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Technologies for Climate-Resilient Fisheries

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List of Acronyms

AI	Artificial Intelligence
AIS	Automatic Identification Systems
ASV	Autonomous Surface Vehicles
AUV	Autonomous Underwater Vehicles
BDC	Berring Data Collective
DOLFIN	Data for Oceanographic Learning and Fisheries Intelligence Needs
EDF	Environmental Defense Fund
EU	European Union
eMOLT	Environmental Monitoring on Lobster Traps and Large Trawlers
FAME	Futuristic Aviation and Maritime Enterprises
FOOS	Fishery and Oceanography Observing System
GCM	Global Climate Model
IPCC	Intergovernmental Panel on Climate Change
MSE	Management Strategy Evaluation
NASA	National Aeronautics and Space Administration
NOAA	National Oceanic and Atmospheric Administration
NGO	Non-Governmental Organization
PRiSM	Predictive Spatial Modeling
SAPO	Sistema de Alerta, Prediccion, y Observacion
SSF	Small-scale fishery
SST	Sea Surface Temperature
U.S.	United States
USAID	United States Agency for International Development
VMS	Vessel Monitoring System
VIAME	Video and Image Analytics for Marine Environments

FIGURE 1: A fisher in Mexico throws his net into changing seas. *iStock*

Introduction

Climate change also raises the stakes by threatening broader food security and local economies, making the food and jobs that fisheries provide even more important.

Fish are an essential protein source for over 3.2 billion people and in some tropical countries represent as much as 70% of the local diet.[1] Fisheries also contribute approximately US$150 billion to the global economy and support the livelihoods of more than 120 million people.[2,3] Over half of the global catch is landed by small-scale fisheries distributed largely throughout the developing tropics where they play an outsized role in the maintenance of community livelihoods, food security, structure and culture.[4]

Effectively managing fisheries has always been difficult—34% of fisheries are currently considered overfished[5] —but climate change is magnifying that challenge significantly. Impacts to fisheries from climate change are already occurring and are likely to accelerate over the coming decades. It has been projected that landings of sustainably-caught fish will decline by as much as a 25% by the end of the century if greenhouse gas emissions continue on their current trajectory.[6] Climate change also raises the stakes by threatening broader food security and local economies, making the food and jobs that fisheries provide even more important. Governments, policy-makers and fishery stakeholders must work to make fisheries and fishing communities sufficiently resilient to survive the climate-driven changes that are set to intensify in the near future.

1 FAO. (2020). The State of World Fisheries and Aquaculture 2020: Sustainability in action. Rome https://doi.org/10.4060/ca9229en
2 Ibid. FAO. (2020).
3 Ibid. FAO. (2020).
4 Arthur, R. I., Skerritt, D. J., Schuhbauer, A., Ebrahim, N., Friend, R. M., & Sumaila, U. R. (2022). Small-scale fisheries and local food systems: Transformations, threats and opportunities. Fish and Fisheries, 23(1), 109–124. https://doi.org/10.1111/faf.12602
5 Ibid. FAO. (2020).
6 IPCC, 2019: Special Report on the Ocean and Cryosphere in a Changing Climate [H.-O. Pörtner, D.C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama, N.M. Weyer (eds.)].

What is climate resilience? The Intergovernmental Panel on Climate Change (IPCC) defines resilience as a "*system's capacity to anticipate and reduce, cope with, and respond to and recover from external disruptions*."[7] Under this definition, resilience includes the ability to resist and adapt to environmental disturbance, as well as the ability of individuals, communities and institvutions to prepare for, cope with and adapt to such changes.[8] In the context of fisheries, increasing *economic resilience* means improving and diversifying market access, broadening fishery portfolios and improving fishers' bottom lines such that they and their communities are in a better position to withstand shocks to their livelihoods. Increasing *social resilience* means improving social capacity for learning and adaptation, as well as improving social buffers such as health care and financial reserves. Promoting *ecological resilience* means providing buffers against systemic shocks and increased variability and managing adaptively to detect and respond to changes in timely and strategic ways. While short-term tensions between economic and ecological resilience exist, and often arise through the need to balance increased market access—which can incentivize higher levels of fishing effort—with a need to allow stocks to rebuild, over the longer term they are very much aligned. Building the resilience of fishing communities to climate change is a multi-faceted challenge that will require sustained investment, cooperation and action from all stakeholders—from the smallest fishing operations to the largest multi-lateral institutions. And while there is no panacea, new and emerging technologies can help fishers, managers and communities improve fisheries climate-resilience.

Digital tools already play a valuable role in helping fisheries with the fundamentals of good management which are essential for climate resilience: catch accounting, fisheries science, bycatch avoidance, enforcement of regulations, market transparency and ecosystem monitoring, among others. These applications are described in detail in a comprehensive review of technology in fisheries published in 2021 by Environmental Defense Fund (EDF).[9] By contrast, this report seeks to focus on a few of the most promising ways technology can help to meet the biggest climate challenges facing fisheries. Specifically, these are: 1) understanding the ecosystem impacts of changing ocean conditions; 2) adapting to shifting fish stocks; 3) managing in the face of change; and 4) increasing the climate resilience of vulnerable small-scale fishing communities. This report provides examples of the technologies helping to address each of these specific climate challenges which are offered as illustrations of what is useful and promising but are by no means exhaustive.

Building the resilience of fishing communities to climate change is a multi-faceted challenge that will require sustained investment, cooperation and action from all stakeholders—from the smallest fishing operations to the largest multi-lateral institutions.

The goal of this report is to discuss specific mechanisms for improving the climate resilience of fisheries and illustrate how they can be strengthened by the application of new and emerging technologies. It aims to increase awareness of climate-response tools as well as current directions and salient lessons from a field where rapid innovation often outpaces the ability of managers and stakeholders to track what is possible and available.

7 Denton, F., T.J. Wilbanks, A.C. Abeysinghe, I. Burton, Q. Gao, M.C. Lemos, T. Masui, K.L. O'Brien, and K. Warner, 2014: Climate-resilient pathways: adaptation, mitigation, and sustainable development. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1101-1131.

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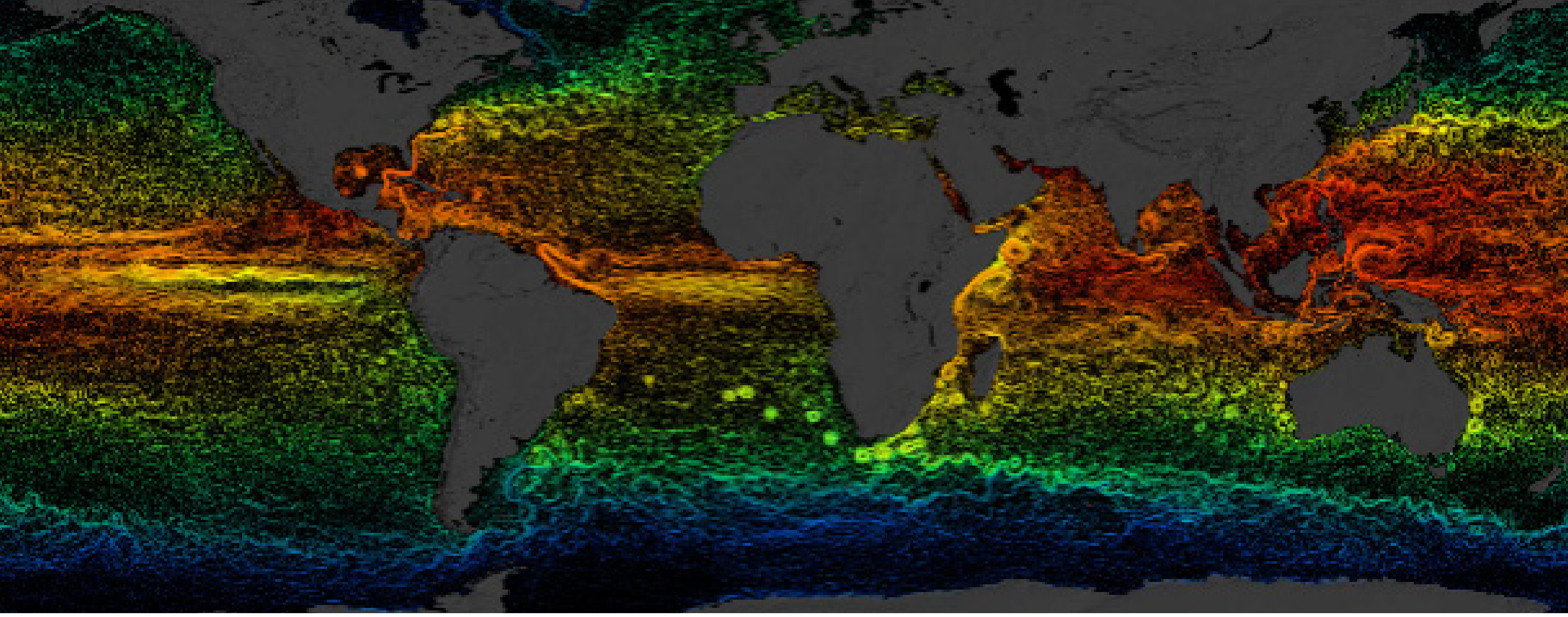

SECTION 1

Climate challenge — understanding the ecosystem impacts of changing oceanographic conditions

FIGURE 2: A warming climate is altering global currents. Image (and animation) constructed from satellite and ship readings. *NASA/Goddard space flight center scientific visualization studio*

Impacts

Climate change is altering the natural cycles of marine ecosystems, generating more variable and extreme conditions.[10] As greenhouse gases trap more energy from the sun, the oceans absorb more heat resulting in an increase in ocean temperatures, melting ice caps and a rising sea level. Changes in ocean temperatures and currents can in turn lead to dangerous shifts in global climate patterns.[11] For example, warmer waters are linked to the development of stronger storms in the tropics which cause property damage and loss of life. Warming also affects the productivity and distribution of fish populations as the distribution of preferred temperatures changes. Emissions of carbon dioxide from the combustion of fossil fuels not only results in warming, but also change the chemistry of seawater, making it more acidic. Increased ocean acidity makes it more difficult for certain organisms, such as corals and shellfish, to build their skeletons and shells.[12] Warming ocean temperatures also alter primary and secondary production patterns, impacting fisheries productivity.[13]

The lack of observed *in situ* ocean data in these areas limits forecasting, productivity modeling and climate change monitoring and can lead to inaccurate predictions that can undermine decision making.

Changes in environmental conditions can significantly impact fisheries by increasing the frequency or intensity of disease, parasites or biotoxin outbreaks such as withering syndrome in abalone, sea star wasting disease and harmful algal blooms. For example, extremely warm temperatures contributed to a harmful algal bloom off the U.S. West Coast in 2015–2016 that led to the closure of California's US$50 million Dungeness crab fishery. Extreme marine heat waves and strong storm activity have contributed to a dramatic reduction in kelp distribution on the U.S. West Coast, with detrimental effects on species that depend on kelp for food and habitat, such as abalone and red sea urchins.[14] In East Asia, fisheries productivity has declined by as much as 35% since 2012 due to climate change impacts.[15]

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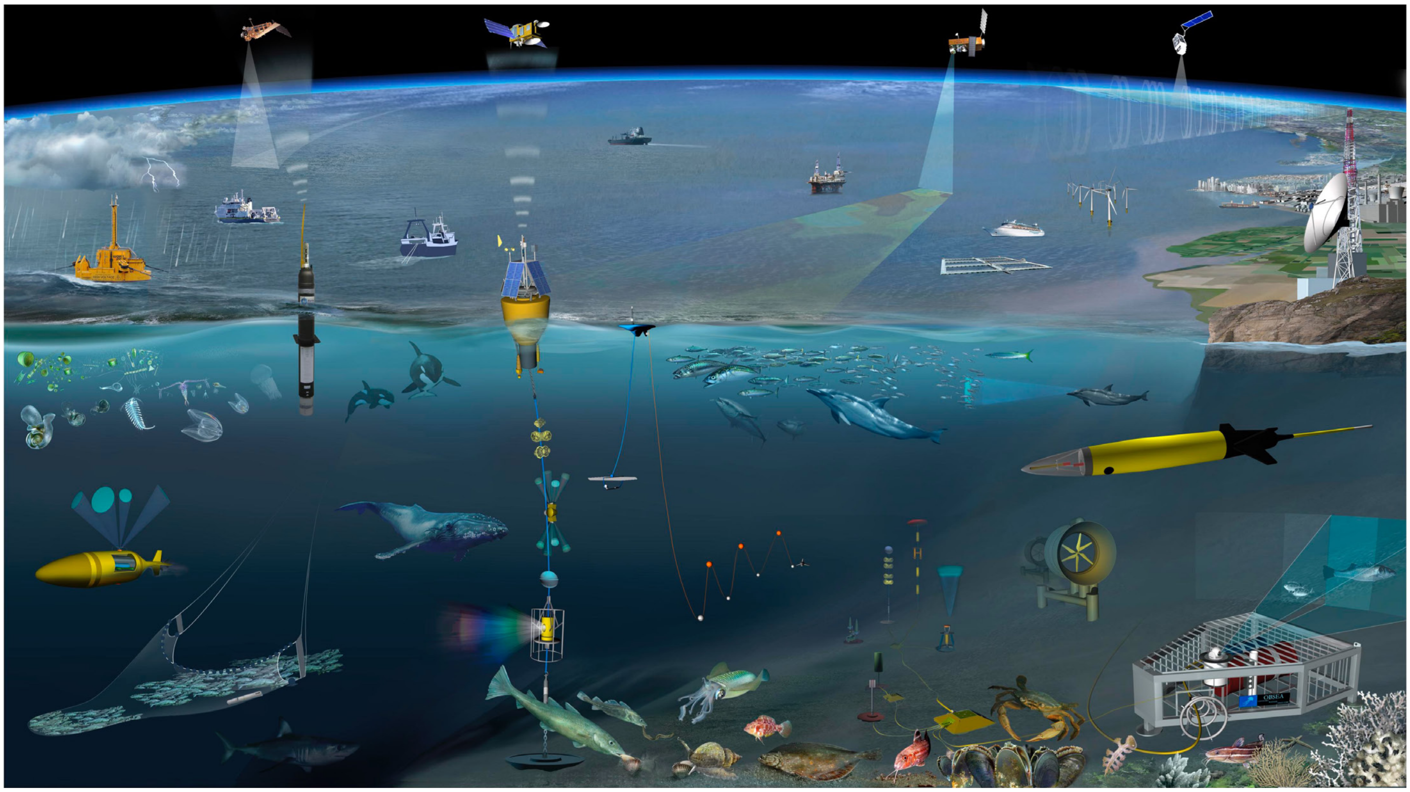

FIGURE 3: Oceanographic sensing platforms and technologies. *Illustration by Glynn Gorick and NeXOS project*

Current tools and their limitations

To better understand these changing oceanographic conditions and predict their impacts, researchers have a wide range of technologies and data collection platforms at their disposal beyond traditional oceanographic research vessels. For example, satellites can detect sea surface temperature (SST), ocean color, ocean height, chlorophyll content and bathymetry. Autonomous underwater vehicles, buoys and gliders can collect data on temperature, salinity, chlorophyll, wave height, currents and other parameters. These existing tools are particularly effective at collecting data in the open ocean environment, but shelf and nearshore waters, where most fishing activity occurs, often lack reliable sub-surface data vital to accurate oceanographic and productivity models. The lack of observed *in situ* ocean data in these areas limits forecasting, productivity modeling and climate change monitoring and can lead to inaccurate predictions that can undermine decision making.[16]

Additionally, while global climate models (GCMs), like those developed for use by the Inter-governmental Panel on Climate Change (IPCC) have greatly increased scientific understanding of the effects of climate change on a global level, these global scale models often need to be downscaled to better understand impacts of highly variable regional and local scale phenomena on species and ecological processes. These are the impacts and scales that most fish stocks and fisheries respond to and that are most relevant to fisheries management. At these smaller scales, regional or local processes such as winds, internal waves, tides and local biological processes can be incorporated as model drivers.[17] However, finer scale data are necessary for more local scale modeling. Collecting local and regional oceanographic and biological data using traditional research vessels is difficult, expensive and can be a challenge to coordinate.[18] Nearshore data collection, such as via sensors mounted to fishing boats or gear can be a valuable means of informing downscaled climate models and ground-truthing their results.[19]

16 Van Vranken, C., Vastenhoud, B. M. J., Manning, J. P., Plet-Hansen, K. S., Jakoboski, J., Gorringe, P., & Martinelli, M. (2020). Fishing Gear as a Data Collection Platform: Opportunities to Fill Spatial and Temporal Gaps in Operational Sub-Surface Observation Networks. *Frontiers in Marine Science*, 7. https://www.frontiersin.org/article/10.3389/fmars.2020.485512

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Oceanographic sensors on fishing gear

Commercial fishing vessels and gear such as bottom trawls, pots, traps and longlines can act as platforms for sensors, which can collect fine-scale physical oceanographic data at the sea surface and at depth during normal fishing operations.[20] There are a range of examples from across the globe, including in New Zealand, the United States and Europe that illustrate how equipping fishers with the latest autonomous sensor technology can help advance our understanding of changing oceanographic conditions. These examples also illustrate how this enhanced understanding can benefit fishers through better fisheries science and marine forecasting which can, in turn, improve production, profits and safety at sea.

New Zealand

In New Zealand, the Moana Project is a new initiative where science and management agencies have partnered with the New Zealand-based company Zebra-Tech Ltd. and the fishing community to expand the spatial and temporal coverage of subsurface temperature observations.[21] The Moana Project aims to outfit hundreds of commercial fishing vessels operating in New Zealand with sensors and to enable recreational fishers and citizen scientists to collect ocean temperature measurements. These data are then integrated into ocean forecasts designed specifically to inform fishing operations. To date, temperature, wind, wave and current forecasts are now available to anyone via Swellmap, and marine heat wave forecasts are continually being improved through the application of artificial intelligence (AI).

United States

The Environmental Monitoring on Lobster Traps and Large Trawlers (eMOLT) program, a collaboration between industry and government, has been operating successfully for almost 20 years. In this program, researchers mount temperature sensors on fishing gears and pair them with on-vessel satellite telemetry systems to collect data on temperature at depth. These data have been incorporated into the lobster stock assessment to correct for temperature-dependent changes in lobster catchability,[22] contribute to oceanographic modeling and weather

FIGURE 4: Zebra-tech's Mangōpare temperature sensor attached to a trawl net. *Moana Project*

FIGURE 5: A temperature sensor on a lobster trap in the eMOLT project. *Jack Carrol*

20 Foster, D., Gagne II, D. J., & Whitt, D. B. (2021). Probabilistic Machine Learning Estimation of Ocean Mixed Layer Depth From Dense Satellite and Sparse In Situ Observations. *Journal of Advances in Modeling Earth Systems*, 13(12), e2021MS002474. https://doi.org/10.1029/2021MS002474

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forecasting in the region[23] and are made available to fishers in real-time. Pairing oceanographic data with catch data in this way represents a critical opportunity to advance ecosystem-based fisheries management by relating species distribution to oceanographic conditions. Developing an understanding of these relationships will become increasingly important in a changing climate, enabling predictions about future stock health and fishery productivity.[24]

Europe

In Italy, managers with the Fishery and Oceanography Observing System (FOOS) work with a range of fishing vessels including mid-water trawlers, bottom trawlers and seiners to collect temperature, salinity and meteorological data along with geo-referenced information on catch. The FOOS program not only helps improve forecast models and stock assessments, but also provides valuable information directly back to the fishers. This includes customized oceanographic model outputs (wave height, wind stress, marine currents, etc.), as well as mesoscale maps of variables such as SST, chlorophyll *a distribution derived from satellite data.*[25]

The French Research Institute for Exploitation of the Sea runs the Recopesca program which aims to advance an ecosystem approach to fisheries management by integrating oceanographic and catch data from vessels into stock assessment and management. The project includes trawlers, longliners, pot vessels and gillnetters outfitted with a wide range of sensors for variables including temperature, salinity, dissolved oxygen and chlorophyll fluorescence.[26] The data are integrated into a broader EU monitoring network called the Copernicus Marine Environment Monitoring Service's Thematic Assembly Center that maintains a dashboard with downloadable data.

Regional efforts like these are accelerating thanks in part to the work of a new organization, the Berring Data Collective (BDC), that is dedicated to advancing cooperative research and data collection, with an initial focus on the European Union (EU). BDC has helped to dramatically increase the number of vessels participating in oceanographic data collection in the region.[27] This rapid growth speaks to the value of the data to managers, scientists and participating fishers. As the capabilities of sensors and analytical capacity continue to increase, the region is poised to demonstrate what can be achieved with sufficient investment and broad scale engagement.

Going forward

Cooperative data collection creates new lines of communication that facilitate broader collaboration between researchers, managers and industry for more nimble and effective adaptation and management.

The data collected by fishers can be a valuable contribution to broader observing networks such as the Copernicus Marine Environment Monitoring Service in the EU mentioned above, the Integrated Ocean Observing System in the United States, and the Ocean Data Network in New Zealand. Collectively these data provide a valuable means of improving our understanding of changing ocean conditions and fish stocks. However, the benefits of engaging fishers in science are not limited to just using their vessels and gear as data collection platforms. Cooperative data collection creates new lines of communication that facilitate broader collaboration between researchers, managers and industry for more nimble and effective adaptation and management.[28] This is an important outreach and education opportunity and helps to democratize science and data collection.[29] Moreover, fishers have a unique understanding of the marine environment and are often aware of changing conditions before scientists are, allowing them to provide important contributions to the development of new ocean observing strategies and data products. There is also

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27 https://marine.copernicus.eu/news/fishing-data-meet-vessels-helping-monitor-and-map-north-sea. (Accessed September 3, 2021 9/3/21)

28 Ibid. Von Vranken et al. (2020).

29 Gawarkiewicz, G., & Malek Mercer, A. (2019). Partnering with Fishing Fleets to Monitor Ocean Conditions. *Annual Review of Marine Science*, 11(1), 391–411. https://doi.org/10.1146/annurev-marine-010318-095201

FIGURE 6: Peruvian fishing vessels. *iStock*

growing potential for fishers to be paid for their data by integrating it into products aimed at other parts of the blue economy. For example, fisher-collected data could inform the high-resolution marine forecasts used by the shipping industry to adaptively re-direct ships to the most economically efficient routes with the most favorable ocean conditions.

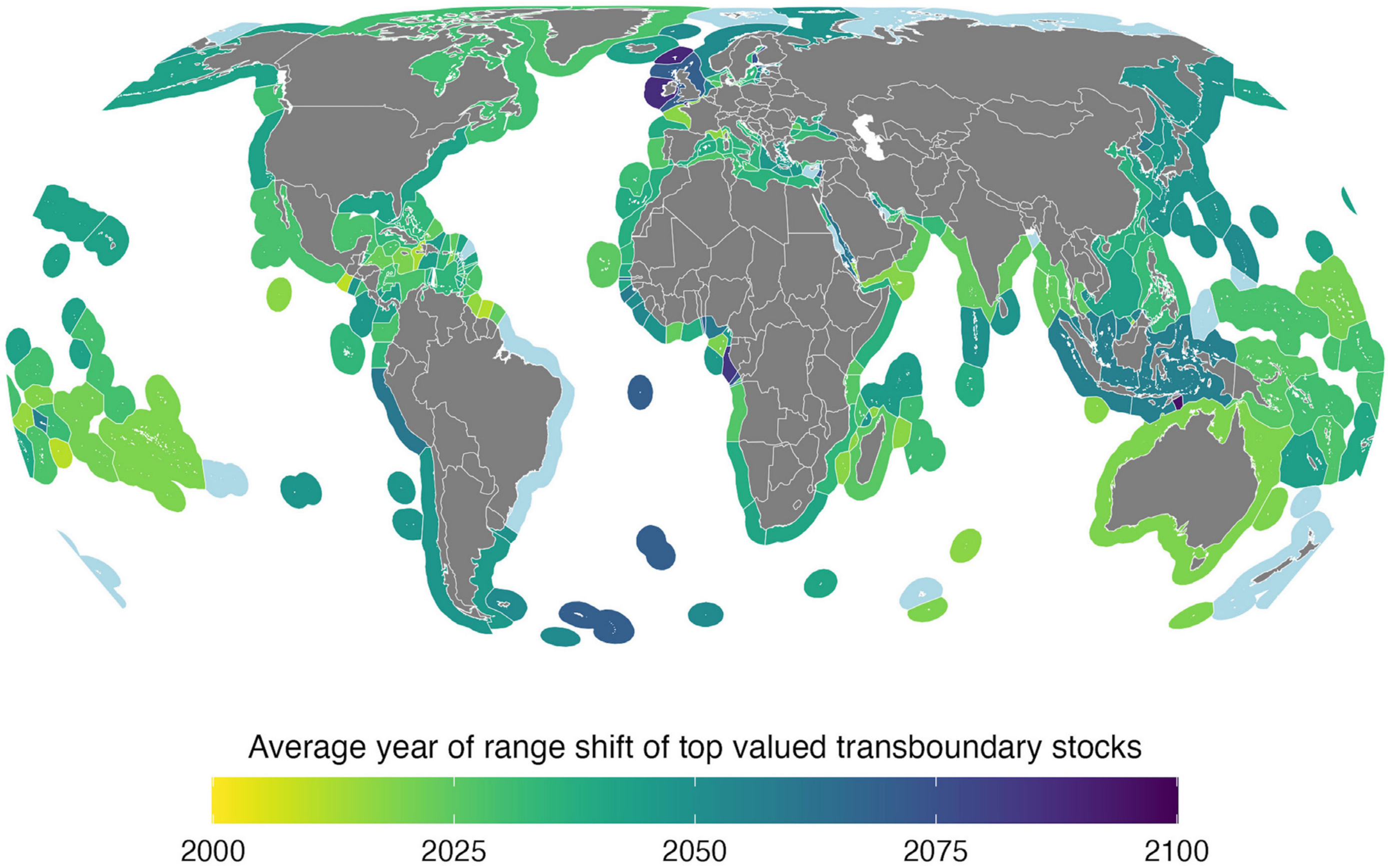
Climate early warning systems

As climate impacts continue to be felt, regions are beginning to develop ocean "early warning systems" designed to better understand oceanographic processes and compile the data managers need to anticipate the changes that will impact fisheries and coastal communities. The United Nations defines these as "systems that use integrated communication systems to help communities prepare for hazardous climate-related events".[30] One such system is currently taking shape in the Humboldt Current region along the west coast of South America. The Humboldt Current is subject to highly variable oceanographic conditions that in turn drive wide swings in the productivity and abundance of marine species. Climate change is amplifying this variability and appears to be driving even greater fluctuations in ocean chemistry, fisheries productivity, species distributions and other environmental parameters.[31] To understand these changes and anticipate their impact, the governments of Ecuador, Chile and Peru are working to define the goals and strategies of an early warning network called Sistema de Alerta, Prediccion, y Observacion (SAPO). This region is home to the largest fishery in the world by volume, the Peruvian anchoveta fishery, as well as a diverse group of small-scale nearshore fisheries that can be outfitted with a range of autonomous sensors to collect data.

One of the foundations of SAPO will be a unified observing network using a range of tools and technologies to provide a tri-national coalition of managers, scientists and other stakeholders with the data they need to develop and continually refine new oceanographic and productivity models.[32] These include satellite remote sensing, buoys, autonomous vehicles and, importantly, fishing vessels. The data will improve forecasted model outputs, inform stock assessments and guide harvest policies. And by integrating the fishing fleet into data collection, industry buy-in and compliance with any resulting management measures is expected to increase.

Early warning systems like SAPO and others taking shape in the Caribbean and Europe represent a core and growing component of climate-resilient fisheries management. The UN recently set a five-year goal for expanding the development of early warning systems globally.[33] As these systems diversify, expand and integrate the latest technologies, ensuring that fishers are core partners can improve and promote buy-in to the management decisions that result.

30 https://www.un.org/en/climatechange/climate-solutions/early-warning-systems. (accessed September 4, 2021)
31 Cunningham, E., Kleisner, K., Parks, B., Palma, S., Amoros-Kohn, S., Burden, M. (2020). *Toward climate-resilient fisheries in the Humboldt Current — developing a scientific foundation for improved adaptive management.* Environmental Defense Fund.
32 Ibid. Cunningham et al. (2020).
33 Keaten, J. (2022, March 23). UN sets 5-year goal to broaden climate early warning systems. *AP NEWS.* https://apnews.com/article/wildfires-climate-science-weather-antonio-guterres-d47f7cff87b6ea081f5af1035f74d2eb



SECTION 2

Climate challenge — adapting to shifting fish stocks

FIGURE 7: The average year of range shift of individual countries' top five most valuable transboundary stocks.[37] *Palacios et al. 2022*

Impacts

The changes in water temperature, currents and ocean chemistry discussed in Section 1 are affecting the distribution and productivity of fish and other marine species.[34] As temperatures climb, some species may not be able to move to more suitable habitats due to their need for specific types of habitat, or due to limited mobility or dispersal, resulting in reduced productivity and abundance. Many fish species naturally migrate in response to seasonal temperature changes, moving northward or into deeper waters in the summer and migrating back in the winter. However, as the oceans become warmer year-round, species are adapting by shifting their base distributions into deeper waters and/or toward the poles. As smaller prey species shift their habitats, larger predator species may follow them.[35] It is estimated that 25-85% of marine species have already shifted at least part of their geographical range, moving at an average rate of ~70 km per decade.[36] These shifts can mean that a fishery's target species may leave its historical grounds or that new species move in. These shifts affect participation in commercial and recreational fisheries and have significant implications for fisheries management, fishing communities and the global seafood supply chain.

While some areas could see new fishing opportunities as stocks move in or increase in abundance, overall, shifting stocks are expected to negatively impact fisheries, with impacts

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35 Melbourne-Thomas, J., Audzijonyte, A., Brasier, M. J., Cresswell, K. A., Fogarty, H. E., Haward, M., Hobday, A. J., Hunt, H. L., Ling, S. D., McCormack, P. C., Mustonen, T., Mustonen, K., Nye, J. A., Oellermann, M., Trebilco, R., van Putten, I., Villanueva, C., Watson, R. A., & Pecl, G. T. (2022). Poleward bound: Adapting to climate-driven species redistribution. *Reviews in Fish Biology and Fisheries*, 32(1), 231–251. https://doi.org/10.1007/s11160-021-09641-3

36 Ibid. Melbourne-Thomas et al. (2021).

37 Palacios-Abrantes, J., Frölicher, T. L., Reygondeau, G., Sumaila, U. R., Tagliabue, A., Wabnitz, C. C. C., & Cheung, W. W. L. (2022). Timing and magnitude of climate-driven range shifts in transboundary fish stocks challenge their management. *Global Change Biology*, 28(7), 2312–2326. https://doi.org/10.1111/gcb.16058

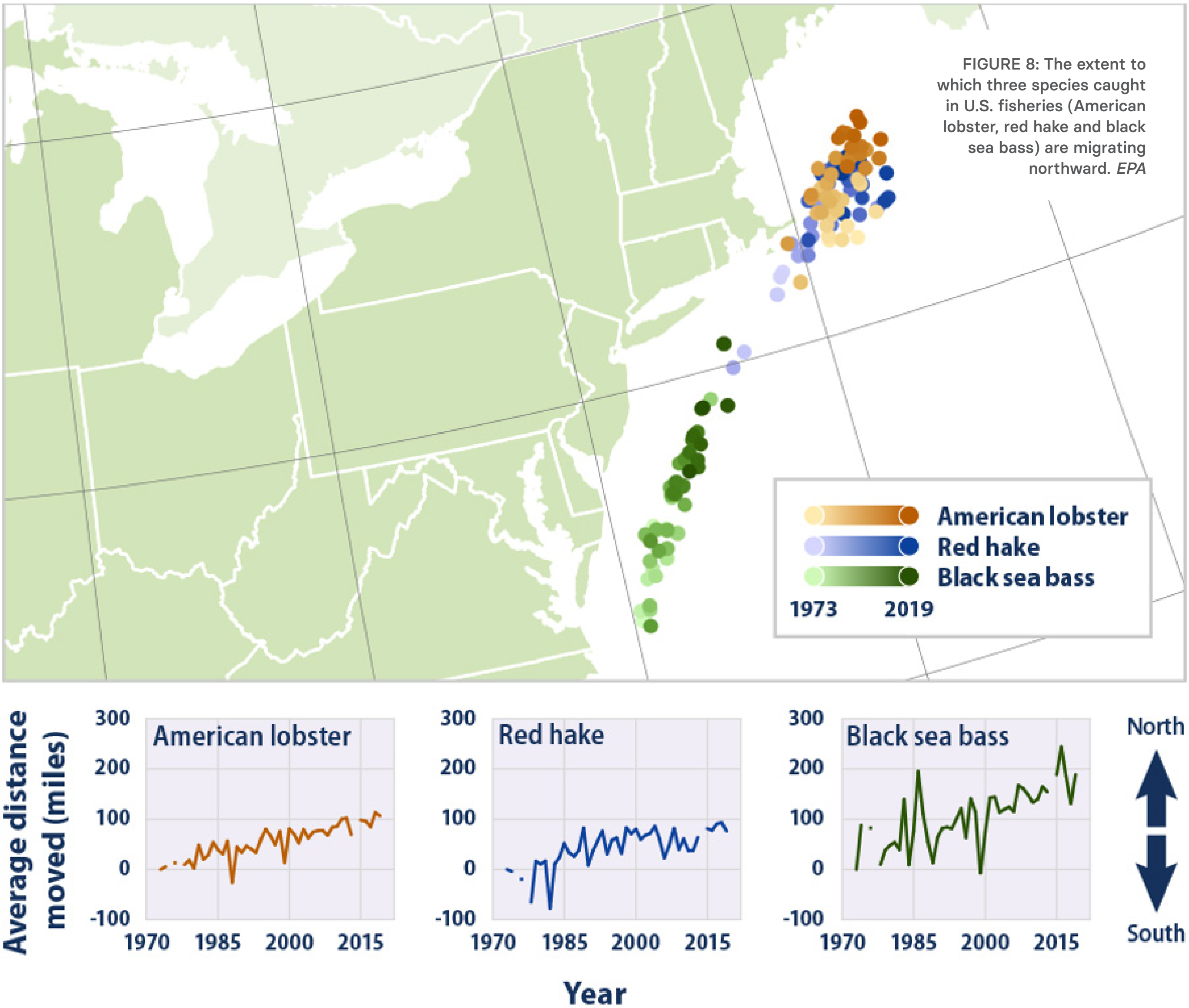

FIGURE 8: The extent to which three species caught in U.S. fisheries (American lobster, red hake and black sea bass) are migrating northward. *EPA*

higher in some regions than others.[38] For example, a 2019 study looking at potential impacts in the northeastern United States found that 64 of the 85 fishing communities in the region are projected to have access to fewer fish due to shifting species by 2050.[39] Fishers that are reliant on heavily impacted stocks like Atlantic cod and witch flounder, such as communities of small groundfish trawlers in Maine, are particularly at risk.[40]

In addition to target stocks, species such as whales and sea turtles may shift or expand their ranges into areas where they are more likely to be caught as bycatch.[41] This can have significant management consequences for the fisheries in the region. For example, warming temperatures in the Northwest Atlantic are expanding the range of loggerhead sea turtles and bringing the species into increasing contact with longlines, gillnets and scallop dredges.[42] As this trend continues, increased bycatch rates may lead to new spatial closures, monitoring requirements and gear restrictions. Finally, in addition to these more permanent range shifts, climate change is increasing the variability of stock distribution. This variability can lead to atypical and difficult-to-predict seasonal and interannual distributions of both target and bycatch species that can pose challenges to fishers and managers alike.

Warming temperatures in the Northwest Atlantic are expanding the range of loggerhead sea turtles and bringing the species into increasing contact with longlines, gillnets and scallop dredges.

38 Ibid. Free et al. (2019).
39 Rogers, L. A., Griffin, R., Young, T., Fuller, E., St. Martin, K., & Pinsky, M. L. (2019). Shifting habitats expose fishing communities to risk under climate change. *Nature Climate Change*, 9(7), 512–516. https://doi.org/10.1038/s41558-019-0503-z
40 Ibid. Rogers et al. (2019).
41 Grose, S. O., Pendleton, L., Leathers, A., Cornish, A., & Waitai, S. (2020). Climate Change Will Re-draw the Map for Marine Megafauna and the People Who Depend on Them. *Frontiers in Marine Science*, 7. https://www.frontiersin.org/article/10.3389/fmars.2020.00547
42 Patel, S. H., Winton, M. V., Hatch, J. M., Haas, H. L., Saba, V. S., Fay, G., & Smolowitz, R. J. (2021). Projected shifts in loggerhead sea turtle thermal habitat in the Northwest Atlantic Ocean due to climate change. *Scientific Reports*, 11(1), 8850. https://doi.org/10.1038/s41598-021-88290-9

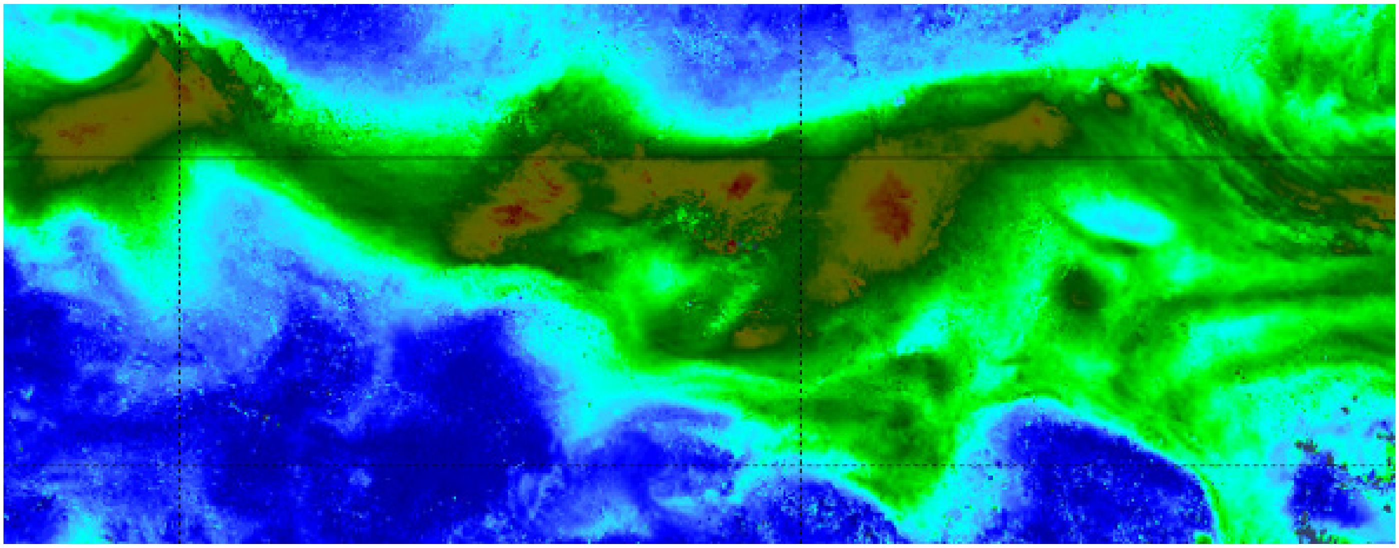

FIGURE 9: The DOLFIN platform provides fishers and fleet managers with comprehensive views (plankton shown) and AI-derived guidance on where to fish. *Woods Hole Group*

Predictive mapping

Shifting species distributions will continue to impact fisheries over the coming decades. However, providing managers and fishers with new tools and flexibility can help ensure that they are as resilient to these changes as possible. This includes more flexible permitting, better information flows and cross-jurisdictional cooperation for addressing newly transboundary stocks. New technologies have an important role to play in meeting this challenge, perhaps most significantly through advances in spatial modeling and predictive mapping. Predictive maps bring together diverse data sets that can help fishers continue to effectively locate shifting target species while avoiding new or increasing numbers of bycatch species and can help managers design management measures that are more tailored, adaptive and effective. Improved communication at sea via better satellite communications will also likely help fishers track target species and avoid bycatch. While there is overlap between these uses, this section explores each of them in turn.

Increasing target catch

As target species shift from their historical range or become harder to locate due to increased oceanographic variability, mapping tools can help keep fisheries profitable and efficient. There are several companies that provide synthesized predictive maps to fishers, but the potential of this technology is perhaps best illustrated by a recent application designed by the Woods Hole Group in Massachusetts. Their Data for Oceanographic Learning and Fisheries Intelligence Needs (DOLFIN) platform is a cutting edge analytical and mapping package that integrates a wide array of current and historic oceanographic, atmospheric and fishery-dependent data.[43] AI is then used to develop correlations between conditions and fishing states that are customized to each fishing operation. These relationships and resulting maps help direct fishers to the most productive fishing grounds. This saves time and fuel while increasing catch.

DOLFIN is aimed at well-resourced operations and its price tag may be out of range of many small-scale fishers. However, there are efforts to make state-of-the-art platforms such as DOLFIN more accessible through sliding price scales and financial support. And as is often the case with new technology, prices tend to come down over time and software becomes sufficiently streamlined to run on smartphones. Tools like DOLFIN show what is possible and what the future likely holds for a broader class of fishers. It's worth noting that as the power of big data and machine learning becomes more accessible, such technologies may go beyond helping fishers adapt to the challenges of climate change and may pose risks of overfishing in some regions or in some fisheries. Managers will need to consider the overall impacts of these tools as they become more widespread and regulate accordingly.

43 https://fisheries.groupcls.com/fishermen/fisheries-intelligence/ (assessed September 7, 2021)

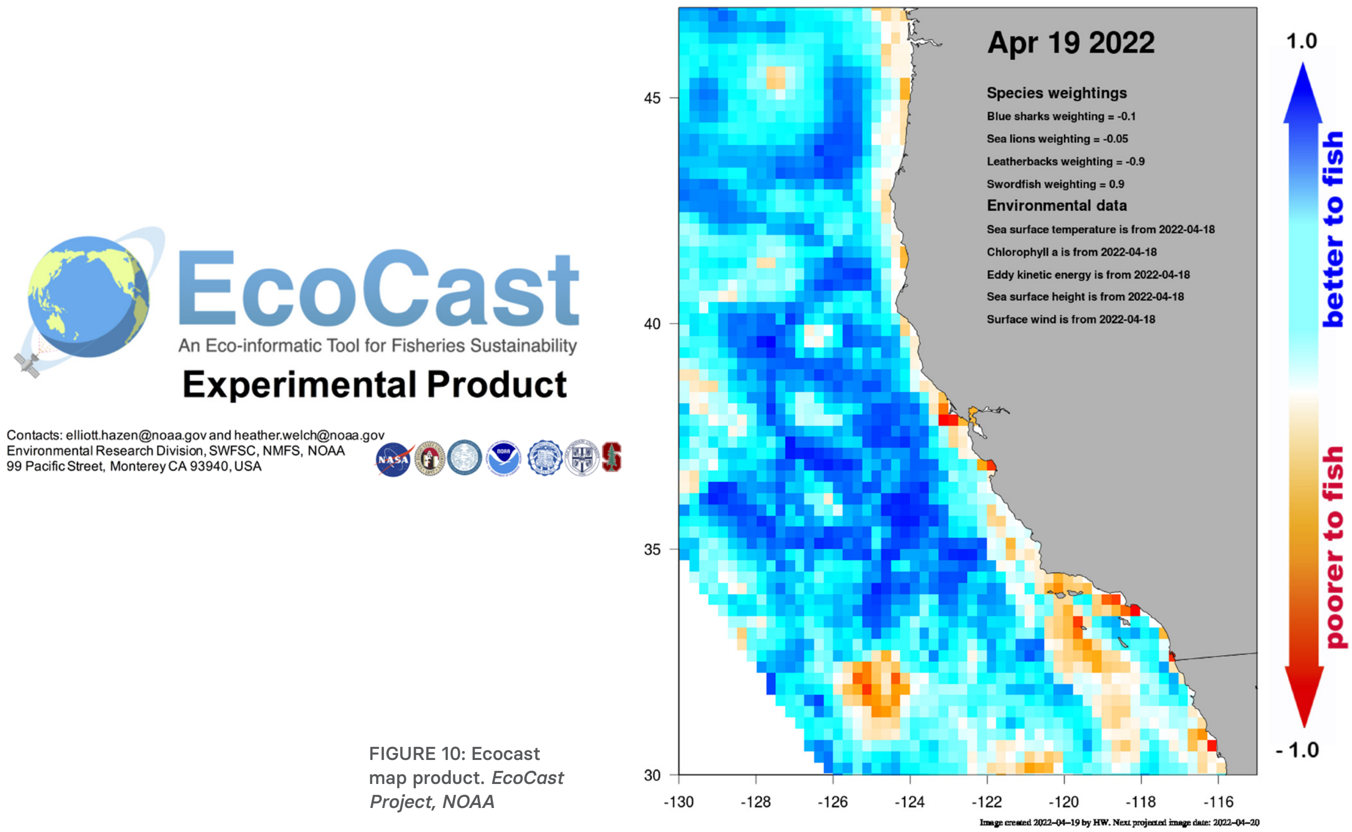

FIGURE 10: Ecocast map product. *EcoCast Project, NOAA*

Avoiding bycatch

Certain fisheries have a higher risk of interacting with protected or sensitive species such as whales, turtles and sharks. These interactions not only represent conservation concerns, but they can also be costly to the fishery in the form of regulatory restrictions and gear loss. There is a growing number of predictive mapping tools that are helping fisheries avoid these species and minimize these challenges. For example, on the U.S. West Coast, the drift gillnet fishery targeting swordfish and thresher shark has also documented interactions (some fatal) with critically-endangered leatherback turtles and other bycatch species including blue sharks and sea lions. In response, managers at the National Oceanic and Atmospheric Administration (NOAA) and a group of academic institutions developed an online mapping tool called EcoCast. EcoCast integrates near real-time oceanographic data with historical catches of swordfish and leatherbacks to assign probabilities of catching each in a given area. Efforts are underway to expand and adapt the tool for use in other fisheries including the California Dungeness crab fishery, the sablefish trap fishery and other fixed gear fisheries on the U.S. West Coast to address concerns over whale entanglements.[44]

In Alaska's Bering Sea, trawl vessels target pollock in the second largest fishery in the world by volume. This fishery illustrates what is possible when predictive mapping capabilities are coupled with strong underlying incentives and a well-organized, well-resourced fleet. Here chinook and chum salmon are the principal bycatch species of concern, with high incidental takes potentially resulting in the closure of the fishery. This has created powerful incentives for the fleet to cooperatively develop a system to collectively avoid areas where salmon bycatch is likely. SeaState Inc. is a private fleet management service developed in conjunction with the fishing industry to help direct the pollock fleet to areas with low bycatch risk and to impose voluntary closures where the risk is high. The company integrates oceanographic information with real-time catch and bycatch data from vessels and implements rolling hotspot closures under a fleetwide agreement. This system has been highly effective at reducing salmon bycatch and is often held up as a gold standard of adaptive co-management.

44 https://media.fisheries.noaa.gov/2021-03/2020_West_Coast_Whale_Entanglement_Summary.pdf?null= (accessed September 3, 2021)

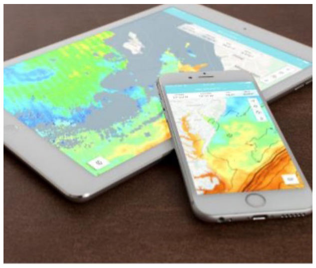

FIGURE 12: Predictive mapping tools can be made available to a broad class of fishers through powerful connected mobile devices. *FishTrack*

This creates the opportunity to move away from static closures and towards more responsive management approaches that better reflect the increasingly dynamic conditions on the ocean.

Designing closed areas

Predictive mapping is also helping managers manage more adaptively in the face of more climate-driven variability. Closed areas are an essential tool for protecting sensitive species but can come with a high cost for fishers and communities if not carefully designed. Using closed areas for migratory or transitory species in particular can be challenging due to the range and movement patterns of the species, along with increasingly dynamic ocean conditions.[45] In response, NOAA has developed a mapping tool known as HMS-Predictive Spatial Modeling (PRiSM) to help better manage longline fisheries on the East Coast of the United States. PRiSM uses observer, oceanographic and vessel data to produce spatial models that predict fishery interactions with bycatch species including sea turtles, billfish and a number of shark species. Instead of helping to direct fishery effort in open areas, PRiSM is designed to help managers assess the effectiveness and potential re-design of closed areas.

Tools like PRiSM could also help optimize the location, size and timing of potential new rolling closed areas that move based on changing bycatch probabilities. More dynamic closures like this that only close areas when and where risk is high could potentially achieve comparable bycatch risk reduction at a tenth of the size of the static closed areas, thereby increasing fishing opportunities.[46] PRiSM can also identify areas that should be closed for discrete periods of time, months in advance. This creates the opportunity to move away from static closures and towards more responsive management approaches that better reflect the increasingly dynamic conditions on the ocean.[47] Ultimately, these tools can help reduce bycatch of sensitive species while maintaining or providing increased fishing opportunities to fishers.

Predictive mapping is the confluence of a diverse suite of technologies and approaches to help guide fishing behavior and management strategies. As those component technologies (satellite sensing, oceanographic platforms, electronic monitoring, etc.) continue to improve, so will the resulting model outputs. The main challenge will be to make predictive mapping affordable and accessible to a broader class of fishers and managers—a challenge that mobile computing, inexpensive wireless communications and inexpensive data provision promise to overcome.

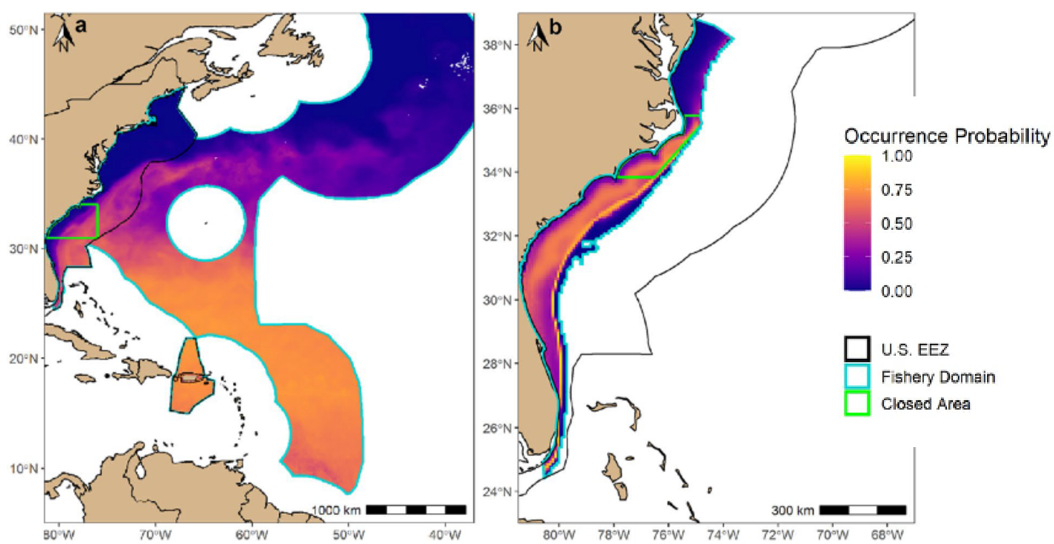

FIGURE 11: PRiSM model outputs showing billfish and dusky shark occurrence probability during average February conditions from 2016 to 2018. *Crear et al. 2021*

45 Crear, D. P., Curtis, T. H., Durkee, S. J., & Carlson, J. K. (2021). Highly migratory species predictive spatial modeling (PRiSM): An analytical framework for assessing the performance of spatial fisheries management. *Marine Biology*, 168(10), 148. https://doi.org/10.1007/s00227-021-03951-7

46 Hazen, E. L., Scales, K. L., Maxwell, S. M., Briscoe, D. K., Welch, H., Bograd, S. J., Bailey, H., Benson, S. R., Eguchi, T., Dewar, H., Kohin, S., Costa, D. P., Crowder, L. B., & Lewison, R. L. (2018). A dynamic ocean management tool to reduce bycatch and support sustainable fisheries. *Science Advances*, 4(5), eaar3001. https://doi.org/10.1126/sciadv.aar3001

47 Lewison, R., Hobday, A. J., Maxwell, S., Hazen, E., Hartog, J. R., Dunn, D. C., Briscoe, D., Fossette, S., O'Keefe, C. E., Barnes, M., Abecassis, M., Bograd, S., Bethoney, N. D., Bailey, H., Wiley, D., Andrews, S., Hazen, L., & Crowder, L. B. (2015). Dynamic Ocean Management: Identifying the Critical Ingredients of Dynamic Approaches to Ocean Resource Management. *BioScience*, 65(5), 486–498. https://doi.org/10.1093/biosci/biv018

FIGURE 13: Vericatch's FisheriesApp in Lampung, Indonesia. *EDF*

SECTION 3

Climate challenge — managing in the face of change

Impacts

Climate change impacts such as shifting species distributions, changes in stock-recruitment relationships and greater variability in many measurable physical and ecological variables are making fisheries management more difficult and uncertain. Effectively managing fishery resources in a changing climate depends on quickly detecting, understanding and responding to shifts in the ecosystem.[48] Management systems must become more flexible and responsive, moving away from measures such as static closures and historically derived catch limits and effort controls, and toward approaches that are more dynamic and responsive to shifting distributions and levels of abundance. However, more adaptive management requires more accurate, near real-time data on catch, effort and environmental conditions—something that has historically been expensive and challenging to collect. Digital data collection and wireless communications have been out of reach of most fishers and the models that can make sense of huge data sets have only recently reached the point of practical applicability.[49] However, below are some inspiring examples of recent advances that are helping to collect, transmit, analyze and make informed decisions with data to make management more adaptive and responsive to climate change.

Collecting and transmitting data

At the dock

The near-ubiquitous smartphone presents a widespread opportunity to easily collect catch data at the dock. Smartphones can provide near real-time information for adaptive management as digital data can quickly be transmitted and analyzed.[50] Better data on catch quantities and composition can form the basis for data-limited stock assessments, provide information for setting catch limits and help improve access to sustainability-conscious markets. EDF is currently partnering with Vericatch to deploy a smartphone-based data collection tool called FisheriesApp that can be used at the dock (or at sea) to collect vital information on catch. The tool is being used in small-scale fisheries in Indonesia, Chile, Belize and Peru where it is providing readily available catch data aimed at making management more adaptive and fisheries more resilient.[51]

48 Bahri, T., Vasconcellos, M., Welch, D. J., Johnson, J., Perry, R. I., Ma, X., & Sharma, R. (2021). *Adaptive management of fisheries in response to climate change.* FAO Fisheries and Aquaculture Technical Paper No. 667. Rome, FAO. https://doi.org/10.4060/cb3095en

49 Bradley, D., Merrifield, M., Miller, K. M., Lomonico, S., Wilson, J. R., & Gleason, M. G. (2019). Opportunities to improve fisheries management through innovative technology and advanced data systems. *Fish and Fisheries,* 20(3), 564–583. https://doi.org/10.1111/faf.12361

50 Ibid. Cusack et al. (2021).

51 Cusack, C. (2019, October 9). Behind the scenes: *The future of sustainable crabmeat.* EDFish. https://blogs.edf.org/edfish/2019/10/09/behind-the-scenes-the-future-of-sustainable-crabmeat/

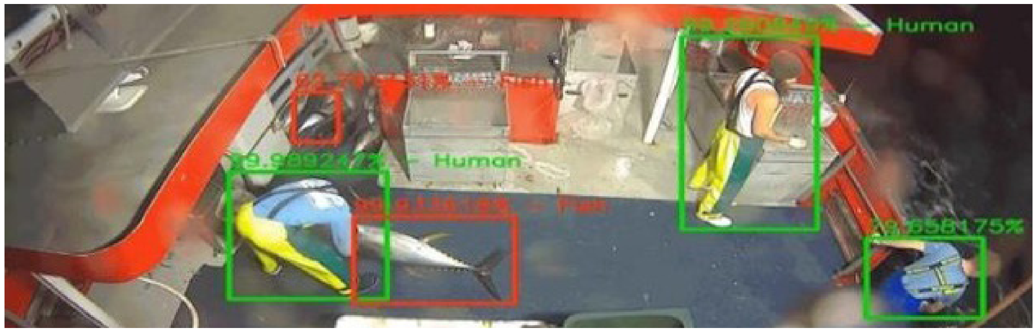

FIGURE 14: Activity recognition on a longline vessel. *AFMA*

On deck

While offloading sites might be the best place to collect data on fish that are landed, managers also need accurate and current information on what is being discarded during fishing operations. For decades, many countries have deployed human observers to monitor fishing activity while at sea, but this is expensive and comes with a logistical burden to fishers. Over the last decade, the use of onboard cameras (electronic monitoring) has begun to emerge as an alternative. However, challenges remain in terms of making electronic monitoring significantly more cost-effective than human observers. Video cameras can record what is discarded at sea, but reviewing large volumes of video footage is time consuming and expensive, something that has limited the number of fisheries where this kind of data collection is feasible.[52] However, new AI-enabled camera systems hold promise for reducing both the cost of data collection and the time required to integrate that data into management. These smart systems drastically reduce the amount of video to be stored, transmitted and analyzed by recognizing the specific activities that need to be recorded, such as hauling back, sorting or discarding fish overboard.[53] For example, in the Hawaii longline fishery, where vessels are at sea for months at a time, NOAA has successfully used AI activity recognition software to reduce the amount of video that needs to be stored and reviewed.[54] On the U.S. West Coast, EDF is working with partners SnapIT, Teem Fish and CVision AI to not only use activity recognition to reduce video review costs, but also to eliminate the need for shipping hard drives by distilling and compressing the video enough to transmit it wirelessly into the hands of managers.[55]

AI can also be used to then review the more focused video footage and automatically identify species, count fish and measure fish size or weight.[56,57] For example, in Alaska's groundfish fishery, NOAA has partnered with the University of Washington to use AI to review footage and automatically identify species and size fish passing through a discard chute.[58] The approach is becoming used more widely, and new companies like New England Marine Monitoring, Ai.Fish and CVision AI are specializing in using AI to review fisheries-related video and efficiently generate data for managers. While these systems have reduced the need for human video review, they have not yet eliminated it. In the not-too-distant future, however, it is likely that AI-enabled cameras could review video files and transmit only summary data reports to managers rather than bulky video files.[59] With AI-related cost reductions and improved satellite coverage, electronic monitoring could expand into smaller-scale fisheries where there is a critical need for improved accountability and rapid access to better data.[60]

In the not-too-distant future, however, it is likely that AI-enabled cameras could review video files and transmit only summary data reports to managers rather than bulky video files.

52 Helmond, A. T. M. van, Mortensen, L. O., Plet-Hansen, K. S., Ulrich, C., Needle, C. L., Oesterwind, D., Kindt-Larsen, L., Catchpole, T., Mangi, S., Zimmermann, C., Olesen, H. J., Bailey, N., Bergsson, H., Dalskov, J., Elson, J., Hosken, M., Peterson, L., McElderry, H., Ruiz, J., … Poos, J. J. (2020). Electronic monitoring in fisheries: Lessons from global experiences and future opportunities. *Fish and Fisheries*, 21(1), 162–189. https://doi.org/10.1111/faf.12425

53 Woodward, B., Hager, M., & Cronin, H. (2020). *Electronic monitoring: Best practices for automation* (p. 18). Gulf of Maine Research Institute.

54 Qiao, M., Wang, D., Tuck, G. N., Little, L. R., Punt, A. E., & Gerner, M. (2021). Deep learning methods applied to electronic monitoring data: Automated catch event detection for longline fishing. *ICES Journal of Marine Science*, 78(1), 25–35. https://doi.org/10.1093/icesjms/fsaa158

55 Mahoney, M., & Jud, S. (2021, March 1). Computer-assisted monitoring technologies are set to revolutionize fisheries. *EDFish*. https://blogs.edf.org/edfish/2021/03/01/computer-assisted-monitoring-technologies-are-set-to-revolutionize-fisheries/

56 Khokher, M. R., Little, L. R., Tuck, G. N., Smith, D. V., Qiao, M., Devine, C., O'Neill, H., Pogonoski, J., Arangio, R., & Wang, D. (2021). Early lessons in deploying cameras and artificial intelligence technology for fisheries catch monitoring: Where machine learning meets commercial fishing. *Canadian Journal of Fisheries and Aquatic Sciences*. https://doi.org/10.1139/cjfas-2020-0446

57 Tseng, C.H., & Kuo, Y.F. (2020). Detecting and counting harvested fish and identifying fish types in electronic monitoring system videos using deep convolutional neural networks. *ICES Journal of Marine Science*, 77(4), 1367–1378. https://doi.org/10.1093/icesjms/fsaa076

58 Ferdinand, J. (2020). *Fisheries Information System National Observer Program FY 2021 Project Proposal*. https://apps-st.fisheries.noaa.gov/pims/main/public?method=DOWNLOAD_PROPOSAL&record_id=4150

59 Michelin, M., & Zimring, M. (2020). *Catalyzing the growth of electronic monitoring in fisheries, progress update*. The Nature Conservancy https://www.nature.org/content/dam/tnc/nature/en/documents/Catalyzing-EM-2020report.pdf

60 Bartholomew, D., Mangel, J., Alfaro Shigueto, J., Pingo Paiva, S., Jimenez Heredia, A., & Godley, B. (2018). Remote electronic monitoring as a potential alternative to on-board observers in small-scale fisheries. *Biological Conservation*, 219. https://doi.org/10.1016/j.biocon.2018.01.003

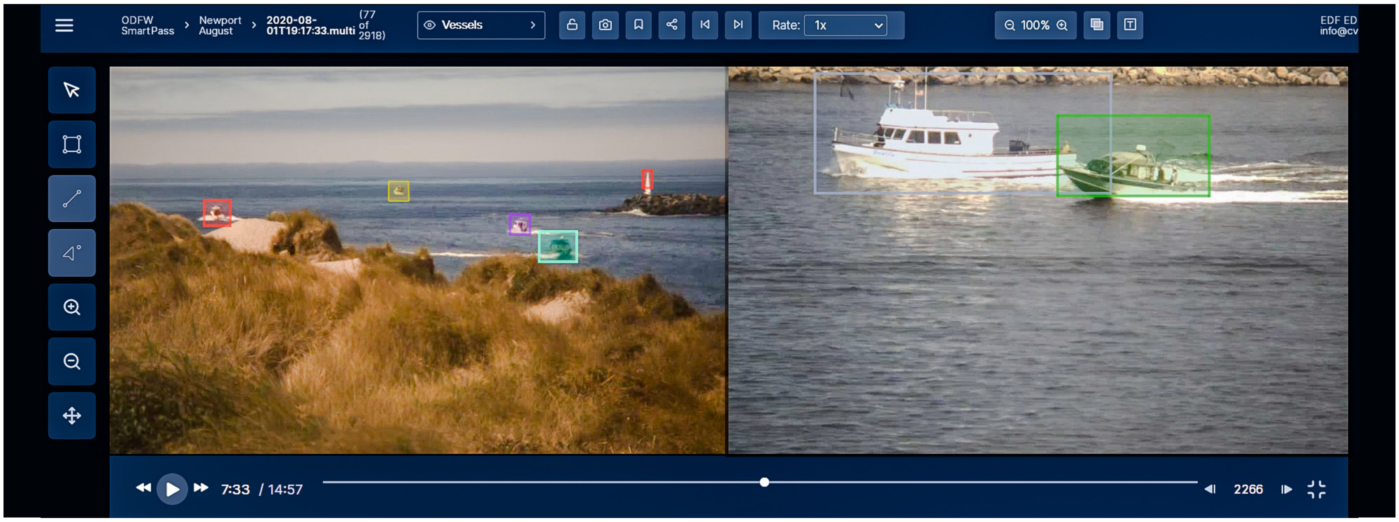

FIGURE 15: View from a SmartPass camera setup which can reliably detect fishing vessels with 90% accuracy within a range of 365m from the lens. *CVision AI*

In processing plants

Data collection for management typically happens before fish are processed. However, the conveyor belts used inside many plants can present good opportunities and views for cameras to efficiently collect data. In Alaska for example, NOAA is using cameras positioned over conveyor belts and species identification algorithms to detect and quantify salmon bycatch in groundfish trawl deliveries.[61] Efficient AI-based species recognition and sorting systems are also being designed to improve the efficiency of seafood processing. Machine vision conveyor systems such as those from Cabinplant are now available and capable of identifying and measuring up to 320 fish per minute. While these systems are designed to enhance plant operations and not to collect management data, potential dual use could be an example of how public and private sectors could partner to collect the data needed to make management more adaptive and fisheries more resilient.

From shore

Many small-scale fisheries are not well monitored or managed and are at risk of overfishing. As the climate changes, these risks can increase and new cost-effective means of measuring and controlling harvest will be needed to improve resilience. Data on fishing effort is vital. While many large-scale fisheries are required to submit detailed logbooks describing their effort, it can be harder to quantify effort in small-scale commercial fisheries and recreational fisheries, both of which can have significant impacts on fish stocks. In recreational fisheries, fishers are rarely required to report their effort and recreational surveys are expensive and can be challenging to conduct.[62]

AI-enabled shore-side camera systems can record vessel activity and quantify patterns in fishing effort and allow for adaptive adjustments in monitoring or enforcement in real-time. These systems place no burden on fishers and if properly placed, shoreside cameras can monitor diffuse vessel activity. EDF and partners have developed and piloted an approach called SmartPass where cameras are placed at a coastal bottleneck such as a pass, river mouth, port or harbor to continually count and provide a live view of passing vessels. Video data are analyzed by a set of algorithms custom to that location that can differentiate between vessel types. The data generated provide valuable information on not only the number of vessels fishing, but also on seasonal patterns, responses to weather, and pulse or high effort periods.[63] SmartPass systems have been installed in the Gulf of Mexico to assess effort in the recreational red snapper fishery, in Oregon to better understand recreational fishing effort, and in Indonesia's Lampung province to help monitor the blue swimming crab fishery. As with vessel-based camera systems, the future direction is to run the algorithms on the camera system itself, which will reduce storage and transmission costs. EDF is partnering with CVision AI and Ai.Fish to explore this model which will help scale the approach to a broader suite of fisheries and geographies.

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61 Ibid. Ferdinand. (2020).

62 Hartill, B. W., Taylor, S. M., Keller, K., & Weltersbach, M. S. (2020). Digital camera monitoring of recreational fishing effort: Applications and challenges. *Fish and Fisheries*, 21(1), 204–215. https://doi.org/10.1111/faf.12413

63 Haukebo, S., Poon, S., Cusack, C., Garren, M., Kenyon-Benson, J., Schindler, E., Tate, B., & Ai, Cv. (2021). SmartPass: *An Innovative Approach to Measure Fishing Effort Using Smart Cameras and Machine Learning*. Environmental Defense Fund.

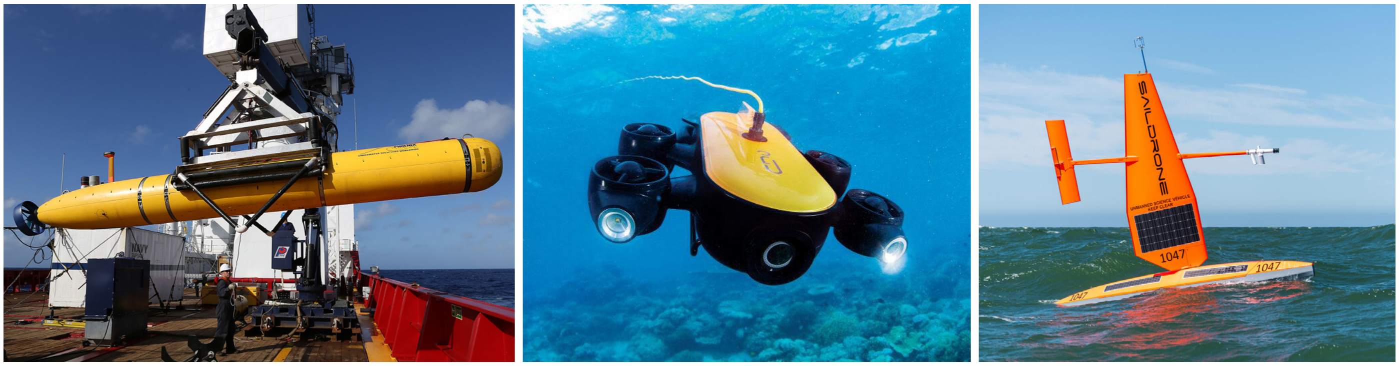

FIGURE 16: Examples of *in-situ* data collection platforms. *Alamy, Geneinno, Saildrone*

Data processing

In the context of climate change, having a diversity of data streams and indicators is vital to detecting and responding to changing conditions. One of the fastest growing applications of new technology in fisheries is the collection of data *in-situ* by cameras and other sensors towed by boats, fixed to the seabed, mounted to autonomous underwater vehicles (AUVs), autonomous surface vehicles (ASVs), aerial drones, or to fishing gear. The data can improve fisheries stock assessments and provide other information that can make fisheries management more adaptive.

However, the amount of data generated by *in-situ* cameras and sensors can be overwhelming and easily exceed processing and analytical capacity.[64] As one means of addressing this challenge, NOAA has developed an open-source Video and Image Analytics for Marine Environments (VIAME) toolbox which contains machine learning algorithms for automated object detection, tracking and classification for use across different data collection platforms. The VIAME toolbox has been applied to underwater camera surveys aimed at informing stock assessments for a wide range of species including Gulf of Mexico reef fish, Northeast sea scallops and Bering Sea walleye pollock. NOAA estimates that the system reduces analytical costs by as much as 75%.[65] Due to the speed of AI-based video processing, results are fed into stock assessments within months rather than years, helping to ensure that management is responsive and adaptive.[66]

Decision support tools

The data that technology produces are only as useful as the decisions they help to inform. Understanding the significance of data, and the tradeoffs associated with different

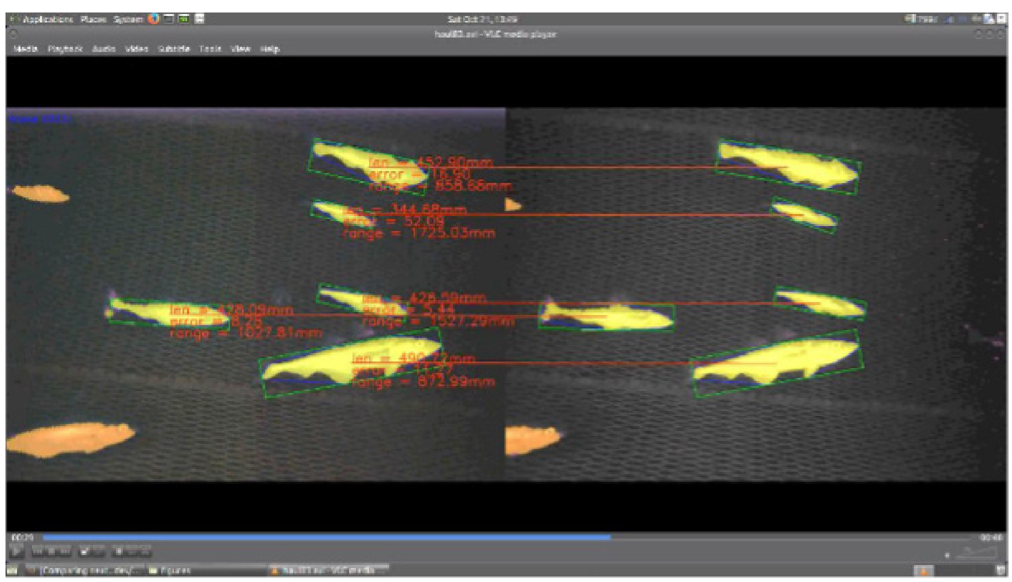

FIGURE 17: Walleye pollock in a camera survey are measured in the VIAME platform. *NOAA*

64 Hoogs, A., Richards, B., & Dawkins, M. (2017). *Underwater video datasets and the VIAME open-source framework for fisheries stock assessment.*
65 Michaels, E. W. L., Handegard, N. O., Malde, K., & Hammersland-White, H. (2019). *Machine Learning to Improve Marine Science for the Sustainability of Living Ocean Resources* (NOAA Technical Memorandum NMFS-F/SPO-199; p. 108).
66 Red Snapper Science Improves Fishery Estimates. (2021, June 7). *The Fishing Wire.* https://thefishingwire.com/red-snapper-science-improves-fishery-estimates/

FIGURE 19: EDF's FISHE stepwise assessment and adaptive management process. *EDF*

management responses is critical to improving a fishery's ecological and economic resilience. Decision support tools are becoming integral to linking fisheries data collection and analysis to the adaptive management process. They represent a state-of-the-art connection between good science and sound policy by helping to compare various management responses and identifying the optimal choice based on the goals of the fishery.

One class of these tools perform what is generally known as management strategy evaluation (MSE). MSE uses computer simulation models to test and compare the performance of a set of candidate management strategies while taking uncertainty into account. MSEs do this by simulating the behavior of fish stocks and the ecosystem, the effect of different levels of exploitation and harvest strategies on the fished stocks and the ecosystem, data collection, data analysis and assessment.[67] Open source MSE software is available, and stepwise MSE-based tools that can be used even in data-limited fisheries such as the Data Limited Methods Toolkit (DLMtool) are increasingly being used to guide management choices and determine the most important data to collect.

Another class of decision support tools is specifically aimed at fisheries with more limited data availability. Here the focus is on integrating fisheries stakeholder input with the best available science through a facilitated participatory process. The two main tools in this category are EDF's Framework for Integrated Stock and Habitat Evaluation (FISHE) which is being used as the basis for improving multispecies fisheries management in the Philippines, Indonesia, Portugal, Belize, Mexico, Cuba and Chile, and The Nature Conservancy's FishPath.[68] Both are increasingly used in small-scale fisheries to identify collaborative management approaches and pinpoint the most efficient and effective ways to focus data collection efforts. While all of these decision support tools and frameworks are effective ways of turning data into decisions, future iterations should also identify the technological approaches that are available to help users implement the management and data collection strategies that they recommend.

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68 Karr, K. A., Miller, V., Coronado, E., Olivares-Bañuelos, N. C., Rosales, M., Naretto, J., Hiriart-Bertrand, L., Vargas-Fernández, C., Alzugaray, R., Puga, R., Valle, S., Osman, L. P., Solís, J. C., Mayorga, M. I., Rader, D., & Fujita, R. (2021). Identifying Pathways for Climate-Resilient Multispecies Fisheries. *Frontiers in Marine Science*, 8. https://www.frontiersin.org/article/10.3389/fmars.2021.721883

SECTION 4

Climate challenge — Improving the climate resilience of vulnerable small-scale fisheries and communities

Photography by
Pablo Sanchez Quiza

Impacts

Small-scale fisheries account for over half of the world's wild-caught seafood, involve over 90% of all fishers globally and provide employment for over 100 million people.[69,70,71] However, small-scale fisheries and the communities that depend on them are also the most vulnerable to climate change impacts due to a range of interlinked social, ecological and economic factors that limit their ability to adapt to changing conditions.[72] Many small-scale fisheries communities are highly-dependent on local marine resources for food and livelihoods and often have few alternatives to meet these needs.[73] The poleward species shifts described in the previous section are likely to disproportionately impact small-scale fisheries, with the greatest negative impacts projected in the tropics.[74,75] Based on model estimates, tropical countries may lose 15% of their fish species by 2100 under a moderate emissions scenario, or more than 40% under a higher emissions scenario.[76] Additionally, more violent storms and sea-level rise jeopardize fishers' safety and can lead to large-scale small-scale fisheries community displacement.[77]

Based on model estimates, tropical countries may lose 15% of their fish species by 2100 under a moderate emissions scenario, or more than 40% under a higher emissions scenario.

Often, many of the technological advancements discussed in previous sections, such as on-deck electronic monitoring, automated data logging, satellite communications and

69 FAO (2020). The State of World Fisheries and Aquaculture 2020: Sustainability in action. Rome https://doi.org/10.4060/ca9229en

70 FAO (2015) Voluntary Guidelines for Securing Sustainable Small-Scale Fisheries in the Context of Food Security and Poverty Eradication. Rome. http://www.fao.org/documents/card/en/c/I4356EN

71 Béné, C., Macfadyen, G., & Allison, E.H. Increasing the contribution of small-scale fisheries to poverty alleviation and food security. FAO Fisheries Technical Paper. No. 481. Rome, FAO. 2007. 125p. http://www.fao.org/3/a0965e/a0965e.pdf

72 Bahri, T., Vasconcellos, M., Welch, D. J., Johnson, J., Perry, R. I., Ma, X., & Sharma, R. (2021). *Adaptive management of fisheries in response to climate change*. FAO. https://doi.org/10.4060/cb3095en

73 Hanich, Q., Wabnitz, C. C. C., Ota, Y., Amos, M., Donato-Hunt, C., & Hunt, A. (2018). Small-scale fisheries under climate change in the Pacific Islands region. *Marine Policy*, 88, 279–284. https://doi.org/10.1016/j.marpol.2017.11.011

74 Pinsky, M. L., Reygondeau, G., Caddell, R., Palacios-Abrantes, J., Spijkers, J., & Cheung, W. W. L. (2018). Preparing ocean governance for species on the move. *Science*, 360(6394), 1189–1191. https://doi.org/10.1126/science.aat2360

75 Ojea, E., Lester, S. E., & Salgueiro-Otero, D. (2020). Adaptation of Fishing Communities to Climate-Driven Shifts in Target Species. *One Earth*, 2(6), 544–556. https://doi.org/10.1016/j.oneear.2020.05.012

76 Oremus, K. L., Bone, J., Costello, C., García Molinos, J., Lee, A., Mangin, T., & Salzman, J. (2020). Governance challenges for tropical nations losing fish species due to climate change. *Nature Sustainability*, 3(4), 277–280. https://doi.org/10.1038/s41893-020-0476-y

77 Hauer, M. E., Fussell, E., Mueller, V., Burkett, M., Call, M., Abel, K., McLeman, R., & Wrathall, D. (2020). Sea-level rise and human migration. Nature Reviews Earth & Environment, 1(1), 28–39. https://doi.org/10.1038/s43017-019-0002-9

FIGURE 19: FAME transponder in the Philippines. *FAME/ oceanspartnership.org*

on-board predictive mapping are not yet feasible for widespread uptake in small-scale fisheries. These fisheries require solutions that take their economic and infrastructural limitations into account, which include:

- Limited resources to fund the purchase and use of technologies
- Poor internet connectivity on land and at sea
- A lack of reliable electricity sources (batteries, generators) on vessels to run and charge equipment
- Lack of protected, dry and temperature-controlled environments on vessels leads to rapid deterioration and corrosion of equipment
- Education and familiarity with technology use can be low[78]

Given these limitations, technologies that improve the climate resilience of small-scale fisheries and their communities are well-centered on fundamental needs such as 1) increasing safety at sea, 2) enhancing markets for small-scale fisher products, and 3) community building around resource management.[79] This section examines each of these uses.

Improving safety at sea

Fishing is a dangerous occupation and small-scale fishers are exposed to even higher levels of risk than their counterparts in more industrialized fisheries.[80] In the developing tropics, increasingly violent and unpredictable storms due to climate change are amplifying this risk, putting lives and communities in greater danger. For example, in 2017 Cyclone Ockhi killed hundreds of fishers at sea off coastal India,[81] and in 2011 an unusually severe tropical storm that was not forecasted destroyed hundreds of boats and killed thousands at sea off Myanmar.[82] Increasing unpredictability of the timing and strength of these weather events reduces the effectiveness of traditional ecological knowledge systems that fishers rely on to predict when, where and how they can operate safely, and reduces authorities' ability to predict and communicate potentially lifesaving information.[83]

New technologies can increase safety at sea by providing timely and accurate weather forecasts, including information about wave patterns and wind directions, and by providing reliable communication systems that allow fishers to connect with each other and their communities in emergencies. There are an increasing number of smartphone apps that fishers can use while in cell phone range that focus on ensuring safety at sea, including mFisheries in the Caribbean, Fisher Friend and mKRISHI in India, and Abalobi in South Africa.

78 Ibid FAO (2020)
79 Ibid FAO (2020)
80 Zytoon, M. A., & Basahel, A. M. (2017). Occupational Safety and Health Conditions Aboard Small- and Medium-Size Fishing Vessels: Differences among Age Groups. *International Journal of Environmental Research and Public Health*, 14(3), 229. https://doi.org/10.3390/ijerph14030229
81 Martin, M. (2017, December 13). Confusion, apathy defeated Cyclone Ockhi warnings and killed fishers. *India Climate Dialogue*. https://indiaclimatedialogue.net/2017/12/13/headline-confusion-apathy-defeated-cyclone-ockhi-warnings-killed-fishers/
82 *Over 3,700 Burmese Fishermen Still Missing, Presumed Dead*. (n.d.). Retrieved September 13, 2021, from https://www2.irrawaddy.com/article.php?art_id=21012
83 Sainsbury, N. C., Genner, M. J., Saville, G. R., Pinnegar, J. K., O'Neill, C. K., Simpson, S. D., & Turner, R. A. (2018). Changing storminess and global capture fisheries. *Nature Climate Change*, 8(8), 655–659. https://doi.org/10.1038/s41558-018-0206-x

There is also growing organic use of group messaging through WhatsApp globally to obtain and relay information on sea conditions.[84] However, shifting and increasingly variable stocks can require fishers to venture farther from port in search of their catch, often out of range of land-based cell phone towers.

The ability to continue to communicate in real-time as fishers move further offshore and to transmit a vessel's location is vital to safety. Currently, traditional satellite-based vessel location tracking devices that incorporate an Automatic Identification System (AIS) or Vessel Monitoring System (VMS) are often out of reach for small-scale fishers. While an increasing number of low-cost satellite VMS systems such as Navcast's Skymate and Alon units and Collecte Localisation Satellites' NEMO are coming to market, these systems are still financially out of reach for the majority of small-scale fisheries.[85,86] Constellations of thousands of interconnected broadband communication satellites are also coming online rapidly. Starlink, for example, has projected it will be able to provide global high speed maritime coverage by mid 2022.[87] And while these services will also initially be out of financial reach ($99 to $499/month plus hardware[88]), costs are likely to decrease significantly over time. As an alternative to satellite communication, lower-cost ($15/month) radio transponders are available from manufacturers such as Futuristic Aviation and Maritime Enterprises (FAME) and are in use in locations like the Philippines.[89] FAME transponders use radio frequencies to send and receive location data in real-time up to 50 km from shore, which is extended further through a mesh network of other transponders. The devices have an integrated SOS button and allow for ship-to-shore and shore-to-ship personal communications without cell service.[90] These systems allow fishers to exchange information with each other and with community members on shore who have access to up-to-date weather conditions.

Improving the economics of small-scale fisheries

Poor infrastructure, weak institutions and lack of alternative revenue opportunities can trap fishers and their communities in poverty and leave them particularly vulnerable to climate change. Long supply chains with low transparency can also inhibit market access, and a lack of pricing information can contribute to low ex-vessel revenue. Inability to access credit and financing from traditional banks can also prevent small-scale fishers from increasing their operational efficiency and can force some to turn to predatory lenders. Technological solutions are enabling small-scale fishers to overcome some of these obstacles and increase their economic resilience.

Better prices

Inability to access credit and financing from traditional banks can also prevent small-scale fishers from increasing their operational efficiency and can force some to turn to predatory lenders.

For example, new mobile applications that allow fishers to sell their catch directly to the marketplace or direct to the consumer can increase revenue, income security and encourage social enterprise within fishing communities. Other online platforms such as government-sponsored fish markets and Facebook buy-and-sell groups can also serve this role.[91] Essentially, these technologies eliminate the middleman, allowing fishers to sell their product at fair value into a wider variety of markets. Abalobi's *marketplace* app offers a prime example, enabling fishers to sell directly to various types of buyers in local markets while providing logistical support to process and ship products. Abalobi's local buyers, including restaurants, retailers, home cooks and others, pay using rapid electronic payments through the app at prices up to four times higher than those previously paid by processors.[92]

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84 Ibid. FAO. (2020). see Appendix 3, Table 8 which lists mobile apps, their focal uses and regions of use.

85 *SkyMate M1600 type approved by BFAR for Philippine fisheries.* (n.d.). NAVCAST. Retrieved September 13, 2021, from https://www.navcast.com/press-release-1

86 Small-scale Fisheries NEMO System. (n.d.). *CLS Fisheries.* Retrieved September 13, 2021, from https://fisheries.groupcls.com/sustainable-fisheries-administrations/nemo-for-small-scale-fisheries/

87 Arevalo, E. J. (2021, November 13). SpaceX Starlink Internet Network Will Have Global Maritime Coverage By Mid-2022. Tesmanian. https://www.tesmanian.com/blogs/tesmanian-blog/starlink-sats-1

88 Sheetz, M. (2022, February 2). SpaceX rolls outs "premium" Starlink satellite internet tier at $500 per month. CNBC. https://www.cnbc.com/2022/02/02/spacex-starlink-premium-satellite-internet-tier-at-500-per-month.html

89 *Safer at sea: The unexpected benefit of traceability for small-scale fishers.* (2019, November 12). Mongabay Environmental News. https://news.mongabay.com/2019/11/safer-at-sea-the-unexpected-benefit-of-traceability-for-small-scale-fishers/

90 Ibid. FAME – *The Oceans and Fisheries Partnership.*

91 Swanson, G., & Rechio-Blanco, X. (2021, April 28). Sustainable Finance of Small-Scale Fisheries in the Face of the COVID-19 Crisis. https://www.americanbar.org/groups/environment_energy_resources/publications/natural_resources_environment/2020-21/spring/sustainable-finance-smallscale-fisheries-the-face-the-covid19-crisis/

92 Stone, I. S. (2019, January 15). This App Is Providing Job Security to Traditional South African Fishers. Saveur. https://www.saveur.com/south-africa-fishing-app-abalobi/

Examples of other fisher-to-marketplace apps include OurFish, used in Honduras, Belize, Myanmar, Indonesia and Mozambique, Odaku in India, and Aruna in Indonesia. Aruna, an Indonesian start-up, enables the 21,000 fishers on its platform to sell their products into both local and international markets in Asia and North America through its digital marketplace. The platform also provides the necessary infrastructure to collect, quality check, process and package products for wide distribution.[93] Like Abalobi, the end result is an increase in fishers income, with fishers earning three to ten times more on Aruna than previously.[94]

New markets

To access some markets, particularly those with sustainability-conscious consumers, traceability is a necessity. Traceability may be integrated into marketplace apps or used in freestanding platforms. For example, Abalobi's marketplace app as well as the Aruna app attach a unique QR code to each sale, enabling a form of traceability from fisher to consumer. Trafiz, developed by the United States Agency for International Development (USAID) for Indonesian fisheries, is a mobile catch documentation app where fish buyers and suppliers record traceability data at the point of landing.[95] Although not yet integrated into any of the marketplace apps geared to small-scale fishers, blockchain technology is emerging as a traceability tool for high value fish.[96] Notable initiatives include FishCoin, a start-up that attempts to make the fisheries sector more sustainable by incentivizing data reporting by providing crypto tokens in exchange for data. Other initiatives that use blockchain to track individual fish are Provenance for tuna and OpenSC for Patagonian toothfish. Greater use of traceability technologies will not only help promote sustainable fishing but can help enhance the economic health and resilience of fishing communities through access to diverse and high-value markets.

Financial technology

Access to financial technology, known collectively as fintech, can also open new opportunities to fishing communities. Fintech tools can enable fishers to maintain and grow their businesses and conduct transactions via mobile marketplace apps that link users to online financial tools, such as savings accounts, microcredit, digital money, cryptocurrency transfers and insurance. As an example, following sale of their catch fishers can immediately pay their crew via money transfer through a marketplace app.[97] Some of the marketplace apps, like Abalobi and Aruna, have built or are building linkages to these fintech tools with an initial focus on loans and obtaining insurance for vessels and equipment.

Women and technology

New efforts should focus on determining what tools and platforms would best serve women in their supply chain roles and invest significantly in their development.

It is important to highlight that while these mobile technology tools are primarily directed at commercial fishers, who are predominantly male, they also benefit women, who make up 47% of small-scale fishery workers.[98] Although only 11% of small-scale fishing activity is carried out by women, they constitute 85-90% of the post-harvest processing workforce and often serve as the initial fish buyers and traders.[99,100] Both Abalobi and Aruna have created jobs for women in the seafood processing sector, and both apps track post-harvest processing activity. New efforts should focus on determining what tools and platforms would best serve women in their supply chain roles and invest significantly in their development. This can have an outsized impact on increasing the resilience of small-scale fishery communities.

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93 Shu, C. (2021, July 21). Indonesia "sea-to-table" platform Aruna hooks $35M led by Prosus and East Ventures Growth Fund. TechCrunch. https://social.techcrunch.com/2021/07/21/indonesia-sea-to-table-platform-aruna-hooks-35m-led-by-prosus-and-east-ventures-growth-fund/
94 Deep blue sea(food): How Indonesian marine fisheries startup Aruna being recognized at the international level – Endeavor Indonesia. (2021, May 20). https://endeavorindonesia.org/deep-blue-seafood-how-indonesian-marine-fisheries-startup-aruna-being-recognized-at-the-international-level/
95 Trafiz – *The Oceans and Fisheries Partnership*. (n.d.). Retrieved January 5, 2022, from https://www.seafdec-oceanspartnership.org/traceability-tools/trafiz/
96 Turns, A. (2021, June 9). Hook to plate: How blockchain tech could turn the tide for sustainable fishing. The Guardian. https://www.theguardian.com/environment/2021/jun/09/hook-to-plate-how-blockchain-tech-can-turn-the-tide-for-sustainable-fishing-aoe
97 Ibid. Stone. (2019).
98 Biswas, N. (2018). Towards Gender-Equitable Small-Scale Fisheries Governance and Development: A Handbook. UN. https://doi.org/10.18356/e999fb85-en
99 Harper, S., Adshade, M., Lam, V. W. Y., Pauly, D., & Sumaila, U. R. (2020). Valuing invisible catches: Estimating the global contribution by women to small-scale marine capture fisheries production. *PLOS ONE*, 15(3), e0228912. https://doi.org/10.1371/journal.pone.0228912
100 Ibid Biswas. (2018).

FIGURE 20: Aruna's e-commerce platform employs women in its processing facilities in Indonesia. *Australian Embassy, Jakarta, Indonesia*

Empowering communities

Along with reducing poverty, a key challenge to building climate resilience in small-scale fisheries can be a lack of organization, self-governance and community development as small-scale fisheries s are often dispersed and often focused on essential day to day operations. Indonesia, for example, has over 17,000 islands and over 2.8 million fishers with a total fisheries workforce of over 12 million people speaking a variety of languages and dialects. At the same time, national resource management agencies are typically underfunded and understaffed with low capacity for engaging with fishing communities.[101,102]

Communication technologies have the potential to facilitate community organization and development by better linking individuals within the community and connecting the community to outside resources. These technologies include social media and instant messaging apps like WhatsApp which are regularly used by fishing communities in some places to communicate with each other individually or as chat groups.[103] Improved connectivity via wi-fi extenders and repeaters and/or low-cost satellite service, and applications that can work when connectivity is sporadic may be especially important in these contexts. Global platforms aimed specifically at small-scale fisheries can also serve this function. For example, the Small-Scale Fisheries Resource and Collaboration Hub (SSF Hub) is a low-data requirement website available in twenty languages that helps connect and provide resources for small-scale fisheries. The SSF Hub provides the potential for collaborative learning through an interactive, globally accessible, multilingual platform that hosts information exchanges via discussion groups, topic fora, resource libraries and event listings.

Beyond core catch and effort data collection by fishers, collaborative scientific research involving community groups, non-governmental organizations (NGOs) and research institutions provides a valuable way to inform decision making in developing countries with under-resourced government agencies. Additionally, programs that involve non-scientists in scientific research can increase interactions between stakeholders, increase willingness

101 Wongbusarakum, S., De Jesus-Ayson, E.G., Weimin, M. & DeYoung, C. 2019. Building Climate-resilient Fisheries and Aquaculture in the Asia-Pacific Region – FAO/APFIC Regional Consultative Workshop. Bangkok, Thailand, 14-16 November 2017. Bangkok, FAO. https://www.fao.org/3/ca5770en/CA5770EN.pdf
102 https://www.nature.org/en-us/about-us/where-we-work/asia-pacific/indonesia/stories-in-indonesia/indonesia-fisheries/ (assessed October 1, 2021)
103 Ibid. FAO. (2020).

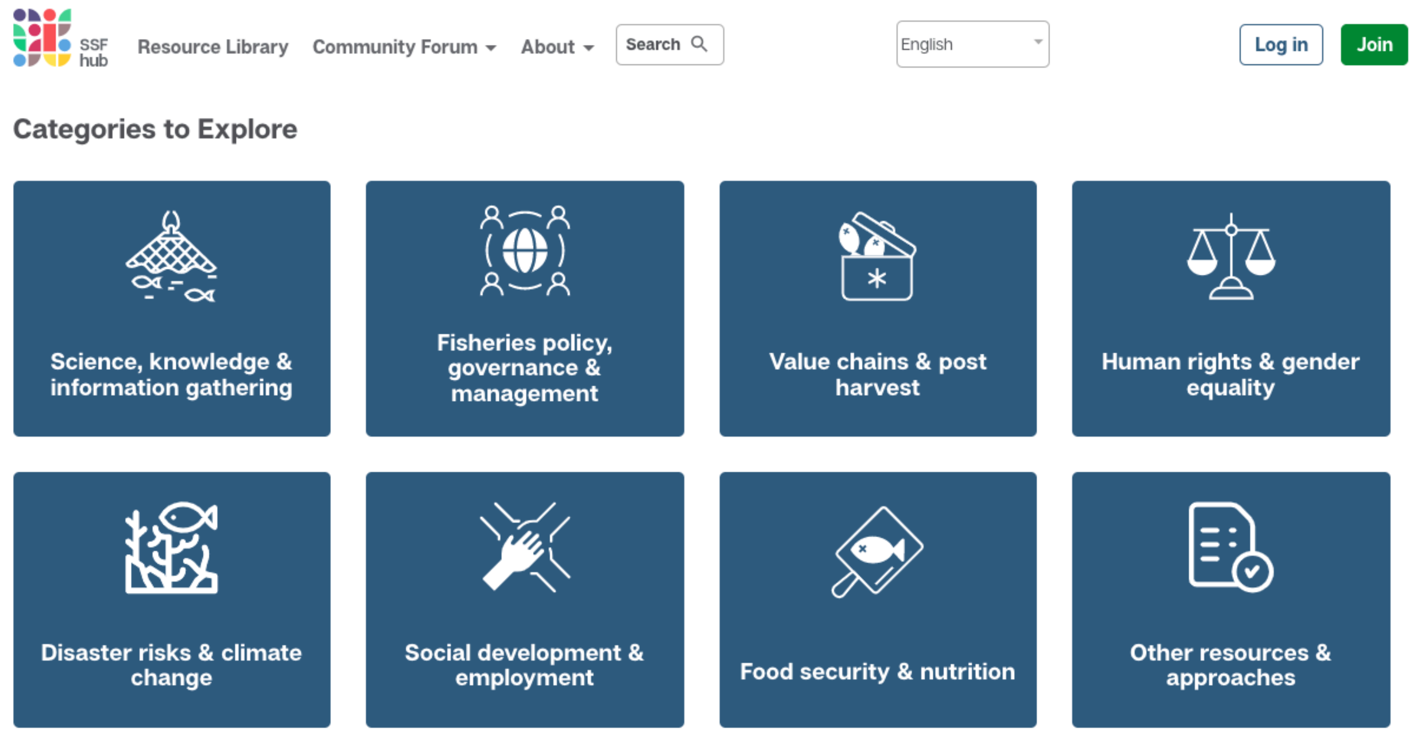

FIGURE 21: Categories available for exploration and discussion on the Small-Scale Fisheries Resource and Collaboration Hub (SSF Hub) *ssfhub.org*

to participate in and support marine resource management, increase adaptive capacity and promote overall resilience.[104] As an example, data collected by community members in underwater surveys in Mexico were used to support the creation of a network of marine reserves and evaluate federal protected areas.[105] Technology platforms, such as the globally accessible app iNaturalist can significantly aid with the identification and spatial and temporal tracking of marine species to inform management.[106]

Conclusion

As past, current, and future emissions inevitably alter our oceans, technological tools can help keep fisheries sustainable, resilient, profitable and safe. We are at an inflection point in the current digital revolution and are just beginning to glimpse technology's power to both conserve and harvest natural resources. This rapid innovation and refinement is outpacing the ability of most authorities to track the tools that are available and cost-effective for prosecuting and managing their fisheries. This means that efforts to share lessons, build partnerships and generate awareness of what's possible are more important than ever. While technologies constitute powerful tools, they are most effective as a means of implementing the broader policy, development and engagement strategies needed to protect our fisheries and coastal communities.

104 Fulton, S., López-Sagástegui, C., Weaver, A. H., Fitzmaurice-Cahluni, F., Galindo, C., Fernández-Rivera Melo, F., Yee, S., Ojeda-Villegas, M. B., Fuentes, D. A., & Torres-Bahena, E. (2019). Untapped Potential of Citizen Science in Mexican Small-Scale Fisheries. *Frontiers in Marine Science*, 6, 517. https://doi.org/10.3389/fmars.2019.00517
105 Ibid. Fulton et al. (2019).
106 Ibid. Fulton et al. (2019).

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