have gained enough traction to gain the attention of large stakeholders like development banks and multilaterals, many blockchain-based startups (e.g., Bext360)[355] are still emerging into the market with the support of accelerators like the Techstars Sustainability Accelerator (see table 4.7).

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[341] https://sea-ahead.com/
[342] https://www.shipin.ai/
[343] https://www.innovasea.com/
[344] https://unreasonablegroup.com/companies/efishery/
[345] http://www.algaeba.com/
[346] https://www.hatch.blue/
[347] https://f3tech.org/
[348] https://fishcoin.co/
[349] https://aboutseafood.com/
[350] https://www.ibm.com/blockchain/solutions/food-trust
[351] https://www.aboutseafood.com/press_release/nfi-and-ibm-launch-seafood-blockchain-pilot/
[352] https://sirfonline.org/
[353] https://www.iadb.org/en/about-us/overview
[354] https://www.iadb.org/en/idb-launches-blue-tech-challenge-us2m-funding-blue-economy-proposals
[355] https://www.bext360.com/

4.2.3 Exceptions to increasing trends

Although most practitioners surveyed indicate that funding opportunities are increasing, there are a few exceptions:

- Less attention has been focused on technologies for small-scale fisheries from private financiers. There are few companies servicing small-scale fisheries with new technologies for business purposes such as processing and harvesting, let alone fisheries management. This translates into limited opportunities for investment. If there were more demand for technology related products in the future, small-scale fisheries may represent a significant opportunity for innovations that could make small margins across a wide market.
- Changing priorities and budget restrictions have reduced some funding opportunities. For example, WWF's Smart Gear Competition,[356] which was financed by philanthropy and NOAA, was cut recently due to funding constraints.
- Some organizations have shifted away from funding technology projects towards funding projects that improve the human resources and data management systems that collect, analyze and use the data.
- Foundations are funding FIPs and some vessel monitoring work, but NGOs and foundations have become less likely to circulate RFPs for technology providers directly. This may be driven in part by uncertainty from the FIPs and foundations about exactly what they want or need from the technology, as well as a hesitancy to 'pick winners' in the technology space.
- Several philanthropic funding sources have shifted their oceans programs away from supporting MPA work toward plastic pollution,[357] climate change, advocacy and public policy issues. The number of startups focused on plastics reduction is rapidly increasing.
- Interest has grown in encouraging new innovative approaches via technology incubators, venture capital and social impact investment, but this may come at the cost of supporting or maintaining existing technologies. The relatively recent proliferation of accelerators in the ocean technology space may be on track to outpace the presence of high-quality companies to fill those accelerators. The Sustainable Ocean Alliance announced an ambitious goal[358] to take on forty ocean tech companies in their Ocean Solutions Accelerator[359] with founders under 35 years old in 2020. Later, they had to shift to take on for-profit or non-profit organizations with founders of any age, because there were not enough candidates to fill the open positions.

4.3 Future outlook

The weight of momentum in fisheries and oceans technology is particularly strong in the areas of supply chain transparency, data integration and management, institutional capacity building, improving local conditions for technology implementation and small-scale fisheries monitoring.

4.3.1 Transparency

Increasing the transparency of the fishing industry, from identifying illegal or unsustainable fishing practices, to illuminating the supply chain has, and will continue to have, significant funding momentum. Seafood traceability projects are perhaps the most common focus for transparency initiatives. As traceability and supply chain issues are much more advanced in other industries, such as the global fruit and vegetable industry or the pharmaceutical industry, technological solutions from those industries have provided a foundation for building — and funding — fishery-specific solutions. There is substantial interest in detecting (e.g., Global Fishing Watch) and potentially thwarting (e.g., OceanMind) IUU fishing operations. Global Fishing Watch has been very successful in attracting donor support for using satellites and VMS to track and detect IUU fishing activity. Addressing IUU is a challenge heavily funded by foundations, NGOs and governmental agencies. For example, Oceans5 and the Walton Family Foundation have led global initiatives that employ transparency technologies like vessel tracking and catch documentation systems. The Walton Family Foundation has been particularly dedicated to improv-

[356] https://www.worldwildlife.org/initiatives/international-smart-gear-competition
[357] Plastic pollution is a topic that has received significant attention but is generally not considered directly related to fisheries. As of 2018, approximately $120 million has been committed for investment in plastics reduction startups, and plastics reduction makes up 12% of the projects documented by Ritter & Cheung (2019). Some of the organizations that are particularly interested in marine plastics include: Althelia SOF, Oak Foundation, Benioff, Packard, Ocean Fisheries Working Group, and the German Development Bank.
[358] https://www.forbes.com/sites/jeffkart/2019/01/28/accelerator-plans-100-new-ocean-startups-by-2021/#6f832f93509b
[359] https://www.soalliance.org/ocean-solutions-accelerator/

ing supply chain traceability and look set to continue work in this area — the new 2025 environment strategy[360] includes key initiatives focused on driving innovation and using markets to advance sustainability. In Indonesia, Oceans5 is supporting the Kemitraan Partnership working to secure a new transparent monitoring program for 4,000 industrial fishing vessels.

4.3.2 Data integration, access and use

A significant amount of recent funder interest has focused on downstream data systems and better use of data, among other things how best to use the data produced by those technologies to inform science and management. This starts with updating data collection systems, which requires putting infrastructure in place to support electronic data capture. Technologies that help to integrate a growing array of data are needed and technologies that increase access to this data have also been attracting interest — for example, Global Fishing Watch, which brings together open-source data from a variety of sources and makes it easy for anyone to explore. Challenges with data integration and increased data access, including data privacy, remain significant barriers to a robust solution in this space, and potential areas for increased funding in the future.

The Net Gains Alliance[361] is working towards more modern and integrated data systems, and a common complaint is the lack of support from NOAA and state management agencies for developing integrated fishery data systems. These agencies are largely siloed rather than operating with integrated systems where data can be used for multiple purposes. The Kingfisher Foundation is focused on engaging relevant fisheries stakeholders to resolve information policy questions regarding data rights and responsibilities, common data protocols and data review protocols, all of which have a substantial impact on the cost and useability of information for fisheries management.

NMFS recently conducted a fisheries information management modernization (FIMM) workshop[362] to review and evaluate practical and tangible actions to modernize fisheries data and information systems, which fits within NOAA's priority of 'effective, user-friendly, state-of-the-art data and information management'. Many of the recommendations could be aided by a learning community of practice within NOAA that brings together staff from different regional science centers, as well as a shift in mindset that many staff beyond the IT department will need to be data literate and understand the basics of data governance to facilitate future adoption of new technologies.

4.3.3 Institutional capacity building

There is a widely acknowledged need for capacity building to strengthen the ability of institutions to implement and use existing technologies. Institutional capacity building is a necessary step in increasing access for ocean technology companies to private capital as, for funding to be successful, pathways for data use and the creation of value from data need to be identified. Development of financial literacy, management experience and business planning capacity are necessary skills for entrepreneurs to showcase when looking for investments from project developers (De Vos et al., 2020). Some examples of capacity building are providing mid- and senior career scientists with training in modern programming tools like R,[363] increasing managers' exposure to innovative technology, or helping decision makers demand more useful outputs from existing systems. In the United States, the Net Gains Alliance[364] is seen as a leader in this area whose work helps to inform funding priorities.

Many foundations and NGOs are focused on capacity building. The Nippon Foundation,[365] a Japanese foundation focused on global change and innovation, supports blue economy capacity building through their Nereus Program.[366] The program is responsible for funding various research projects and sponsors several ocean scientists. The studies published with the Nippon Foundation's support are used to inform sustainable marine and climate change focused policy decisions. The Ocean Foundation is also participating in capacity building with its 71% Initiative,[367] which has three pillars: building community capacity through advising services and corporate sustainability counseling, fostering collaboration between stakeholders by hosting workshops and summits and moderating panels and expanding ocean literacy by supporting research and participating in a global information-exchange network. Finally, Future of Fish[368] focuses on capacity building through its platforms. For example, their Seafood Industry Traceability Toolkit[369] includes a mix of guides, a glossary and implementation strategies focused on topics such as "Leveraging Data & Tech to Defend Against Potential Fraud". The World Bank is also focused on funding institutional capacity building through the PROBLUE trust fund, which has a strategic pillar focused on building government capacity to manage marine resources.

4.3.4 Implementation conditions

Many parties in this space are beginning to focus on the enabling conditions required to successfully implement technologies for sustainable fisheries. This work includes proactive engagement with the fishing industry, designing policies to accompany technology and growing technology markets, among many others.

Lack of engagement with the fishing industry to secure their participation and understand their needs during the beginning stages of a technology-based project has often limited successful implementation and scaling. Fisheries trusts may be able to play an important role in working with fishermen

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[360] https://www.waltonfamilyfoundation.org/strategy2025#environment
[361] https://www.netgainsalliance.org/
[362] https://www.netgainsalliance.org/webinars/nga-webinar-3
[363] https://www.r-project.org/about.html
[364] https://www.netgainsalliance.org/
[365] https://www.nippon-foundation.or.jp/en
[366] https://nereusprogram.org/
[367] https://oceanfdn.org/wp-content/uploads/2019/09/71-One-Pager.pdf
[368] https://futureoffish.org/
[369] http://futureoffish.org/resources/grids/seafood-industry-traceability-toolkit

and technology developers to tailor new technology solutions to meet the needs of fishermen in a way that improves the current system and generates appropriate incentives. SMTP is particularly interested in the role non-profit fisheries trusts can play as they are both immersed in the fishing community and concerned about the long-term sustainability of the fishery and currently work with the Monterey Bay Fisheries Trust to support Get Hooked Restaurant Week.[370]

Developing and implementing policies can ensure technology adoption and enable compliance and, in return, technologies can help to improve fisheries policy. Global Fishing Watch informs advocacy efforts aimed at improving fisheries policy and its approach has gained a lot of traction and the funding to support it. As another example, the Kingfisher Foundation funds projects that inform stakeholders on data review, rights, responsibilities and common protocols and their respective roles in policy.

4.3.5 Small-scale fisheries

There is likely to continue to be significant interest in finding ways that technology can enable improved sustainability and equity around small-scale fisheries. This includes both community-managed small-scale fisheries, and artisanal coastal fisheries. The largest funder for small-scale fisheries is the World Bank (World Bank and United Nations Department of Economic and Social Affairs, 2017). Other funders including WWF,[371] WorldFish[372] and the Oak Foundation[373] are interested in supporting small-scale fisheries work, although not all of their initiatives are focused on technologies. The Stanford Center for Ocean Solutions has a specific Small-Scale Fisheries & Technology Initiative[374] which is funded by the university in partnership with EDF and WorldFish.

Several organizations, including Abalobi[375] and OurFish[376] are creating innovative technologies to estimate the level and effort of catch in small-scale fisheries. These technologies are supported by funders including Indonesia's Ministry of Marine Affairs,[377] the Oak Foundation[378] and the Waterloo Foundation.[379] There is also some interest in adapting existing technologies to make lower-cost solutions that will work across a range of fisheries, including small-scale and subsistence fisheries. The Anthropocene Institute is developing one such type of solution: its Marine Monitor (M2)[380] system, which combines off-the-shelf radars with its own open source software.

Some donors have become more interested in fisheries over the past few years due to the relationship between fisheries and food security and livelihood improvement. For those donors, although interest in the role that new technologies can play is common, it is hard to attract funding to technology-based approaches without a focus on livelihood impacts and nutritional outcomes. Oak Foundation's small-scale fisheries strategy[381] emphasizes food security when describing the importance of small-scale fisheries.

WorldFish works on sustainable aquaculture and small-scale fisheries, at the intersection of food security, livelihoods and nutrition. They are currently partnered with Pelagic Data Systems and the Ministry of Agriculture and Fisheries of Timor Leste, creating a sophisticated data collection system and dashboard[382] that allows for tracking fishing activities in small-scale fisheries. This work was initially funded by Norway's Fisheries Sector Support Program (Norad)[383] and is being continued under a US$100,000 Inspire Challenge Grant[384] from the CGIAR Platform for Big Data in Agriculture.[385]

WorldFish, Duke University, and FAO are collaborating on the Illuminating Hidden Harvests Project,[386] which is accounting for the contribution of small-scale fisheries to sustainable development. The partners are collecting and integrating disparate data on small-scale fisheries from around the world to draw attention to the information gaps, guide decision-making by policy-makers and attract greater investment to the sector. This work is supported by Norad, the Swedish International Development Cooperation Agency (Sida),[387] Oak Foundation and the CGIAR Trust Fund.[388]

It is also important to consider the differential impacts technology might have on small-scale compared to large-scale fisheries. The Ocean and Coastal Policy Program at Duke University looks at the spatial overlap between large and small-scale fisheries and the potential costs and benefits of expanding zoning regulations that exclude the former to protect the latter, enforced with satellite monitoring technology (Belhabib et al., 2020). This work is supported by the Nippon Foundation through its research branch, the Nereus Program.[389]

[370] https://www.gethookedmontereybay.com/
[371] https://www.wwfmmi.org/what_we_do/fisheries/transforming_small_scale_fisheries/
[372] https://www.worldfishcenter.org/content/resilient-small-scale-fisheries
[373] https://oakfnd.org/programmes/environment/
[374] https://oceansolutions.stanford.edu/key-initiatives/small-scale-fisheries-tech
[375] http://abalobi.info/
[376] https://rare.org/story/tracing-fish-and-finances/#.W9SKOxNKjoA
[377] https://www.linkedin.com/company/mmaf-id
[378] https://oakfnd.org/
[379] http://www.waterloofoundation.org.uk/
[380] https://www.anthropoceneinstitute.com/oceans/overfishing/marine-monitor/
[381] https://oakfnd.org/wp-content/uploads/2019/11/environment-ssf-strategy-summary.pdf
[382] https://bigdata.cgiar.org/blog-post/timor-leste-launches-world-first-monitoring-system-for-small-scale-fisheries/
[383] https://norad.no/en/front/thematic-areas/climate-change-and-environment/fisheries/fisheries-aid/
[384] https://bigdata.cgiar.org/inspire/inspire-challenge-2018/an-integrated-data-pipeline-for-smallscale-fisheries/
[385] https://bigdata.cgiar.org/
[386] https://sites.nicholas.duke.edu/xavierbasurto/our-work/projects/hidden-harvest-2/
[387] https://www.sida.se/English/
[388] https://www.cgiar.org/funders/trust-fund/
[389] https://nereusprogram.org/topic/fisheries/

4.3.6 Scientific research

Scientific institutions are largely focused on how technologies can improve their research practices. A lot of effort is currently being made in working with the fishing industry to deploy at-sea electronic data loggers, oceanographic sensors, traceability systems and tagging and tracking of fish and shark species. Due to their role in industry development and their expertise in the field of marine technologies, these research institutions play a key role in collaborating with other funders to attract investment in the blue economy (De Vos et al., 2020). There is a noted overlap in the funders that are supporting scientific research on fish population biology and those that are interested in sustainable fisheries.

The groups of funders that are most interested in supporting scientific research institutions like Marine Applied Research and Exploration (MARE) Group and the Woods Hole Oceanographic Institution in the United States are predominantly governmental agencies (e.g., NOAA), foundations or NGOs. These funders provide support for research by giving grants or collaborating through partnerships. For example, MARE[390] has had multiple NGOs provide support as partners on fisheries-related projects, including Oceana and The Nature Conservancy, and has received funding from the Resources Legacy Fund Foundation.[391]

4.3.7 Emerging interests

In addition to the areas discussed in this section, a few others were identified as emerging interests for some funders:

- There is emerging interest in improved electronic tagging and tracking of fish aggregating devices (FAD). Pew and the Gordon and Betty Moore Foundation have funded392 efforts to pilot and scale this technology in the Pacific.
- In the United States, there is increasing interest in the use of rope-less fishing traps and other interventions to avoid whale entanglement. In New Brunswick,[393] the snow crab industry received US$2 million in 2019 to research and test technologies that could reduce right whale interactions, and the California Dungeness Crab Fishing Gear Working Group[394] is testing technologies to reduce humpback entanglements.
- Many of the major NGOs working on oceans and fisheries are interested in technologies that can give more precise information about the systems they are seeking to influence. This information is essential for proper program evaluation, real-time decision making and adaptive management, among many other purposes. For example, Skytruth's work with governments to provide monitoring and enforcement support[395] is enabled by its access to radar satellite imagery and AIS data.
- There is an increasing emphasis on measurement of impact and effectiveness, and the technologies that can support it. This is a cornerstone in the approach of Bloomberg Philanthropies' Vibrant Ocean Initiative.[396] They believe, "if you can't measure it, you can't manage it" and are using data systems to track the measurable results of their initiatives. The focus on impact metrics is related to the expansion of impact investing, the Global Impact Investing Network (GIIN),[397] the priorities of foundations like Rockefeller and those of bi-lateral organizations like USAID.
- There is emerging interest in training machine learning algorithms to identify fish species and classify fishing activity in order to cut down on the human review or analysis time needed to process video footage. This fits within a rising interest in developing more efficient technologies in general, including increased use of AI and automation. However, there are currently no fully integrated EM AI solutions that are market ready (Michelin & Zimring, 2020).
- There is growing interest in improving fisheries data collection efforts in small-scale, artisanal and subsistence fisheries. The interest may be in part due to the allure of making a data-opaque sector more transparent on a massive scale, which is something that the technology industry has done successfully outside of the ocean context. One limitation may be the failures of early efforts to successfully engage fishermen and their needs in product design and pilots. Future efforts should learn from these failures, but still may be faced with lack of trust from fishermen as a major obstacle. This emerging interest is not yet backed by sufficient, coordinated capital to achieve meaningful impact at scale. Fish Landing[398] and Abalobi are examples of recently developed mobile apps that are more fisher-centric in their design and are working to help fishery stakeholders track fisheries data and empower small-scale fishers in the value chain.

[390] https://www.maregroup.org/
[391] https://resourceslegacyfund.org/
[392] https://www.pewtrusts.org/en/research-and-analysis/fact-sheets/2014/09/electronic-tracking-of-fish-aggregating-devices
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