Received: 9 October 2022 | Accepted: 14 March 2023

DOI: 10.1111/1365-2664.14412

Journal of Applied Ecology | BRITISH ECOLOGICAL SOCIETY

RESEARCH ARTICLE

Estimating abundance of fish associated with structured habitats by combining acoustics and optics

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Funding information
Fisheries Research and Development Corporation

Handling Editor: Tadeu Siqueira

Abstract

1. The diversity and abundance of fish inhabiting complex reef habitats poses some challenges to surveys based on optical techniques, especially for schooling fish which are difficult to enumerate with such methods. Acoustic surveys are often used effectively to estimate the abundance and distribution of schooling fish but suffer from boundary effects and limited species discrimination.
2. To reconcile these drawbacks, we present an integrated acoustic–optical survey method, to estimate the abundance of fishes in a subtropical reef habitat in Shark Bay, Western Australia, exploiting the unique benefits of each method.
3. Acoustic backscatter attributed to multi-species groups was partitioned to species with the help of concurrent unbaited remote underwater video. This allowed estimation of the abundance of the important fishery sparid, *Chrysophrys auratus*, as well as 17 other members of the diverse fish community.
4. The study addresses some of the challenges of assessing abundance of fish species that may be aggregated, but sparsely distributed, associated with a structured habitat, and mixed within a diverse assemblage of other aggregating or solitary fishes in an area where direct capture fisheries survey gears cannot be used.
5. *Synthesis and applications*. The acoustic–optical survey method provides data that are vital for the assessment of fish species in ecosystems which are difficult, or impossible

for certain species, to survey with existing methods. These assessments are, in turn, essential for either ecosystem-based fishery management or multiple single-species quota management, which allow for the sustainable management of the associated fisheries.

KEYWORDS
acoustics, echosounder, fisheries independent surveys, geostatistical conditional simulations, optics, structured habitat, survey design, unbaited remote underwater video (RUV)

1 | INTRODUCTION

Diverse fish communities, living in complex habitats, such as rocky or coral reefs, present significant challenges in estimating their abundance, particularly large-bodied fishes that may school or aggregate for a variety of behavioural or biological reasons (Sadovy & Domeier, 2005). Schools can be dense, but sparsely distributed and may comprise of single or multiple species, with behaviour varying over time of day, life stage, habitat type or context, such as spawning, feeding and predator–prey interactions (Goodale et al., 2020).

These communities are often targeted by recreational and commercial fisheries. The effective management of any fishery requires a sustainable or optimal harvest, which, in turn, requires an assessment of stock status (Merrick, 2018). These stock assessments typically include fishery-dependent data, such as catch (at age or length, and, sometimes, with effort), as well as fishery-independent (survey) data (Rotherham et al., 2007). Many fish surveys are conducted using active capture methods (e.g. trawls, traps, line fishing) to estimate relative numbers at age or size in the population. However, structured habitats like coral or rocky reefs cannot be sampled effectively using such capture methods. Furthermore, in many regions, these methods are prohibited due to the potential destruction of habitats and associated high mortality (Sciberras et al., 2018). Alternative, less invasive, methods are therefore needed.

One of the most commonly used fishery-independent sampling methods for surveying abundance or diversity of fish in reef systems are underwater camera and video-optical surveys (Mallet & Pelletier, 2014). However, determination of the abundance of schooling fish with optical methods using a maximum number of individuals in view (MaxN) or average number in view (MeanCount) tend to underestimate counts or have highly variable estimates (Schobernd et al., 2014). Furthermore, optical surveys may be biased if the sampling design (e.g. replication, location of sites) does not adequately encounter aggregations or is complicated by the difficulty of observing and counting very high numbers within the field of view (Schobernd et al., 2014), never mind the need for clear waters to detect these fishes.

Acoustic surveys are used extensively to survey pelagic species that form monospecific schools (Simmonds & MacLennan, 2005). Exploiting the long-range propagation of underwater sound, these surveys cover large spatial extents relatively quickly, at high resolution, and gather data from extended range, akin to remote sensing, but suffer from boundary effects and limited species discrimination. Acoustic backscatter is proportional to abundance when the scattering properties of the target species are known. To some degree, acoustic backscatter can be separated into species based on the acoustic characteristics of the aggregations (e.g. frequency response, echotrace morphology) and their geographical distribution or habitat associations (Campanella & Taylor, 2016; Gastauer et al., 2017). However, additional evidence is often required to confirm the identity of the species of interest, their size and, ideally their orientation (Fernandes et al., 2016). There are examples of acoustic surveys conducted for species in reefs (Campanella & Taylor, 2016; Egerton et al., 2017) and seamounts (Ryan & Kloser, 2016) when they form monospecific spawning aggregations.

These two techniques (optical and acoustic surveys, see Supp. Mat for a detailed description of both) are rarely integrated, even though there are many reef fish which form monospecific aggregations (e.g. for spawning), easily detected with acoustics and known to be attracted to baited and unbaited underwater cameras.

The large sparid *Chrysophrys auratus* is an important commercial and recreational fishery species throughout its mostly temperate distribution in Australia and New Zealand (Fowler et al., 2018; Parsons et al., 2014). In Western Australia (WA), spawning aggregations occur at predictable times at several well-known locations, typically adjacent to, or within embayment's, for example Shark Bay and Cockburn Sound (Jackson, 2012; Wakefield, 2010). Assessment models for the oceanic Shark Bay stock, where the primary commercial fishery for this species has operated historically, have relied solely on fishery-dependent catch per unit effort (CPUE) data as an index of abundance. However, there have been substantial changes to the management of the fishery over time, which traditionally focused on limiting the total allowable commercial catch. Recently, an area known for *C. auratus* aggregations, and consequently where a seasonal fishery was heavily focused on, has been closed to fishing (Jackson et al., 2020). This has led to changes in the composition of the fleet and the spatial extent of the fishery, raising concerns about CPUE as a temporally consistent index of abundance. Additionally, fine-scale knowledge of the distribution, habitat use and behaviour of aggregating *C. auratus* within the peak spawning season is limited, raising further doubts about whether the CPUE was reflective of abundance. There is, therefore, a need for fishery-independent surveys of this resource, to improve both the stock assessment and knowledge of the stock's spatial distribution.

In this paper, we present the concept of an integrated acoustic–optical survey for use in situations which include multiple species, some of which tend to school or aggregate, in complex habitats. We describe a workflow for estimating fish abundance and biomass, with an appropriate estimate of sampling uncertainty, including methods for partitioning acoustic backscatter attributed to multi-species groups to length stratified species groups, using data based on information derived from concurrent optical data. To demonstrate the acoustic–optical survey method, we conducted a survey of fish communities in an area of Shark Bay closed to fishing for *C. auratus*, known locally as 'pink snapper'. While *C. auratus* is the primary species of interest, given its fishery importance, the methods described are applicable to other populations of fish that aggregate around structured habitat.

2 | MATERIALS AND METHODS

2.1 | Survey design and implementation

An acoustic–optical survey was conducted during daylight hours from the 14th to 22nd July 2020 onboard the 26.2 m commercial hook-and-line fishing vessel (FV) *Ada Clara*. It took place within an area closed to fishing for *C. auratus* north of Bernier Island, Shark Bay (see Figure 4), focusing on a sub-region in 20–70 m depth, which produces high catches of *C. auratus* as they migrate inshore to spawn (Moran et al., 2003).

Depth and habitat information along with local ecological knowledge (LEK) from fishers were used to determine sampling strata for the survey design (Farmer et al., 2017). Design principles followed those of Simmonds et al. (1992) and ICES WKSAD (ICES, 2005). For *C. auratus*, LEK suggested that the species forms dense, but numerous aggregations associated with structured patchy habitat inside the closed area but may also occupy areas between patches. We used a multi-stage survey design to collect acoustic and optical data: stage one surveyed the inter-patch area and consisted of a series of widely spaced (500 m apart) east to west parallel transects perpendicular to depth contours along the greatest rate of change. Stage two surveyed known patches of structured habitat and comprised of narrowly spaced (20–50 m) east to west transects. The starting point was randomly assigned to reduce potential sampling bias. Survey speed was 7–10 knots depending on sea conditions.

2.2 | Data collection

2.2.1 | Acoustic data collection

Acoustic data provided information on fish density in aggregations. A calibrated (Demer et al., 2015) Simrad Wideband Transceiver (WBT), mini echosounder, was used, connected to a dual frequency Simrad 38/200 combi C transducer (38 kHz, 3 sector split-beam; and 200 kHz, single beam; both with 18° beamwidth). The transducer was positioned ~1 m below the water surface, side mounted on a pole. Narrowband, 0.512 s duration pulses, was transmitted at 250 W (38 kHz) and 120 W (200 kHz) power. Data were logged to greater than twice the bottom depth and merged with GPS and motion reference data. At an average survey depth of 23.13 m, water column temperature averaged 22.31°C, and salinity averaged 35.52 psu so that sound speed in water averaged 1529 ms^{-1}. This gave sound absorption coefficients of 0.00751 $dB\,m^{-1}$ and 0.08252 $dB\,m^{-1}$ at 38 and 200 kHz, respectively.

2.2.2 | Video sampling

As acoustic methods provide a realization of the distribution of fish without intervention of bait, we used unbaited remote underwater video (RUV) stereo cameras (Langlois et al., 2020). Each RUV comprised two Canon LEGRIA HF M52 cameras fixed 70 cm apart, with an 8° angle of convergence, sitting 40 cm above the seabed in a steel frame using available light. When a suitable aggregation of fish was detected by the echosounder, the vessel immediately returned to the location and one or more RUVs were deployed from the aft of the vessel with the cameras recording. The cameras soaked for ≥90 min before retrieval. Each RUV stereo camera was calibrated in water using a SeaGIS calibration cube (SeaGIS, 2021).

Ethical review and approval were not required for the animal study because videos analysed in this article were collected by Western Australian Department of Primary Industries and Regional Development (DPIRD, authors Fairclough and Jackson). In Western Australia, the Animal Welfare Act 2002 does not require the DPIRD to obtain a permit to use animals (fish) for scientific purposes unless the species are outside the provisions of the governing legislation (i.e. Fish Resources Management Act 1994 and Fish Resources Management Regulations 1995). Nonetheless, all sampling was undertaken in strict adherence to the DPIRD policy for the handling, use and care of marine fauna for research purposes. No marine fauna was collected, injured or required to be euthanized for the purposes of this study.

2.2.3 | Ancillary data collection

Geographical position was recorded for each acoustic, optical, biological and environmental sample (Figure 1). Water column temperature and salinity profiles were recorded throughout the survey using a Castaway CTD. Biological information was collected with hook-and-line gear (2–5 hooks per line, deployed via hydraulic reels), before (dawn) and after (dusk) each day's survey activities, with the vessel anchored (Figure 5). Fork lengths (*FL*) of *C. auratus* were measured to the nearest 0.5 cm, and total weight of all fish caught were measured to the nearest kg. Total catch weight of other commercial fish species was also recorded. Length distributions were compared with those derived from RUVs using a Kolmogorov–Smirnov (KS) test.

2.3 | Analysis

The data sources and analytical methods applied to the acoustic–optical survey are summarized in Figure 1. This includes the

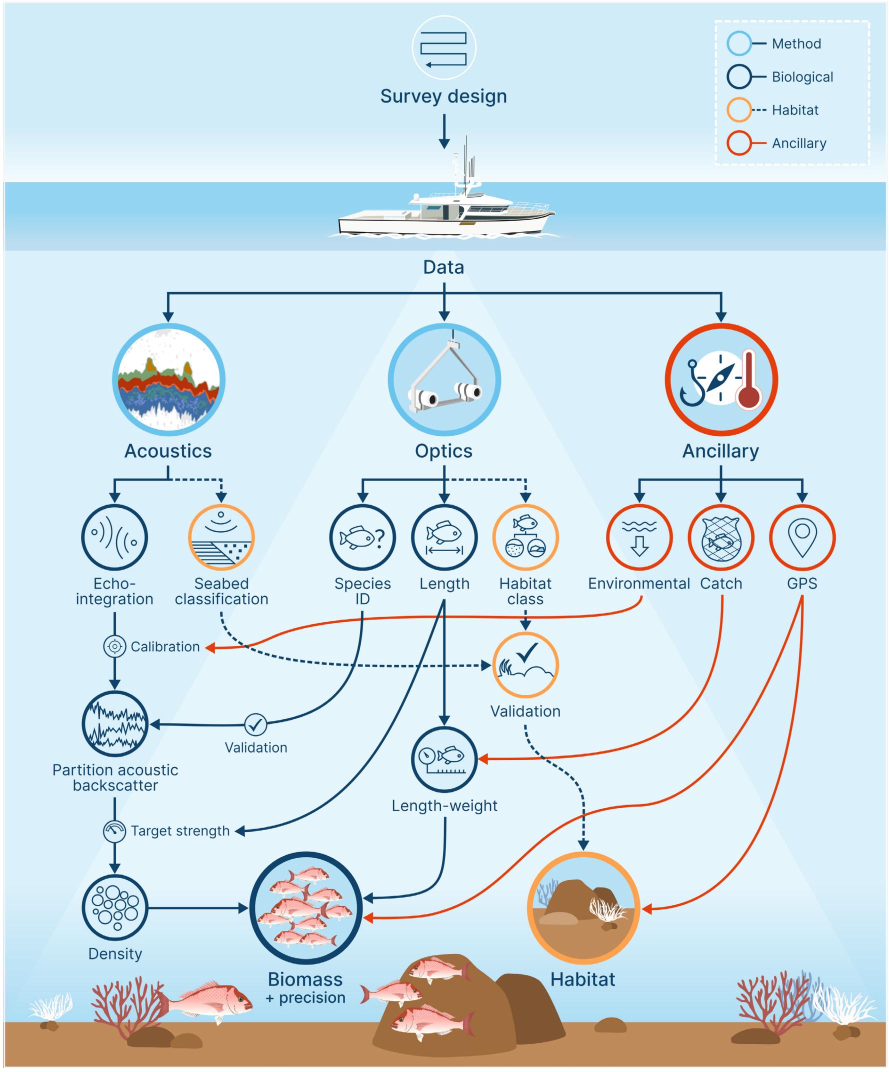

FIGURE 1 Flow graphic of the analytical methods applied to an acoustic–optical survey, moving from raw data sources and types to combined acoustics and optics species-specific density estimates and habitat information.

interpretation and analysis of the acoustic and optical data, habitat mapping, geostatistical conditional simulations (GCS) and partitioning of acoustic backscatter.

2.3.1 | Interpretation and analysis of acoustic data

Acoustic data were processed in Echoview version 11.0.244 (Echoview, 2021). Prior to further analysis, acoustic data from inter-transects, drop-camera/hydrographic stations and stereo camera events were removed. The seabed was detected using Echoview's 'best candidate bottom' algorithm and was manually corrected where required. Fish aggregations (i.e. non-resolvable targets) were detected using Echoview's school detection algorithm. The aggregations were manually classified (based on size, shape, and texture, e.g. Figure 2a) as either: (1) snapper-like (in reference to *C. auratus*); (2) probable yellowtail scad, *Trachurus novaezelandiae*; or (3) unknown small pelagic fish, which includes possible *T. novaezelandiae*. Echo-integration was then performed on all aggregations between the depths of 3.5 m (beyond the near-field of the transducer) and 0.1 m above the detected seabed (to avoid inclusion of seabed echoes). The key quantities in abundance estimation (after Maclennan et al., 2002) are as follows: (1) backscattering cross-section (σbs, m^2) and its logarithmic form target strength (*TS*, dB re 1 m^2); (2) volume backscattering coefficient (s_v, m^{-1}) and its logarithmic form, (mean) volume backscattering strength (MVBS or S_v, dB re 1 m^{-1}); and (3) nautical area scattering coefficient (s_A, m^2 nmi^{-2}) which was averaged over 50 m intervals. Fish density was then estimated as $\rho v = s_A / 4\pi \langle \sigma_{bs} \rangle$. The mean backscattering cross-section can be estimated from an existing species or species group specific *TS-L* equation, as $\sigma bs = 10^{\wedge(TS/10)}$. *TS* is usually estimated as a function of fish length (*L*, cm): $TS = a_{TS} LOG_{10}(L) + b_{TS}$, where a_{TS} is the slope and b_{TS} is the intercept. Here, the *TS-L* equation for *C. auratus* was estimated from ex situ *TS* measurements of 10 large individuals (see Supporting Information for details). In total 21,622 single-target echoes were detected at 38 kHz, with a mean *TS* of −25.07 dB re 1 m^2 at 38 kHz for a *C. auratus* with a mean *FL* (fork length) of 82.7 cm. Mean *TS* was calculated from the mean of the backscattering cross-section according to $10\log_{10}(\langle \sigma_{bs} \rangle)$. Given fish with gas-filled swimbladders generally have $a\ TS = 20$ (Love, 1977), *TS-L* was then:

$$TS = 20\ log\ 10\ (FL) - 63.4.$$

All species (other than *C. auratus*) were assigned to a representative *TS-L* group, based on morphological similarities (Figure 2b). These were snapper-like (Lutjanids, Haemulids and Mullidae), trevally-like (Carangids and the Sciaenid *Argyrosomus japonicus*, i.e. mulloway), cod-like (Epinephelids and Serranids, i.e. rockcod/grouper species), and small-pelagic-like (Carangids, i.e. *T. novaezelandiae*). *TS-L* equations for these groups (Figure 2b) were based on the best available data in the literature (Table S3).

2.3.2 | Interpretation and analysis of optical data

The first 2 minutes of video camera recordings (Rasmuson et al., 2022), from the time the RUVs hit the bottom, were used to partition the acoustic data, minimizing temporal and spatial mismatch. SeaGIS EventMeasure (SeaGIS, 2021) was used to analyse video footage from the left-side camera. For each 2-min episode, each fish species was identified and a MaxN recorded (Ellis & DeMartini, 1995) by a single researcher, to minimize observer bias.

For each 2-min video recording, *FL* were measured for all individuals of each species at the time when the MaxN was observed. This ensured that the same individuals were not counted twice. *FL* to total weight (*W*, g) for *C. auratus* was based on catches made in Shark Bay from 2018 to 2022, where $W = 2.8416 * l(FL) - 9.8054$. When available *L-W* relationships for other fish species were taken from the DPIRD, WA database (Table S4). When empirical relationships were not available, constants from the linear regression equation $W = a_{LW} * L^{b_{LW}}$ were taken from the available literature (Table S4).

2.3.3 | Habitat mapping

Habitat was classified based on video footage of the seabed collected routinely along the survey track using a GoPro Hero 7 on a 6 mm drop line with a 10 kg weight attached (3–4 deployments per transect at approx. equal spacing, Figure 5) and from stereo camera deployments. Habitat was classified as being (1) structured (i.e. reefs which may comprise of coral, sponges, rocks or a combination), (2) sand or (3) sand with patches of biogenic growth. Habitat maps were produced using indicator kriging following Gastauer et al. (2017). These maps were used to inform the partitioning of acoustic backscatter to individual species.

2.3.4 | Geostatistical conditional simulations

GCS, using the zero inflated methods of Woillez et al. (2009) (involving a data transformation through Gaussian anamorphosis and Gibbs sampler to evaluate values where zeros occur) were used to interpolate the integrated data by acoustic category

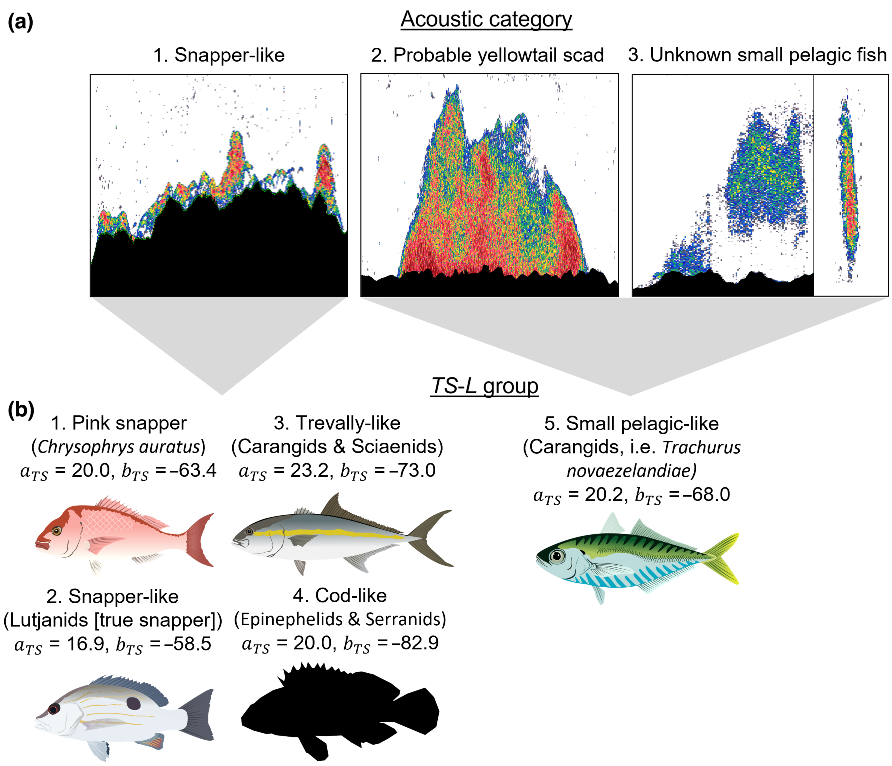

FIGURE 2 (a) The three acoustic categories (snapper-like, probable yellowtail scad and unknown small pelagic fish), and (b) the five-target strength (TS) to length (L) groups used in the interpretation and analysis of the acoustic data. Group TS-L equations are given at 38 kHz, where a_TS is the slope and b_TS is the intercept.

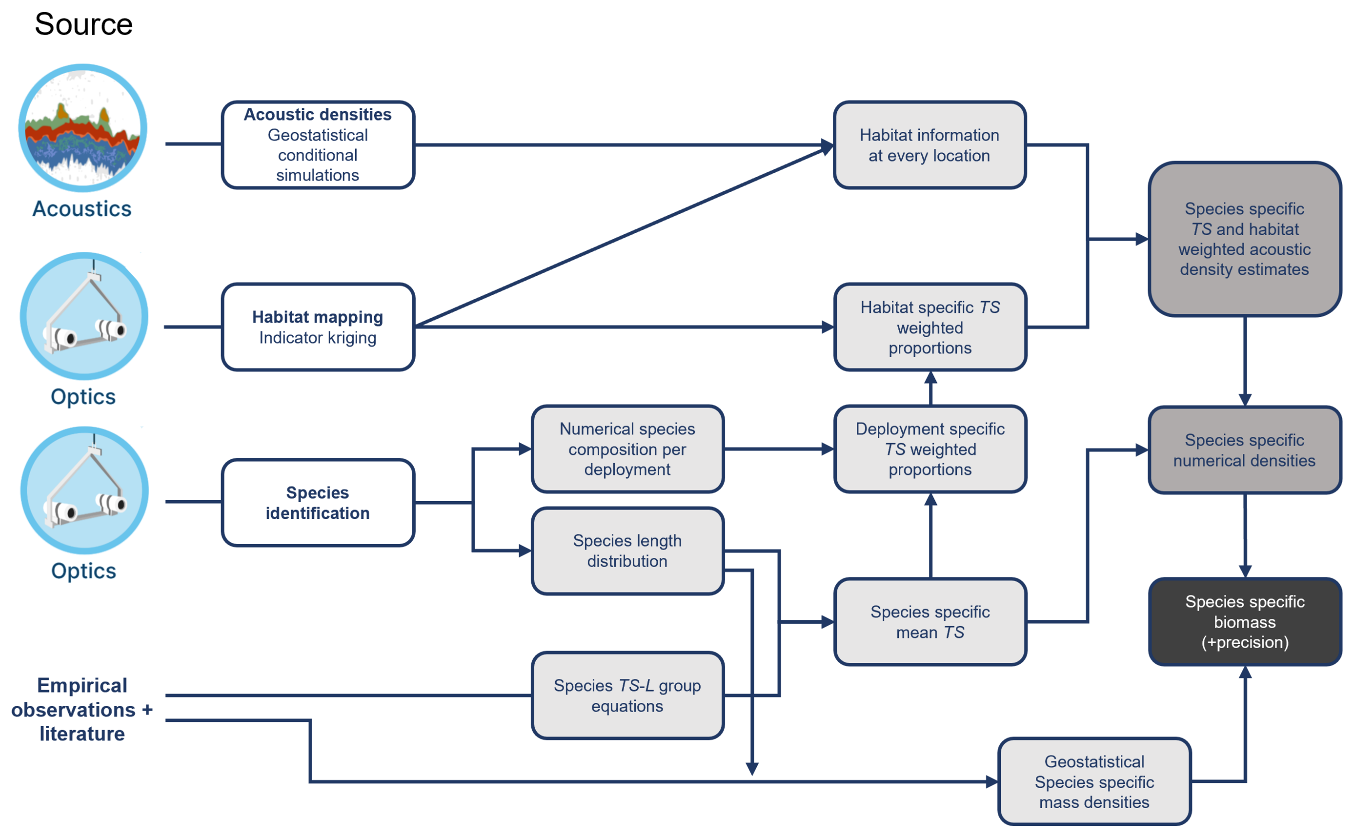

FIGURE 3 Workflow used to partition acoustic backscatter and estimate biomass of aggregating fish species. Acoustic densities of snapper-like, probable yellowtail scad and unknown small pelagic fish are interpolated for each point within the survey area through Geostatistical conditional simulations. Habitats are structured according to a combination of optical and acoustic information at each location within the survey area. For each location, the acoustic densities are disaggregated according to habitat specific, TS-weighted proportions, informed by optical recordings (identification, abundance and numerical composition, length).

(Figure 2a), and to evaluate the sampling uncertainty associated with acoustic recordings. Sets of 100 simulations were performed for s_A attributed to (1) snapper-like echotraces; (2) probable yellowtail scad echotraces and (3) unknown small pelagic fish echotraces and sampling coefficient of variations (CV) were evaluated.

2.3.5 | Partitioning acoustic backscatter

Based on the optical data, species-specific mean lengths were computed, and the corresponding *TS* was generated, following the group *TS-L* equations (Figure 2b). Habitat-specific fish assemblage proportions were computed based on a combination of optically derived numerical proportions, weighted by *TS*. It is important to weigh the numerical proportions by *TS*, as the numerical proportions for different species do not necessarily scale linearly with the acoustically scattered energy. Simulated acoustic densities were then split following the habitat type specific *TS*-weighted species proportions. Species-specific acoustic densities were then converted into biomass using the species-specific *TS-L* and *L-W* relationships. The processing workflow is shown in Figure 3.

3 | RESULTS

3.1 | Acoustic observations

In total, 162 nautical miles of transects were completed over the surveyed area of 182 km^2. The highest snapper-like concentrations were recorded in the central southern part of the area, whilst the highest probable yellowtail scad concentrations were recorded in the northeast corner (Figure 4). Unknown small pelagic fish were detected throughout the area but were more common in the west (Figure 4). The largest s_A (nautical area scattering coefficient, m^2 nmi^{-2}) corresponding to snapper-like, probable yellowtail scad and unknown small pelagic fish were 126,449, 108,517 and 27,283 m^2 nmi^{-2}, respectively. Echotraces of snapper-like concentrations consisted of loosely aggregated individuals and dense schools and varied in acoustic density, size, shape and texture (Figure 2 and Figure S3), most often close to reef structures. Probable yellowtail scad echotraces consisted mostly of dense schools and were relatively consistent in appearance (varying only by size), concentrated largely over sand. Unknown small pelagic fish echotraces were less dense than probable yellowtail scad echotraces and were typically observed away from the seafloor over both reef and sand.

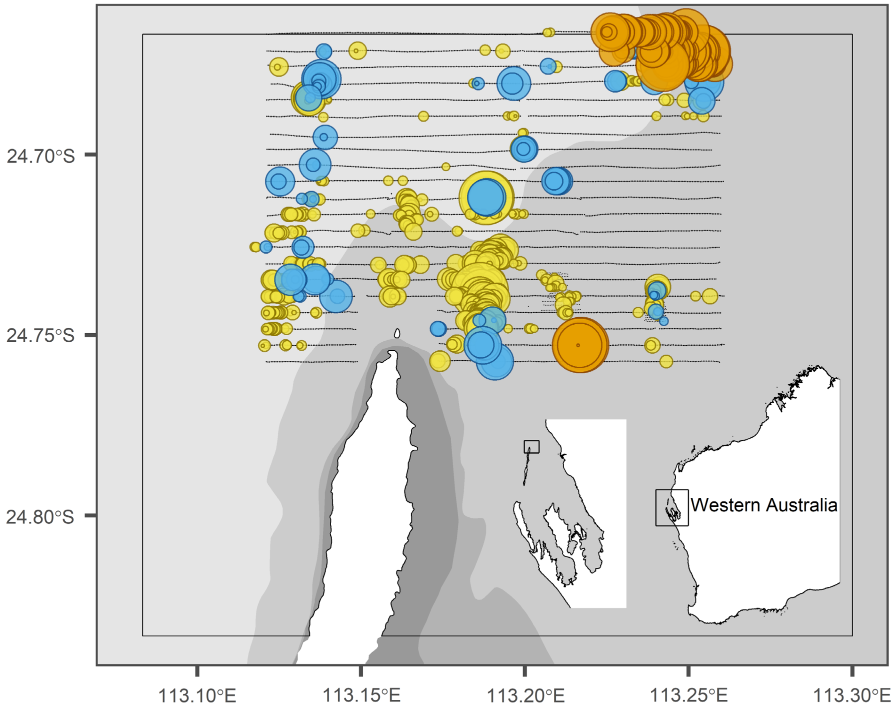

FIGURE 4 Map of the survey area (closed fishing area) with integrated backscatter (circles proportional to √sA, scaled to the largest observation of 126,449 $m^2\,nmi^{-2}$) of snapper-like (yellow), unknown small pelagic fish (blue) and probable yellowtail scad (orange) by 50 m intervals along the cruise track during the 2020 acoustic–optical survey at 38 kHz. The black lines show the cruise track. The inset maps show Western Australia (right) and Shark Bay (left), with the black rectangles showing Shark Bay and closed fishing area, respectively.

TABLE 1 List of aggregating fish species observed by the unbaited remote underwater video cameras. Mean fork length (in cm, ±1 SD) was determined from stereo length measurements.

Common name	Species	Mean fork length (cm, ±SD)	Biomass Total (t)	Biomass CV (%)
Pink snapper	*Chrysophrys auratus*	44.9 (±10.6)	18.02	28.49
Blacksaddle goatfish	*Parupeneus spliurus*	24.3 (±4.5)	0.18	25.44
Brownstripe snapper	*Lutjanus vitta*	26.8 (±1.8)	0.11	16.78
Goldspotted sweetlips	*Plectorhinchus flavomaculatus*	41.3 (±5.8)	0.74	13.11
Moses' snapper	*Lutjanus russellii*	36.1 (±6.2)	1.43	23.70
Painted sweetlip	*Diagramma pictum labiosum*	53.3 (±8.3)	4.62	23.90
Saddletail snapper	*Lutjanus malabaricus*	61.8 (±11.8)	2.41	22.78
Stripey snapper	*Lutjanus carponotatus*	35.1 (±4.9)	0.18	22.38
Yellowtail scad	*Trachurus novaezelandiae*	19.6 (±4.8)	2.41	35.73
Yellowband fusilier	*Pterocaesio chrysozona*	9.7 (±4.0)	0.35	38.87
Unknown baitfish	NA	–	6.08	54.19
Amberjack	*Seriola dumerili*	91.8 (±28.7)	20.83	9.00
Golden trevally	*Gnathanodon speciosus*	70.9 (±15.8)	3.37	15.40
Longnose trevally	*Carangoides chrysophrys*	65.9 (±2.6)	1.83	12.85
Mulloway	*Argyrosomus japonicus*	99.3 (±5.6)	1.87	14.27
Onion trevally	*Carangoides coeruleopinnatus*	56.6 (±5.1)	10.80	12.05
Trevally	*Carongoides* sp	29.4 (±2.7)	1.99	14.48
Goldspotted rockcod	*Ephinephelus coioides*	73.5 (±13.8)	10.96	24.52

3.2 | Optical observations

In all, 29 successfully targeted RUV samples were obtained for optical validation at depths ranging from 28.4 to 66.6 m. Eight occurred over sandy substrates, 11 occurred over reef and 10 occurred over sand with patches of biogenic growth. All but three of the RUVs were deployed in the high intensity strata (Figure 5). In all, 18 aggregating (Table 1) and 24 non-aggregating fish species were observed (Table S5). Five of the aggregating fish species were observed to aggregate only once (Blacksaddle goatfish, stripey snapper, brownstripe snapper, goldspotted rockcod and goldspotted sweetlips). The five *TS-L* groups, *C. auratus*, snapper-like, small pelagic fish, cod-like and trevally-like, consisted of 1, 7, 3, 1 and 6 species, respectively (Table S4). Several species of shark and ray, moray eels and a humpback whale were also observed. All aggregating fish species possessed gas-filled swimbladders. The numerical proportions (in terms of total MaxN) of aggregating species observed varied across the surveyed area (Figure 5).

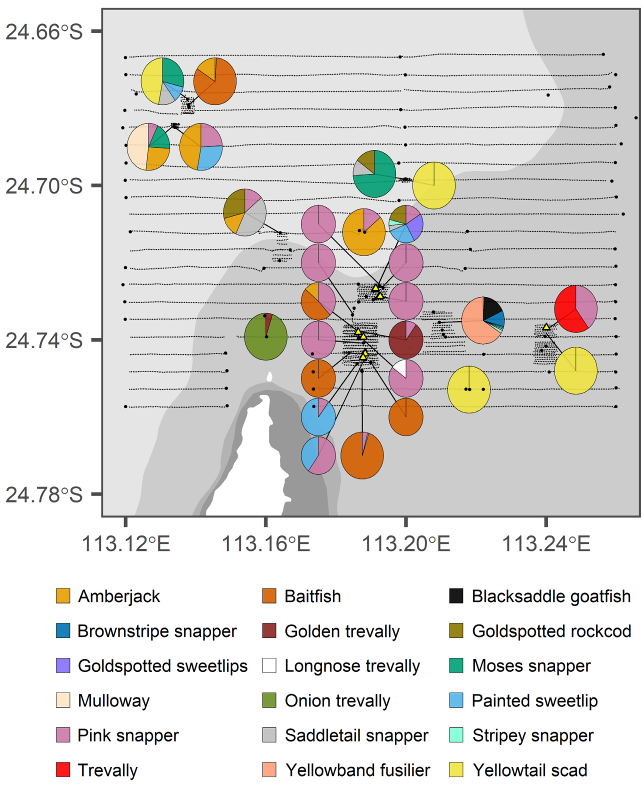

FIGURE 5 Map of the closed fishing area in Shark Bay, Western Australia showing the vessel cruise track (black dotted line) during the Chrysophrys auratus acoustic–optical survey in July 2020. The survey consisted of broadscale transects (500 m spacing) and a series of fine resolution surveys (20–50 m spacing). The pie charts point to the locations of remote unbaited video (RUV) stereo camera deployments with the pieces showing the proportions of different aggregating fish species. The black dots show the locations of camera drops used to validate acoustic habitat classification. The yellow triangles show the locations of the hook-and-line fishing events. Grey shading indicates bathymetry to a maximum depth of 70 m.

Chrysophrys auratus was observed in 19 RUV deployments (66% of those analysed). Of those deployments, 14 had a *C. auratus* MaxN <4, indicating *C. auratus* were mostly loosely aggregated (74% of the time). Yellowtail scad and other baitfish species made up ≥50% of the total number of aggregating fish observed nine times (47%). Other aggregating fish species dominated the other 10 RUV deployments where *C. auratus* was observed (53%; Figure 5).

Respective totals of 306 and 1059 *C. auratus* were measured from stereo camera deployments and from hook-and-line fishing. Although a greater number of small *C. auratus* (<320 mm) were recorded by stereo cameras than from line fishing, the mean lengths of 45.2 cm (SD = 10.6) and 48.3 cm (SD = 9.4 cm) were not significantly different (KS two-sample test: $D = 0.23$, $p > 0.05$).

3.3 | Habitat classification

A total of 38 stereo camera and 65 drop camera observations were made of the seabed in the surveyed area, with 31%, 43% and 27% of the drops occurring on reef, sand and sand with patches of biogenic growth, respectively. The reefs were complex with a range of relief and rugosity, primarily comprised of rock with coral and algae communities (i.e. coral and algae attached to rock), interspersed with large areas of sand or sand with biogenic growth (Figure S2).

3.4 | Biomass estimates

Overall, trevally-like species had a much greater biomass across the surveyed area than the snapper-like species (Table 1). Amberjack had the greatest estimated biomass (20.83 t) and the lowest CV (9.0%). *Chrysophrys auratus* were the second most abundant aggregating species observed with a biomass of 18.02 t (CV = 28.49%; Table 1). Although rarely observed to aggregate, the widely distributed and large bodied goldspotted rockcod had the third highest biomass (10.96 t, CV = 24.52%). The two least abundant species were the blacksaddle goatfish and brownstripe snapper with biomasses of 0.18 t (CV = 29.2%) and 0.11 t (CV = 16.2%), respectively.

4 | DISCUSSION

In this paper, we present an example of how acoustics and optics can be combined as a method for estimating the biomass of multiple fish species that aggregate in structured habitats, or where direct capture methods (e.g. trawls, traps, line fishing) are not amenable (e.g. Boldt et al., 2018; Rasmuson et al., 2022). It combines the benefits of rapid acoustic sampling, which allows for the enumeration of schooling fish as well as other fish, with the benefits of optics to determine species composition. Operating alone, optical methods would fail to quantify these fish accurately, particularly schooling fish, and acoustics could not determine the composition of the numerous species. We estimated the abundance of the target species, *C. auratus* and

17 other species from the diverse fish community, using unbaited stereo cameras to provide the additional evidence (species identification, numbers and length) needed to partition acoustic backscatter (Figures 3 and 5, Tables 1 and Table S4; Fernandes et al., 2016). We were able to provide relatively precise indices of *C. auratus* and several other schooling species: of the 18 species estimated here, almost half (eight species) had abundance estimates with coefficients of variation less than 20% and have, therefore, demonstrated the effectiveness of the survey methods for subsequent incorporation to multiple single-species stock assessments.

The acoustic–optical survey method relies on unbiased estimates of fish species composition, fish abundance and fish sizes in different habitats. Fish detectability using echosounders depends on various factors including fish behaviour, acoustic frequency and beam dimensions, distribution near the seabed ('acoustic deadzone', ADZ), vessel noise, fish acoustic properties (acoustic impedance) and size (e.g. De Robertis & Handegard, 2013). Although the ADZ is likely amplified in rocky reef areas, we did not consider its effect in this study due to the relatively shallow depths. Whilst RUVs may provide some useful information for estimating the effects of the ADZ, they might not be adequate in all situations. Instead, a mobile optical platform (e.g. a remotely operated vehicle) could be used to assess the degree to which different species are present within the relief (e.g. next to rocks) versus above. Future applications of acoustic–optical surveys should consider the water depth, relief and rugosity of the reef, and the equipment being used so that an appropriate ADZ correction can be applied.

Accurate acoustic partitioning and estimation of abundance and biomass of target and co-habiting species requires an understanding of their *TS* properties, ideally measured in situ on free-swimming fish. However, in this study, *TS* could not be measured in situ due to uncertainty in attributing individual fish species to individual echoes. Instead, the *TS-L* equation for *C. auratus* was based on ex situ measurements of larger individuals in Cockburn Sound, WA. This may not be appropriate as *TS* measurements made on different size-classes of the same species can result in very different *TS-L* equations (Scoulding & Kloser, 2021), and, therefore, differences in biomass estimates. There were no published *TS-L* equations available for some of the other aggregating fish species, introducing an unknown but systematic error to their biomass estimates. Future surveys should focus on gathering *TS-L* data for target and related species to improve biomass estimates. However, the utility of the estimates as biomass indices is robust to the assumption about *TS* because it acts as a consistent scaling factor.

In this study, we used stationary RUVs to observe acoustically detected fish aggregations without any significant negative effects on fish behaviour (e.g. Rooper et al., 2020; Schobernd et al., 2014; Somerton et al., 2017). Although less common than baited RUVs (BRUVs) in fisheries surveys, unbaited RUVs likely cause less bias towards scavenger and predator species (Harvey et al., 2007), providing a more accurate representation of species proportions for partitioning acoustic data. None of the 18 aggregating fish species observed in this study actively avoided the RUVs, although we may have failed to see all aggregations of fast-moving fish or those that abruptly left the site upon deployment of the RUVs (Bacheler & Shertzer, 2015). Combining fixed camera installations with RUV deployments at the same locations may help to address uncertainties and improve accuracy of fish surveys. The use of RUVs is further reinforced when we consider the evidence from hooks and lines. In our study, *C. auratus* accounted for >98% of the individuals caught by hook and line, due to their aggressive feeding behaviour and high abundance (Harasti et al., 2018). If these data were used to apportion the acoustic backscatter of snapper-like echotraces, the estimated *C. auratus* biomass would have been far higher than the biomass estimated using RUVs. Although not suitable for validating these acoustic observations, hook and line was beneficial in confirming estimates of length made from RUVs.

The use of RUVs in acoustic–optical surveys presents challenges including time-consuming image analysis, visibility, identification of small or distant fish and limited sampling. To reduce annotation time and the likelihood of observing fish not detected by acoustics, we analysed the first 120 s of video footage, consistent with Rasmuson et al. (2022). To increase sample size, acoustic–optical surveys should determine appropriate sample sizes for characterizing species proportions, and consider compact drop cameras as an alternative to traditional RUV platforms (e.g. Boldt et al., 2018; Fernandes et al., 2016; Rasmuson et al., 2022). The efficiency of extracting data from video or drop camera samples may also be improved by adopting deep learning methods of species identification and counting, as has been demonstrated for *C. auratus* in Shark Bay (Connolly et al., 2021; Marrable et al., 2022).

When the economic value of a stock is relatively low, as is the case for *C. auratus*, the cost of a fishery-independent survey may need justification. The time and costs required to conduct acoustic–optical surveys is probably no more than would be the case for other fisheries surveys, but special equipment in the form of a scientific echosounder needs to be purchased initially, and then deployed on a vessel. Although robust portable systems are now available these can be expensive, as are some of the effective signal processing software systems. The analysis also requires some specialized knowledge, but general texts and guidelines are available (Rudstam et al., 2009; Simmonds & MacLennan, 2008), and some signal processing software providers offer extensive guidance and training courses. The continuous nature of sampling the whole water column using acoustics also provides detailed information on the horizontal and vertical distribution of these fishes. So in addition to abundance estimates, the method also provides information for ecological studies of behaviour, predator–prey interactions (Lawrence et al., 2016) and distribution (e.g. in relation to covariates, such as substrate and oceanography, Jones et al. (2012) and Egerton et al. (2018)). Therefore, the acoustic–optical survey method brings potential benefits not only to the fisheries science community, but also to the wider group of marine ecologists.

Existing stock assessments in the Gascoyne demersal scalefish fishery, as well as other demersal fisheries in Western Australia, suffer from a lack of fishery independent survey data. Current assessments, using biomass-dynamic models to estimate stock dynamics, are based primarily on fishery-dependent length and age data, and catch-effort indices. Independent surveys can improve integrated assessments by either providing fully independent biomass estimates from the survey, or improved data for length- or cohort-structured assessments (Ault et al., 2018; Richards et al., 2016). The acoustic–optical survey method provides both and can be used for estimating the abundance of multiple fish species which is an important future consideration for ecosystem-based fishery management as well as any existing multiple single-species stock assessments. However, prior to incorporation into integrated assessments, further investigation is needed. An index of abundance needs to be representative of the stock dynamics at the spatial scale being assessed and derived via an appropriate sampling design that avoids hyperstability and reflects stock trends in the wider population (see ICES, 2005). Understanding stock dynamics of *C. auratus* and other species and the local environment will, therefore, be essential to utilizing such indices in stock assessments which are vital for sustainable fisheries management.

AUTHOR CONTRIBUTIONS

Ben Scoulding, David Fairclough, Gary Jackson, Brett Crisafulli and Nick Jarvis collected the data; Ben Scoulding, Sven Gastauer, Paul Fernandes and Candice Untiedt analysed the data. Ben Scoulding, Paul Fernandes, Chris Taylor and Sven Gastauer led the writing of the manuscript. Ben Scoulding, Sven Gastauer, Chris Taylor, David Fairclough, Kevin Boswell, Patrick Sullivan, Kyle Shertzer, Fabio Campanella, Nathan Bacheler, Matthew Campbell, Reka Domokos, Zeb Schobernd and Ted Switzer contributed to the development of the acoustic–optical survey method through attendance of a workshop held in Florida in 2019 and contributed critically to the drafts and gave final approval for publication.

ACKNOWLEDGEMENTS

The authors would like to extend our thanks to the crew and skipper of the *FV* Ada Clara. Ben Scoulding, Gary Jackson, David Fairclough, Nick Jarvis and Brett Crisafulli would like to thank the Australian Government via the Fisheries Research and Development Corporation (FRDC) for funding this research. We would like to thank Stacey McCormack from Visual Knowledge for creating the graphics in the manuscript. The authors would like to thank Avery Paxton and Emily Fisher for providing reviews of the manuscript. We would like to extend our thanks to the two reviewers and handling editor for providing detailed reviews of the manuscript. The scientific results and conclusions, as well as any views and opinions expressed herein, are those of the authors and do not necessarily reflect those of any government agency.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

Data available from the CSIRO Data Access Portal https://doi.org/10.25919/7s7x-th98 (Scoulding et al., 2023).

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

Figure S1. A 38 kHz volume backscatter (S_v, dB re 1 m^{-1}) echogram showing an aggregation of pink snapper on a structured reef habitat: aggregations like these can often form into distinctive shapes or echotraces that may be indicative of the species. Individual fish appear as 'banana' shaped echotraces close to the seabed and in the water column. The dark red thick line is the seabed and the horizontal-colored band at the surface is the transmit pulse. Acoustic density is color coded according to the legend with higher values in pink/red and lower values in blue/grey.

Figure S2. Indicator kriging maps of three seabed types (reef, sand, and sand with patches of biogenic growth) based on 103 optical observations.

Figure S3. Example 38 kHz S_v (dB re 1 m^{-1}) echograms (left) showing echo-types manually classified as snapper-like or baitfish-like aggregations. The images (right) show frames from near-concurrent deployments of remote underwater video.

Table S1. Advantages and disadvantages of acoustic techniques for assessing reef fish.

Table S2. Advantages and disadvantages of sampling fish in a complex structured habitat using video methods.

Table S3. *TS-L* constants (a_{TS} and b_{TS}) at 38 kHz for different fish species used to represent the six acoustic groups described in the main manuscript.

Table S4. List of aggregating fish species observed by the unbaited remote underwater video cameras.

Table S5. List of non-aggregating fish species observed by the unbaited remote underwater video cameras. Mean fork length (*FL* in cm, ±1 SD) was determined from stereo length measurements.

How to cite this article: Scoulding, B., Gastauer, S., Taylor, J. C., Boswell, K. M., Fairclough, D. V., Jackson, G., Sullivan, P., Shertzer, K., Campanella, F., Bacheler, N., Campbell, M., Domokos, R., Schobernd, Z., Switzer, T. S., Jarvis, N., Crisafulli, B. M., Untiedt, C., & Fernandes, P. G. (2023). Estimating abundance of fish associated with structured habitats by combining acoustics and optics. *Journal of Applied Ecology*, *00*, 1–12. https://doi.org/10.1111/1365-2664.14412