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Review of Methods for Sampling Fish in Structured Habitats

Nathan M. Bacheler

Southeast Fisheries Science Center, National Marine Fisheries Service, Beaufort, North Carolina, USA

ABSTRACT
Structured aquatic habitats such as coral reefs, mangroves, and shipwrecks often harbor higher densities of fish than unstructured habitats, but sampling fish in structured habitats is difficult. Structured habitats can snag and damage, or be damaged by, sampling gears and provide refugia that obscure fish. Here, the diverse literature on sampling fish in structured habitats was reviewed and synthesized, focusing on the strengths and drawbacks of 24 sampling approaches that were classified as conventional, visual, acoustic, tagging, and novel methods. A number of key conclusions emerged from this review. First, no single gear can sample all fish species consistently across all structured habitats; optimal sampling gears depend on the morphology and behavior of the species, the physical characteristics of the habitat, and objectives of the study. Second, combining sampling gears provides a more complete picture of fish communities in structured habitats and, in some cases, can account for imperfect detection. Third, novel approaches like environmental DNA (eDNA), close-kin mark-recapture (CKMR), and autonomous vehicles deserve more research attention because they have the potential to revolutionize fish sampling in structured habitats. Improved sampling of fish in structured habitats will enhance fisheries management, benefiting the fish, their habitats, and those who rely on healthy fish populations.

KEYWORDS
Untrawlable; UVC; ROV; AUV; eDNA; CKMR

Introduction

Fish are important to humans for myriad reasons including food, recreation, ecotourism, and biodiversity. Long-term sustainability of fish stocks in the face of various threats is typically achieved using policy and regulations that are based on scientific data collection and population models (Hilborn and Walters 1992). A critical component of fisheries management is inference from scientific surveys that provide abundance, age, and biological information for various fish species (Hoshino et al. 2012; Dennis et al. 2015). Yet, surveying fish across the vast array of aquatic habitats is challenging. Fish occur in nearly all aquatic environments on Earth, from the arctic to the equator, shallow ponds and tidepools to deep oceanic trenches, and freshwater to hypersaline seas. In the ocean, some fish live near the surface or mid-water column, but many species associate with seafloor habitats like sand, rock, reefs, or human-created structures (Ilich et al. 2021). To persist and thrive in these habitats, fish have evolved a remarkable variety of sizes, morphologies, and behaviors (Helfman et al. 2009). Consequently, surveys are greatly challenged to sample the enormous diversity of fishes in a representative way across these highly variable habitat types.

The abundance and diversity of fish are generally highest in habitats containing complex structure (Luckhurst and Luckhurst 1978; Chabanet et al. 1997). Structured habitats are highly variable and include coral reefs, oyster reefs, mangroves, seagrasses, rocks, kelp, and artificial structures like shipwrecks, oil rigs, or pipelines (Figure 1). Structured habitats, also commonly called "untrawlable" habitats, can harbor high fish abundance and diversity because they provide refuge from predators and typically have more abundant prey than unstructured habitats (Webster and Hixon 2000; Stewart and Jones 2001). Although structured habitats can support high fish abundance and diversity, they are also particularly challenging to sample.

No sampling gear captures all of the available sizes and species of fish in perfect proportion to their availability, meaning that all sampling gears are selective (Dalzell 1996). For instance, gill nets and trawls

CONTACT Nathan M. Bacheler nate.bacheler@noaa.gov Southeast Fisheries Science Center, National Marine Fisheries Service, Beaufort, North Carolina, USA.
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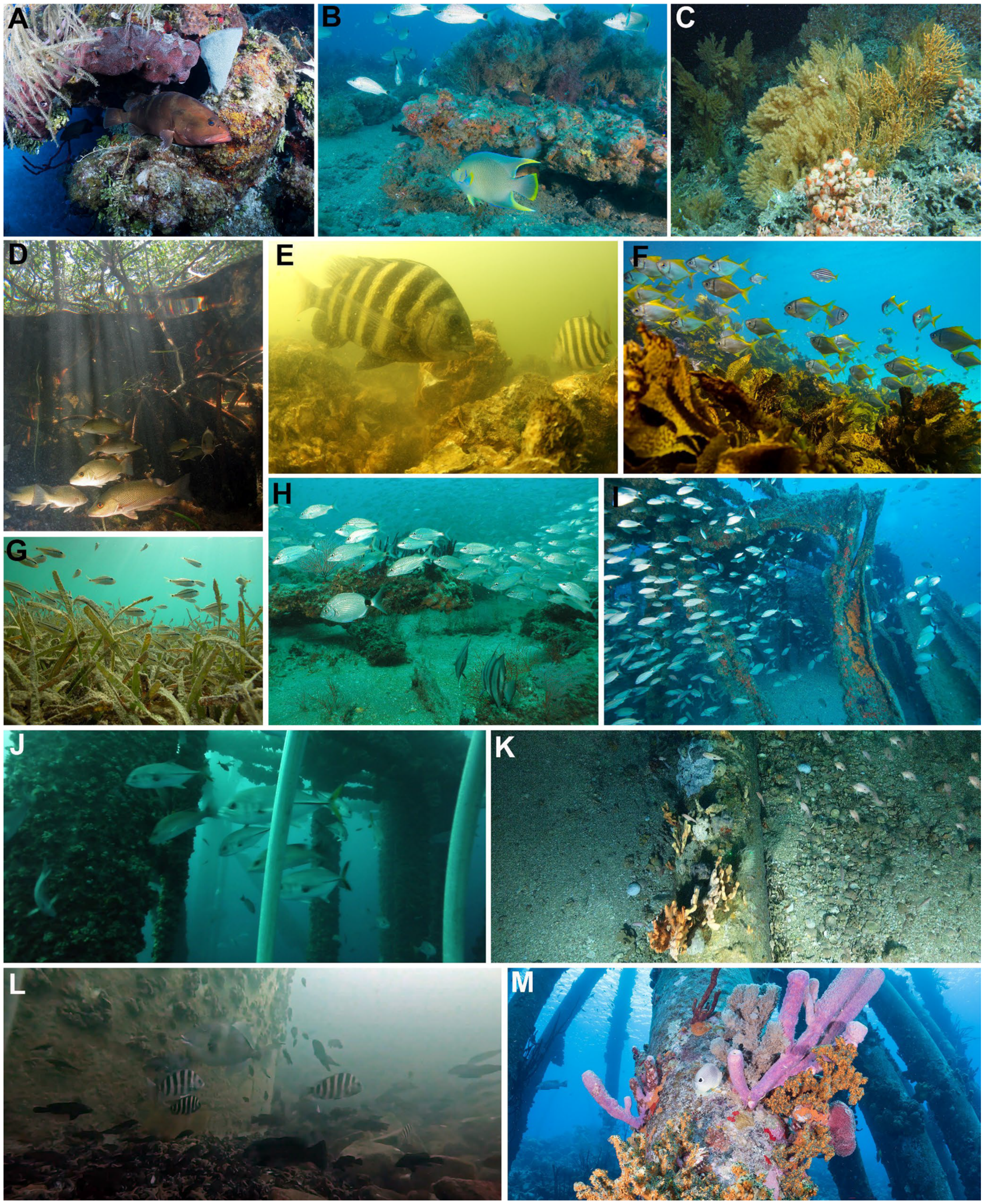

Figure 1. Various types of structured aquatic habitats. (A) Tropical coral reef in Half Moon Caye, Belize; credit: Kate Overly. (B) Temperate reef at the 210 Rock, North Carolina, USA; credit: John McCord, ECU Coastal Studies Institute. (C) Cold-water coral reef at the summit of the Galway coral carbonate mound, Rockall Bank, northeast Atlantic Ocean; credit: J.M. Robert, Changing Oceans Expedition, 2012. (D) Red mangroves (*Rhizophora mangle*) in Biscayne Bay, Florida, USA; credit: Evan K. D'Allesandra, University of Miami. (E) Eastern oyster (*Crassostrea virginica*) reef at West Bluff Oyster Sanctuary in Pamlico Sound, North Carolina, USA; credit: NCDMF Oyster Sanctuary Program. (F) Golden kelp (*Ecklonia radiata*) forest at Seal Rocks, New South Wales, Australia; credit: Aaron Eger, Kelp Forest Alliance. (G) Turtle grass (*Thalassia testudinum*) in Bermuda; credit: Annie Glasspool. (H) Artificial reef in coastal North Carolina, USA; credit: Doug Kesling. (I) Shipwreck ("Barge Wreck") in Long Bay, North Carolina, USA; credit: John McCord, ECU Coastal Studies Institute. (J) Oil rig off Louisiana, USA; credit: Gulf Fishery Independent Survey of Habitat and Ecosystem Resources. (K) Subsea gas pipeline in Australia; credit: Dr. Dianne McLean, Australian Institute of Marine Science. (L) Wind turbine monopile and scour protection at the Coastal Virginia Offshore Wind area; credit: Northeast Fisheries Science Center. (M) Coastal pier in Bonaire; credit: Kate Overly.

capture a wide variety of mobile species but are size-selective, while baited traps capture a wider variety of sizes but are mostly limited to predator or scavenging species (Rudstam et al. 1984; Lucchetti et al. 2021; Bacheler 2024). Ideally, sampling gears should sample fish with the same efficiency regardless of the habitats being sampled, the biology and behavior of the species of interest, or the goals of the study (Blaber et al. 1985; Willis et al. 2000). Therefore, designing a survey for one or more fish species requires careful consideration. There is an increasingly large and disparate literature pertaining to sampling fish in various types of structured habitats, and a synthesis of these studies is sorely needed.

Here, the large body of research focused on sampling fish in structured habitats was reviewed and synthesized. This review begins with a description of the primary types of structured habitats with which fish associate. Next, a broad overview of each sampling method was provided, including their strengths, weaknesses, and optimal applications. To facilitate commonalities and comparisons among gears, various sampling methods were categorized into conventional, visual, acoustic, tagging, and novel approaches. To conclude, previous work was synthesized and seven key take-home messages for sampling fish in structured habitats were provided given the specific goals of the survey and the types of habitats encountered. While the focus was on estimating abundance and species richness in estuarine and marine systems, the themes and key messages of this work are highly relevant to structured habitats in freshwater systems as well.

Types of structured habitats

Structured aquatic habitats occur in various forms around the world, from the equator to the poles and from rivers, lakes, and estuaries to the deep sea. Most of these are naturally occurring habitats like coral reefs, oyster reefs, or mangroves, but important artificial (human-made) structured habitats are described as well. Before reviewing gears that can sample fish in structured habitats, it is important to discuss the various types of structured habitats with which fish associate (Figure 1).

Tropical coral reefs

Tropical coral reefs are formed by colonies of stony coral polyps that excrete calcium carbonate as exoskeletons, which form highly rugose reefs. Corals exist as a thin layer of living organisms covering the accumulation of many previous generations of coral excretions. Tropical coral reefs are mainly found in shallow, clear waters throughout tropical and semi-tropical environments (Maragos et al. 1996). Coral reef ecosystems are well known for their high biodiversity of fishes and productivity (Connell 1978), which is due to both the complex structural habitat formed by corals and the biodiversity of the corals themselves (Komyakova et al. 2013; Coker et al. 2014). More than a quarter of all fish species on Earth associate with coral reefs, making them one of the most biodiverse ecosystems on Earth (Allen 2008).

Temperate reefs

Temperate reefs occur poleward from tropical coral reefs and are typified by rocky substrates containing various types of attached biota including soft corals, sponges, bryozoans, and macroalgae (Parsons et al. 2016). Temperate reefs are highly productive, biodiverse, and seasonal ecosystems (Hughes et al. 2002), but their composition is different than tropical coral reefs. While topographically complex (Gres et al. 2024), temperate reefs generally lack the immense structural complexity of tropical coral reefs (Ebeling et al. 1991). Moreover, temperate reefs tend to occur in large, continuous swaths along coastlines, whereas tropical coral reefs are patchy and typically associated with tropical islands (Ebeling et al. 1991). Temperate reefs have immense ecological value and support many biodiverse communities, but they also have substantial economic worth *via* tourism and fishing (Mineur et al. 2015; Bennett et al. 2016).

Cold-water reefs

Cold-water reefs are found in boreal, arctic, and deep-water regions around the world. The simplest cold-water reefs are places where bare rock emerges from the substrate, but in many locations, cold-water corals and sponges attach to these rocky substrates (Bryan and Metaxas 2006; Dullo et al. 2008). Cold-water corals are found in all oceans on Earth, but are concentrated on continental slopes, seamounts, fjords, and submarine canyons (Freiwald et al. 2004; Huvenne et al. 2011). Cold-water coral habitats are similar to tropical coral reefs in that corals create rock habitat, increasing habitat complexity and biodiversity (Buhl-Mortensen et al. 2010), but different in that they experience very slow growth and very long lifespans (Prouty et al. 2011). Compared to adjacent soft-bottom habitats, cold-water coral reefs support much higher biodiversity of fishes (Ross and Quattrini 2007).

Mangroves

Mangroves are a group of approximately 80 related tree or shrub species that line the shorelines of tropical and subtropical estuaries and coasts. They are rare among plants for being salt-tolerate and able to withstand various levels of saltwater inundation. Many subtropical shorelines are fringed by one or a few mangrove species, while tropical mangrove forests can consist of many species in a complex zonation pattern along shorelines (Hutchings and Saenger 1987). The prop roots from mangroves form dense stands that provide the dominant nearshore structural habitat for many billions of tropical and subtropical fish species (Faunce and Serafy 2006; zu Ermgassen et al. 2025). The complex, shallow-water habitat provided by mangroves is thought to reduce predation and increase prey for juvenile fishes (Laegdsgaard and Johnson 2001), many of which then migrate to coral reefs as they age (Mumby et al. 2004; Nagelkerken 2007).

Invertebrate-dominated substrates

Invertebrate-dominated substrates also provide important structural habitat for fish (Smaal et al. 2019). Oysters reefs are found in estuaries and along coasts of temperate and sub-tropical environments (Beck et al. 2011). Oysters are considered ecosystem engineers because they form rugose reefs by settling and growing on the shells of previously deceased or living oysters or other hard substrates; these reefs can extend vertically off the bottom or grow horizontally from shorelines (Luckenbach et al. 1999). Mussel beds also occur in temperate habitats worldwide, forming dense mats on hard substrates such as intertidal rocks (Paine 1994). Other invertebrate-dominated substrates important for fish include bryozoan thickets, sponge gardens, and tubeworm mounts (Anderson et al. 2019). Invertebrate-dominated substrates increase habitat complexity and tend to harbor much higher fish species richness than surrounding habitats (Coen et al. 1999; Martínez-Baena et al. 2022).

Macroalgae

There are many species of macroalgae found throughout temperate and tropical seas that provide important structured habitat for fish (Fulton et al. 2020). Most species of macroalgae grow attached to the benthos on continental shelves where there is sufficient light (Marzinelli et al. 2015), but there are some species that are entirely pelagic (Brooks et al. 2018). The most well-known group of macroalgae is kelp, which provides immense structural habitat and direct and indirect sources of food for numerous fish species in cold-water marine habitats across the globe (Steneck et al. 2002). Macroalgae often support higher species richness than surrounding habitats (Anderson and Millar 2004; Trebilco et al. 2015), both because of the structural habitat it provides as well as its ability to increase secondary production and consumer biomass (Duggins et al. 1989; Salomon et al. 2008). In addition to kelp, there are many lesser known types of macroalgae that provide similarly important habitat for fish around the world (Schneider 1976; Fulton et al. 2020).

Submerged aquatic vegetation

Submerged aquatic vegetation consists of flowering plants that live in marine benthic environments and form large monospecific or mixed-species meadows. They are widespread, occurring in lakes, estuaries, and shallow seas of all continents except Antarctica (Unsworth et al. 2019). Seagrass meadows are one of the most biologically productive biomes on Earth (Duarte 2002) and provide structural habitat and food for fish and invertebrates (Beck et al. 2001), in addition to numerous ecological services such as carbon sequestration, shoreline stabilization, and water filtration (Walter et al. 2020). Submerged aquatic vegetation serves as nursery habitat for many fishery species by providing abundant food, especially small epibenthic crustaceans, and shelter from predators (Pollard 1984; Whitfield 2017). Many studies indicate that fish densities are much higher in submerged aquatic vegetation than surrounding habitats (Hemminga and Duarte 2000).

Artificial reefs

Artificial reefs are non-natural material or structures that have been deliberately deployed by humans onto the seabed to concentrate or enhance populations of aquatic organisms (Seaman 2007; Sutton and Bushnell 2007). The use of artificial reefs began in the 1600s in Japan but blossomed worldwide in the mid-twentieth century and beyond as a tool to attract fish, increase fishing opportunities, enhance fisheries, or restore habitat (McGurrin et al. 1989; Stone et al. 1991).

Today, artificial reefs are widely distributed across North America, Europe, Africa, South America, Asia, and Australia (Seaman 2002). These artificial reefs are highly variable in size and shape and the material used can include concrete modules, concrete pipes, bridge material, metal ships, or decommissioned energy platforms (Paxton, Newton, et al. 2020; Paxton, Shertzer, et al. 2020; Paxton, McGonigle, et al. 2024; Paxton, Steward, et al. 2024). In general, artificial reefs often support similar patterns of fish abundance, biomass, richness, and diversity as natural reefs (Paxton, Newton, et al. 2020; Paxton, Shertzer, et al. 2020).

Shipwrecks

Ships can become benthic fish habitat when they are intentionally sunk to create artificial reefs or through unintentional sinking due to storms, wars, collisions, or capsizing. There are approximately three million shipwrecks around the world (UNESCO 2017), which range in size from small canoes or rafts to large freighters or ocean-going ships that create extensive horizontal and vertical structure (Paxton, McGonigle, et al. 2024; Paxton, Steward, et al. 2024). Shipwrecks can strongly attract marine organisms, especially in areas with soft sediment lacking structure, and increase fishery production (Layman et al. 2016, 2020; Paxton et al. 2021). Various functional groups of fishes can occupy areas above, near, or inside shipwrecks, including baitfish, pelagic predators, and many types of demersal fishes (Paxton et al. 2019; Paxton, Newton, et al. 2020; Paxton, Shertzer, et al. 2020).

Oil and gas rigs

Humans have been extracting fossil fuels from offshore oil and gas fields since the 1940s, and today, over 7500 offshore oil and gas production platforms are spread across the world's oceans (Parente et al. 2006; Andaloro et al. 2013). These oil and gas rigs (hereafter, "rigs") are typically steel structures extending from pilings driven into the seafloor to a superstructure at the surface consisting of pumps, production equipment, and living quarters (Dugas et al. 1979; Lewis and Mavraki 2024). Rigs provide immense vertical structure that is used by fish in specific ways (Torquato et al. 2017). Not only do functioning rigs provide fish habitat, but after decommissioning, rigs can remain in the ocean to continue to provide fish habitat at substantial cost savings to oil and gas companies (i.e. "Rigs-to-reefs" program; Macreadie et al. 2011; Meyer-Gutbrod et al. 2020). Not surprisingly, the density of many fish species is much higher in the immediate vicinity of rigs compared to the surrounding habitats (e.g. Løkkeborg et al. 2002; Soldal et al. 2002).

Pipelines and cables

There are hundreds of thousands of kilometers of pipelines and cables laid on the seafloor to transport oil or gas from extraction rigs to end users and markets, discharge wastewater offshore, or transmit signals (Allen et al. 1976; Bond et al. 2018). Pipelines and cables vary in diameter and their position in relation to the seafloor, with some being mostly or completely buried, others resting on the seafloor, and some where sections of pipe or cables are above the seafloor, creating a span (Love and York 2005; McLean et al. 2017). Fish densities around pipelines and cables are typically much higher than surrounding habitats (McLean et al. 2021; Schramm et al. 2021), especially in areas lacking other structured habitat or when pipelines and cables were undercut (Love and York 2005; McLean et al. 2017).

Wind turbines

In recent years, there has been an increase in renewable energy sources that do not rely on fossil fuels (Krupp and Horn 2008; Boehlert and Gill 2010). The primary large-scale renewable energy source in the marine realm is wind power, where wind turbines are sited in clusters called "offshore wind farms" (Degraer et al. 2020). The benefits of placing wind farms offshore instead of on land include stronger wind speeds, less competition for space, and reduced visual disturbance (Taylor 2004). Wind turbine foundations are commonly constructed of a single cylindrical monopile, but the soft sediments around monopile foundations can be scoured *via* water movement, compromising their stability (Sumer and Fredsøe 2002). Therefore, scour protection is often deployed up to 40 m around each monopile, which typically consists of gravel and rock (Whitehouse et al. 2011). Many fish species are attracted to the vertical structure provided by the wind turbine, the rocky scour protection surrounding the foundation, or both (Reubens et al. 2013; van Hal et al. 2017; Bicknell et al. 2025).

Coastal development

Humans have modified coastal aquatic environments in myriad ways that have degraded some fish habitats (Munsch et al. 2017). In some cases, however, the introduction of structurally complex artificial habitat (e.g. docks, jetties, ports, marinas) can have positive benefits for invertebrate and fish species richness (Dafforn et al. 2015). As with other structurally complex habitats, various types of coastal development can attract fish if it provides food and reduced predation, and is especially sought after by fish when located in areas lacking natural, structurally complex habitats.

Methodological approaches

Numerous gears can sample fish in structured habitats, but each have strengths and weaknesses and may be better suited for sampling some habitats over others. Here, the most commonly used fish sampling gears are reviewed below, organized in five broad categories: conventional, visual, acoustic, tagging, and novel approaches.

Conventional approaches

Conventional sampling gears are named as such because they are the primary gears used by the fishing industry and include lines, nets, or traps to capture fish (Figure 2). Conventional sampling gears have a long history of being used in various aquatic habitats, but their efficacy can be limited in structured habitats for various reasons. The biggest strength of using conventional gears to sample fish is that fish are captured, so biological samples are available or fish can be tagged and released. Conventional gears are also the most conducive to working with the fishing industry. There are also downsides of using conventional gears to sample fish in structured habitats (Table 1), however, as described below.

Trawl

Trawling involves towing a conical net behind a vessel, along the seafloor or in the water column (Gunderson 1993). Trawling can occur in the water column off the bottom ("mid-water trawling") to primarily target pelagic species or along the bottom to target demersal species. Bottom trawling is a commonly used sampling gear in soft-bottom habitats, and is particularly effective for catching small, sedentary fish species (Wells et al. 2008). Fish densities can be estimated as catch-per-unit-area swept by the bottom trawl, assuming perfect catchability (Kimura and Somerton 2006). There are two major drawbacks of using bottom trawls to sample structured habitats, however. First, bottom trawls get hung on or damaged by most structured habitats, creating problems with standardization (Link and Demarest 2003). Second, when used in structured habitats like low-relief reefs, bottom trawls can significantly damage seafloor habitats (Kaiser et al. 2002;

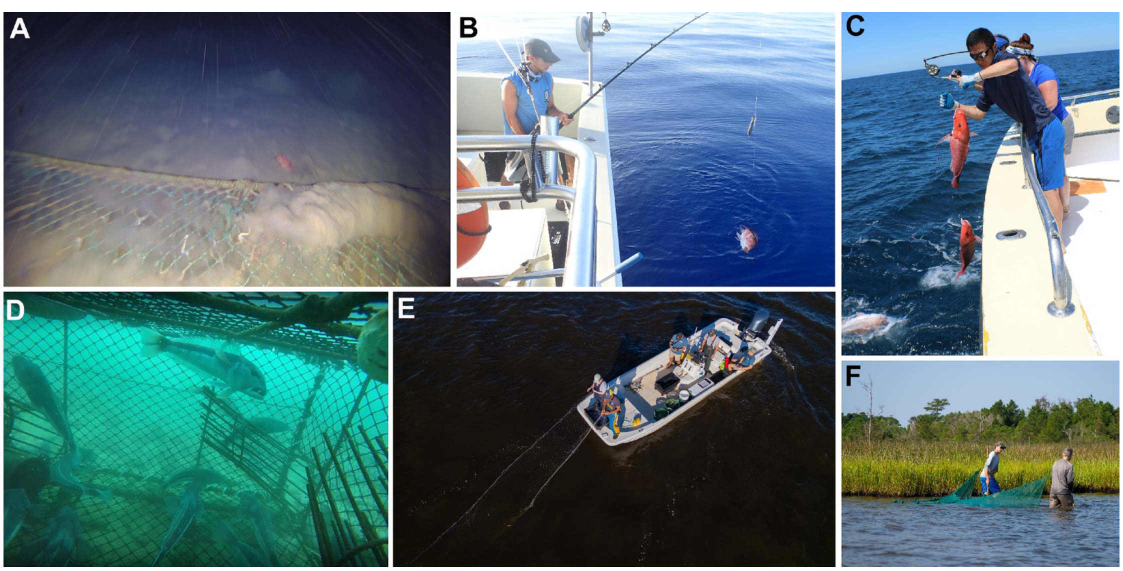

Figure 2. Examples of conventional sampling gears. (A) Using cameras to quantify catchability of scampi (*Metanephrops challengeri*) in trawls on the Chatham Rise, New Zealand; credit: Cawthron Institute, New Zealand. (B) Sampling reef fishes using repeated timed drop hook-and-line fishing, Florida, USA; credit: FLFWC-FWRI. (C) Retrieving vertical longline in the Alabama Artificial Reef Permit Zone, Alabama, USA; credit: University of South Alabama Fisheries Ecology Laboratory. (D) Blue cod (*Parapercis colias*) in a fish trap in Marlborough Sounds, New Zealand; credit: National Institute of Water and Atmospheric Research (NIWA). (E) Retrieving a gill net in the Pasquotank River, North Carolina, USA; credit: John McCord, ECU Coastal Studies Institute. (F) Seining fish and shrimp in Stumpy Point Bay, North Carolina, USA; credit: John McCord, ECU Coastal Studies Institute.

Table 1. Strengths and weaknesses of conventional gears for sampling fish in structured habitats.

Gear	Strengths	Weaknesses	Useful in which structured habitats?
Trawl	Can estimate fish density; can efficiently capture small fish in unstructured habitats; biological samples available; effective regardless of water clarity	Cannot be used in most structured habitats; damages bottom habitat; fish rarely survive the capture process; bycatch often high	Seagrass
Hook-and-line	Can be used in most structured habitats; catch can track abundance at low population size; biological samples available; effective regardless of water clarity	Catch rates affected by catches of other species and angler ability; catches can be hyperstable; selects for predatory and scavenging species; size-selective; hook damage	All structured habitats
Longline	Can track abundance at low population size, especially when using hook timers; biological samples available; effective regardless of water clarity	Can get hung on or damage structured habitats; hyperstable catches; multi-species competition for hooks; size- and species-selective; hook damage	Low-relief reefs; seagrass
Trap	Flexible design can be tailored to particular habitats and species; biological samples available; effective regardless of water clarity; fish often survive the capture process	Multi-species interactions in and around traps; saturation possible; selects for predatory and scavenging species; catch influenced by environmental conditions and habitat; can get hung in vertical structure; can continue ghost fishing if lost	All structured habitats, but traps can get hung on high relief or structurally complex habitats
Gill net	Mesh size can be chosen to target specific fish sizes; biological samples available; effective regardless of water clarity	Strongly size-selective; bycatch of protected species can be high; can get hung on structured habitats; continues ghost fishing if gear lost; selects for mobile species; fish can be injured or die from capture	Seagrass; low-relief reefs
Seine	Fish are captured alive; biological samples available; effective regardless of water clarity	Selects for small fish; gets hung in most structured habitats	Seagrass

Heifetz et al. 2009). The only structured habitat where bottom trawls could be potentially considered for use is seagrass meadows (Cappo et al. 2004; French et al. 2021), but caution is advised because the extent of seagrass damage inflicted by trawls is unclear (Meyer et al. 1999).

Hook-and-line

Hook-and-line refers to the use of one or more baited hooks attached by vertical line to a rod at the surface. Hook-and-line can be used to target a wide variety of species and sizes of fish depending on the sampling location and gear used, but it generally selects for larger-bodied predatory and scavenging species (Alós et al. 2008; Parker et al. 2016). When deployed concurrently, catch rates from hook-and-line surveys can track those from baited and unbaited video (Cullen and Stevens 2020; Willis et al. 2000) and underwater visual census (UVC) (Starr et al. 2010; Karnauskas and Babcock 2012). Hook-and-line has been used to successfully survey fish in a variety of structured habitats around the world (Rudershausen et al. 2008; Harms et al. 2010). There are significant drawbacks to hook-and-line sampling, however, including multi-species interactions, angler ability level, and hyperstability that can uncouple catch rates from abundance (Lennox et al. 2017; Kuriyama et al. 2019; Henderson et al. 2022). Hook-and-line sampling also strongly selects for a much narrower range of species and sizes than most other sampling gears (Parker et al. 2016). Hook-and-line surveys are best suited to sampling aggressive predatory or scavenging species at low population abundance, where catch rates are more likely to track abundance (Kuriyama et al. 2019).

Longlines

Longlines consist of a horizontal or vertical mainline to which multiple branch-lines are attached, each with a single baited hook. Longlines can be pelagic or demersal, and the main difference between longline and hook-and-line sampling is that longlines are unattended for some time before retrieval. While there are some examples where fish in structured habitats have been surveyed with bottom longlines (e.g. Olavo et al. 2011; Mitchell et al. 2014), their use in these habitats is limited because they can damage benthic habitat and get snagged (Sampaio et al. 2012). Instead, fish in structured habitats are more commonly sampled with vertical longlines that reduce habitat damage and entanglements with structure (Campbell et al. 2014; Plumlee et al. 2020). Most of the other shortcomings of hook-and-line sampling also apply to vertical and bottom longlines, namely hyperstability and multi-species competition for hooks (Ricker 1975; Godø et al. 1997; Rodgveller et al. 2008). It may be possible to ameliorate some of the gear saturation and interspecific competition effects of longlines using hook timers, which provides time-to-capture data for each hook (Somerton et al. 1988). Vertical longlines are superior to bottom longlines for sampling structured habitats, but, like hook-and-line, they tend to mostly catch a narrow range of aggressive predatory and scavenging species and best track abundance when abundance is low (Somerton and Kikkawa 1995).

Traps

Fish traps are enclosed, three-dimensional, mesh containers of various shapes and sizes with one or more entrances that, in theory, make fish entry easy but escape difficult (Bacheler 2024). Fish traps are commonly baited and attached to a surface buoy with a line, but sometimes they are attached to multiple other traps along a mainline rope (Stevens 2021). Traps have a long history of being used to sample fish in reef habitats (Munro 1974; Munro et al. 1971), but have been used in most other structured habitats as well (Bacheler 2024). Trap catch has been used to reliably estimate relative abundance in some situations and there are many characteristics (e.g. low cost, flexible design, and ability to sample many habitats) that make them a desirable sampling gear (Shertzer et al. 2016; Bacheler and Ballenger 2018). Traps also have downsides including being selective for relatively few predatory and scavenging species and variable catches due to environmental conditions, habitat effects, predator-prey interactions, competition, conspecific attraction, or trap saturation (Robichaud et al. 2000; Stoner 2004). Traps are suited to sampling small to medium-sized predatory and scavenging fish species in structured habitats that are difficult to sample with other gears due to poor visibility, high-relief structure, or concerns over damaging sensitive habitats (Bacheler 2024).

Gill nets

Gill nets are rectangular walls of netting oriented vertically, with weights along the bottom line and floats attached to the top line, that enmesh or tangle fish in one or more meshes (Potter and Pawson 1991). Gill nets with a single mesh size are strongly size-selective – small fish can pass through the mesh and large fish tend to not get tangled easily (Hamley 1975; Lucchetti et al. 2020). Gill net selectivity is driven in part by encounter rates, so species with high movement rates tend to be selected over highly site-attached species (Rudstam et al. 1984). But, because they are not strongly species-selective, gill nets are plagued by the accidental catch of various sensitive or protected species (Murray 2009; Žydelis et al. 2009; Reeves et al. 2013). Gill nets can also damage sensitive habitats (Dias et al. 2020) or get snagged on structured habitats and lost, in which case they can continue catching and killing marine organisms *via* ghost fishing (Erzini et al. 1997; Matsuoka et al. 2005). Gill nets are a useful tool for sampling fish in structured habitats when a narrow size range of fish is targeted, the risk of losing nets is low, and sensitive bycatch species are rare or absent (Løkkeborg et al. 2002; van Hal et al. 2017).

Seines

A seine is a fine-mesh net that hangs vertically in the water, with weights on the bottom line and floats on the top line, that is used to surround and capture fish in the water column. There are three main types of seines. Beach seines are typically deployed from shore in shallow water, purse seines have bottom lines that can be drawn tight and are deployed by boats or ships, and Danish seines have weighted lines and a trawl-like net that is deployed in a circle and retrieved by boat (Pravin and Meenakumari 2016; Vieira et al. 2020). In unstructured habitats, seining can often effectively catch a wide range of sizes and species of fish (Boardman et al. 2023), but, especially for purse seiners, catch rates may not reflect actual abundance due to technological improvements in finding fish schools (Fonteneau et al. 1999). Seining is often used in seagrass habitats but cannot sample in most other structured habitats without significant gear modifications (Boardman et al. 2023). Seagrass is likely the only structured aquatic habitat that can be sampled efficiently by seining (Jennings et al. 2009).

Visual approaches

Visual gears include divers and video and are the most common sampling approaches for fishes in structurally complex habitats when the water is relatively clear (Figure 3). Visual gears have numerous advantages over conventional sampling gears including that they are relatively nondestructive, conceptually simple, widely applicable, and fish behavior and habitat can also be quantified (Murphy and Jenkins 2010). The drawbacks of visual gears are that water clarity has to be relatively good, deep deployments may require artificial lights that can influence fish behavior, conspicuous fish are detected more easily than small, cryptic, or burrowing species, and biological samples are typically not available (Table 2; Ackerman and Bellwood 2000; Brock 1982).

Underwater visual census

UVC is when divers or snorkelers count fish visually over a given amount of area or time (Brock 1954). UVC has been the primary sampling approach for reef fishes in highly rugose habitats because numerous species can be counted in a nondestructive manner and fish density can be estimated if the survey area

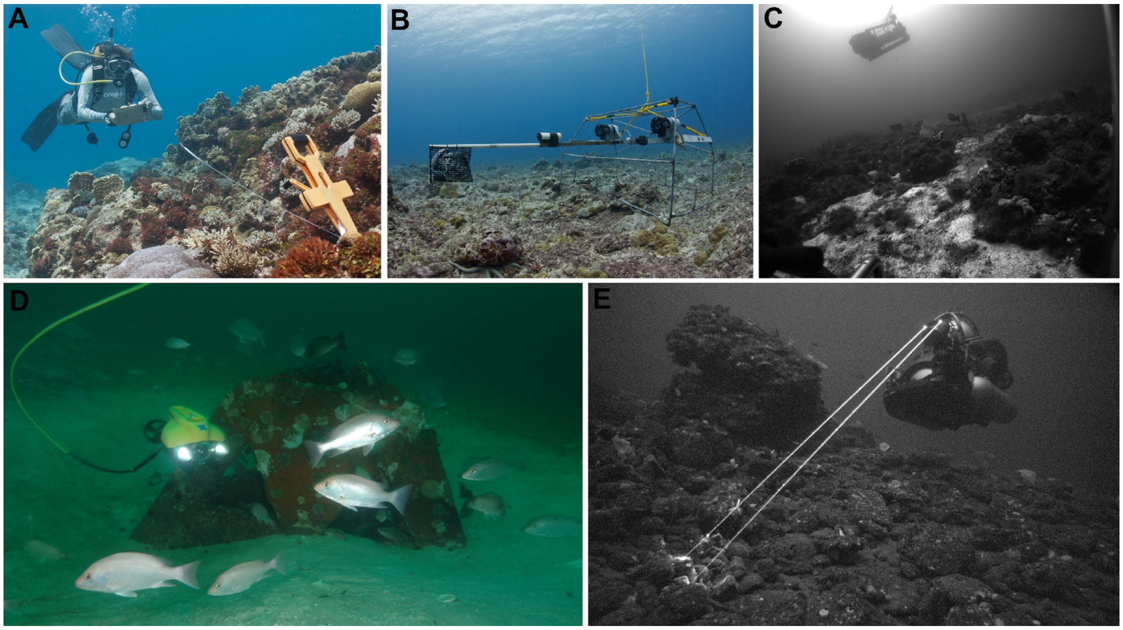

Figure 3. Examples of visual sampling gears. (A) Underwater visual census survey by divers in Guam; credit: Steve Lindfield. (B) Baited remote underwater video survey in Guam; credit: Steve Lindfield. (C) Camera-Based Assessment Survey System (C-BASS), an example of a towed video system, on the West Florida Shelf, Florida, USA; credit: Chad Lembke, University of South Florida, and Matthew Campbell, NOAA-Fisheries. (D) Using a remotely operated vehicle (ROV) to monitor fish at an artificial reef site in Florida, USA; credit: David Doubilet. (E) Submersible used to count and measure fish (with lasers) near the Channel Islands, California, USA; Tom Laidig, NOAA-Fisheries.

Table 2. Strengths and weaknesses of visual gears for sampling fish in structured habitats.

Gear	Strengths	Weaknesses	Useful in which structured habitats?
Underwater visual census	Nondestructive; fish behavior and habitat can be quantified; fish density can be calculated; fish lengths can be estimated visually; can be used to sample high-relief habitats	Relatively shallow water only; experienced, trained divers required; fish can be wary of divers; measuring fish lengths and survey area is challenging; requires good water clarity; no biological samples available; conspicuous fish detected better than small, cryptic species	All structured habitats that occur in clear, shallow, and safe water
Remote stationary video	Nondestructive; fish behavior and habitat can be quantified; high replication possible; useful in all water depths or when conditions are unsafe for divers; can be baited or unbaited; stereo-video useful for measuring fish lengths	Substantial video reading time required by trained readers; requires good water clarity; no biological samples available; lights required in deep water; when baited, selects for predatory and scavenging species	All structured habitats with sufficient water clarity
Towed divers or video	Nondestructive; habitat can be quantified; can survey broad areas rapidly and efficiently; fish lengths can be estimated visually or using stereo-video	Requires good water clarity; no biological samples available; highly selective toward conspicuous fish species; can influence fish behavior; can get hung or lost in high-relief habitats; divers limited to shallow depths; species identification can be difficult; experienced divers or video readers required	Low-relief habitats in relatively clear, shallow water
Remotely operated vehicle	Nondestructive; habitat and fish behavior can be quantified; fish density can be estimated; stereo-video can be used to measure fish lengths; can be used to sample high-relief habitats	Requires good water clarity; no biological samples available; site-attached conspicuous fish detected better than small, cryptic, or highly mobile species; can influence fish behavior due to vehicle movement and sound	All structured habitats with sufficient water clarity
Submersible	Nondestructive; habitat and fish behavior can be quantified; fish density can be estimated; stereo-video can be used to measure fish lengths; can be used to sample high-relief habitats	Requires good water clarity; no biological samples available; site-attached conspicuous fish detected better than small, cryptic, or highly mobile species; can influence fish behavior due to vehicle movement and sound	All structured habitats with sufficient water clarity

is measured (Murphy and Jenkins 2010). The most common UVC approaches are transect surveys, roving or timed surveys, and point count surveys (Bortone et al. 1989; Samoilys and Carlos 2000; Beck et al. 2014). UVC can provide a rapid assessment of fish abundance, community structure, and fish lengths

(Harvey et al. 2001). The drawbacks of UVC are that the approach can only be used in relatively clear, safe, and shallow waters (Hagen and Baxter 2005), the approach requires highly experienced and trained divers (Thompson and Mapstone 1997), many fish can avoid detection (Brock 1982; Willis 2001; Bozec et al. 2011), fish can flee from divers (Willis et al. 2000; Emslie et al. 2018), and divers have difficulty measuring the sampling area and lengths of fish accurately underwater (Harvey et al. 2001, 2004; Edgar et al. 2004). UVC can be used to survey fish in nearly all structured habitats as long as water is clear, shallow, and safe, divers are well trained, and rebreathers are used to minimize disruption.

Remote stationary video

Counting fish using remotely deployed, stationary video cameras has become a common approach to monitor species in structured habitats (Mallet and Pelletier 2014). There are numerous remote stationary video approaches including baited remote underwater video systems, cameras with 360° views, rotating cameras, and long-term cabled observatories (Aguzzi et al. 2013; Mallet et al. 2014; Whitmarsh et al. 2017; Hemery et al. 2022; Matthews et al. 2024). Remote video provides a permanent record of fish observations, can be deployed quickly to achieve high replication, and provides an alternative to UVC when conditions are unsafe such as in deep water or near dangerous animals (Murphy and Jenkins 2010; Piggott et al. 2020). Stereo-video systems can be used to measure lengths of fish (Harvey and Shortis 1998; Harvey et al. 2012). Video arrays can be baited to increase counts of predatory or scavenging species, or unbaited to facilitate a more accurate comparison of counts across species (Harvey et al. 2007; Bernard and Götz 2012; Hannah and Blume 2014). There are various methods for counting fish on video, including *MaxN*, MeanCount, and time-at-first-arrival (Ellis and DeMartini 1995; Priede and Merrett 1996; Schobernd et al. 2014). The downsides of remote stationary video are that water must be relatively clear, fish density cannot be easily estimated because the effective sampling area of baited video is generally unknown, and video reading is time-consuming and requires extensive training, although automated video reading approaches may eventually alleviate this drawback (Murphy and Jenkins 2010; Mallet and Pelletier 2014). Moreover, video detection of fish is variable (Bacheler et al. 2025) and can be low for small, cryptic species (Watson et al. 2005; Bacheler et al. 2017). Remote video is ideally suited to sampling fish in structured habitats where water is relatively clear, predatory and scavenging species are of primary importance, high replication is required, and experts are available to read videos.

Towed divers or video

Fish can also be surveyed by towing observers or video cameras behind a vessel moving at a constant speed. Manta tows involve pulling a diver behind a vessel *via* rope while they hold a manta board to control their depth; this technique is suited to quickly surveying conspicuous organisms (Endean and Stablum 1973; Richards et al. 2011). Identifying most species of fish while being towed can be difficult and observers generally have to hold onto manta boards with two hands, making data recording challenging (Zimmerman and Burton 1994). In recent years, manta tows have been largely replaced by towed benthic video sleds or platforms that hover above the seafloor because they are safer and can be deployed for much longer periods of time and in deeper water (Jones et al. 2009). Towed video can be highly efficient, sampling up to tens of kilometers per day (Lembke et al. 2017). Towed video also provides spatially distinct observations of fish along transects, improving our understanding of species-habitat relationships (Galaiduk et al. 2017). The downsides of towed video are that fish show a wide variety of positive and negative reactions to moving divers or platforms (Stoner et al. 2008; Campbell et al. 2021), systems can be difficult to operate in structurally complex habitats (Rooper 2008), and identifying many fish species can be difficult or impossible (Logan et al. 2017). Towed video is ideal for surveying conspicuous fish species occurring in low-relief habitats (e.g. pipelines, cables, and low-relief reefs) where substantial sampling effort is needed (Stoner et al. 2008; Campbell et al. 2021).

Remotely operated vehicles

Remotely operated vehicles (ROVs) are unoccupied, maneuverable vehicles that are operated by a person in a surface vessel, to which the ROV is connected *via* a tether (Macreadie et al. 2018). Most often, the ROV is outfitted with video cameras and flies above the seafloor to count fish over some estimated transect area, thus allowing fish density to be estimated (Sward et al. 2019). ROVs are widely used to survey fish in marine structured habitats and have similar strengths and drawbacks as other visual gears (i.e. they mostly detect conspicuous fish, water clarity must be good), but there are some important differences (Schramm et al. 2020). First, an ROV is more amenable to sampling high-relief vertical structures like oil and gas platforms and shipwrecks than towed video (Andaloro et al. 2013; Ajemian et al. 2015; Love et al. 2020). Second, an ROV can fly closer to the substrate than towed video, improving fish identification. Third, over a given amount of time, an ROV typically samples more area than UVC and remote video but less than towed video (Lembke et al. 2017). Research is also mixed about which visual gears detect the most fish species, likely due to differences in the fish communities being sampled and the vagaries of the various sampling approaches (Andaloro et al. 2013; Raoult et al. 2020; Bond et al. 2022). Like towed video and UVC, the primary drawback of ROV sampling is the variable reactions of fish to sampling gears that move and emit noise (Laidig et al. 2013; Campbell et al. 2021; Hellmrich et al. 2023). ROVs can be a useful gear to count conspicuous, site-attached fish across a wide array of structured habitats (Bond et al. 2022), but fish behavior around the ROV must be understood to estimate abundance reliably (Stoner et al. 2008; Campbell et al. 2021).

Submersible

Submersibles are crewed underwater vehicles that can be used to survey fish without being connected to, or controlled from, surface vessels (Wynn et al. 2014). Submersibles are typically controlled by crew inside the vehicle itself, and cameras or acoustics can be used to count fish and quantify habitat (Schobernd and Sedberry 2009; Robertson et al. 2022; Echave et al. 2023). The strengths and weaknesses of submersibles as a fish survey tool are very similar to those of an ROV above – they can sample in deep water and fish densities can be estimated, but fish may react to the movement, sound, and lights of submersibles, conspicuous species are detected more than cryptic species, and water clarity must be good (Stoner et al. 2008; Campbell et al. 2021). Submersibles are much more expensive than a typical ROV; however, some evidence suggests that fish react less strongly to submersibles than to an ROV and submersibles can typically sample in deeper water (Laidig et al. 2013; Wynn et al. 2014). If fish behavior around submersibles can be understood, they can be a flexible approach to count conspicuous, site-attached fish in various structured aquatic habitats (Jones et al. 2020; Robertson et al. 2022).

Acoustic approaches

Hydroacoustics uses sound to detect aquatic organisms and understand their environment, and encapsulates the broad fields of active and passive acoustics (Figure 4; Webb et al. 2008). Active acoustics involves generating and emitting sound waves into water; the timing and strength of the reflected acoustic returns

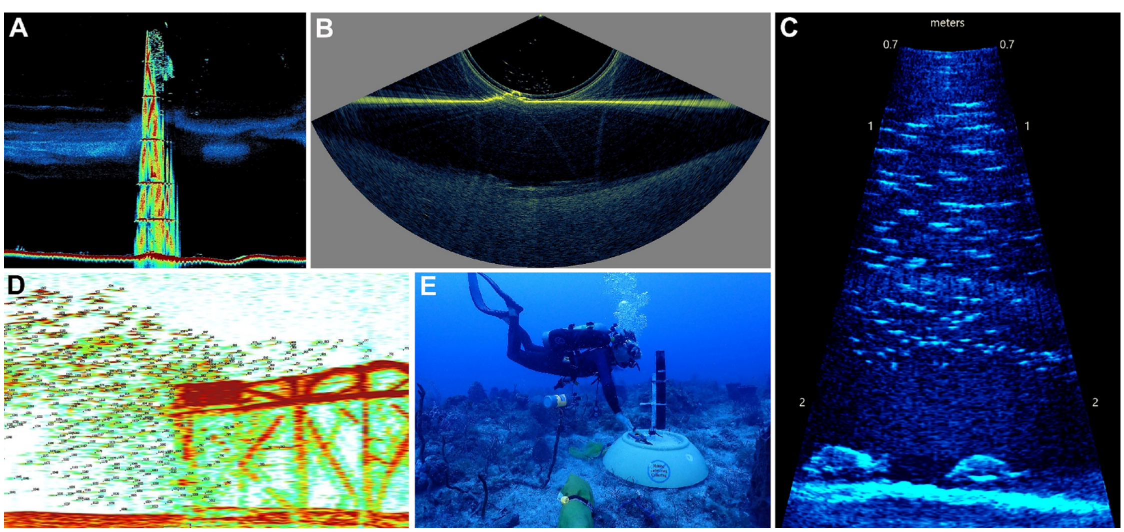

Figure 4. Examples of acoustic sampling gears. (A) Split-beam sonar echogram of a fish school around the top of a decommissioned oil and gas platform at the Flower Gardens National Marine Sanctuary, Texas, USA; credit: NOAA-NCCOS Seascape Ecology and Analytics. (B) Multibeam sonar echogram showing fish in the water column and seafloor bathymetry at a shipwreck (ex-USS Schurz) in North Carolina, USA; credit: NOAA-NCCOS Seascape Ecology and Analytics. (C) Acoustic camera image of fish at the Deep Bay Oyster Sanctuary in Pamlico Sound, North Carolina, USA; credit: Jim Morley, East Carolina University (Grimes et al. 2024). (D) Fish detected by side-scan sonar around a toppled oil rig off southern Texas, USA; credit: Mike Bollinger and Rick Kline, UTRGV. (E) Passive acoustic hydrophone deployment in Western Dry Rocks, Florida Keys National Marine Sanctuary, Florida, USA; credit: Ben Edmonds, NOAA.

are used to detect and count objects in the water column and determine the depth and composition of the seafloor (Misund 1997; Horne 2000). Active acoustic approaches have numerous strengths including being noninvasive, unaffected by water clarity, ambient light, and current, and able to sample efficiently over large areas (Martignac et al. 2015). The downsides are that active acoustics requires substantial ground-truthing to identify the species and sizes of fish detected (unless that information is not necessary for the specific objectives of the study), can be limited in noisy environments, very shallow water, or near the seafloor, must be calibrated for the water body being sampled, and fish can change their behavior in the presence of vessels (Table 3; Misund 1997; De Robertis et al. 2019). Passive acoustics uses sensors to noninvasively detect sounds emitted by organisms into the water, which can be used to monitor sound-producing organisms over space and time (Gannon 2008; Luczkovich et al. 2008).

Split-beam sonar

Split-beam sonar is a type of single-beam sonar that uses a transducer to emit single beams of sound into the water, with sound waves forming an overlapping "×" shape that can be used to identify the exact position of fish in the water column (Balk and Lindem 2000). The depth of objects is calculated based on the time it takes for a sound wave to travel to the object and back, and the strength of the returning sound is related to the size and composition of the object. Split-beam sonars typically operate between 18 and 200 kHz, with lower frequencies being more useful in deep water and higher frequencies providing greater resolution (Misund 1997). Split-beam sonar is often conducted from vessels driving transects (Kimura and Somerton 2006; Becker et al. 2023), but transducers can also be placed in fixed locations (Stanley and Wilson 1997; Boswell, Miller, et al. 2007; Boswell, Wilson, et al. 2007). Split-beam sonar is well-suited to counting fish in the water column, but there are some challenges. First, substantial ground-truthing is required to identify species so that acoustic signals can be partitioned (McClatchie et al. 2000), although multi-frequency and broadband sonar have recently been used to begin to discriminate species (Campanella and Taylor 2016; Boswell et al. 2020; Gugele et al. 2021). Second, it is impossible at present to distinguish fish near the seafloor ("acoustic dead zone;" Ona and Mitson 1996) without the use of comprehensive, depth-specific ground-truthing data (Jones et al. 2012; Rasmuson et al. 2022). Split-beam sonar is well suited to surveying fish in places with low species richness, especially if those species are different sizes or shapes, occupy different places in the water column, are not strongly associated with the seafloor, and are amenable to ground-truthing using other sampling gears (Boswell, Miller, et al. 2007; Boswell, Wilson, et al. 2007; Gurshin et al. 2013; Domokos 2021).

Table 3. Strengths and weaknesses of acoustic gears for sampling fish in structured habitats.

Gear	Strengths	Weaknesses	Amenable to which structured habitats?
Split-beam sonar	Unaffected by water clarity; can survey large areas efficiently; fish position in water column, schooling behavior, and benthic habitat can be determined; nondestructive	Substantial ground-truthing needed to identify fish to species; noisy environments can cause interference; cannot be used in very shallow water or very deep water; fish cannot be detected in the "acoustic dead zone" near the seafloor; most useful in areas with low species richness	All structured habitats where fish species richness is low and fish are not closely associated with structure
Multibeam sonar	Unaffected by water clarity; can survey large areas extremely efficiently; fish position in water column, schooling behavior, and benthic habitat can be determined; ideal for mapping benthic habitat; nondestructive	Substantial ground-truthing needed to identify fish to species; noisy environments can cause interference; cannot be used in very shallow water or very deep water; fish cannot be detected in the "acoustic dead zone" near the seafloor; most useful in areas with low species richness; lower object resolution than split-beam sonar; calibration difficult	All structured habitats where fish species richness is low and fish are not closely associated with structure
Side-scan sonar	Unaffected by water clarity; can survey large areas efficiently; good for mapping benthic habitat features; cheaper than multibeam sonar; nondestructive	Not as useful as split-beam sonar for detecting fish around structured habitats; substantial ground-truthing needed to identify fish to species; noisy environments can cause interference; lower object resolution than split-beam sonar; calibration very difficult	All, but more useful mapping habitat than detecting fish
Acoustic camera	Unaffected by water clarity or light levels; provides near photographic-like images of fish; nondestructive	Small sampling volume; fish can be difficult to identify to species; fish can be obscured by other fish	Structured habitats in turbid water, e.g. rivers, estuaries
Passive acoustics	Unaffected by water clarity or light levels; hydrophones can monitor sounds over large areas and periods of time; nondestructive	Only some fish are soniferous; sound-truthing required; interference from background noise; data analysis often requires automated methods; abundance may not be proportional to sound production	All structured habitats

Multibeam sonar

Multibeam sonar uses an array of transducers to emit a fan-shaped sonar beam under a ship that greatly expands the sampling volume compared to split-beam sonar (Gerlotto et al. 1999). The primary use of multibeam sonar has been to map the seafloor, and two types of data are typically available from these systems: bathymetry (i.e. depth), which is computed from the time it takes sound to reflect off an object and return to the transducer, and backscatter, which is a measure of the intensity of the sound echo (Brown and Blondel 2009; Pirtle et al. 2015). Multibeam sonar has been used to quantify fish aggregation dynamics (Holmin et al. 2012), swimming speeds (Misund and Aglen 1992), predator-prey interactions (Benoit-Bird et al. 2004), and, in some cases, fish biomass (Gerlotto et al. 1999; Feng et al. 2023). The strengths and weaknesses of multibeam sonar are similar to split-beam sonar, including challenges with species identification, detecting fish in the acoustic dead zone near the seafloor, and high cost (Trenkel et al. 2008). Multibeam sonar can sample a much wider swath than split-beam sonar, being especially useful for behavioral studies of individuals or schools naturally or in reaction to vessels, but with increased width comes lower object resolution (Trenkel et al. 2008). Multibeam sonar is best suited to quantifying aggregation and schooling dynamics of pelagic fishes, particularly when combined with split-beam sonar (Korneliussen et al. 2009; Taylor and Ebert 2012), but is not ideal on its own for counting benthic fishes closely associated with the seafloor or structured habitats.

Side-scan sonar

Side-scan sonar uses transducers to emit a wide-angle acoustic signal, and the intensity of the returned signal is used to generate an acoustic image of the seabed and organisms in the water column (Kenny et al. 2003; Ridgway et al. 2024). Side-scan sonar units are typically towed behind a vessel or outfitted on underwater vehicles, ideally moving at a constant height above the seafloor as acoustic signals are emitted outward from, and then received by, a transducer array. Low frequencies (50–100 kHz) are have a greater sampling volume but lower resolution than high frequencies (Kenny et al. 2003). Like multibeam sonar, side-scan sonar is primarily used to characterize seafloor habitats, but there are some examples where side-scan sonar has been used to estimate the abundance of fish around artificial reefs (Bollinger and Kline 2017) or describe fish aggregations around coral reefs (Rivera et al. 2006). Side-scan sonar units are generally cheaper than multibeam sonar units for mapping the seafloor and can be used to count fish in various situations, but note that side-scan sonar calibration is often very difficult or impossible (Bollinger and Kline 2017; Lawson et al. 2020; Ridgway et al. 2024).

Acoustic cameras

Acoustic cameras use high-frequency multibeam sonar to produce near photographic-like images of fish, including morphological characteristics and swimming behavior (Martignac et al. 2015). By using high-frequency sound, acoustic cameras greatly increase the resolution and detail of fish compared to other sonar approaches but at the expense of reduced detection range (<40 m; Jones et al. 2021; Sibley et al. 2023). There are two primary acoustic cameras used for fish: Duel-Frequency Identification Sonar (DIDSON) emits frequencies in the range of 1–2 MHz (Belcher et al. 2002), while Adaptive Resolution Imaging Sonar (ARIS) operates at even higher frequencies to provide greater resolution (Shahrestani et al. 2017; Jones et al. 2021). The primary strength of acoustic cameras is that it can count fish in places or areas where visual methods are not possible, hence their primary use in rivers, estuaries, or turbid coastal waters (e.g. Moursund et al. 2003; Viehman and Zydlewski 2015; Plumlee et al. 2020). The drawbacks include a small sampling volume, morphologically similar species can be difficult to distinguish, fish can be obscured at high densities, and fish at certain angles to the sonar can be difficult to detect (Tušer et al. 2014; Jones et al. 2021). Acoustic cameras are especially useful in structured habitats when fish species richness is low, species are morphologically unique, and visual sampling cannot be used (Martignac et al. 2015; Sibley et al. 2023). Note that, similar to video-based approaches, substantial processing time is required to count fish following field sampling (Dunn et al. 2022).

Passive acoustics

Many fish make sounds to communicate with one another for courtship, mating, or fighting or incidentally while feeding or swimming (Fine et al. 1977; Hawkins et al. 2025). Fish can make sounds in various ways including grinding teeth or other hard parts or by vibrating muscles against the swim bladder or other parts of the body (Kaatz 2002; Ladich 2004). Passive acoustics uses listening devices to detect naturally occurring sounds emitted by fish to understand their distribution, habitat use, and spawning locations

(Gannon 2008; Rowell et al. 2012; Elise et al. 2022). The strengths of using passive acoustics to study fish populations are that it can be used in areas where visual approaches are not efficient (Rountree et al. 2006; Picciulin et al. 2019), arrays of hydrophones can be used to monitor sound production over large areas and time periods (Gannon 2008), and fish locations can be estimated precisely using triangulation (Putland et al. 2018). There are some significant drawbacks of a passive acoustic approach: only some fish species are soniferous (Kaatz 2002), it is challenging but important to sound-truth (i.e. validate) sounds coming from fish using captive or field studies (Lobel 2002; Okumura et al. 2002), data analysis can be difficult due to the large volume of data collected (Lin et al. 2018), and background noise can reduce detection ranges and mask sounds of interest (Gannon 2008; Mann et al. 2008). While passive acoustics has potential to elucidate spawning behavior, habitat use, and predator-prey dynamics of soniferous fishes, it is tenuous to use passive acoustics to estimate fish abundance because sound detection can be influenced by myriad factors including the presence of predators, fluctuating environmental conditions, and variable detection distances (Gannon 2003; Biggs and Erisman 2021).

Table 4. Strengths and weaknesses of tagging approaches for sampling fish in structured habitats.

	Strengths	Weaknesses	Useful in which structured habitats?
Conventional tagging	Can be used to estimate abundance, mortality, or movement rates; creates a known group of fish that can be followed over space and time	Requires the capture of live fish for tagging; fish must survive capture and tagging or the mortality rate must be known; fish must mix with untagged fish; fish cannot emigrate or emigration rate must be known; tag loss rate must either be 0% or known; some studies require knowledge of the tag reporting rate	All structured habitats
Electronic tags	Can be used to estimate abundance, mortality, or movement rates; accurate fish positions possible; additional data from sensors is also possible	Requires the capture of live fish for tagging; fish must survive capture and tagging to collect data; fish must mix with untagged fish to make population-level inferences; tags and hydrophones are expensive; remote listening stations require data downloads; noisy environments influence detection	All structured habitats, although structure may limit detection

Tagging approaches

Fish have been tagged for myriad scientific reasons over the past century, and these studies have contributed enormously to our understanding of fish movement, stock structure, habitat use, mortality rates, and abundance (McKenzie et al. 2012; Thorstad et al. 2013). Tagging fish is particularly advantageous because it creates a known group of fish from the population that can be followed through space or time (Pine et al. 2012). There are numerous ways that tagging studies can be designed using conventional tags, telemetry transmitters, or both (Pine et al. 2003). Most tagging studies rely on the capture of fish from conventional gears (Thorsteinsson 2002). Typically, fish survival from the capture and tagging process must be estimated, and tagged fish must be well mixed with, and thus representative of, untagged fish (Table 4; Pine et al. 2003). Below the two broad categories of tagging studies are described – conventional and electronic tagging (Figure 5).

Conventional tagging

Conventional tagging involves attaching tags or marking fish in a way that the tags or marks can be detected upon the fish's recapture (Seber 1973; Ricker 1975). Marks and tags are highly variable and include fin clips, natural distinctive markings, anchor tags, coded wire tags, passive integrated transponder tags, and visible implant elastomer tags (Pine et al. 2012). Conventional tagging studies can address numerous objectives across widely varying aquatic systems (see review by Pine et al. 2003), but most require fish to be recaptured for reliable information to be collected. Conventional tagging studies have been used to estimate abundance of fish in various structured habitats such as natural reefs (Shertzer et al. 2020; Kohler et al. 2023) and oil and gas platforms (Osowski and Szedlmayer 2022). Conventional tagging studies, however, come with strong assumptions that must be satisfied for mortality or abundance to be estimated accurately (Pine et al. 2003): spatial closure is commonly assumed (Shertzer et al. 2020), the rate of tag loss must either be 0% or known (Hyun et al. 2012), the recapture probability of tagged fish is assumed to

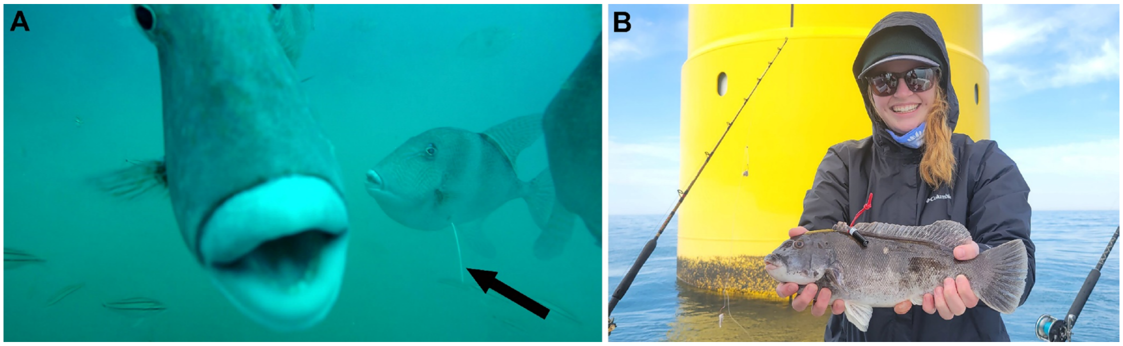

Figure 5. Examples of tagging approaches. (A) Gray triggerfish (*Balistes capriscus*) tagged with a conventional (internal anchor, indicated by black arrow) tag at the Chicken Rock, North Carolina, USA (Shertzer et al. 2020); credit: NOAA-Fisheries. (B) External attachment of an ultrasonic transmitter to tautog (*Tautoga onitis*) at an offshore wind monopile, Virginia, USA; credit: Brendan Runde, The Nature Conservancy.

be the same as untagged fish (Pine et al. 2003), and some studies depend on the fishing industry to report tags, in which case the reporting rate must be 100% or estimable (Pine et al. 2012). In most cases, auxiliary data can be collected to either test these assumptions or account for their violation (Pollock 2002). Conventional tagging studies are best used to estimate fish abundance for species that survive the capture and tagging process and do not change their behavior after tagging.

Electronic tags

Various types of electronic tags have been applied to fish to study their movements, habitat use, and mortality rates. Acoustic and radio telemetry involves attaching, implanting, or inserting a tag that periodically emits a unique radio or ultrasonic signal that is detected by a receiver (Thorstad et al. 2013). When an array of submersible receivers is used, it is possible to position fish accurately using a time-difference-of-arrival algorithm (Espinoza et al. 2011). Telemetry has been used widely to study fish movements, but is also now a leading method to estimate mortality rates of fish, especially natural and discard mortality (Hightower et al. 2001; Bacheler et al. 2009; Rudershausen et al. 2025). While it may be possible to estimate abundance using telemetry directly (Clement et al. 2015), it is much more powerful as a complementary tool to estimate abundance in conjunction with other sampling approaches such as conventional tagging or video counts (Dudgeon et al. 2015; Shertzer et al. 2020; Zulian et al. 2025). Telemetry can also be used to quantify the effective sampling area or efficiency of conventional sampling gears (Lees et al. 2018; Bacheler et al. 2022). The primary drawbacks of telemetry are that equipment can be expensive, animals must survive the capture and tagging process, and remote hydrophones must be recovered and downloaded to access data (Pine et al. 2003; Espinoza et al. 2011). Data storage (i.e. archival) tags can collect information on depth, temperature, or other parameters, but the primary limitation is that data can only be accessed if the animal is recaptured (Godø and Michalsen 2000). Pop-up satellite archival tags transmit information on light, temperature, and depth to scientists *via* satellites once the tag is shed so that positions can be estimated, but the downsides are that positions are often imprecise and missing data are common (Thorstad et al. 2013).

Novel approaches

Fish surveys are expensive and the data collected during these surveys are often limited in space and time. Instead, marine organisms could be monitored with the use of various autonomous vehicles (Table 5; Figure 6; De Robertis et al. 2019; Harris et al. 2019; Whitt et al. 2020). In addition to autonomous sampling, there are some emerging, cutting-edge genetic approaches that are revolutionizing our understanding of various aspects of fish biology and ecology (Figure 6; Casas et al. 2023).

Autonomous underwater vehicles

Uncrewed autonomous underwater vehicles (AUVs) follow pre-programmed tracks to collect various types of video, environmental, and acoustics data (Seiler et al. 2012; Wall et al. 2017; Lembke et al. 2018; Maslin et al. 2021). Some uncrewed AUV use propellers for propulsion, while gliders use buoyancy control with hydrofoils to glide forward while ascending and descending in the water column. Uncrewed AUV can often collect some (but not all) of same

Table 5. Strengths and weaknesses of novel methods for sampling fish in structured habitats.

Gear	Strengths	Weaknesses	Useful in which structured habitats?
Autonomous underwater vehicles	Can carry cameras and numerous acoustic and environmental sensors; data collection cheaper than large research vessels	Initial cost is substantial; potential loss of AUVs; difficultly planning complex missions; recovering AUVs is complicated, often requiring research vessels; ground-truthing of acoustics data often not possible	Low-relief structured habitats with sufficient water depth
Autonomous aircraft systems	Can carry various cameras and thermal sensors; good for detecting fish near the surface in clear water	Most fish not amenable to detection, especially those in structured habitats; only relatively large, conspicuous, pelagic fish are detected; pilots need training	Shallow, clear waters only
Autonomous surface vehicles	Can carry numerous acoustic and environmental sensors; can survey large areas over long periods of time at fraction of the cost of research vessels; ASVs do not influence fish behavior like research vessels	Initial cost is substantial; potential loss of ASVs; sea state influences data collection and navigation; limited transducers compared to research vessels; use may be restricted in some areas; ground-truthing of acoustics data often not possible	All structured habitats where fish species richness is low and fish are not closely associated with structure.
eDNA	Sample entire fish community at a site from a simple water sample; species presence and in some cases relative abundance can be determined; ideal for cryptic, hard to sample, and rare species; amenable to pairing with other gears.	False positives and false negatives can occur; eDNA concentrations affected by habitat being sampled; water currents can transport eDNA, spatially decoupling observations from the sampled population	All structured habitats
Close-kin mark-recapture	Absolute abundance can be estimated at the stock level; samples can be taken from live or dead fish; robust to variable capture probability; no traditional recaptures needed	Not useful for rare, long-lived, highly abundant, clonal, or semelparous species; complicated likelihoods; can be biased for species with limited dispersal and nonrandom sampling; various life history parameters must be known; fish must be captured for genetic samples to be extracted	All structured habitats
Combining gears	Can improve understanding of or ground-truth one gear, provide a more complete understanding of the fish community, and be used to estimate detection or catchability; improvements often occur in terms of accuracy and precision of data	Additional cost to sample with two or more gears; combining data from two gears into a single analysis can be complicated	All structured habitats

types of data as large oceanographic research vessels but at a reduced cost (Greene et al. 2014). Uncrewed AUV have been used to collect fine-scale environmental data (Liblik et al. 2016), listen passively for fish (Luczkovich and Sprague 2022; Cauchy et al. 2023), track acoustically tagged fish (Cypher et al. 2023), use active acoustics to detect fish (Greene et al. 2014), and carry multiple sensors simultaneously (Lembke et al. 2018). Fleets of uncrewed AUV can also be deployed off research vessels to greatly increase their efficiency and provide a system of sustained ocean observations, but the primary challenges are the initial cost of purchasing uncrewed AUV, the potential loss of uncrewed AUV that have malfunctioned, planning complex missions, and the difficulty recovering fleets of uncrewed AUV at sea (Thompson and Guihen 2019). The most efficient use of uncrewed AUV is mapping the seafloor, collecting passive acoustic data on fish sounds, collecting active acoustics data to determine fish distribution and abundance, and listening for acoustically tagged fish.

Uncrewed aircraft systems

Uncrewed aircraft systems (UAS or "drones") can collect information on fish and their habitats from the air, and are much cheaper than crewed aircraft (Harris et al. 2019; Ganie et al. 2025). Uncrewed aircraft systems can carry a wide variety of sensors allowing them to collect data such as multispectral photography, thermal imagery, and light detection and ranging images (i.e. LIDAR; Espriella et al. 2023). Uncrewed aircraft systems costs vary widely and come in two primary styles: multi-rotor UAS for surveying smaller areal extents and fixed-wing UAS for surveying larger areas (Harris et al. 2019). Uncrewed aircraft systems have improved fisheries science in a variety of ways, including monitoring illegal fishing activities in marine protected areas (Reis-Filho et al. 2022), estimating fishing effort (Dainys et al. 2022), identifying critical fish habitats such as nursery or spawning areas (Ventura et al. 2016; Scoulding et al. 2024), collecting imagery to count large epipelagic marine organisms like sharks or spawning salmon in clear water (Kiszka et al. 2016; Groves et al. 2017), and detecting telemetry tagged fish (Oleksyn et al. 2021). The major downsides of UAS for use in fisheries science are that there are relatively limited ways in which UAS can be used to improve our knowledge of fish in structured habitats, pilots need experience and licensing, there are limits to the places UAS can fly, and data analyses can be challenging (Harris et al. 2019).

Figure 6. Examples of novel sampling approaches. (A) Autonomous underwater vehicle (glider) carrying various acoustical sensors to detect grouper spawning aggregations in St. Croix, USA. Virgin Islands; credit: NOAA-NCCOS Seascape Ecology and Analytics. (B) Uncrewed aircraft system (drone) to understand movements of sharks at the Rachel Carson Reserve, North Carolina, USA; credit: Duke Marine Robotics and Remote Sensing Lab. (C) eDNA sampling for endangered Asian arowana (*Scleropages formosus*) in Bukit Merah Lake, Perak, Malasia; credit: Norli Fauzani Mohd Abu Hassan Alshari, Universiti Malasia Terengganu. (D) Autonomous surface vehicle ("DRiX") collecting acoustic data in Malina Bay, Kodiak Island, Alaska, USA; credit: Bryan Begun. (E) Taking fin clip of red snapper (*Lutjanus campechanus*) for a close-kin mark-recapture study to estimate absolute abundance as part of the South Atlantic Red Snapper Research Program; credit: FLFWC-FWRI. (F) Paired chevron trap, video, and diver survey (Bacheler et al. 2017); credit: Brad Teer, Cooperative Institute for Marine and Atmospheric Studies, University of Miami.

Uncrewed aircraft systems hold the most promise for surveying highly visible fish or their habitats in shallow, clear water and determining the locations of fishing activities.

Autonomous surface vehicles

Autonomous surface vehicles (ASVs) are various types of uncrewed sailboats (i.e. "saildrone") or kayaks, most of which use wind for movement and solar panels for generating electrical energy to power on-board oceanographic and meteorological sensors (Handegard et al. 2024; Sun et al. 2025). ASVs can operate autonomously over long timeframes, providing an efficient method of collecting data at the air-ocean interface over large spatial scales (Meinig et al. 2019). For fish surveys, the most commonly used sensors on ASV are split-beam echosounders for active acoustics and hydrophones for passive acoustics and telemetry (Mordy et al. 2017). There are some major strengths of ASV, including their ability to survey large areas over long periods of time at a small fraction of the cost of research vessels while producing comparable data (De Robertis et al. 2019, 2021), detect fish near the surface due to shallow transducer depth (Handegard et al. 2024; Komiyama et al. 2025), and, perhaps most importantly, not influence fish behavior like many research vessels (De Robertis and Handegard 2013; Evans et al. 2023, 2024). The primary drawbacks of ASV are that sea state can affect their ability to navigate and collect clean data due to interference with bubbles (Handegard et al. 2024), the number of transducers (and therefore data resolution) is typically limited compared to research vessels (Komiyama et al. 2025), and data validation is required (De Robertis et al. 2021). Currently, the best use of ASV is to collect active and passive acoustics data on fish in places where species richness is relatively low (e.g. arctic waters) and ground-truthing data from research or fishing vessels are available (Bolser et al. 2023; Handegard et al. 2024).

Environmental DNA

Fish release DNA into the water when they die and decay or when they shed skin cells, scales, tissues, or feces (Creer et al. 2016). Environmental DNA (eDNA) is a noninvasive approach where sloughed DNA from fish can be detected in the environment (e.g. water) without the need for collecting organisms themselves (Thomsen and Willerslev 2015). Fish DNA introduced into the water column degrades over time but often lasts long enough (days to weeks) to be detected in water samples (Barnes et al. 2014; Collins et al. 2018). The use of eDNA sampling to detect the presence and distribution of fishes has rapidly expanded in the last decade, being particularly useful for rare, cryptic, or invasive species that are poorly sampled with other sampling gears (Bessey et al. 2023; Alshari et al. 2025). In some situations, eDNA concentrations of fish have tracked well with catches from independent sampling gears in the same areas (Shelton et al. 2019, 2022; Andres et al. 2023; Luo et al. 2023; Guri et al. 2024). The strength of eDNA is being able to sample an entire fish community simply by collecting a water sample (Abidin et al. 2022; Zamani et al. 2022). Drawbacks of eDNA are that both false positives and false negatives can occur (Port et al. 2016), eDNA concentrations are affected by the habitat being sampled (Stat et al. 2019; Lafferty et al. 2021), and water currents can uncouple eDNA concentrations and fish abundance from the location of origin (Abidin et al. 2022; Thompson 2024). eDNA is a promising approach that can best be used to complement and understand various other sampling gears (Stat et al. 2019; Bessey et al. 2023; Clark et al. 2024).

Close-kin mark-recapture

Close-kin mark-recapture (CKMR) is a relatively new approach to estimate the abundance of animals using the frequency of relatedness from genetic samples (Bravington, Grewe, et al. 2016; Bravington, Skaug, et al. 2016; Trenkel et al. 2022). CKMR is a type of mark-recapture approach where fish are "marked" by being present in the sample and "recaptured" if the sample contains one or more close relatives (e.g. half-siblings; Ruzzante et al. 2019). For a given level of genetic sampling, more close relatives are expected in small populations compared to large populations (Bravington, Grewe, et al. 2016; Bravington, Skaug, et al. 2016). CKMR has been used to estimate absolute abundance of several high-profile fish species (Bravington, Grewe, et al. 2016; Bravington, Skaug, et al. 2016; Hillary et al. 2018; Delaval et al. 2023). The strengths of CKMR are that it can provide robust estimates of absolute abundance, samples can be acquired from live or dead fish without the need for recapturing fish, and it is robust to many problems associated with variable capture probability (Bravington, Grewe, et al. 2016; Bravington, Skaug, et al. 2016; Marcy-Quay et al. 2020). Drawbacks of CKMR are that it cannot be easily applied to clonal, semelparous, abundant, long-lived, or rare species, fish must be captured for DNA samples to be extracted, detailed reproductive, age, and life history information are needed for the species of interest, and CKMR can be biased under certain situations (Bravington, Grewe, et al. 2016; Bravington, Skaug, et al. 2016; Conn et al. 2020; Trenkel et al. 2022). CKMR is most amenable for species with well understood life histories, the species is neither extremely rare nor abundant, and scientists are able to obtain a sufficient number of samples (Bravington, Grewe, et al. 2016; Bravington, Skaug, et al. 2016; Trenkel et al. 2022).

Combining gears

All gears select for certain sizes or species of fish and sampling efficiency may vary across habitats, so combining sampling gears can reduce the inherent biases in each technique and provide a more accurate picture of the entire fish community (Willis et al. 2000; Bacheler et al. 2017). Using multiple gears or combining datasets from various gears has become common because, in most situations, improvements in accuracy and precision have outweighed the costs of adding another gear (Watson et al. 2005; Conn 2010; Gibson-Reinemer et al. 2017). There are three primary ways in which combining sampling gears can improve fish sampling compared to single gears, ranging from simple to more complex approaches.

The first and simplest reason gears may be paired is to use one gear to modify or inform estimates from a second (primary) sampling gear. A classic example is using video to determine the sizes or species of fish missed, habitat damage, and bycatch rates of various conventional sampling gears (Grant et al. 2004; Kilpatrick et al. 2011; Bacheler et al. 2014). Another example is that acoustic returns from split-beam hydroacoustic surveys commonly need to be partitioned into various species using independent sampling gears like trawls or video (Ressler et al. 2009; Jones et al. 2012; Scoulding et al. 2023). Moreover, visual gears like UVC and remote video are strengthened when they are ground-truthed using other visual gears, eDNA, or tagging (Pelletier et al. 2011; Fernández et al. 2021).

The second reason gears can be used together is to generate independent estimates that provide a more complete understanding of a species or community than using any single gear by itself. There are many examples of paired gears being used in tandem to survey fish around the world, the most common pairings being conventional gears with non-extractive visual gears (Bacheler and Ballenger 2018; López-González et al. 2022), visual gears being used together (Watson et al. 2005; Lowry et al. 2011; Logan et al. 2017), and eDNA being combined with various other gears (Sato et al. 2021; Alexander et al. 2022). Some of these studies present separate, gear-specific indices of abundance (e.g. Bacheler and Ballenger 2018), but it is also possible to combine disparate indices into a single index of abundance using various modeling approaches (Conn 2010; Gibson-Reinemer et al. 2017; Peterson et al. 2021).

The last way that data from paired gears can be used is to produce a single, integrated estimate *via* models that use information from both or all gears. The simplest version is using one sampling gear to catch fish for mark-recapture experiments and another (e.g. video) for "recapture" (Shertzer et al. 2020; Dennis et al. 2024). Occupancy models use presence-absence data from repeated observations (e.g. multiple divers) of a species to estimate occupancy and detection rates (Katsanevakis et al. 2012). Occupancy models typically assume temporal closure, but paired gears can be used instead of repeated observations to estimate occupancy and detection rates, eliminating the need to assume temporal closure (Coggins et al. 2014). *N*-mixture and related state-space models can use count data from repeated observations or paired gears to estimate abundance and catchability (Gwinn et al. 2019; Madsen and Royle 2023; Zulian et al. 2025). Integrated population models and stock assessments are very similar and combine survey data from various gears with demographic data to estimate various population parameters (Riecke et al. 2019; Schaub et al. 2024). The primary benefits of occupancy, *N*-mixture, and integrated population models is that they combine the strengths of each sampling gear to create robust estimates while explicitly accounting for imperfect detection or catchability; the challenges are that they can be data hungry and have trouble accommodating over-dispersed or zero-inflated data.

Synthesis

Many fish species associate with structured habitats. While structured aquatic habitats often account for a small proportion of the seafloor, they tend to harbor higher fish densities and diversity than unstructured habitats (Trebilco et al. 2015; Ilich et al. 2021). Fish are attracted to structured habitats because they generally provide increased food resources and reduced predation threat (Webster and Hixon 2000; Stewart and Jones 2001). The abundance and distribution of fishes associated with structured habitats, however, are changing due to habitat degradation, fishing, pollution, and environmental variability (Pandolfi et al. 2003; Beck et al. 2011; Goldberg et al. 2020). It is thus critical to survey fish in structured habitats, but that can be difficult because gear can be snagged and lost, sensitive habitats can be damaged, and fish are often not sampled in proportion to their abundance (Murphy and Jenkins 2010).

Many approaches can be used to sample fish in structured habitats. Here, 24 of the most common sampling approaches were reviewed, and the strengths, weaknesses, and most useful applications of each were described. A key takeaway from this review is that there is no ideal sampling gear that can be used for all fish species in all structured habitats. Instead, the optimal sampling gear depends on the morphology, biology, and behavior of the species of interest, the physical characteristics of the habitats being sampled, and the objectives of the study (Blaber et al. 1985; Willis et al. 2000). For instance, visual approaches are well suited to sampling fishes in clear waters like coral reefs, but perform poorly at turbid oyster reefs (Donaldson et al. 2020). Acoustic cameras can effectively sample mid-sized fish around oyster reefs, but poorly sample small, cryptic fish species (Tušer et al. 2014). eDNA is an ideal approach to sample cryptic fishes in various places including oyster reefs but is currently much better suited for determining presence or absence than estimating abundance (Andres et al. 2023; Luo et al. 2023). Given that all gears have strengths and weaknesses, the goal of this review was to provide a guide to researchers and scientists that would allow them to sample fishes in structured habitats effectively.

Another key finding is that no sampling gear has perfect detection or catchability. As one example, UVC only detected 18–65% of the species present and 23%

of the individuals associated with tropical reefs (Brock 1982; Willis 2001; MacNeil et al. 2008). Even eDNA often misses a significant portion of the fish species known to be present (Port et al. 2016; DiBattista et al. 2017). Two ways of dealing with the imperfect detection of fish by sampling gears are recommended. The first is to combine sampling gears so that fewer fish species are missed and the strengths and weaknesses of each gear can be better understood (Stewart and Beukers 2000; Stat et al. 2019; Alexander et al. 2022). The second is to use methods that account for imperfect detection like occupancy, state-space, *N*-mixture, or integrated population models (MacKenzie et al. 2002; Royle 2004; Gwinn et al. 2019).

It is also clear that some methods have the potential to transform fish sampling in structured habitats and deserve more research focus and widespread use. For instance, eDNA deserves broader application given how easily it pairs with other sampling gears and its power to detect a wide array of fish species (Alexander et al. 2022; Lin et al. 2022). More attention should also be given to attempting to estimate relative abundance (or biomass) from eDNA, which, if broadly feasible, could revolutionize fish sampling (Shelton et al. 2019, 2022; Andres et al. 2023). The use of autonomous underwater, surface, and aerial vehicles will allow for more efficient data collection or fill in gaps from research vessels, as long as vehicle loss can be minimized and challenges with recovering vehicles are improved (Lembke et al. 2018; De Robertis et al. 2019; Harris et al. 2019). If the objective is to estimate absolute abundance at the population level, CKMR may become more popular because of its many advantages over traditional mark-recapture techniques (Bravington, Grewe, et al. 2016; Bravington, Skaug, et al. 2016; Trenkel et al. 2022). While these novel approaches may revolutionize fish surveys, they all have strengths and weaknesses that need to be accounted for and none will likely ever become a panacea (Pitcher and Lam 2010).

Another key finding is that water clarity and depth often broadly influence which gears can be used to sample structured habitats. In clear water, visual approaches like UVC and video are commonly used (Figueroa-Pico et al. 2020), whereas conventional and acoustic gears tend to be more effective when water is turbid. Water depth also influences the choice of sampling method. Some gears such as UVC and acoustic cameras cannot be easily used in deep water, while others such as ROV, AUV, and most sonar approaches have limited utility in especially shallow water (Misund 1997; Murphy and Jenkins 2010). Most conventional gears, eDNA, and tagging methods are generally unaffected by the water clarity or the depth of structured habitats being sampled.

It is also important to note that not all structured habitats are equal. Seagrass tends to be somewhat unusual among structured habitats in that gear hangs and tangles are rare, so trawling and seining are possible (Harmelin-Vivien and Francour 1992; Guest et al. 2003). Some structured habitats including tropical, temperate, and cold-water coral reefs are particularly sensitive and can be easily damaged by sampling gears (Fosså et al. 2002; Anderson and Clark 2003). On the other end of the spectrum, the immense vertical structure provided by shipwrecks, oil and gas platforms, and wind turbines are especially difficult to sample effectively: UVC can only be used near the surface (Cote and Perrow 2006), ROV tethers can get tangled in structure (Greene 2015), hook-and-line sampling primarily targets a small subset of species (Willis et al. 2000), water clarity can vary throughout the water column (Ajemian et al. 2015), and fish movement around structure complicates their detection, counting, and capture (Ajemian et al. 2015).

Whether fish need to be captured for biological sample extraction, tagging, or recapture is an important consideration that strongly influences the choice of sampling gear. Most modern stock assessments methods, for instance, require fish ages to be determined from otoliths and reproductive characteristics to be determined from histological samples, and, as of now, these can only be obtained *via* direct capture (Hilborn and Walters 1992). Only conventional sampling gears allow capture for biological samples or tagging, although note that fish may be "recaptured" using video or UVC (Shertzer et al. 2020). Given the numerous challenges of using conventional gears to sample fish in structured habitats, pairing conventional gears with eDNA, video, or other approaches may be optimal when biological samples are required (Lin et al. 2022). In other situations, it may be necessary to sample fish in places where extractive gears are prohibited, such as marine reserves; here, all gears except conventional gears may be considered (see review by Murphy and Jenkins 2010).

Additionally, bait is an important consideration when designing and evaluating a fish survey. Bait is commonly used in trap and remote video surveys because it attracts predatory and scavenging fish species to the sampling gear, greatly increasing their detection, trap catches, or video counts (Dorman et al. 2012; Hardinge et al. 2013). There are downsides of using bait, however. For instance, the catches or counts of predatory and scavenging species increase with bait but other fish species do not, influencing community-level analyses (Harvey et al. 2007). Fish can also move among habitats due to their attraction to bait, confounding habitat selection studies (Stewart et al. 2019). Bait also attracts predatory and scavenging fish species from some broader unknown area (i.e. the "effective sampling area;" Bacheler et al. 2022); most baited surveys necessarily assume that the effective sampling area is constant over space and time (Stoner 2004). If the effective sampling area of baited gears could be determined, however, it would allow relative abundance estimates from baited gears to be converted to density estimates (Lees et al. 2018; Bacheler et al. 2022). Further comparison of baited versus unbaited trap and remote video deployments would help to resolve the effects of bait on fish relative abundance and diversity estimates (Harvey et al. 2007; Matthews et al. 2024).

Conclusion

The sustainable management of fish resources depends critically on scientific surveys that estimate abundance and other population parameters accurately, precisely, and efficiently (Dennis et al. 2015; Goethel et al. 2023). This is particularly challenging for the vast majority of fish species that associate with structure because structured habitats tend to be fragile, can snag or hang sampling gears, and can obscure fish, generally making them much harder to sample than fish in unstructured habitats. To overcome these challenges, it is recommended to (1) combine sampling gears to obtain a more complete picture of fish assemblages in structured habitats, (2) focus more research attention on novel approaches such as eDNA, CKMR, and autonomous vehicles, which may eventually be able to provide the most accurate, precise, and efficient data for fish, and (3) choose the optimal sampling gear(s) based on the species of interest, characteristics of the physical structure to be sampled, the specific objectives of the study, and operational constraints. Improved sampling of fish in structured habitats will increase the accuracy and precision of stock assessments and improve fisheries management, which will benefit fish, their habitats, and all those who rely on healthy fish populations for food, jobs, and recreation.

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ORCID

Nathan M. Bacheler http://orcid.org/0000-0003-1955-6044

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