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Review Article

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A review and synthesis of the benefits, drawbacks, and considerations of using traps to survey fish and decapods

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Abstract

Traps (or pots) are one of the oldest and most widespread scientific survey gears for fish and decapod crustaceans around the world. Here, I review and synthesize the extensive scientific literature describing the various benefits and drawbacks of using traps as a survey gear in scientific studies. The widespread use of traps in fish and decapod surveys is due to several characteristics like their low cost, flexible design, ease of use, ability to fish unattended, and being amenable to pairing with other gears. However, there are a number of significant drawbacks of using traps, including highly variable catches due to environmental fluctuations or behavioral interactions or lost traps that continue catching and killing animals, that must be considered and accounted for when initiating trap surveys. This study highlights the types of habitats and species most and least suited for monitoring by traps, and emphasizes the importance of matching the goals and objectives of a trap survey with the correct trap design, mouth entrance, bait type, soak time, and pairing of gears. Pilot studies are also recommended before surveys are initiated to quantify the selectivity patterns of traps and identify the various factors that may influence trap catch.

Keywords: trap; pot; index of abundance; relative abundance; bycatch; habitat; entanglement; ghost trap; derelict trap; mesh size; soak time; biodiversity

Introduction

For thousands of years, humans have used various types of traps to catch fish. The oldest traps were weirs made out of stones, reeds, or wood that captured fish moving with the current or tide or while they migrated up or down rivers (Bathgate 1949, Kroeber and Barrett 1960, Byram 2002, Hale 2005, Connaway 2007, Jeffery 2013, Stewart 2018). Remnants of stone or wood weirs are still visible in places like Japan, Taiwan, Madagascar, the British Isles, the coasts of North America, or islands in the South Pacific, some of which have been dated to >5000 years old (Petersen et al. 1994, Gabriel et al. 2005, Connaway 2007) and others that continue to be used today (Fig. 1; Jeffery 2013). For instance, the Phoenicians developed a method to trap giant bluefin tuna (*Thunnus thynnus*) during their annual migration in the Mediterranean Sea (the "mattanza") a few thousand years ago, a tradition that still periodically occurs today in southern Italy (Gabriel et al. 2005, Di Natale 2018).

A great variety of traps are still used today by artisanal, commercial, and, in some instances, recreational fishers to harvest fish, decapod crustaceans (i.e. crabs, lobsters, shrimp, and crayfish), mollusks, and gastropods (Fig. 2). Fish weirs and pound nets are temporary or semi-permanent structures typically consisting of a series of leads and funnels and open to the air above, while fyke nets are similar to fish weirs but are shaped like cylinders and are typically deployed entirely underwater and made mostly of netting (Gabriel et al. 2005, Collins et al. 2015). Throw or enclosure traps are typically thrown or dropped into the water column and surround a fixed and known area of surface water (Kushlan 1981, Jordan et al. 1997). The last main category is a trap or pot, which typically refers to relatively small, enclosed, three-dimensional metal, wood, or mesh containers of various shapes and sizes that have a small entrance funnel, making entry easy and escape difficult. These traps or pots are often (but not always) baited and attached to a surface buoy via a rope for retrieval. Traps can be set individually or attached together along a mainline rope in a series called a trawl, fleet, long-line, or rig (Stevens 2021).

In addition to their prominence in harvest fisheries, traps are also one of the oldest scientific survey gears for fish and decapod crustaceans around the world (Jackson and Harvey 1997). The reputation of traps as an effective, simple, and versatile sampling gear increased after the seminal publications of Munro et al. (1971), Munro (1974), and Miller (1990). Although traps are now most often used in rocky or reef habitats where it is difficult or impossible to use trawls, nets, or visual census due to seafloor rugosity or depth (Newman and Williams 1995), they can and have been used in myriad aquatic habitats (Vadziutsina and Riera 2020). For instance, traps have been used to survey aquatic organisms in New Zealand lakes (Hayes 1989), Alaskan rivers (Bryant 2000), estuarine saltmarshes (Sheaves 1992, Kneib and Craig 2001), reef habitats in tropical, subtropical, and temperate oceans (Munro et al. 1971, Munro 1974, Ferry and Kohler 1987, Recksiek et al. 1991, Evans and Evans 1996, Langlois et al. 2015, Bacheler and Smart 2016, Miller et al. 2023), and the deep sea (Clausen and Fujioka 1988, Priede et al. 1994, Jones et al. 2003).

This review details the benefits and drawbacks of using traps as a biological sampling gear for scientific surveys, updating the comprehensive review by Miller (1990) and expanding it to include fish in addition to decapod crustaceans. This review is focused on individual, portable fish traps that

Figure 1 Stone-walled fish weir in Maap Municipality, Yap, Federated States of Micronesia, built sometime before Spanish contact in 1528 but is actively maintained and continues to be used to catch a variety of fishes today (photo credit: William Jeffery, College of Liberal Arts and Social Sciences, University of Guam).

are deployed on the seafloor, commonly baited, and hauled after a specified soak time (Fig. 3). The widespread use of traps in fish and decapod surveys is due to a number of convenient characteristics like their low cost, ease of use, and ability to fish unattended (Miller and Hunte 1987, Gomes et al. 2014, Bacheler et al. 2017, Miller et al. 2023). But there are also some significant drawbacks of using traps as a survey gear, including highly variable catches due to environmental fluctuations or behavioral interactions among species, that complicate or preclude using traps to make inferences about abundance or diversity (Table 1; Addison and Bell 1997, Stoner 2004, Bacheler et al. 2017). After reviewing the various benefits and drawbacks of traps as a sampling gear, I provide a roadmap that outlines the types of habitats and species most and least suited for population monitoring by traps. I conclude by emphasizing the importance of matching the goals and objectives of a trap survey with the correct trap design, mouth entrance, bait type, soak time, and pairing of gears. I also strongly recommend conducting pilot studies before surveys are initiated to quantify the selectivity patterns of traps and identify the various environmental, habitat, and behavioral factors that may influence trap catch.

Benefits of using traps as a survey gear

Cost

Surveys using fish traps are relatively inexpensive compared to other commonly used sampling gears such as trawls, nets, video cameras, or SCUBA divers (Table 1; Miller and Hunte 1987, Miller 1990, Ganias et al. 2021). This is especially true of small minnow traps (∼$10 US each) or several varieties of homemade fish traps used in many artisanal fisheries, which can often be deployed from small boats or from shore (Garrison et al. 1998, Agar et al. 2008, Chen et al. 2012, Gomes et al. 2014, Vadziutsina and Riera 2020). The price can be much higher, however, for large traps like those used for crabs that are made from materials like tar-treated knotted nylon mesh or plastic-coated galvanized wire (∼$1500 US each), which are heavily weighted so they can be deployed in deep water (Zhou and Shirley 1997). Traps are also durable and generally require fewer repairs than trawls, gillnets, seines, and longlines (Table 1). Costs are also dependent upon the number of traps needed in a survey. Generally, surveys that use shorter soak durations require fewer traps because they can be redeployed repeatedly throughout the day, while surveys deploying traps for longer soak durations require more traps to achieve comparable sample sizes. But the purchasing of traps is not the only cost incurred by trap surveys; ancillary trap gear (e.g. lines, floats), bait, and the costs of deployment and retrieval (e.g. ship time, labor, fuel) also must be included in the overall cost. Generally, fishing with passive gears like traps has both fewer direct costs and fewer environmental costs than active gears like trawling (Suuronen et al. 2012).

Flexible design

Traps are one of the most versatile sampling gears for aquatic organisms and habitats owing to their enormous diversity in size, shape, color, mesh size, material, and bait (Miller 1990,

Figure 2 Four examples of traps used by artisanal or commercial fishers to harvest aquatic organisms (a) wood and net traps covered in coconut leaves on the bow of an artisanal fishing boat used to catch squid in Rayong Province, Thailand (photo credit: Charuay Sukhsangchan, Kasetsart University). (b) Commercial Dungeness crab (*Metacarcinus magister*) pot from Puget Sound, Washington, USA (photo credit: Natural Resources Consultants, Inc.). (c) Commercial European lobster (*Homarus gammarus*) and brown crab (*Cancer pagurus*) traps in Inisheer, Aran Islands, Ireland (photo credit: Nathan M. Bacheler). (d) Artisanal wire fish traps that are used to target deep-water snapper (i.e. lutjanid) species, taken in the municipality of Cabo Rojo, Puerto Rico (photo credit: Juan Agar).

Mahon and Hunte 2001, Carreira and Gonçalves 2009). Traps can be small and made with fine mesh or plexiglass to sample larval, juvenile, or small fishes (Fisher and Bellwood 2002, Merilä et al. 2013) or shrimp (Struhsaker and Aasted 1974), or they can be very large in size with large mesh to target large fishes or crabs (Zhou and Shirley 1997). In general, the choice of trap design will strongly influence the species and size ranges caught (Laarman and Ryckman 1982, Clausen and Fujioka 1985, Miller 1990). For instance, snow crab (*Chionoecetes opilio*) traps that included a vertical panel reduced the catch of soft-shelled and smaller female crabs that fishers wanted to avoid while maintaining the same catch rate of commercially valuable crabs (Hébert et al. 2001), similar to blue crab (*Callinectes sapidus*) traps with cull rings in North Carolina (Rudershausen and Turano 2009). Larger traps also tend to have higher catches, all else being equal, which may be due to their higher visibility or reduced saturation effects (Wolf and Chislett 1974, Miller 1990), but larger traps are more difficult to deploy than smaller traps (Ferry and Kohler 1987) and, as described above, more expensive. Some traps can be highly selective and take advantage of specific behaviors of target species, like Gittings traps that selectively capture invasive lionfish (*Pterois volitans* or *P. miles*) by providing structural habitat that they strongly prefer (Gittings et al. 2017, Harris et al. 2020, 2023). Mesh size, bait type and amount, and the size, number, and orientation of mouth openings also strongly influences trap catch (Luckhurst and Ward 1987, Bohnsack et al. 1989, Karnofsky and Price 1989, Miller 1990, Sheaves 1995, Mahon and Hunte 2001).

Ability to sample diverse aquatic habitats

Unlike many other sampling gears, traps can be used to sample fish or decapods across a wide variety of habitats and environmental conditions. Traps are one of the rare sampling gears that can be deployed in diverse aquatic habitats like streams (Reebs et al. 1995), wetlands (Langston and Kent 1997), tidal estuaries (Sheaves 1992, Kneib and Craig 2001), reefs (Bacheler et al. 2022a, Miller et al. 2023), kelp forests (Shester and Micheli 2011), and the deep sea (King 1987, Priede et al. 1994, Jones et al. 2003). Traps are particularly useful for sampling highly rugose habitats like rocky or coral reef habitats that cannot be sampled efficiently with trawls (High and Ellis 1973, Wolff et al. 1999). Traps can also effectively sample in turbid waters where video is not particularly effective (Bacheler et al. 2014, Plumlee et al. 2020). Perhaps the only habitats where traps may be difficult to deploy is in aquatic environments with strong currents like fast-flowing rivers, estuaries with strong tides, or strong ocean currents; heavy weights and multiple mouth openings may allow traps

Figure 3 Three examples of traps used by scientists to survey fish or decapod crustaceans. (a) Annual snow crab (*Chionoecetes opilio*) survey using baited traps to estimate relative abundance and monitor animal health in Notre Dame Bay, Newfoundland, Canada, aboard the Canadian Coast Guard Ship Vladykov (photo credit: Darrell Mullowney). (b) Mesh-enclosed wooden pots used to survey western rock lobster (*Panulirus cygnus*) populations in Western Australia (photo credit: Ash Miller). (c) Chevron or arrowhead traps used to monitor reef-associated fish species by the Southeast Reef Fish Survey along the southeast United States Atlantic coast (photo credit: NOAA).

Table 1. Qualitative comparison of various survey attributes for six common sampling gears.

	Trap	Trawl	Longline	Gillnet	Divers	Video
Cost	Medium	High	Medium	Low	High	Medium
Durability	High	Low	Low	Low	High	Medium
Size selectivity	High	Medium	High	Medium	Low	Low
Species selectivity	High	Low	High	Medium	Low	Low
Bycatch	Low	High	High	Medium	None	None
Habitat damage	Low	High	Medium	Medium	Low	Low

to sample effectively in these habitats even when water current is strong (Karnofsky and Price 1989).

Ability to sample unattended

Most sampling gears like trawls and hook-and-line require people to actively fish gears, but traps are advantageous because they catch fish or decapods passively without the need for fishers to be present (Miller 1990, Vadziutsina and Riera 2020). No attendance means that traps can be deployed in larger quantities simultaneously than actively fished gears, which is possible in many situations given their relatively low cost (Beliaeff et al. 1992).

Trap selectivity

No gear samples the available sizes and species of aquatic organisms perfectly (Willis et al. 2000, Parker et al. 2016, Bacheler et al. 2017). Selectivity of a fishing gear is the fraction of various age or size classes a gear retains compared to what is available (Mahon and Hunte 2001). Traps have been described as non-selective (Stevenson 1978, Beliaeff et al. 1992), suggesting that they capture most or all variety of available species and size, but can also be quite species- and size-selective (Murphy and Jenkins 2010, Harvey et al. 2012, Bacheler et al. 2017, Kalogirou et al. 2019, Christiansen et al. 2020, 2022).

These contrasting perspectives likely stem from the different objectives of the specific fishery, project, or survey. From a commercial or artisanal fisheries perspective, it is generally desirable for traps to only catch legal sizes of allowable species with no bycatch, but a wider array of non-target and sub-legal target species are often caught in trap fisheries, giving the impression that they are relatively unselective (Stevenson 1978, Beliaeff et al. 1992, Mahon and Hunte 2001, Rudershausen et al. 2008). When traps are used in multi-species surveys, however, they often detect fewer total species and from a narrower size range than many other gears such as underwater visual census, video, or trawls, so they appear relatively selective (Harvey et al. 2012, Bacheler et al. 2017, 2022, Finucci et al. 2019).

Most research indicates that baited traps select for benthically oriented predatory and scavenger species of fish or decapods, while poorly sampling other functional groups of aquatic organisms like detritivores, planktivores, or herbivores (Murphy and Jenkins 2010, Harvey et al. 2012, Bacheler et al. 2017, Vadziutsina and Riera 2020). Many fishery-targeted and managed species are predators or scavengers, so traps tend to be suited well to sampling species with management importance. For instance, Bacheler and Smart (2016) used long-term trap catches to infer changes in reef fish community structure over time along the southeast United States Atlantic coast, but noted that their results only pertained to the species effectively sampled by traps and not the entire fish community. Sometimes a highly selective trap is desirable in a scientific survey, like those using traps to selectively catch invasive species like lionfish (Harris et al. 2020, 2023).

Captures animals alive

For some sampling gears, including trawls, gill nets, or longlines, a significant portion of the catch can die from the sampling process due to physical injuries or the side effects of immobilization (Poisson et al. 2010, Tsagarakis et al. 2018). In contrast, the survival of fish and decapods caught in traps is generally much higher because animals can move freely in the trap and only rarely suffer physical injuries or predation (Miller 1990). Thus, traps are particularly useful for capturing fish for tagging (Bacheler et al. 2018, Lees et al. 2018, Runde et al. 2019, 2021), genetic studies (Miller et al. 2015), or in protected areas (Sedberry et al. 1998, Pickens et al. 2021) where the goal is to maximize animal survival after release. The biggest sources of mortality for fish caught in traps are predation in traps before retrieval (e.g. Fjälling 2005) or barotrauma effects during retrieval (Bohnsack et al. 1989), which can in some cases be mitigated by changes in trap design (Lunneryd et al. 2003, Hemmingsson et al. 2008) or avoidance of sampling in deep water.

Species identification

Many aquatic organisms are difficult to identify to the species level. Identification of fish to the species level is particularly challenging for visual, video, or acoustic surveys where fish can be detected in various ways but not captured (Horne 2000, Able et al. 2014, Bacheler et al. 2022a). Even using morphological characteristics like gill raker or dorsal fin ray counts for captured fish may be insufficient to identify some challenging taxa like juvenile *Seriola* (Galbraith et al. 2022) or Pacific rockfishes (Pearse et al. 2007) to the species level. In cases where identification to the species level is needed, genetic analyses may be required, which is often only possible when fish can be captured by sampling gears like traps (Bacheler et al. 2022a).

Obtaining biological samples

By capturing fish directly, traps allow for biological samples to be extracted from individual fish, which is not typically possible from visual, video, or acoustic surveys (Miller 1990). Various biological samples taken from fish during surveys can be important inputs for stock assessments (Hilborn and Walters 1992, Walters and Martell 2004). Lengths and weights are commonly collected from captured animals in surveys. So too are otoliths or scales for aging, which are important for estimating recruitment and selectivity in age-structured stock assessments (Hilborn and Walters 1992, Campana 1999). Reproductive samples can be extracted from fish to estimate size or age at maturity, the timing and length of the spawning season, and fecundity (Jakobsen et al. 2016). Fin clips may be taken from fish caught in traps for genetic analyses to estimate, for instance, absolute abundance (Bravington et al. 2016) or ages of fish (Weber et al. 2022). Diet samples can be taken from fish to understand key predator–prey and competitive interactions in ecosystem models (Fowler 1999, Hanson and Chouinard 2002). Numerous other biological samples and health assessments can be taken from fish captured during trap surveys.

Estimation of relative abundance

There are many examples where trap catches have been used to infer relative abundance of fish and decapod species around the world. Miller and Hunte (1987) showed that squirrelfish (*Holocentrus adscensionis*) catches in unbaited traps were strongly correlated with estimates of local density from divers on reefs in Bardabos, although the total number of trap deployments was quite low ($N = 19$). Trap catches and diver counts were strongly correlated for both American lobsters (*Homarus americanus*) and Atlantic rock crabs (*Cancer irroratus*), suggesting both tracked patterns of local abundance (Miller 1989). Catches from a multi-species fish trap survey along the southeast United States Atlantic coast have also been used to estimate relative abundance for some species over space and time (e.g. Bacheler and Ballenger 2016, 2018).

Other studies have shown that trap catch can asymptote not due to space limitation or intraspecific interactions, but because an equilibrium is reached between entry and exit rates at a catch level that reflects local abundance (Bacheler et al. 2013a, Shertzer et al. 2016). Bacheler et al. (2017) showed that the ability of chevron traps to estimate relative abundance of reef fishes was highly variable across species, being very useful for some species (e.g. black sea bass, *Centropristis striata*) but not others (e.g. gray snapper, *Lutjanus griseus*). Note that it is difficult or impossible to compare trap catches to actual abundance in most situations (similar to most other passive sampling gears), so inferences are often made by comparing trap catches to estimates from other sampling gears, which is not ideal. Many have therefore questioned the utility of traps to provide reliable relative abundance data for numerous environmental or behavioral reasons that are described below (Fogarty and Addison 1997, Jackson and Harvey 1997, Rozas and Minello 1997).

Estimating density or absolute abundance

Surveys that can provide estimates of absolute abundance are much more useful to stock assessments than those providing relative abundance (Maunder and Piner 2015). But to estimate absolute abundance using traps, the area over which the bait (or trap itself) attracts fish to the trap (i.e. effective fishing area) must be estimated (Miller and Hunte 1987, Miller 1990, Bacheler et al. 2022b). The actual effective fishing area is the area around a baited trap in which all animals have a

100% probability of capture (Miller 1975), but almost certainly a decreasing fraction of animals would be caught at increasing distances from the trap (Miller 1990, Bacheler et al. 2018, 2022b). Thus, the effective fishing area can be difficult to estimate because it is a theoretical concept and not the actual area from which animals captured in the trap were drawn from, which is a larger area (Bell et al. 2001, Watson et al. 2009). It is also unlikely the effective fishing area of a baited trap is circular given water current and bait plume dynamics (Winger and Walsh 2011, Bacheler et al. 2022b).

To my knowledge, four approaches have been used to estimate the effective fishing area of baited traps. The first approach has been to combine an understanding of the sensory and movement biology of the study species with a model of bait plume dynamics to estimate the effective fishing area (Sainte-Marie and Hargrave 1987, Priede et al. 1994). The second and most common approach uses underwater visual census, bottom photography, trawling, or tag-recapture to estimate animal densities with which trap catches can be compared in order to estimate the effective fishing area of traps (Morgan 1974, Miller 1975, Brêthes et al. 1985, Miller and Hunte 1987, Himmelman 1988, McQuinn et al. 1988, Recksiek et al. 1991, Acosta et al. 1994, Smith and Tremblay 2003). The third approach estimates a circular effective fishing area by deploying baited traps at different spacing along a line; as the distance declines between traps, the overlap in effective fishing areas increases and catches decline (Eggers et al. 1982). Each of these first three approaches has very strong assumptions that generally limit their usefulness.

The last approach is to quantify the fine-scale movement behavior of fish or decapods around bait. Some have used laboratory or mesocosm experiments to quantify behavior (Zhou and Shirley 1997, Watson et al. 2009), while others have used tracking studies in natural settings (Løkkeborg and Fernö 1999, Bacheler et al. 2018, 2022b, Lees et al. 2018). Ultimately, these tracking approaches quantify the area from which captured animals were drawn, which, as noted above, is not synonymous with the effective fishing area (Miller 1975, 1990, Bacheler et al. 2022b). So while it is theoretically possible to quantify the effective fishing area of baited gears to estimate actual abundance or density from baited traps, in practice, there are few reliable examples where this has been accomplished successfully. Thus, estimating absolute abundance or densities of targeted species from traps is theoretically possible but elusive in practice.

Quantifying biodiversity

Some studies have used trap catches of fish or decapods to make inferences about patterns in species richness or biodiversity. McLeod and Costello et al. (2017) reviewed the use of light traps to sample marine biodiversity and concluded that they could fill an important gap in quantifying biological diversity, assuming environmental effects and variability in trap design is accounted for. Bacheler and Smart (2016) used catches from a long-term, multi-species, baited trap survey to show that non-fishery-targeted species declined more than fishery-targeted species. However, the authors noted that, since baited traps generally capture predators and scavengers, their results mostly apply to that segment of the fish community and not the entire fish community. Olsen et al. (2021) used baited fish traps and gillnets to elucidate patterns of species richness along Sudan's Red Sea coast and showed that species richness from traps was highest in places where fishing pressure was lowest. Most studies using traps to infer biodiversity suggest caution when interpreting results because traps only sample a portion of the total available species in an area, often missing many functional groups (Yonekura et al. 2004, Harvey et al. 2012, Bacheler et al. 2017, 2022a, Bosch et al. 2017, Costello et al. 2017), similar to most other sampling gears.

Amenable to pairing with other gears

It is generally understood that most gears do not sample the entire fish or decapods community in perfect proportion to their abundance across a landscape or detect all species that are present (Willis et al. 2000, Parker et al. 2016, Bacheler et al. 2017). A common approach to try to overcome this limitation is to combine traps with other sampling gears to sample the fish or decapod communities more comprehensively (e.g. Jackson and Harvey 1997). This can involve deploying each gear separately throughout the study area (Jackson and Harvey 1997, Wells et al. 2008, Harvey et al. 2012, Haynes et al. 2013) or physically pairing sampling gears (Bacheler et al. 2017, Bacheler and Shertzer 2020). The most common pairing of sampling gears is traps and video (Fig. 4; Harvey et al. 2012, Langlois et al. 2015, Christiansen et al. 2020, 2022, Bacheler et al. 2022a, Zhang et al. 2023), but underwater visual census has also been paired with traps (Bacheler et al. 2017). In all of these examples, data from paired gears have been analyzed separately to make inferences about the selectivity patterns, detection probability, and relative fishing power of each gear and overall relative abundance and biodiversity of fishes.

There are also examples where data from paired gears have been combined into a single analysis that provided much better information than either gear alone. Haynes et al. (2013) used occupancy models to estimate gear- and species-specific detection probabilities for several fish species in boreal lakes in Alaska, USA. Coggins et al. (2014) used an occupancy model built on paired baited trap and video samples to quantify the ways in which environmental conditions influenced red snapper (*Lutjanus campechanus*) detection probabilities from traps and video. More recently, Gwinn et al. (2019) developed a Bayesian state-space model that combined baited trap catches and video counts to estimate a single integrated index of abundance for vermilion snapper (*Rhomboplites aurorubens*) that accounted for variation in catchability for both sampling gears. A key for paired gear surveys is that gears are independent, so that catches from one gear do not influence catches or counts from other gears (Bacheler et al. 2017). Therefore, pairing traps with sampling gears like video or environmental DNA will likely be more fruitful than pairing them with other extractive gears.

Drawbacks of traps as a survey gear

Relatively few species captured

Traps are fairly inefficient at sampling fish and decapod communities (Karnofsky and Price 1989, Jury et al. 2001, Watson et al. 2009, Bacheler et al. 2017). Like longlines and hook-and-line, baited traps preferentially capture animals that are attracted to bait, while poorly sampling functional groups like herbivores or detritivores (Table 1; Murphy and Jenkins 2010, Bacheler et al. 2017). Indeed, traps generally capture only a small portion (<40%) of the fish community documented by other gears like underwater visual census, video, or trawling,

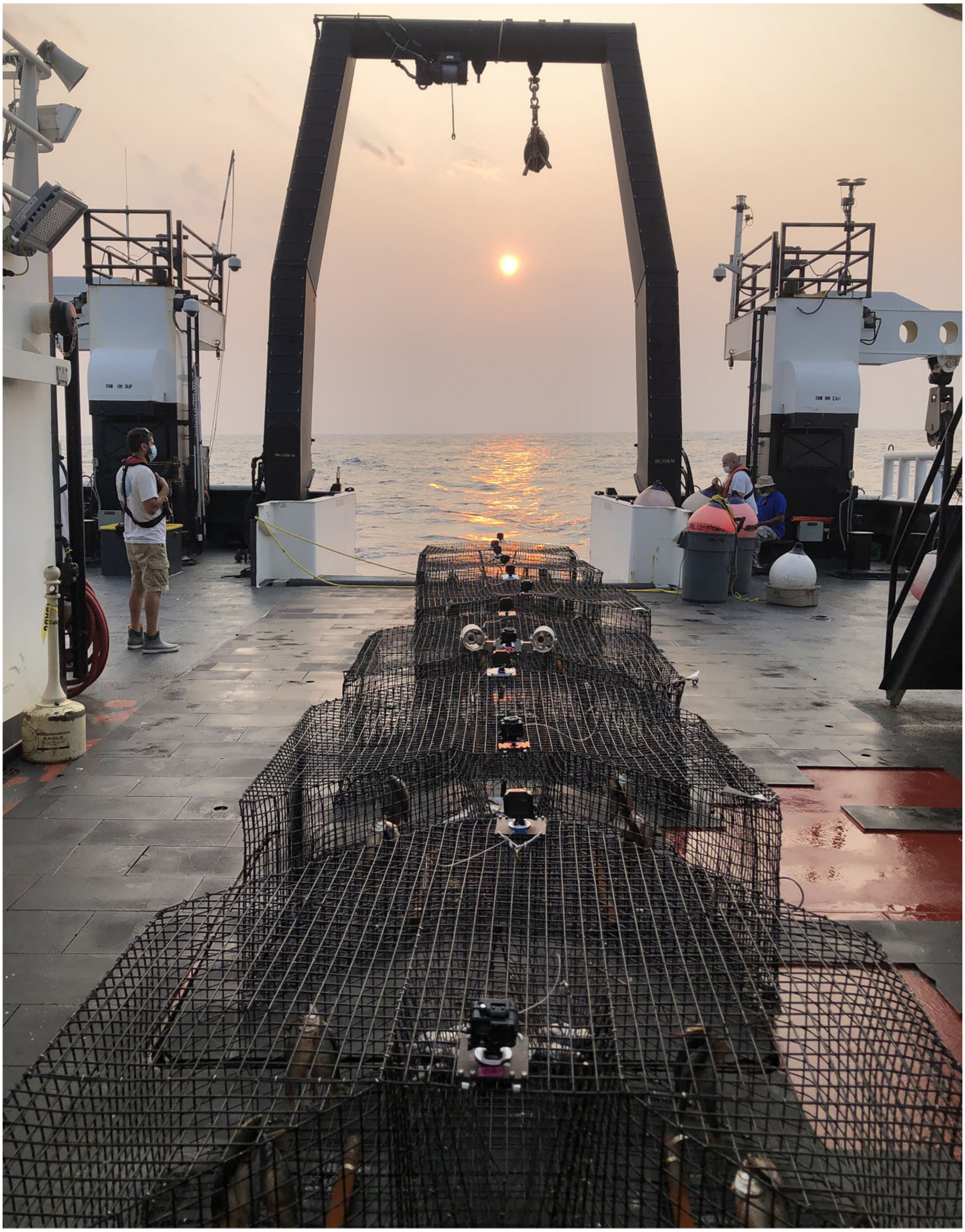

Figure 4 Traps are amenable to being paired with other sampling gears, such as underwater video cameras as shown here from the Southeast Reef Fish Survey (see Bacheler et al. 2022a for more details) (photo credit: David Hoke).

leading to dramatically underestimated species richness or diversity of a region (Harvey et al. 2012, Bacheler et al. 2013a, Parker et al. 2016, Bacheler et al. 2017). The underestimation of species richness by trap surveys is nearly universal and has been observed across different habitat types, depths, and geographic regions (Jackson and Harvey 1997, Jones et al. 2003, Vadziutsina and Riera 2020). There are numerous and complex reasons for traps being an inefficient sampling gear for aquatic communities, including various predator–prey interactions in and around traps, other behavioral interactions between individuals, differences in bait attraction among species, differences in movement rates among species, habitat interactions, variable trap saturation effects, and fluctuations in environmental conditions that influence the sensory abilities, movements, and feeding motivation of target species (High and Beardsley 1970, Munro 1974, Morrissy 1975, Bennett and Brown 1979, Parrish 1982, Karnofsky and Price 1989, Robichaud et al. 2000, Jury et al. 2001, Mahon and Hunte 2001, Bacheler and Shertzer 2020). In some cases, strongly selective traps are advantageous to catch and remove invasive species with low rates of bycatch (Hein et al. 2007, Harris et al. 2020, 2023).

Size selection

Like most sampling gears, traps do not typically catch target organisms of the same size distribution as they are found in the environment, but instead selectively capture certain sizes of organisms more efficiently than others. The size-selection of traps has received much attention in the literature, including two thorough reviews by Dalzell (1996) and Mahon and Hunte (2001). In the simplest sense, the mesh size of the trap controls the smallest organisms retained by the trap (i.e. ascending limb of the selection curve), while the mouth opening shape or size or trap volume will determine the largest individuals that can enter it (Luckhurst and Ward 1987, Bohnsack et al. 1989, Winger and Walsh 2011). Selectivity of traps is typically either assumed to be flat-topped, where selectivity increases with fish size to a maximum of 1.0 and remains there for all larger fish, or dome-shaped, where selectivity declines for the largest fish that are less likely to enter a trap (Mahon and Hunte 2001, Rudershausen et al. 2008, Mitchell et al. 2014, Langlois et al. 2015, Christiansen et al. 2020, 2022). Knowing the selectivity pattern of traps is important when an index of abundance is included in a stock assessment, since it indicates the portion of the population to which the index applies. Estimating the descending limb of the selectivity curve of traps can be particularly challenging because bigger fish are often somewhat rare (Mitchell et al. 2014, Langlois et al. 2015, Christiansen et al. 2020, 2022).

But the effects of mesh size on the sizes of organisms caught in traps are more complicated than simply determining the ascending limb of the selection curve (Mahon and Hunte 2001). For instance, traps with a smaller mesh size almost universally tend to catch more fish of both small and large sizes (Ward 1988, Luckhurst and Ward 1987, Bohnsack et al. 1989, Moran and Jenke 1990). One hypothesis for this observation is that fish are more attracted to small mesh traps (out of curiosity, for food, or refuge; Randall 1963, Stone et al. 1979) because they appear more solid and have more wire per unit area than larger mesh traps (Samples and Sproul 1985, Bohnsack et al. 1989). Others have not found evidence for the visual image hypothesis, instead suggesting that the reduced fishing power of larger mesh traps is due to larger fish squeezing through the larger mesh (Hartsuijker 1982, Robichaud and Hunte 1997, Robichaud et al. 1999).

Other behaviors in and around traps can influence the sizes of organisms caught by traps (Miller 1979, Addison 1995, Frusher and Hoenig 2001). For instance, large southern rock lobsters (*Jasus edwardsii*) often prevent smaller lobsters from entering traps (Frusher and Hoenig 2001, Frusher et al. 2003). Therefore, declines in abundance of large lobsters may result in increased trap catches of small lobsters, which would incorrectly appear as increased lobster recruitment when in fact the catchability of small lobsters increased rather than their abundance (Frusher et al. 2003). Large crabs, lobsters, and crayfish also commonly exclude smaller individuals from traps (Miller 1990, Jury et al. 2001, Ogle and Kret 2008), suggesting the potential for widespread trap selection pressures among decapod crustaceans due to territorial behaviors. Obviously, behavior is an important component to the size-selection of aquatic organisms from passive sampling gears like traps (Luckhurst and Ward 1987).

Highly variable catches

Trap catches are often assumed to be proportional to relative abundance, but a large body of research has shown that a wide range of complex environmental, habitat, and behavioral factors can uncouple trap catches and local abundance (High and Ellis 1973, Addison and Bell 1997, Jackson and Harvey 1997). For instance, High and Ellis (1973) showed that there was no single reason why fish entered traps—some did it out of hunger, others out of curiosity, others reacted to the capture of fellow species, and some entered as predators to eat fish already captured. Jackson and Harvey (1997) used five different sampling gears in several Canadian lakes to show that both positive and negative interactions occurred between fish in and around sampling gears; not even the rank order of species' abundances was consistent among gears. Below I review in detail a number of reasons why trap catches can be highly variable.

Effects of environmental conditions

In his comprehensive review, Stoner (2004) described how catches from baited fishing gears were strongly influenced by the feeding motivation, activity patterns, sensory abilities, and locomotor capabilities of the target species, all of which were tied to water temperature. In fact, Stoner (2004) noted that water temperature is the environmental factor that most strongly influences the metabolism of fishes. Aquatic organisms will generally increase feeding, swim speeds, and growth up to some threshold temperature, but then these processes will decrease or abate above that threshold (Brett 1979, Hayward and Arnold 1996). Numerous researchers have shown that the detectability or catchability of fish and decapods is influenced by water temperature, with most showing a positive relationship between trap catchability and water temperature (Stott 1970, Morrissy 1975, Miller 1990, Bacheler et al. 2014, Bacheler and Shertzer 2020). For instance, the trap catchability for most reef-associated fish species was strongly and positively related to water temperature, but the catchability of two remaining colder-water species were unaffected or negatively related to water temperature (Bacheler and Shertzer 2020). Most studies have noted that variation in water temperature must be accounted for in order to produce accurate indices of abundance in trap surveys; unfortunately, water temperature often influences the local abundance and catchability of aquatic organisms, and it is often difficult to disentangle these effects in practice.

Numerous other environmental conditions can potentially influence the trap catch of aquatic organisms. Water current can influence catchability in traps by affecting: (i) the bait plume and thus the effective fishing area of the gear (Eggers et al. 1982, Engås and Løkkeborg 1994), (ii) the ability of fishes and decapods to move and feed (Fernö et al. 1986, Bacheler et al. 2019, 2021), or (iii) the orientation of the trap mouth opening relative to water movement, with mouth openings facing down-current typically catching the most animals (Karnofsky and Price 1989, Miller 1990, Kneib and Craig 2001, Bacheler et al. 2014). Other environmental factors that can influence the trap catchability of fishes and decapods include light levels, water clarity, time of day, seasonality, or lunar phases (Sutcliffe 1956, Chittleborough 1970, Munro et al. 1971, King 1987, Miller 1990, Dalzell and Aini 1992, Varghese et al. 2017).

Effects of habitat

The habitat in which traps are deployed also influences their likelihood of capture, so assuming catch is proportional to local abundance across habitat types is tenuous (Robichaud et al. 2000). A nearly universal finding is that traps deployed in rugose habitats have lower catchability for nearly all species than traps deployed in adjacent flat, unstructured habitats (High and Ellis 1973, Parrish 1982, Hixon and Beets 1989, Acosta et al. 1994, Wolff et al. 1999, Geraldi et al. 2009, Bacheler et al. 2014, Bacheler and Shertzer 2020). The most likely explanation is that traps are perceived as attractive habitat when placed in simple, unstructured habitats, but their attractiveness wanes in high-relief, structured habitats (Wolff et al. 1999, Robichaud et al. 2000, Sturdivant and Clark 2011, Bacheler and Shertzer 2020). Other explanations include the potentially higher movement rates of organisms in unstructured habitats that cause traps to be more easily found (Geraldi et al. 2009, Topping and Szedlmayer 2011) or baited traps that produce larger and more persistent bait plumes in unstructured habitats (Tremblay and Smith 2001). It is important to account for the variable catchabilities of aquatic organisms in traps across habitat types (Bacheler and Shertzer 2020).

Effects of animal personality

There can be enormous variability in the behavioral responses of organisms to baited traps that are typically considered differences in behavioral types or personalities because they cannot be explained by size, age, sex, or any external features (Watson et al. 2009, Michelangeli et al. 2016). Almost every study examining individual variability in bait responses has documented behavioral differences among similar-looking individuals (Jernakoff and Phillips 1988, Karnofsky and Price 1989, Skajaa et al. 1998, Watson et al. 2009, Bacheler et al. 2022b). For instance, in a mesocosm experiment, three American lobster individuals were responsible for a large percentage of all approaches toward bait but only a single capture, while 40% of the large lobsters in the tank were never caught despite being offered 20 different baited traps (Karnofsky and Price 1989). It was unclear if these lobsters were permanently untrappable (Karnofsky and Price 1989), which would have enormous implications for trap surveys that attempt to estimate relative abundance (Watson et al. 2009). It is not always inevitable, however, that behavioral differences among individuals will lead to a trapping bias (Michelangeli et al. 2016). It should be noted that behavioral variability complicates the sampling process for all sampling gears, not just baited traps.

Predator–prey interactions

For trap surveys that target fish communities composed of potential predators and prey, interactions in and around the trap can influence trap catches and confound indices of abundance for any particular species. There are three types of predator–prey interactions that can influence trap catch. First, the capture of prey species in a trap first can attract and lead to the capture of predators that otherwise would not enter traps (High and Ellis 1973, Munro 1974, Luckhurst and Ward 1987, Mahon and Hunte 2001, Renchen et al. 2012). For instance, divers noted that groupers and nurse sharks (*Ginglymostoma cirratum*) were strongly attracted to traps after prey species were caught and especially when prey frantically tried to escape (High and Ellis 1973). This phenomenon is not universal, however (Richards et al. 1982, Mahon and Drayton 1990, Robichaud et al. 2000). For instance, Robichaud et al. (2000) did not detect an influence of prey catches on predator catchability during trap sampling in heavily exploited Barbadian waters, but the authors suggested that prey effects on predators may be more pronounced in systems with lower fishing pressure. Second, the capture of a predator in a trap can deter prey from entering a trap (High and Beardsley 1970, Chittleborough 1974, Anders et al. 2017), which was observed by Robichaud et al. (2000), although the authors noted that the effects were fairly small. And third, predators can directly consume prey that have been caught in a trap (Ritchie 1972, Wada et al. 1991, Bagdonas et al. 2012). For instance, seal predation of salmon caught in set traps in the northern Baltic Sea was estimated at 61% (Fjälling 2005), although gear modifications were able to reduce predation rates (Lunneryd et al. 2003, Hemmingsson et al. 2008). Predator–prey interactions can also substantially influence catch rates for most other sampling gears, including hook-and-line, longlines, gillnets, trawls, and video.

Feeding motivation

Baited traps, longlines, baited video, and hook-and-line gears primarily catch fish and decapods via attraction to the odor of bait, so the ability of traps to catch organisms in large part depends on their feeding motivation (Munro et al. 1971, Miller 1990). But the feeding motivation of aquatic organisms is rarely constant, instead varying across diel, seasonal, and lunar periods (Chittleborough 1970, Miller 1990, Newman and Williams 1995). Miller (1990) listed a large number of decapod crustaceans that displayed diel variation in activity, with most peaking around dawn and dusk. Newman and Williams (1995) found that 90% of all lutjanid fishes caught in a trap survey were captured at night, although some other fishes rest at night and can only be caught during the day (High and Ellis 1973, Bacheler et al. 2019). The feeding motivation of crabs and lobsters is also strongly affected by molting cycle (Chittleborough 1970, Ennis 1978, Miller 1990). Generally, the catchability of crustaceans in baited traps declines as molting approaches, is close to zero for several days around the molt when feeding ceases, and then increases quickly once the new shell is hard enough for feeding to resume (Chittleborough 1970, Miller 1990). There can even be differences in feeding motivation and catchability between the sexes (Templeman and Tibbo 1945, Branford 1979, Miller 1990).

Competition

There are two categories of competition that can decouple the relationship between trap catch and local abundance. The first type is exploitative competition, where some individuals or species consume the bait rapidly or efficiently in the trap, thereby reducing the effectiveness or catchability of the baited trap for subsequent individuals (Miller 1990). One example of intraspecific exploitative competition is when larger individuals of one species outcompete smaller individuals for food (Hart 1993), such as large Pacific halibut (*Hippoglossus stenolepis*) winning nearly all direct interactions with smaller halibut over bait (Stoner and Ottmar 2004). An example of interspecific exploitative competition was provided by Løkkeborg et al. (1989), who found that more haddock (*Melanogrammus aeglefinus*) responded to baits but Atlantic cod (*Gadus morhua*) were much more aggressive and thus were hooked more often. The presence of competitors is not always negative in terms of catch because feeding motivation can sometimes increase in the presence of competitors (Shardlow 1993, Stoner 2004, Stoner and Ottmar 2004).

The second type of competition that can influence trap catches is interference competition, whereby some individuals or species actively prevent access to bait by others. Agonistic interactions between conspecifics in and around traps have been shown to strongly influence the entry and catch rates of various organisms like American lobsters (Jury et al. 2001, Watson et al. 2009), southern rock lobsters (Frusher and Hoenig 2001, Frusher et al. 2003), red rock crabs (*Cancer productus*; Miller 1978), rusty crayfish (*Orconectes rusticus*; Ogle and Kret 2008), and fish like grouper and parrotfish (High and Ellis 1973). Most of these interactions are territorial in nature, where larger individuals or more dominant species protect and defend the bait or trap from others, preventing others from entering (Frusher and Hoenig 2001, Jury et al. 2001, Watson et al. 2009). Strong territoriality results in trap catches that tend to be fairly even despite organisms often being patchily distributed, suggesting that catch rates cannot be used to index abundance (Addison and Bell 1997). Interspecific agonistic interactions can also occur in and around baited traps, like between Atlantic cod and snow crab (Winger and Walsh 2011).

Conspecific attraction

In some cases, individuals of a species may be attracted into a trap if other individuals of the same species have already been caught (Lyons and Kennedy 1982, Miller 1990, Renchen et al. 2012, Bacheler et al. 2013b). Conspecific attraction can result in very different species dominating the catches of traps set in identical environments (Munro et al. 1971, Luckhurst and Ward 1987). For instance, Munro et al. (1971) and High and Ellis (1973) noted that when white grunt (*Haemulon plumierii*) were already present in a trap, the subsequent catch rates of white grunt were much higher than for empty traps, consistent with *Stenotomus* spp. catches in a trap survey (Bacheler et al. 2013b). Fishes of the same species sometimes swim together on either side of the trap mesh until the fish outside the trap are inadvertently led through the trap entrance (Munro et al. 1971, High and Ellis 1973, Renchen et al. 2012). There can also be sex-specific attraction; for instance, traps baited with live male blue crabs caught significantly more premolt female blue crabs than traps using other baits (Bishop et al. 1984). These studies suggest conspecific attraction can be a major factor affecting species composition and catch in fish traps (Luckhurst and Ward 1987).

Trap saturation

For various reasons, a trap does not continue catching organisms at the same rate over time. Instead, trap catch asymptotes because its present catch reduces its potential for additional catch (Beverton and Holt 1957, Miller 1990). In Munro's (1974) seminal work on trap saturation, he presented a simple theoretical model based on observations where the daily entry rate was constant, escapement was a fixed proportion of the number of fishes captured in the trap, and the catch reached an asymptote at a level where entries were eventually offset by escapement. Subsequent work has built upon these ideas for other various other species (Miller 1978, 1979, Addison and Bell 1997, Fogarty and Addison 1997). Saturation is also important for other sampling gears such as longlines, hook-and-line, gillnets, and trawls.

A number of studies have examined the accumulation of catches in traps over time without emptying traps or observing trap catches with video or underwater visual census, showing that saturation occurs in the time frame of hours to days (Munro 1974, Morrissy 1975, Miller 1979, Powles and Barans 1980, Kennelly 1989, Robertson 1989, Dalzell and Aini 1992, Cole et al. 2004, Bacheler et al. 2013a, Cullen and Stevens 2017). Traps can saturate for many reasons, including a lack of remaining physical space in the trap, behavioral interactions in and around the trap, and an equilibrium being reached between entries and exits at a catch level that may be proportional to local abundance (Munro 1974, Bacheler et al. 2013a, Shertzer et al. 2016). Other characteristics of traps such as the volume of traps, the type and amount of bait, bait consumption rate, size and shape of entrance, and the presence or absence of escape panels will also influence the catch level at which traps saturate (Munro 1974, Miller 1978, 1990, Dalzell and Aini 1992).

Bycatch

Organisms that are incidentally captured by traps and sometimes discarded are considered bycatch. While traps tend to have much lower bycatch rates than other sampling gears like trawls, longlines, or gill nets (Table 1; Alverson et al. 1994, Shester and Micheli 2011, Moffett et al. 2012, Uhlmann and Broadhurst 2015), bycatch from traps can be highly variable (Renchen et al. 2024). One reason bycatch rates from traps are variable is that the definition of bycatch varies depending on culture, socioeconomics, and intensity of exploitation (Hawkins et al. 2007). For instance, in some regions, almost nothing is discarded from traps (Ferry and Kohler 1987, Sary 1995), while in others where catches and sizes are strictly regulated, bycatch can account for >50% of the catch (Sutherland and Harper 1983, Taylor and McMichael 1983, NMFS 1995). The survival of fish bycatch from traps is dependent upon the depth of capture (i.e. barotrauma), stress from hauling and handling at the surface, water temperature, and predation in traps before they are hauled (Bohnsack et al. 1989).

In trap surveys, bycatch of fish or crustacean species tends to be a lesser concern than various trap-based fisheries, since these species can provide useful scientific information to inform stock assessments. For instance, juvenile fish or crustaceans can comprise a significant proportion of trap catches in some fisheries, which could lead to growth overfishing if fishing effort is high (Robichaud et al. 1999, Hawkins et al. 2007), but the catch of juveniles in trap surveys can provide useful information on recruitment. A bigger concern in trap surveys is the incidental capture and death of non-target species of conservation concern. For instance, diamondback terrapins (*Malaclemys terrapin*) are regularly caught in blue crab traps along the East Coast of the United States (Dorcas et al. 2007). Sea otters (*Enhydra lutris*) can be caught in various trap fisheries on the West Coast of the United States (Hatfield et al. 2011). It is also possible that marine mammals like endangered Australian sea lion (*Neophoca cinerea*) pups (Gales et al. 1994) or Kuril seals (Wada et al. 1991) can get stuck in traps while engaging in depredation, although traps generally have low rates of bycatch of sea turtles, marine mammals, pinnipeds, and seabirds (Uhlmann and Broadhurst 2015, Calado et al. 2021) compared to other gears such as longlines or gillnets. Gear modifications and bycatch reduction devices can reduce bycatch rates in most of these situations (Roosenburg and Green 2000, Rook et al. 2010, Mackay and Goldsworthy 2017).

Entanglements with species of conservation concern

A related type of trap bycatch is when species of conservation concern become entangled in lines connecting traps to surface buoys (see review by Stevens 2021). These organisms tend to be long-lived and have a low reproductive capacity, so deaths from entanglements can be one of the biggest threats to their sustainability (Read 2008, Myers et al. 2019). Entanglement in trap gears can result in rapid deaths of animals via drowning or long-term suffering and eventual death via impaired feeding, increased energetic demands, emaciation, or infections (Noke and Odell 2002, Moore and van der Hoop 2012, Harris et al. 2023). For instance, in Southeast Alaska, 52%–78% of humpback whales showed signs of entanglement scars from fishing gears, mostly crab and shrimp pots (Neilson et al. 2009). Along the East Coast of North America, ~12%–25% of endangered North Atlantic right whales (*Eubalaena glacialis*) and humpback whales (*Megaptera novaeangliae*) are entangled each year (Knowlton et al. 2012, Robbins 2012). Entanglement rates in trap gears have increased for North Atlantic right whales in recent years, and now 83% of the population shows scarring from fishing gears (Knowlton et al. 2012). Given that there are now <350 individual North Atlantic right whales remaining, some recommend dramatic changes to trap gears (Knowlton et al. 2022). But it is not just whales that can become entangled in trap lines; there are examples of sea turtles, common bottlenose dolphins (*Tursiops truncatus*), and sharks becoming entangled in, and dying from, trap gears (Noke and Odell 2002, Harris et al. 2023).

There are two broad approaches to reduce entanglement of marine mammals in trap or pot gear (How et al. 2015, Hamilton and Baker 2019, Moore 2019, Stevens 2021). The first is to reduce the overlap between marine mammals and trap gear by reducing the amount of trap gear in the water or using time and area closures (How et al. 2015, Stevens 2021), which may be possible in some places but not others (How et al. 2015, Stevens 2021). The second approach is to physically modify trap gears to reduce entanglements (Laverick et al. 2017). Weak links in the buoy line or reduced-strength ropes that can break away if contacted by marine mammals may reduce entanglements (Knowlton et al. 2015, Laverick et al. 2017, Hamilton and Baker 2019). However, weak links and reduced-strength lines cannot be used in all locations (e.g. deep water) and have not been shown to reduce entanglements in some locations (Moore 2019). Another modification of traps that could reduce entanglements is using "ropeless" traps, where ropes and buoys are contained in a separate trap chamber and are only released after a predetermined amount of time or on demand from an acoustic signal (How et al. 2015, Myers et al. 2019). Ropeless traps would substantially reduce marine mammal entanglements by removing ropes from the water except during retrieval, but release mechanisms can be unreliable and expensive, which has inhibited their implementation (Myers et al. 2019, Stevens 2021).

Habitat damage

It is well known that active sampling gears such as trawls, bottom seines, and dredges can have significant physical impacts on benthic habitats (Watling and Norse 1998). Many fewer studies have examined the ways in which benthic habitats may be influenced by trap or pot deployments (reviewed by Stevens 2021), perhaps because traps are generally perceived to have less impact on benthic habitats (Eno et al. 2001, Kopp et al. 2020). Traps are often set in benthic habitats that contain a variety of sensitive epifauna hard and soft corals, sponges, kelp, and crinoids, so potential damage from trapping is important to evaluate (Sutherland and Jones 1983, Schweitzer et al. 2018, Stevens 2021).

There are three main ways that traps can damage bottom habitats. First, traps can directly crush benthic organisms when coming to rest on the seafloor (Schweitzer et al. 2018). Benthic epifauna are often but not always able to tolerate the weight of traps or pots by bending or supporting the trap weight, resulting in minimal damage (Sutherland and Jones 1983, Eno et al. 2001, Marshak et al. 2008, Shester and Micheli 2011, Grabowski et al. 2014, Schweitzer et al. 2018). The total footprint of most traps is also very small, further minimizing damage compared to other gears like trawls with large tow footprints (Sheridan et al. 2005, Kopp et al. 2020). Second, traps can move on the bottom due to storms, during trap retrieval, or after becoming lost by fishers (Sutherland and Jones 1983, Lewis et al. 2009, Uhrin et al. 2014), which results in a much larger trap footprint that can cause more significant epibenthic damage (Schweitzer et al. 2018). Third, traps can sometimes be connected to one another via ground lines, and these lines can drag along the bottom and damage benthic epifauna (Stone and Shotwell 2007, Schweitzer et al. 2018). So although traps are generally regarded as a sampling gear that has a low impact on benthic epifauna, this can only be realized when traps are deployed independently, no traps are lost, sensitive habitats can be avoided, and traps can be retrieved vertically without dragging (Eno et al. 2001, Marshak et al. 2008, Shester and Micheli 2011, Kopp et al. 2020).

Ghost traps

A potentially large drawback of trap-based fisheries or surveys is when fish traps are lost or abandoned but continue to catch and kill aquatic organisms, a process known as ghost fishing by derelict traps (see reviews by Matsuoka et al. 2005 and Stevens 2021). Traps can be intentionally discarded or unintentionally lost due to storms, theft, vandalism, legal issues, or entanglement with boat propellers, marine mammals, or bottom structure (Sutherland and Jones 1983, Renchen et al. 2014, Yildiz and Karakulak 2016, Vadziutsina and Riera 2020, Humborstad et al. 2021). The number of traps lost each year is generally unknown and difficult to estimate but is thought to be large (Arthur et al. 2014). For instance, Guillory et al. (2001) estimated that ~250 000 derelict blue crab traps are lost in the Gulf of Mexico each year, while ∼100 000 are lost annually in the Chesapeake Bay (Havens et al. 2008).

The number of organisms captured and dying in ghost traps is also difficult to calculate. To estimate the total number of deaths due to ghost traps, estimates are required for the number of traps lost, the length of time traps continue to fish, and the rate of entry and exit (Miller 1990, Uhlmann and Broadhurst 2015). Using experimental ghost traps that were frequently monitored by divers, for instance, it was estimated that ∼4%–7% of the reported catch of Dungeness crabs (*Metacarcinus magister*) died in ghost traps each year along the west coast of North America (Breen 1987, Antonelis et al. 2011). Butler and Matthews (2015) estimated that 637 622 Caribbean spiny lobsters (*Panulirus argus*) die from ghost traps annually in the Florida Keys. The number of ghost traps in the snow crab fishery in the Gulf of St. Lawrence is unknown, but each ghost trap was estimated to kill 84 snow crabs each year (Hébert et al. 2001). In the Gulf of Mexico, Arthur et al. (2020) showed that removing 10% of derelict traps would result in 691 000 kg of fish and crabs that would be prevented from dying. Ghost fishing by traps is ubiquitous and an important issue anywhere there are trap fisheries or surveys, including Portugal (Erzini et al. 2008), Australia (Newman et al. 2011), Oman (Al-Masroori et al. 2004, 2009), Thailand (Sukhsangchan et al. 2020), and South Korea (Kim et al. 2014). The best remedies for preventing ghost fishing by traps are reducing gear loss rates, finding and removing lost traps, and using traps that include biodegradable or galvanic escape panels (Smolowitz 1978, Matsuoka et al. 2005; Antonelis et al. 2011, Renchen et al. 2014, Arthur et al. 2020).

Trap survey considerations

Traps can be both affordable and robust, allowing a large number of trap deployments (Stevenson 1978, Beliaeff et al. 1992) across a wide range of habitat types (Munro et al. 1971, Sheaves 1992). But it is clear that trap surveys can be improved when scientists understand the full breadth of benefits and drawbacks of using traps to survey fish and decapod populations, as detailed above. For instance, like most sampling gears, traps cannot survey all species and sizes in proportion to their abundance in the environment, and attempting to do so will usually result in not sampling anything very well (Miller 1990). Instead, trap surveys should be designed wisely to survey specific species and sizes that are amenable to capture in traps, and pilot studies are necessary to understand the selectivity and catchability of traps before surveys commence (e.g. Tuffley et al. 2018). Given the wide availability of trap sizes, shapes, mouth entrances, mesh sizes, and soak times, I next review a number of technical decisions that must be made when initiating a trap survey.

Trap design

The catch of organisms is influenced by myriad characteristics of the traps themselves, including their size, shape, mesh size, color, and mouth openings (Munro 1974, Sheaves 1995, Archdale et al. 2006, Tuffley et al. 2018, Harris et al. 2023). For instance, larger traps tend to catch more fish or decapods than smaller traps (Munro 1974, Wolf and Chislett 1974, Stevenson and Stuart-Sharkey 1980), perhaps because large traps are more visible (Luckhurst and Ward 1987), it is more difficult for fish to escape from larger traps (Wolf and Chislett 1974), or more animals can physically fit into larger traps (Munro 1974). Catches of organisms can also be affected by trap color (Tran et al. 2020) or the shape of traps. For instance, similarly sized S- and Z-traps caught more fish than arrowhead traps (Munro 1974, Wolf and Chislett 1974, Stevenson and Stuart-Sharkey 1980), perhaps because S- and Z-traps have two mouth openings compared to the single mouth opening of arrowhead traps.

Trap mouth openings are a critical consideration for trap surveys. The ideal trap mouth would allow animals easy access into the trap but simultaneously prevent their escape (Miller 1990). However, the reality is that there are plenty of examples of animals approaching but not entering traps (Karnofsky and Price 1989) and animals exiting regularly from traps (Munro 1974, Bacheler et al. 2013a). The best mouth opening size is a tradeoff between a larger mouth opening for ease of entry and a smaller mouth opening to deter exits. The number of openings can also vary. Traps with two mouth openings provide two pathways to enter traps while also increasing the likelihood that one opening will be facing down-current, allowing organisms to enter traps from the downstream position more easily when there is water current (Miller 1990). The downside of multiple mouth openings is that exit rates from traps tend to be higher (Kneib and Craig 2001, Tran et al. 2020). The shape and location of mouth openings also influence trap catch. For instance, traps with horseneck funnels retained fish better than straight funnels (Luckhurst and Ward 1987, Sheaves 1995) and funnel entrances outperformed slit entrances for crabs (Archdale et al. 2006). Moreover, mouth openings mounted low on exterior walls had over three times the number of attempted entries of snow crabs compared to those mounted higher (Winger and Walsh 2007).

Mesh size

Mesh size strongly influences the sizes and species caught in trap surveys, so care must be taken to select the appropriate mesh size in trap surveys. For instance, if information on recruitment is desired, using a smaller mesh size that captures juveniles of various species should be chosen (Bohnsack et al. 1989, Mahon and Hunte 2001, Tuffley et al. 2018). But a smaller mesh size also tends to catch more larger fish compared to large-mesh traps (Ward 1988, Moran and Jenke 1990, Stewart and Ferrell 2003, Hanamseth et al. 2022), perhaps because small-mesh traps are more visible to fish (Luckhurst and Ward 1987) or fish caught by traps can escape by squeezing through large-mesh traps (Robichaud and Hunte 1997, Robichaud et al. 1999). Small-mesh traps also tend to retain more small-bodied species than large-mesh traps (Bohnsack et al. 1989, Mahon and Hunte 2001). Large-mesh traps could be used if larger fish are targeted and smaller fish are to be avoided, but in general, the benefits of using small-mesh traps in trap surveys outweigh the downsides.

Bait

The baiting of traps is also an important consideration when designing a trap survey (Karnofsky and Price 1989). Some species can be caught well by unbaited traps (High and Beardsley 1970, Munro 1974), especially those species that are attracted to traps as habitat (Parrish 1982, Hixon and Beets 1989, Robichaud et al. 2000). But bait is commonly used to increase the attractiveness of traps for most species of management importance (Karnofsky and Price 1989, Bacheler et al. 2018). Surveys should also be consistent with the type of bait used in traps, because bait type often (Wolf and Chislett 1974, Karnofsky and Price 1989) but not always (High and Ellis 1973) influences trap catch. For surveys of decapods, it should be noted that using dead decapods as bait greatly reduce catches of conspecifics and should be avoided (Miller 1990). When longer soak times are targeted, bait can be kept in a container with holes in it to help the bait last longer (Sheaves 1995).

Soak time

Soak time is one of the most important factors determining the effectiveness of fish or decapod traps, potentially affecting both the numbers and sizes of animals caught (Munro 1974, Smith and Jamieson 1989, Whitelaw et al. 1991, Sheaves 1995, Kneib and Craig 2001). The influence of soak time on catch-per-unit-effort has been studied for many decades, beginning with Van Oosten's (1935) observation that various pound, fyke, and trap nets soaked for 2–5 days in the Great Lakes only caught 16%–63% more fish on average than traps soaked for 1 day. The decreasing catch per day with increasing trap soak time is a universal phenomenon, being confirmed for numerous species and trap designs since that time (e.g. Munro et al. 1971, Munro 1974, Somerton and Merritt 1986, Miller 1990, Dalzell and Aini 1992, Newman et al. 2011, Bacheler et al. 2013a, Cullen and Stevens 2017, Harris et al. 2023). The common approach of simply standardizing trap catch by dividing it by the soak time (e.g. trap catch per hour) when catches saturate would be a serious mistake because catch-per-unit-effort would be lower for traps with longer soak times compared to traps with shorter soak times (Miller 1990, Bacheler et al. 2013b).

Instead, a number of alternative approaches have been developed to standardize or account for variability in soak time. Some early models described the relationship between catch and soak time as a power function (Austin 1977, Miller 1983), but these models are only applicable to short soak times before catches asymptote (Zhou and Shirley 1997). A second class of models describing the relationship between catch and soak times is asymptotic models (Sinoda and Kobayasi 1969, Munro 1974, Miller 1983), which are useful for most situations except where the catch might eventually decline over time. Other models are more flexible and can account for situations where catch eventually declines, such as when soak times are very long (Somerton and Merritt 1986, Smith and Jamieson 1989, Zhou and Shirley 1997, Bacheler et al. 2013b). In general, shorter soak times (i.e. minutes or hours) are preferable in trap surveys to reduce the influence of saturation, obtain greater catches across a wide range of traps, and allow scientists to deploy more traps, increasing sample sizes (Munro 1974, Whitelaw et al. 1991, Sheaves 1995, Cole et al. 2004, Bacheler et al. 2013b). But unless soak times can be perfectly controlled in trap surveys, analysts should use one of the many approaches available for standardizing catches across variable soak times.

Pairing traps with other gears

Given that no gear perfectly samples aquatic communities, the pairing of different sampling gears is becoming more common in surveys. Jackson and Harvey (1997) sampled 43 Canadian lakes with five different sampling gears to show that many fish species were missed by individual gears, so only through a combination of gears could the fish community be sampled comprehensively. All sampling gears are size- and species-selective, so combining sampling gears helps provide a clear picture of fish communities and relative abundance of single species (Willis et al. 2000, Wells et al. 2008, Tuffley et al. 2018). In some cases, paired gears can be complementary, each having different strengths and weaknesses that, together, allow for a robust survey of organisms (Diaz et al. 2003, Bacheler et al. 2017). Bacheler et al. (2022a) recommended pairing traps with underwater video to increase the detection of important species, measure important habitat covariates, or estimate and account for the imperfect detection of either gear (Coggins et al. 2014, Gwinn et al. 2019), but other gear combinations could also be informative. Even simple pilot studies where video is temporarily included with traps can help researchers understand how traps function and operate (e.g. He 1993, Jury et al. 2001, Winger and Walsh 2007, 2011, Watson et al. 2009). Another potentially fruitful pairing is to combine traps and various types of environmental sensors such as temperature sensors, current probes, or devices to measure water clarity. The advantages of pairing gears in order to better understand how each gear samples often far outweighs the costs of adding a second gear.

Characteristics of an ideal trap survey

Despite the numerous pitfalls described above, there are particular situations where traps can likely sample some target species and sizes in proportion to their abundance with very few negative environmental ramifications (Miller 1990). In terms of habitats, traps are most effective in rugose, rocky, and reef substrates (often referred to as "untrawlable habitat") where many traditional sampling gears like trawls, longlines, and gillnets cannot effectively sample (Hixon and Beets 1989, Acosta et al. 1994, Newman and Williams 1995). Given variable catchabilities in traps among habitat types, however, it is suggested that only rocky, reef habitats are targeted unless variable catchabilities among different habitat types can be accounted for (e.g. via pairing traps with video; Bacheler and Shertzer 2020).

Baited traps are also amenable to the targeting of most small or medium sized predatory or scavenging species, which are often but not always the species with the highest management importance (Murphy and Jenkins 2010, Bacheler et al. 2017). Shorter soak times (i.e. <3 h) are generally preferable to longer soak times, which also allow for much larger sample sizes due to the ability of traps to be deployed multiple times per day (Munro 1974, Whitelaw et al. 1991, Sheaves 1995, Cole et al. 2004). Fish are also generally better target species for trap surveys than decapods because, as described above, decapods tend to have stronger behavioral interactions among individuals (Miller 1990, Jury et al. 2001, Watson et al. 2009). Reducing the number of lost traps, using escape panels with biodegradable or galvanic releases, setting traps individually without ground lines, hauling traps vertically, and not setting traps in areas or times with the potential for marine mammal interactions will minimize most of the potential negative outcomes of trapping (Vadziutsina and Riera 2020, Stevens 2021).

Despite the best efforts at planning and designing a trapping survey, it is critically important to account for environmental and soak time variability, habitat effects, and species interactions in and around the trap in order for trap catch to accurately track local abundance (Miller 1990, Maunder and Punt 2004, Kimura and Somerton 2006, Bacheler et al. 2013b, Marriott et al. 2014). After a thorough examination of the trapping literature, it is clear that using trap catches to approximate local abundance should always be avoided unless standardization occurs. Typically, generalized linear models, generalized additive models, zero-inflated models, or other related statistical approaches are used to standardize trap catches (Kimura 1988, Maunder and Punt 2004, Bacheler and Ballenger 2018). Trap catch has been standardized by a variety of important variables such as soak time, depth, water temperature, habitat type, current direction, and tide stage (Kneib and Craig 2001, Kimura and Somerton 2006, Bacheler and Ballenger 2016, 2018).

But some of these parameters are easier to collect than others. For instance, bottom water temperature can be measured using a conductivity–temperature–depth cast on a large research vessel or via a temperature sensor attached to traps on small vessels, depth can be measured with an on-board sonar, and video cameras attached to traps can be used to estimate microhabitat around the trap, current direction, or tide stage (Sheaves 1995, Bacheler et al. 2018). But to standardize for species interactions in and around traps, divers (Munro 1974) or inward- or outward-pointing video cameras attached to traps (Bacheler et al. 2013a, Glasgow 2017) may be required. If trap catches are to be used to index abundance, standardizing for as many relevant factors as possible is critically important yet may still be insufficient (Miller 1989, Kneib and Craig 2001).

The best approach to determine which variables influence trap catch and thus need to be collected and incorporated into standardization is through the use of pilot studies (Miller 1990). Pilot studies should be used to determine which environmental and habitat variables should be collected, but pilot studies can also be used to estimate selectivity patterns and determine the optimal trap design, mouth entrance, soak time, and bait choices for the particular species, habitats, and areas of interest (Miller 1990, Sheaves 1995). Pilot studies can also be used to understand the behavior of target species in and around traps, a key component of any survey using passive sampling gears (Fogarty and Addison 1997).

Conclusion

Traps are widely used as fishing gears in various artisanal and commercial fisheries and as scientific sampling gears in numerous places around the world (Vadziutsina and Riera 2020). Myriad characteristics make them a desirable sampling gear, including their low cost, flexible design, and ability to sample effectively in a variety of habitats (Miller 1990, Tuffley et al. 2018). The choice of bait and trap design usually results in relatively low bycatch rates and non-target animals can often be returned to the water alive. But numerous studies have noted a plethora of drawbacks to trap surveys (similar to many other passive sampling gears), including the fact that catches may not accurately relate to fish and decapod abundance for a variety of complex reasons and several ways that traps may cause environmental and ecological damage. Miller (1990) provided a comprehensive review of many of the benefits and drawbacks of using traps to survey decapods, and here I have updated his review to include numerous studies published since 1990 and broaden the review to include all aquatic organisms that may be surveyed using traps.

In summary, traps (like any other sampling gear) do not sample the available sizes and species perfectly, so care must be taken to match the goals and objectives of a particular trap survey with a suitable trap shape and size, bait type, soak time, and mouth entrance. Miller (1990) recommended making a “large effort” to quantify the selectivity of trap gears before surveys begin by using pilot studies, and I suggest going a step further to determine as many potential environmental, habitat, and behavioral influences as possible that may affect trap catch, so that surveys can understand, quantify, and standardize for these variables. Only when the major variables influencing trap catch are accounted for can we reasonably expect trap catch to provide unbiased information about local abundance.

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Data availability

No new data were generated or analyzed in support of this research.

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