Fish Flow: following fisheries from spawning to supper

Mark A Hixon[1*], Brian W Bowen[1†], Richard R Coleman[1†], Chelsie W Counsell[1,2†], Megan J Donahue[1†], Erik C Franklin[1†], John N Kittinger[3,4†], Margaret A McManus[1†] and Robert J Toonen[1†]

Novel methodologies now make it possible to track the complete geographical movements of seafood species from reproduction to human consumption. Doing so will better inform consumers and assist resource managers in matching fisheries and conservation policies with natural borders and pathways, including stock boundaries, networks of marine protected areas, and fisheries management areas. Such mapping necessitates an unprecedented synthesis of natural and social sciences, including knowledge of adult fish population abundance and movements, egg output, larval dispersal, and recruitment to juvenile and adult habitats, as well as fisheries stock assessment, capture, and distribution through human social networks. The challenge is to fully integrate oceanography, population genetics, ecology, and social sciences with fisheries biology to reveal the patterns and mechanisms of "Fish Flow" from spawning to supper. As practitioners representing all five of these disciplines, we believe that Fish Flow analyses will promote sustainable fisheries management and marine conservation efforts, and may foster public knowledge, wise seafood choices, and appreciation of social–ecological interconnections involving fisheries.

Front Ecol Environ 2022; 20(4): 247–254, doi:10.1002/fee.2449

"Managing fisheries is hard: it's like managing a forest, in which the trees are invisible and keep moving around" – John Shepherd (unpublished lecture at Princeton University, 1978)

Increasing demand for seafood puts escalating pressure on marine resources, incentivizing overfishing and harmful fishing practices that damage marine ecosystems. Over one-third of global fish stocks are currently exploited unsustainably (FAO 2020), and this will likely only worsen as human populations continue to grow. At the same time, the healthiest fish stocks globally are those subject to modern fishery management (Hilborn *et al.* 2020). Beyond conventional management and more recent ecosystem-based approaches (Francis *et al.* 2007), marine conservation efforts in developed nations often focus on consumer choice to curtail industrial overfishing (Oken *et al.* 2012). Various means of educating seafood consumers include online monitoring of fishing vessels (eg Global Fishing Watch), blockchain technology to securely trace seafood supply chains (eg Two Hands), informational cards and smartphone apps (eg Seafood Watch), and seafood sustainability certifications (eg Marine Stewardship Council). The flow of seafood from fisheries to human consumption can be quite complicated, as illustrated by recent mapping efforts at local (Glazier *et al.* 2013), regional (Fuller *et al.* 2017), and global (Ramesh *et al.* 2019) scales; this complexity can hinder effective management and conservation, and impede informed consumer choice regarding seafood sources.

To address this gap, an interdisciplinary "Fish Flow" analysis would allow consumers, fishing communities, conservationists, marine resource managers, and policy makers to resolve the origin, status, and fate of seafood stocks, as well as appreciate the many connections and interdependencies among widely separated marine ecosystems and human communities. Although there have long been calls for multidisciplinary approaches to fisheries, to the best of our knowledge none have focused on spatially explicit mapping of the flow of fish from their origins at spawning to the dinner table. Here, we first briefly review the ecological and social context of Fish Flow, define it explicitly, and list how such analyses will benefit fisheries management and conservation. We then summarize

In a nutshell:

- Most exploited ocean species live in "stocks" or "marine metapopulations" (groups of isolated local populations connected by dispersal of larvae), which have proven difficult to delineate and study
- Recent methodological breakthroughs now allow mapping of fisheries stocks from spawning to human consumption, yet doing so will require unprecedented integration of oceanography, population genetics, ecology, fisheries biology, and social sciences
- Partial examples are now available for this developing synthesis, which will eventually culminate in web-based, interactive "Fish Flow" maps depicting the many connections and interdependencies between marine ecosystems and human communities
- Development of Fish Flow maps will inform sustainable fisheries and marine conservation efforts in unprecedented detail

[1]*University of Hawaii at Manoa, Honolulu, HI* [*]*(hixonm@hawaii.edu);* [2]*current address: Fairfield University, Fairfield, CT;* [3]*Conservation International, Honolulu, HI;* [4]*Arizona State University, Tempe, AZ;* [†]*these authors contributed equally to this work*

recent breakthroughs in the component disciplines, including examples of studies that have partially integrated these components, and explore why a comprehensive Fish Flow analysis has yet to be accomplished. We conclude with our vision of future web-based, interactive Fish Flow maps that inform the public, policy makers, and managers in unprecedented detail, which may also foster wise stewardship based on tangible knowledge of social–ecological interconnections.

Marine metapopulations and the pathways of marine fisheries

Most marine invertebrates and fishes have larval and adult forms so distinct that at times in the past they have been formally described as different species. Adults of most of these species do not move around very much, being either sessile or roaming a localized home range associated with the seafloor. The exceptions are open-ocean (pelagic) species that can migrate over vast ranges. Regardless of adult movements, spawners produce miniscule larvae that are capable of riding ocean currents and can settle either close to the spawning site or be dispersed great distances. This larval dispersal process connects groups of locally open populations into a relatively closed "marine metapopulation", known as a "stock" in fisheries (Kritzer and Sale 2004). Larval dispersal was long one of the great unknowns of marine science, yet recent breakthroughs now both predict and track patterns from spawning to "settlement", the transition from larval to juvenile life for seafloor-associated species (Cowen and Sponaugle 2009). Juveniles eventually undergo "recruitment" to the local population, and if captured as juveniles or adults, to the fishery (Caley *et al.* 1996). The combination of these biological cycles with fishery "stock assessments" (analyses of demographic data determining changes in stock size in response to fishing), as well as patterns and pathways of catch, distribution, and consumption by humans, comprises the complete social–ecological system of a marine fishery.

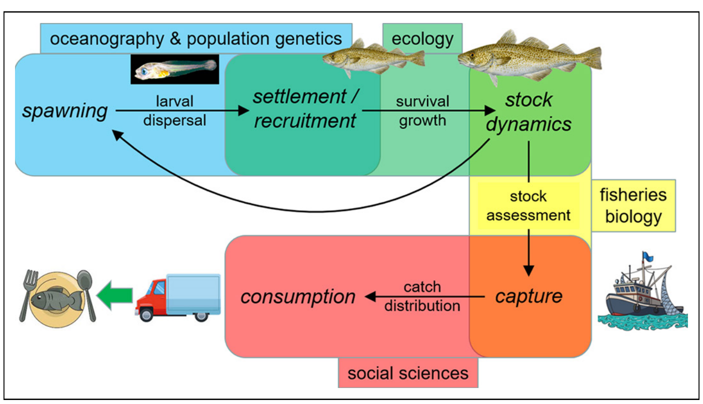

Figure 1. Conceptual diagram of the Fish Flow interdisciplinary approach for tracking fish from spawning to supper. The four colored blocks show the conventional domains of different disciplines: blue (oceanography and population genetics), green (ecology), yellow (fisheries biology), and pink (social sciences). Cumulatively, these blocks and the overlap between adjacent blocks cover the complete life cycle and fisheries of typical seafood species (cod [*Gadus* sp] illustrated). The arrow from *stock dynamics* to *spawning* indicates that the adult population is the source of reproduction.

What is Fish Flow and what are its benefits?

The Fish Flow concept was originally used by social scientists to describe the post-catch distribution of seafood through social networks on land (Severance *et al.* 2013), and has been assessed empirically on shore for some coastal fisheries (eg Glazier *et al.* 2013; Kittinger *et al.* 2015). Here, we incorporate marine natural sciences and expand the concept to be a fully integrated analysis that tracks the movement of seafood from spawning through larval dispersal, then juvenile and adult survival and growth, to capture, distribution, and consumption (Figure 1).

By revealing the details and mechanisms underlying marine metapopulation and fisheries dynamics holistically, a complete Fish Flow analysis will provide a variety of benefits to both management and conservation. Here, we provide just a few examples. Fish Flow will (1) elucidate the geographical boundaries of stocks in unprecedented detail, which is important because mismatches between natural fish population boundaries in the sea and often-arbitrarily delineated management areas can cause major errors in fishery policies (Berger *et al.* 2020); (2) enable biologically realistic design of community-based fisheries management areas, identifying the extent to which adjacent communities are linked both by movement of fisheries species at sea and by catch distribution on shore (Krueck *et al.* 2019); (3) facilitate the design of networks of marine protected areas by helping to pinpoint sites that seed other locations with particularly high numbers of larvae (Pelc *et al.* 2010); (4) identify explicit sources of seafood for consumers, enabling informed decisions regarding environmentally conscious diet choice (Richter and Klöckner 2017); and (5) illustrate the many interconnections between humans and marine ecosystems, which we hope will foster a conservation ethic based on the appreciation that all things are connected (Muir 1911).

Although the scientific benefits of Fish Flow are straightforward, it may be less clear that these analyses are also critical for influencing people's behavior regarding seafood choice. Conservation psychologists report that such behavioral change involves "background knowledge" like that provided by Fish Flow, which increases the willingness of consumers to make environmentally friendly choices (Almeida *et al.* 2015; Richter and Klöckner 2017). In general, knowledge that enhances a sense of connection with nature and appreciation of ecological interconnections (eg a Fish Flow map) tends to foster sustainable behaviors (Nisbet *et al.* 2009).

Fish Flow will integrate breakthroughs in five disciplines

A complete Fish Flow analysis will require an interdisciplinary synthesis of five fields of research. It is important to note that on its own, each discipline can reveal only a portion of the overall system (Figure 1). As practitioners of all five essential disciplines, we believe that fully integrated Fish Flow analyses will be forthcoming soon because of recent methodological breakthroughs, as well as the fact that partial (mostly pairwise) syntheses of the constituent fields are already occurring. Recent advances in each of the five constituent disciplines are discussed in the sections below.

Oceanography

Tracking dispersal of diminutive larvae over vast areas of the world's oceans has until recently been virtually impossible. Coupled physical-biological oceanographic models of ever-higher resolution can now simulate larvae as passive and/or active particles, tracking virtual larvae from spawning to settlement, thereby providing estimates of larval dispersal pathways and population connectivity (Swearer *et al*. 2019). The physical component of these models calculates water movement and physical structure within a defined ocean area, while the biological components attempt to emulate biotic processes during the larval lifespan. Life-history characteristics such as pelagic larval duration, as well as behaviors like depth selection, are critical to the accuracy of these coupled models (Metaxas and Saunders 2009). Although small larvae are typically incapable of swimming against horizontal currents, many can swim vertically (Mileikovsky 1973). A species that can orient itself relative to various physical features can vastly alter its horizontal transport distance (Woodson and McManus 2007).

Population genetics

Genetic techniques are now essential tools for characterizing connectivity in the ocean, revealing patterns of larval dispersal (Weersing and Toonen 2009). Population genetic methods historically used one or a few genomic regions (loci) to describe larval dispersal as gene flow over hundreds to thousands of kilometers. However, these methods are ineffective at identifying patterns of gene flow at smaller spatial scales relevant to ecology and fisheries. Using tiny tissue samples, advances in genomic techniques now allow parentage studies that use hundreds or thousands of loci to track individual larvae from spawning to settlement (D'Aloia *et al*. 2015). Parentage analyses, akin to the DNA fingerprinting used in forensic science, can link the location where the parent spawned to the location of the offspring, thereby resolving patterns of connectivity as well as self-recruitment back to the same local population (Abesamis *et al*. 2017). Fortunately, the costs of genetic analyses are declining rapidly, allowing the large sample sizes required to detect parent-offspring pairs in the sea.

Ecology

Detailed demographic studies of juvenile and adult fish and invertebrates now provide information on the rates of settlement/recruitment, growth, survival, and movements that drive and regulate local population dynamics (Hixon *et al*. 2012). Varying in time and space, these demographic rates ultimately form the foundation of fisheries production. Measures of input to local populations are provided by counts of new settlers (by divers) or of young-of-the-year recruits (by surface-based sampling gear). Demographic tools include mark–recapture studies (Pine *et al*. 2003) and analyses of rings in fish otoliths (calcium carbonate structures in the inner ear of fish that aid in orientation and hearing) (Campana 2005), both of which provide data on growth, survival, and movements. Tracing juvenile and adult movements has benefited from advances in miniature telemetry tags, along with subcutaneous microtags and markings that enable rapid individual identification (Pine *et al*. 2003). Otolith analyses include detection of the duration of the larval dispersal period and microchemical signatures locked in growth rings, which provide information about habitats used during different stages of fish development (Campana 2005). Measurements of egg production and spawning output provide estimates of larval production for the next generation. The rate at which larvae are produced is an essential parameter for calculating the volume of larval dispersal contributing to Fish Flow (Johnson *et al*. 2018). Mapping of spawning locations also reveals the time and place of gamete release that feed into larval dispersal models (Ciannelli *et al*. 2015).

Fisheries biology

Fisheries biology documents interactions among fish populations, the environment, and fishing communities to manage seafood resources. Traditionally, fishery-dependent data provided time series of effort and catch that informed the stock status of exploited species (Hilborn and Walters 1992). More recently, fishery vessel tracking systems collect high-resolution spatial and temporal patterns of effort and catch that support geographic analyses (Gerritsen and Lordan 2011). These systems provide information for examining fishery interactions with target stocks and their habitats, assessing fishing behavior and vessel interactions, and evaluating fishing activity relative to area closures. In addition, fishery-independent surveys provide unbiased data on metapopulation-scale abundance or biomass indices and life-history information for target species (Hilborn and Walters 1992). Of the five disciplines involved in Fish Flow, fisheries biology is the most integrative, with many fisheries scientists now making use of oceanographic models, population genetics, ecology, and social sciences (Essington *et al*. 2017).

Social sciences

Social sciences are as diverse as natural sciences, yet are amalgamated here with respect to how fishery catch connects to the dinner table (Figure 1). Marine social sciences can help illuminate social, economic, and cultural values, drivers, and factors associated with seafood capture, distribution, and consumption. Research on human dimensions of seafood catch distribution has grown in complexity, sophistication, and overall breadth, and is now viewed as critical for informing sustainability dialogues in policy and governance (Bennett 2019). As a prelude to more holistic Fish Flow analyses described here, recent studies have mapped the distribution of seafood among communities on shore, helping elucidate the structure of social networks relating to a fishery, as well as the food and livelihood security function of artisanal fisheries (Glazier *et al.* 2013; Severance *et al.* 2013; Kittinger *et al.* 2015). Related research has focused on the cultural dimensions of fishing activities and the role of social drivers, along with traditional and cultural practices, in determining catch distribution patterns and their value to communities. Social sciences have also focused on characterizing complex value chains for fisheries, examining the extent to which catch is channeled through commercial markets, as well as subsistence use and barter (Grafeld *et al.* 2017). Examples of now-common methodologies that social scientists use to assess Fish Flow include ethnographic and interview-based research, participatory mapping, and social network analysis.

Ongoing interdisciplinary syntheses move toward Fish Flow

In addition to the development of new tools reviewed above, partial (mostly pairwise) syntheses of the constituent Fish Flow fields are already occurring, albeit not yet with the goal of mapping overall movement from spawning to supper. The most extensive integration to date has occurred between marine ecology and fisheries biology. Indeed, "fisheries ecology" is now a recognized subdiscipline that includes tracking fish stocks from spawning to capture (Hidalgo *et al.* 2017). Social sciences, especially socioeconomics, have also long been an essential component of fisheries management, but only recently in the context of mapping catch distribution on land (Figure 2; Kittinger *et al.* 2015).

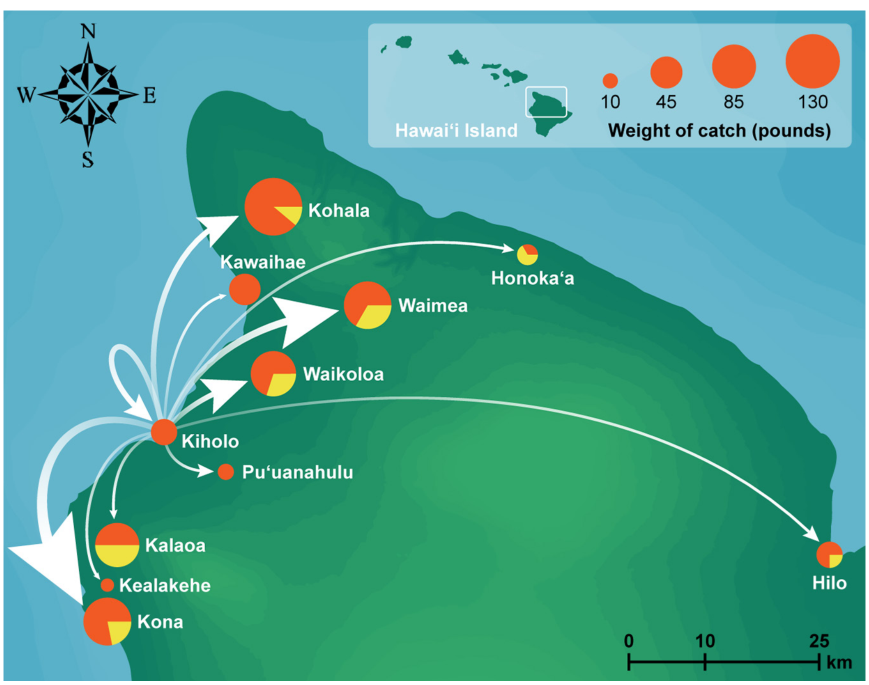

Figure 2. Spatial patterns of reef-fish catch distribution among local communities from landings at Kīholo Bay, Hawaii. The thickness of each arrow represents the number of distribution events studied, and the size of the pie chart indicates the weight of the catch. Within each community's pie chart, orange slices are Kīholo-landed fish that were kept for home consumption, and yellow slices are Kīholo-landed fish that were given away (not sold) for home consumption. Redrawn from Kittinger *et al.* (2015).

Pairwise integration of natural-science disciplines is also evident in the non-fisheries components of Fish Flow, though again, not yet in the context of holistic mapping. Oceanographic models are often now integrated with regional ecological studies. For example, Lipcius *et al.* (2001) found that the effectiveness of marine reserve sites for Caribbean spiny lobster (*Panulirus argus*) in the Bahamas, measured empirically within sites, was a function of connectivity among sites estimated from a larval dispersal model. Studying multiple fishery species, Treml *et al.* (2015) integrated a range of demographic parameters that affect reproductive output into a larval dispersal model for Port Phillip Bay, Australia, and concluded that the primary factors determining recruitment success across species were larval mortality, duration of the pelagic larval stage, and the period over which larvae are competent to settle.

Integration of oceanographic models (predicting larval dispersal pathways) and genetic kinship analyses (documenting actual larval dispersal start and end points) is developing rapidly and at increasing resolution (Cowen and Sponaugle 2009). Examples include studies of reef fishes and invertebrates in Hawaii (eg Christie *et al.* 2010), California (eg White *et al.* 2010), the Red Sea (eg Raitsos *et al.* 2017), and the Great Barrier Reef (eg Bode *et al.* 2019). Genetic studies of larval dispersal have also been integrated with ecological studies of the reproductive output of local populations, providing estimates of the actual volume of larval flow from one location to another (Figure 3; Johnson *et al.* 2018). Such analyses have socioeconomic ramifications. Almany *et al.* (2013), for instance, used genetic kinship analyses to show that larval dispersal from a spawning aggregation of squaretail coral grouper (*Plectropomus areolatus*) located in one community tenure area in Papua New Guinea seeded both that area and adjacent tenure areas. These communities embraced this new knowledge of their ecological interdependence by subsequently establishing a "resource development network" of managed and protected areas to ensure sustainability of their collective fishery resources (Almany *et al.* 2015).

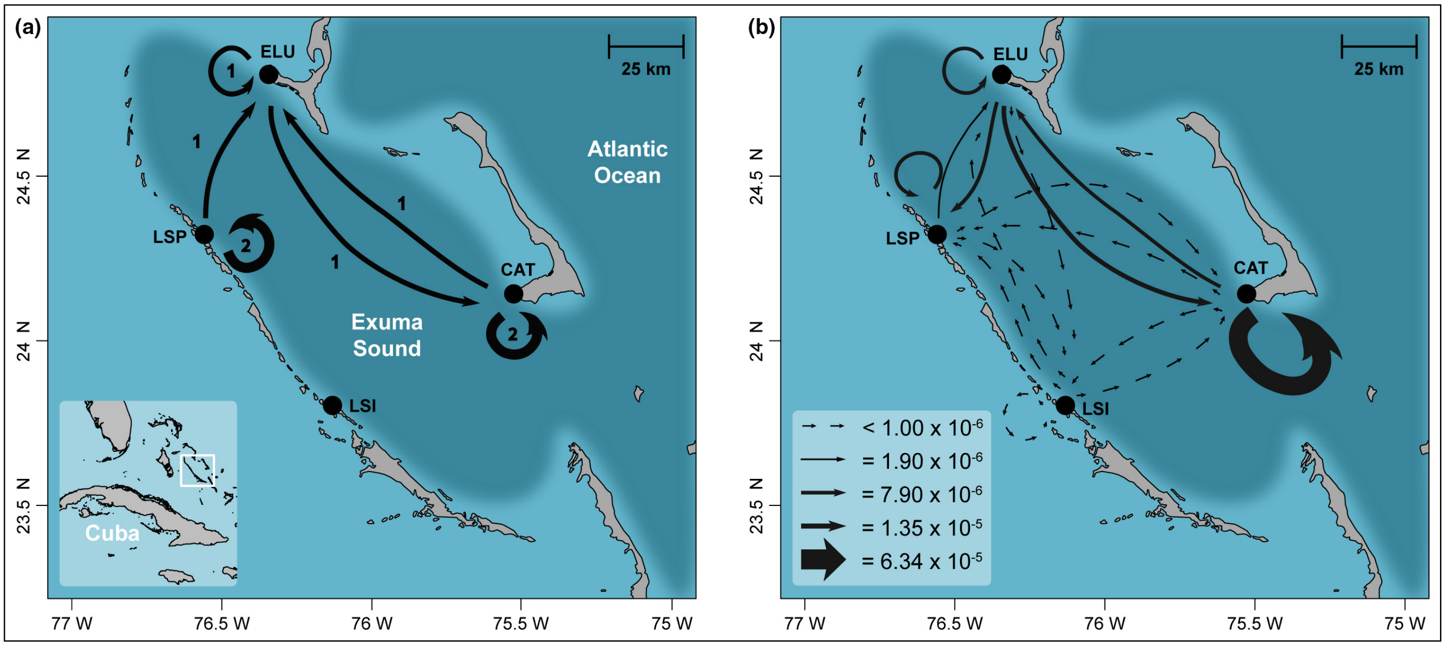

Figure 3. Integration of population genetics with population ecology elucidates larval dispersal of the coral-reef fish *Stegastes partitus* (bicolor damselfish) in Exuma Sound, Bahamas. (a) Number of genetically detected parent–offspring pairs, showing connectivity between sample populations (arrows connecting sites) as well as self-recruitment (circular arrows). (b) Integrating genetic patterns with larval production at each population, "demographic connectivity" is the estimated proportion (illustrated by relative arrow thickness) of eggs produced by each population that survived and dispersed as larvae to other populations (arrows connecting sites) or returned to their natal populations (circular arrows). Eleuthera (ELU), the Exuma Cays Land and Sea Park (LSP), Cat Island (CAT), and Lee Stocking Island (LSI). Redrawn from Johnson *et al.* (2018).

Integration of at least three of the five disciplines required for a full Fish Flow analysis has thus far been relatively rare. A combined suite of oceanographic, ecological, and fisheries models employed 39 years of data to evaluate spatial trends, physical-biological interactions, and biological reference points for Alaskan fisheries in the eastern Bering Sea (Ortiz *et al.* 2016). These models elucidated a cross-shelf gradient of higher variability in physical and biological patterns inshore versus offshore, a latitudinal gradient in the timing of ecological processes, and an effect of temperature on recruitment and recommended fishery yield. In the Philippines, Abesamis *et al.* (2017) compared genetic studies of larval dispersal of the coral-reef fish *Chaetodon vagabundus* (vagabond butterflyfish) with the geographic distribution of community-based marine protected areas for fisheries production. The social-science conclusion was that spatial patterns of larval connectivity demonstrated the importance of instituting cooperative fishery management among local communities within the region.

Challenges to implementing Fish Flow

Why has there not yet been a complete Fish Flow analysis from spawning to supper? Despite recent methodological breakthroughs in the constituent disciplines, as well as partial syntheses (summarized above), there remain several challenges to achieving full implementation. The most general issues plague all large-scale, interdisciplinary projects: silos and funding. Scientific silos – the reluctance to collaborate outside one's discipline – is a social/psychological issue that is fortunately waning as it becomes increasingly clear that solutions to major environmental issues require interdisciplinary collaboration (Cochrane 2017). The fact that limited funding is a perennial issue for interdisciplinary science is common knowledge. There are also some limits to which each of the five constituent disciplines can presently contribute to Fish Flow analyses effectively, constraints that hinder but do not actually preclude Fish Flow analyses and which we believe will soon be overcome. These are discussed in the following sections.

Oceanography

One crucial component that is often excluded from coupled biological-physical oceanographic models – usually due to a lack of relevant information – is larval behavior (Leis 2021). As mentioned above, although small larvae are typically incapable of swimming against horizontal currents, many can swim vertically, and more recent models are exploring ways to successfully integrate this larval behavior (Swearer *et al.* 2019).

Population genetics

Because of larval dispersal, identifying parents and offspring in the sea requires large sample sizes, which can impose daunting logistical constraints. Moreover, although the cost of genetic analyses to identify parent-offspring pairs is declining rapidly, further development of analytical approaches is still needed (Christie *et al.* 2017).

Ecology

Gathering the demographic data required for Fish Flow analyses is labor intensive, and ideally requires study species and systems where individual survival, growth, movement, and reproductive output can be measured directly. Although there are promising new approaches for securing such data from otoliths and other indirect methods, detailed demographic analyses are presently constrained to shallow marine systems, such as temperate rocky reefs and tropical coral reefs (eg Hixon *et al*. 2012; Johnson *et al*. 2018). Fortunately, these systems include major fisheries, especially in developing nations.

Fisheries biology

Collection of fisheries data required for detailed stock assessments – effort, catch, stock abundance, and life-history characteristics – is expensive, and will continue to be for the foreseeable future. Spatial stock assessments can reduce bias in estimates caused by spatial population structure, yet substantial data inputs are required (Punt 2019). We encourage developed nations to continue to share their scientific expertise and fisheries biology resources with developing countries.

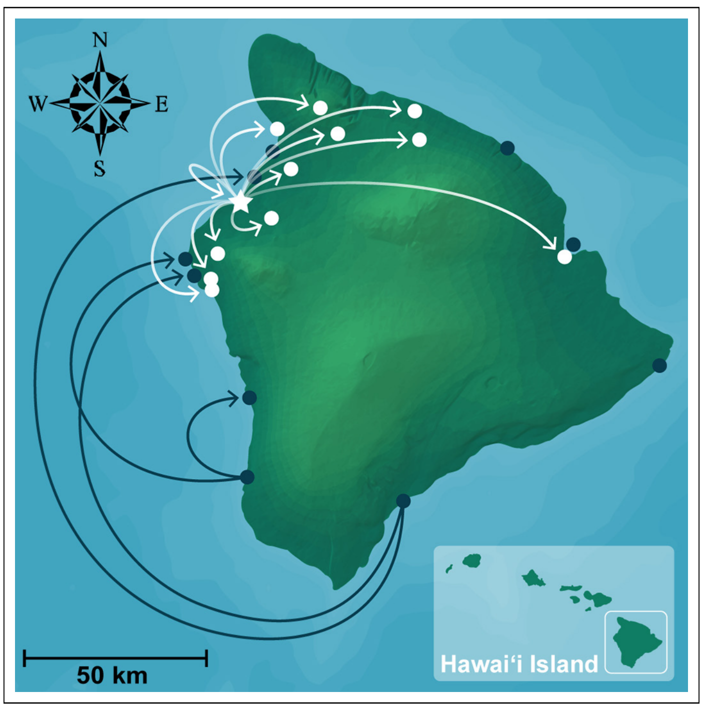

Figure 4. Larval dispersal patterns of a species of surgeonfish among studied coral reefs (dark blue arrows connecting black circles; data from Christie *et al*. [2010]) compared with reef-fish catch distribution patterns among local communities (white arrows connecting white circles) from landings at Kīholo Bay, Hawaii (white star; data from Kittinger *et al*. [2015]). Although the two studies were not integrated originally and did not involve the same species, together they suggest that people on the north side of the Island of Hawaii may depend on fish spawned off the southern end of the island, far from where the fish were captured and landed. If substantiated, such knowledge would inform fisheries management regarding stock boundaries and catch distribution, and may increase public appreciation of and engagement with their connections to island-wide fisheries management and conservation.

Social sciences

Analysis of the social dynamics that affect both fishing effort and post-catch distribution of seafood can require considerable investment in survey efforts. Intensive creel surveys are necessary to monitor and track effort and catch at a meaningful geographic scale (eg Delaney *et al*. 2017), and survey efforts for post-catch use also require extensive planning for successful execution. In addition, designing the scale of social surveys to match the biological scales of pre-catch population dynamics can require substantial investment and planning.

Further considerations

Beyond implementation challenges, non-expert public perception of the relevance of Fish Flow analyses will likely vary with geographical scale. At the scale of islands and isolated archipelagos, such information will be extremely important in fostering a sense of socio–ecological interdependence, as is evident in Papua New Guinea (Almany *et al*. 2013, 2015) and the Philippines (Abesamis *et al*. 2017). At broader scales of continental coastlines, Fish Flow will likely be of interest to people directly or indirectly affected by and concerned about regional fisheries. At global scales, we imagine that those with preexisting environmental perspectives will embrace Fish Flow maps as evidence of planetary interconnectedness, and use this information to support international marine conservation and sustainability efforts.

Future vision of Fish Flow for social–ecological sustainability and resilience

Given recent methodological breakthroughs and successful partial syntheses of oceanographic modeling, population genetics, ecology, fisheries biology, and social sciences summarized here, we believe that the time has arrived for the implementation of full Fish Flow analyses. The timing could not be more critical as the oceans rapidly change in ways that are clearly affecting patterns of connectivity in the sea, causing shifts in the distribution, function, and productivity of marine metapopulations (Gerber *et al*. 2014). The clear challenge will be to implement adaptive management based on changes in these parameters documented by Fish Flow analyses.

We envision that there will be web-based, dynamic, interactive Fish Flow maps depicting the movement of fish from where they were spawned to settlement/recruitment locations to adult population ranges to sites of capture by fisheries and finally to shore-based distribution and consumption. A precursor to such maps can be constructed by combining two recent, albeit unrelated, studies on the Island of Hawaii (Figure 4).

Christie *et al*. (2010) mapped patterns of larval dispersal of the coral-reef fish *Zebrasoma flavescens* (yellow tang), documenting that the western half of the island is seeded by fish populations at the southern end. Kittinger *et al*. (2015) mapped patterns of catch distribution of a variety of other reef-fishery species from a northwestern bay on the island, showing that seafood landed there was distributed across the entire northern region. Taken at face value and assuming these patterns are representative of local fishery species in general, combining these two studies into a single map may convince people living on the northern half of the island that they are connected to and should be concerned about the management and conservation of coral reefs in the southern region. From a fisheries management perspective, this particular synthesis suggests that stock boundaries encompass the entire western shore of the island, delineating the realistic domain of community-based management and networks of marine protected areas. Clearly, the studied fishery landings site is also important to human communities across the northern region of the island. A true Fish Flow map would focus on particular species or groups of species over ecologically and socially relevant scales of space and time, with dynamic arrows whose thicknesses would be proportional to the level of flow of fish both at sea (Figure 3b; eg Johnson *et al*. 2018) and on land (Figure 2; eg Kittinger *et al*. 2015).

Over a century ago, naturalist John Muir warned that, "when we try to pick out anything by itself, we find it hitched to everything else in the universe" (Muir 1911). Visually explicit Fish Flow maps will help to ensure that everyone – from interested non-specialists to high-level policy makers – understand and appreciate how clearly connected and dependent humans are on seafood produced in various, and sometimes very distant, regions of the ocean. In addition to informing fisheries management, such knowledge will help to foster an effective marine conservation ethic, enabling future generations to reap sustainable benefits from resilient ocean ecosystems.

Acknowledgements

We thank our many collaborators, students, and colleagues who shaped our thinking on these topics over the years, as well as the many sources of support we received for research related to Fish Flow. We also thank A Dillon for her excellent artwork (Figures 2, 3, and 4). Our collaboration was generously funded by the Harold KL Castle Foundation (grant 3846) to principal investigator MAH. This is University of Hawaii at Manoa contribution #156 from the School of Life Sciences, #1868 from the Hawaii Institute of Marine Biology, and #11426 from the School of Ocean and Earth Science and Technology.

References

Abesamis RA, Saenz-Agudelo P, Berumen ML, *et al*. 2017. Reef-fish larval dispersal patterns validate no-take marine reserve network connectivity that links human communities. *Coral Reefs* **36**: 791–801.

Almany GR, Hamilton RJ, Bode M, *et al*. 2013. Dispersal of grouper larvae drives local resource sharing in a coral reef fishery. *Curr Biol* **23**: 626–30.

Almany GR, Hamilton RJ, Matawai M, *et al*. 2015. Local benefits of community-based management: using small managed areas to rebuild and sustain some coastal fisheries. *Trad Mar Resour Manage Knowledge Inform Bull* **35**: 3–17.

Almeida C, Altintzoglou T, Cabral H, *et al*. 2015. Does seafood knowledge relate to more sustainable consumption? *Brit Food J* **117**: 894–914.

Bennett NJ. 2019. Marine social science for the peopled seas. *Coast Manage* **47**: 244–52.

Berger AM, Deroba JJ, Bosley KM, *et al*. 2020. Incoherent dimensionality in fisheries management: consequences of misaligned stock assessment and population boundaries. *ICES J Mar Sci* **78**: 155–71.

Bode M, Leis JM, Mason LB, *et al*. 2019. Successful validation of a larval dispersal model using genetic parentage data. *PLoS Biol* **17**: e3000380.

Caley MJ, Carr MH, Hixon MA, *et al*. 1996. Recruitment and the local dynamics of open marine populations. *Annu Rev Ecol Syst* **27**: 477–500.

Campana SE. 2005. Otolith science entering the 21st century. *Mar Freshwater Res* **56**: 485–95.

Christie MR, Meirmans PG, Gaggiotti OE, *et al*. 2017. Disentangling the relative merits and disadvantages of parentage analysis and assignment tests for inferring population connectivity. *ICES J Mar Sci* **74**: 1749–62.

Christie MR, Tissot BN, Albins MA, *et al*. 2010. Larval connectivity in an effective network of marine protected areas. *PLoS ONE* **5**: e15715.

Ciannelli L, Bailey K, and Olsen EM. 2015. Evolutionary and ecological constraints of fish spawning habitats. *ICES J Mar Sci* **72**: 285–96.

Cochrane KL. 2017. An integrated view of fisheries: tunnelling between silos. *ICES J Mar Sci* **74**: 625–34.

Cowen RK and Sponaugle S. 2009. Larval dispersal and marine population connectivity. *Annu Rev Mar Sci* **1**: 443–66.

D'Aloia CC, Bogdanowicz SM, Francis RK, *et al*. 2015. Patterns, causes, and consequences of marine larval dispersal. *P Natl Acad Sci USA* **112**: 13940–45.

Delaney DG, Teneva LT, Stamoulis KA, *et al*. 2017. Patterns in artisanal coral reef fisheries revealed through local monitoring efforts. *PeerJ* **5**: e4089.

Essington TE, Ciannelli L, Heppell SS, *et al*. 2017. Empiricism and modeling for marine fisheries: advancing an interdisciplinary science. *Ecosystems* **20**: 237–44.

FAO (UN Food and Agriculture Organization). 2020. The state of world fisheries and aquaculture 2020: sustainability in action. Rome, Italy: FAO.

Francis RC, Hixon MA, Clarke ME, *et al*. 2007. Ten commandments for ecosystem-based fisheries scientists. *Fisheries* **32**: 217–33.

Fuller EM, Samhouri JF, Stoll JS, *et al*. 2017. Characterizing fisheries connectivity in marine social–ecological systems. *ICES J Mar Sci* **74**: 2087–96.

Gerber LR, Mancha-Cisneros MDM, O'Connor MI, *et al*. 2014. Climate change impacts on connectivity in the ocean: implications for conservation. *Ecosphere* **5**: 33.

Gerritsen H and Lordan C. 2011. Integrating vessel monitoring systems (VMS) data with daily catch data from logbooks to explore the spatial distribution of catch and effort at high resolution. *ICES J Mar Sci* **68**: 245–52.

Glazier E, Carothers C, Milne N, *et al*. 2013. Seafood and society on O'ahu in the main Hawaiian Islands. *Pac Sci* **67**: 345–59.

Grafeld S, Oleson KLL, Teneva L, *et al*. 2017. Follow that fish: uncovering the hidden blue economy in coral reef fisheries. *PLoS ONE* **12**: e0182104.

Hidalgo M, Kaplan DM, Kerr LA, *et al*. 2017. Advancing the link between ocean connectivity, ecological function and management challenges. *ICES J Mar Sci* **74**: 1702–07.

Hilborn R and Walters CJ. 1992. Quantitative fisheries stock assessment: choice, dynamics and uncertainty. London, UK: Chapman and Hall.

Hilborn R, Amoroso RO, Anderson CM, *et al*. 2020. Effective fisheries management instrumental in improving fish stock status. *P Natl Acad Sci USA* **117**: 2218–24.

Hixon MA, Anderson TW, Buch KL, *et al*. 2012. Density dependence and population regulation in marine fish: a large-scale, long-term field manipulation. *Ecol Monogr* **82**: 467–89.

Johnson DW, Christie MR, Pusack TJ, *et al*. 2018. Integrating larval connectivity with local demography reveals regional dynamics of a marine metapopulation. *Ecology* **99**: 1419–29.

Kittinger JN, Teneva LT, Koike H, *et al*. 2015. From reef to table: social and ecological factors affecting coral reef fisheries, artisanal seafood supply chains, and seafood security. *PLoS ONE* **10**: e0123856.

Kritzer JP and Sale PF. 2004. Metapopulation ecology in the sea: from Levins' model to marine ecology and fisheries science. *Fish Fish* **5**: 131–40.

Krueck NC, Abdurrahim AY, Adhuri DS, *et al*. 2019. Quantitative decision support tools facilitate social–ecological alignment in community-based marine protected area design. *Ecol Soc* **24**: 6.

Leis JM. 2021. Perspectives on larval behavior in biophysical modelling of larval dispersal in marine, demersal fishes. *Oceans* **2**: 1–25.

Lipcius RN, Stockhausen WT, and Eggleston DB. 2001. Marine reserves for Caribbean spiny lobster: empirical evaluation and theoretical metapopulation recruitment dynamics. *Mar Freshwater Res* **52**: 1589–98.

Metaxas A and Saunders M. 2009. Quantifying the "bio-" components in biophysical models of larval transport in marine benthic invertebrates: advances and pitfalls. *Biol Bull* **216**: 257–72.

Mileikovsky SA. 1973. Speed of active movement of pelagic larvae of marine bottom invertebrates and their ability to regulate their vertical position. *Mar Biol* **23**: 11–17.

Muir J. 1911. My first summer in the Sierra. Boston, MA: Houghton Mifflin.

Nisbet EK, Zelenski JM, and Murphy SA. 2009. The nature relatedness scale: linking individuals' connection with nature to environmental concern and behavior. *Environ Behav* **41**: 715–40.

Oken E, Choi AL, Karagas MR, *et al*. 2012. Which fish should I eat? Perspectives influencing fish consumption choices. *Environ Health Persp* **120**: 790–98.

Ortiz I, Aydin K, Hermann AJ, *et al*. 2016. Climate to fish: synthesizing field work, data and models in a 39-year retrospective analysis of seasonal processes on the eastern Bering Sea shelf and slope. *Deep-Sea Res PT II* **134**: 390–412.

Pelc RA, Warner RR, Gaines SD, *et al*. 2010. Detecting larval export from marine reserves. *P Natl Acad Sci USA* **107**: 18266–71.

Pine WW, Pollock KH, Hightower JE, *et al*. 2003. A review of tagging methods for estimating fish population size and components of mortality. *Fisheries* **28**: 10–23.

Punt AE. 2019. Spatial stock assessment methods: a viewpoint on current issues and assumptions. *Fish Res* **213**: 132–43.

Raitsos DE, Brewin RJW, Zhan P, *et al*. 2017. Sensing coral reef connectivity pathways from space. *Sci Rep-UK* **7**: 9338.

Ramesh N, Rising JA, and Oremus KL. 2019. The small world of global marine fisheries: the cross-boundary consequences of larval dispersal. *Science* **364**: 1192–96.

Richter IGM and Klöckner CA. 2017. The psychology of sustainable seafood consumption: a comprehensive approach. *Foods* **6**: 86.

Severance C, Franco R, Hamnett M, *et al*. 2013. Effort triggers, fish flow, and customary exchange in American Samoa and the Northern Marianas: critical human dimensions of western Pacific fisheries. *Pac Sci* **67**: 383–93.

Swearer SE, Treml EA, and Shima JS. 2019. A review of biophysical models of marine larval dispersal. *Oceanogr Mar Biol* **57**: 325–56.

Treml EA, Ford JR, Black KP, *et al*. 2015. Identifying the key biophysical drivers, connectivity outcomes, and metapopulation consequences of larval dispersal in the sea. *Movement Ecol* **3**: 17.

Weersing KA and Toonen RJ. 2009. Population genetics, larval dispersal, and demographic connectivity in marine systems. *Mar Ecol-Prog Ser* **393**: 1–12.

White C, Selkoe KA, Watson J, *et al*. 2010. Ocean currents help explain population genetic structure. *P Roy Soc B-Biol Sci* **277**: 1685–94.

Woodson CB and McManus MA. 2007. Foraging behavior can influence dispersal of marine organisms. *Limnol Oceanogr* **52**: 2701–09.