PAPER

An Approach to the Collection, Processing, and Analysis of Towed Camera Video Imagery for Marine Resource Management

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ABSTRACT

A variety of video and photographic imaging platforms are used to survey seafloor habitats and organisms beyond the effective depth of most SCUBA diving (>30 m). Each platform has benefits and shortcomings, with the most frequently limiting factors being (a) access to the most advanced instruments, (b) response of organisms, and (c) resolution of organism identification. Here, we describe the approaches used to collect, process, and analyze video imagery collected with a simple towed camera sled in the Monterey Bay National Marine Sanctuary as part of a larger, ongoing characterization project that began in 2006. We describe the details of deployment, imagery collection, postprocessing, and analyses gleaned from hundreds of hours of underwater video. Data extracted from camera sled imagery have been analyzed using multivariate model comparison techniques and have been represented in a variety of forms to support management needs and public outreach efforts.

Keywords: towed camera, video imagery, seafloor, conservation monitoring, multivariate modeling

Introduction

Video surveys of seafloor habitats and organisms beyond the effective depth of SCUBA operations, although well established (e.g., Uzmann et al., 1977), are becoming increasingly important for marine conservation monitoring and management efforts (Harter et al., 2008; Karpov et al., 2012; Lindholm et al., 2004; Love & Yoklavich, 2008). Although projects directed at gathering seafloor imagery may be burdened by high operational costs and restricted to a narrow window of weather and sea conditions when compared to traditional extractive sampling techniques, the nonextractive nature of image collection aligns well with the goals of monitoring and research in marine protected areas (MPAs).

Access to platforms for imagery collection, such as human-occupied vehicles (HOVs), remotely operated vehicles (ROVs), autonomous underwater vehicles (AUVs), and even simple systems (such as drop cameras and camera sleds), can be limited. Such operations require vessel time, experienced maritime and research personnel to collect useable imagery, the imaging systems themselves, and auxiliary equipment including integrated navigation to operate the undersea platform in a geospatial context. HOVs place scientists in the sampling environment and can provide high-quality imagery of demersal communities in complex high-relief environments (O'Connell & Carlile, 1994) but require considerable surface support capabilities. While they can access complex rocky environments, they can also be operationally expensive depending on the specific platform and the operating depth. Remotely operated and autonomous platforms (ROVs and AUVs) provide a wider range of platforms and also provide high-quality imagery (e.g., Auster et al., 2003). They also often allow for longer dive times, where the vehicle or camera can stay in the water for 10+ h, avoiding the need to recover and re-launch the system to change out life support supplies and personnel. Furthermore, simpler platforms (such as drop cameras and towed sleds) require less operational expertise, are easier to maintain and repair, and typically have lower operational and overall costs. However, given the superior maneuverability of HOVs, AUVs, and ROVs, imagery quality can be greatly increased for a platform whose movements can be decoupled from the support vessel (as in a depressor or clump weight used for ROVs).

Ultimately, the decision to use a given platform will involve a variety

of trade-offs related to scientific questions, operational considerations, and budgetary limitations. Frequently, a relatively inexpensive, rapid characterization of seafloor habitats is needed. Here, we describe the application of a simple towed camera system for seafloor habitat and community monitoring and characterization surveys in MPAs off Central California. We discuss the exchanges associated with the collection, processing, and analysis of imagery collected by the sled and offer insights into the importance of using simple imagery tools for characterizing seafloor habitats and communities.

Collection of Video Imagery

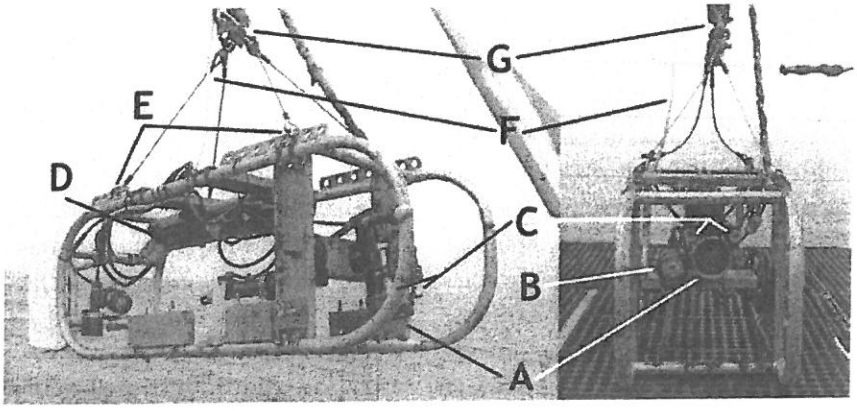
Configuration and Deployment

We used a Towfish Camera Sled System (Deep Ocean Engineering [DOE], Inc., San Jose, CA; Figure 1). The sled, weighing 56.7 kg, consisted of a steel frame (190 × 44 × 52 cm) protecting a single, forward-facing color camera with paired 500-mW lasers spaced at 10 cm, two 250-W Hydrargyrum medium-arc iodide (HMI) lights, an altimeter, and an electronics cylinder. The cylinder served as a junction from the sled to the supply power via the 16-pin 250-m tether. The tether also provided imagery (via a coaxial cable) and vehicle status (depth, heading, altitude) to the surface system.

Topside, the tether fed into a console for a DOE Phantom HD2 ROV, reconfigured to accommodate the lower power demands of the sled (i.e., no thrusters). The console setup consisted of a viewing screen for the video feed with depth, altitude, heading, and date/time overlaid by a DOE onscreen display (OSD-379) device. Camera tilt, power and settings for the lights, and power to the lasers were controlled by the DOE Phantom control box (PCU-78). The video feed with onscreen display was exported from the console to a Sony MiniDV Player and Editor (model GV-HD700E) and recorded on 63-min Panasonic MiniDV tapes. A second Sony MiniDV Player was "daisy-chained" to the first to record an immediate backup of the original tape.

FIGURE 1

The Towfish Camera Sled System, starboard and bow view, showing (A) color video camera with tilt platform, (B) HMI lights, (C) scaling lasers, (D) electronics cylinder, (E) weight-bearing points for the attachment of the bridle, (F) tether, and (G) winch wire bridle.

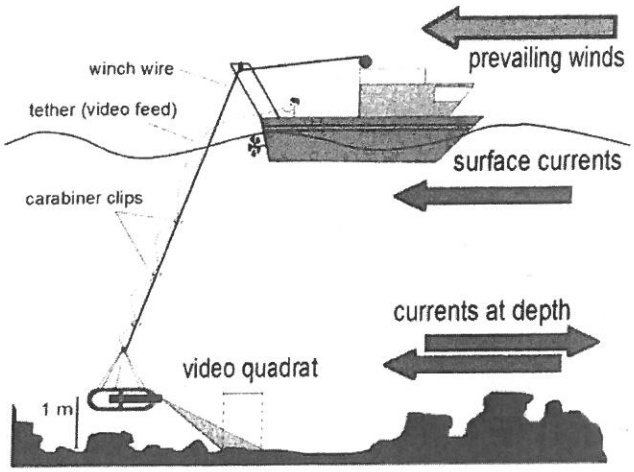


The sled was deployed from the A-frame crane off the fantail of the vessel (most commonly, the National Oceanic and Atmospheric Administration *RV Fulmar*). It was shackled to the ship's winch wire at a bridle and distributed to four weight-bearing points on the aluminum frame (Figure 1) and lowered over the transom. During deployment, the tether was "married" to the winch wire using carabiners and 1/8″ line to prevent midwater and surface currents from separating them. When the sled reached an altitude of approximately 10–20 m (depending on bottom type) over the seafloor, no additional carabiners were added. This allowed for the length of winch wire to be quickly adjusted by an operator while watching the video feed and vertically navigating over the seafloor. The winch wire held the weight of the sled while a tender held the tether to keep slack from feeding out to the water column or near the ship's propellers (Figure 2).

The sled was deployed directly below the ship, with positioning tracked using the ship's GPS and later synchronized with the time code on the video on-screen display. For all surveys, the ship's position was used as a proxy to the position of the sled despite the frequent offset of the sled astern of the boat and occasional horizontal offset in more inclement currents and wind (see Figure 2 and discussion below on ship-sled relative positioning). Because we used the ship's location without an adjustment as a proxy for the sled location, we were able to map the location of a transect with variable precision in reference to high-resolution (2–5 m) multibeam bathymetry. In hindsight, and given the increasing value of using high-resolution multibeam seafloor maps, a system of relative position correction would increase the value of the data

FIGURE 2

Schema representing a transect scenario where prevailing winds were strong enough that the ship headed upwind, towing the sled. Also depicted are metrics used in processing: video quadrat area and optimal 1-m height above the seafloor.



significantly, allowing for better positioning over these maps for subsequent data analyses. We suggest either using a beacon and tracking program software (e.g., Trackpoint II/III, EdgeTech) or manually estimating the distance of the sled from the stern of the ship (e.g., angle measurement and Pythagorean calculation) for more accurate mapping of transects.

Field Conditions

In ideal conditions (i.e., no wind, no current), the ship's captain could slowly maneuver the vessel and thus direct the sled, along a desired heading or along a seafloor feature visible in multibeam maps (when available) by periodically engaging the port or starboard propellers. However, several factors influenced a given transect's length, depth, and direction and, thus, its resulting applicability to address ecological questions.

Both wind and current, along with the vessel speed, can affect the lateral distance between the ship and the sled. Wind was the strongest influence upon the vessel and, consequently, the sled. Due to the use of the sled as a "drop" or "drift" camera, transects were flown in the direction of the prevailing wind, when possible. Along California's central coast, the prevailing direction is from northwest to southeast. Ideally, a gentle wind pushes the boat in this direction as the camera is suspended directly below. In stronger winds, the ship would head into the wind, towing the sled (Figure 2). Fortunately, along central California, isobaths and the continental shelf generally have this orientation, so we were often able to maintain a constant depth, run along shore, and stay on the shelf for lengthy transects (approximately 2–4 km). As winds changed, directionality options depended greatly on the ability of the boat captain to keep a steady heading. When winds or frequent gusts made it difficult for the ship to keep a consistent speed, the transect was aborted. Consistent speed was especially critical in order to keep the sled at a consistent altitude above the seafloor, which, in turn, was important for collecting high-quality imagery for processing.

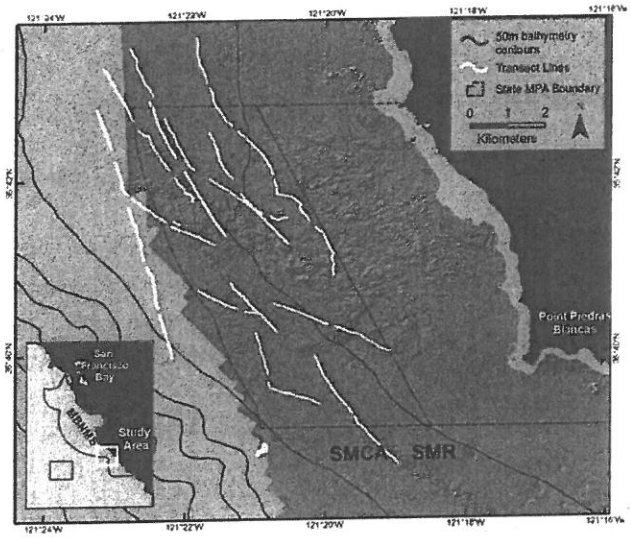
Currents, both surface and subsurface, also affected the ability of the sled to maintain consistency along a transect. A deep subsurface current can thwart the ability to maintain a course along a transect, despite surface conditions. Midwater currents can deceive the tether-tender by pulling strongly on the tether, such that the length of tether exceeds the length of winch wire, creating a potentially dangerous situation of tether tangle or interference with the ship's propellers. Surface currents can push the ship in a different direction than desired, such that the sled could not remain astern of the vessel and, when strong enough, force an end to a transect.

Study Site and Design

Here, we use the Piedras Blancas study site as a case study of data collection, processing, analysis, and application. Point Piedras Blancas is located at the southern end of the Monterey Bay National Marine Sanctuary (MBNMS; 35°39′N, 121°17′W, approximately 5 km north of San Simeon, California; Figure 3), and our study site was specifically located in a California State Marine Conservation Area (SMCA), implemented and protected under the California Marine Life Protection Act of 1999. Transects were conducted in fall of 2007, 2008, and 2011. The general geology of the study area consists of a mixed-relief complex rocky seabed bordered by low-relief unconsolidated sediments to the north and south. Multibeam imagery collected in 2010 by the Seafloor Mapping Lab at CSU Monterey Bay (publicly available at http://seafloor.csumb.edu) shows that these structurally complex features extend seaward from the coast to form the majority of the substrate within the MPA. Unconsolidated sediments border the rocky seabed to

FIGURE 3

Study area at Piedras Blancas. White lines indicate transects conducted in 2007, 2008, and 2011, the majority of which fall within the dashed-line boundary encompassing the SMCA. Multibeam bathymetry (shaded area) shows areas of higher rugosity that are concentrated in the MPAs. Moreover, 50-m isobaths are represented by black lines and show the rapid descent of the continental slope to the southwest. The inset map shows boundaries of the MBNMS and the study location.



the north and south, with rippled scour depressions present in the multibeam data and video imagery adjacent to the reef-sediment interface.

We chose to collect data on seafloor communities and substrate both inside and outside the PBSMCA, an objective of state MPA baseline data collection and monitoring. Dense kelp cover in areas shallower than ~30 m constrained the sampling area to the SMCA, excluding the nearshore no-take State Marine Reserve. Multibeam data were not available until after the 2008 sampling season, so transects encountering the rocky reef were serendipitous to the extent that the protected area was designated to protect the rocky reef. In post-2008 seasons, we aimed to fill in areas that had not yet been sampled, including rocky areas that became evident through the availability of multibeam imagery.

Postprocessing and Data Collection Methods

Viewing Imagery

The video, recorded on miniDV tapes, was reviewed in the laboratory. Although these tapes can be converted to digital computer files, such as AVI, MPG, and MOV for storage on a hard drive and viewing using a variety of software programs, we found it easiest to control (e.g., pause, rewind, fast forward, and slow down) the tapes for better identification by playing back the tapes directly on the Sony miniDV recorders. Three methods for collecting fish, invertebrate, and habitat data are described below: rapid assessment (RA), frame by frame, and organism inventory.

Method 1: RA and Taxonomic Distribution Plots

Viewing the imagery collected in these surveys was time intensive, often multiplying viewing duration by a factor of three over the length of the recording. We developed an RA protocol to provide a realistic snapshot of each transect that was available within hours to days of imagery collection. RA data were collected either *in situ* on the ship as the survey was occurring (and quality checked later in the laboratory) or, more commonly, in the laboratory following data collection. For RA, samples consisting of only the first 20 s of every minute were collected to identify general characteristics of interest. Most commonly, data consisted of the presence (and count) of fish morphologies or complexes (e.g., "flatfishes" or "rockfishes/*Sebastes* spp."), structure-forming invertebrates, select mobile invertebrates, and seafloor features (e.g., sediment mounds/depressions, ledges).

Method 2: A "Frame-by-Frame" Approach, With Formal Statistical Inference

With this method, each sample unit for extracting data from video imagery was a nonoverlapping video quadrat (referred to here as a "frame" *sensu*; Auster et al., 1991; Figure 2). For each frame, organism data were collected in a detection/nondetection (presence/absence) format. If multiple individuals of the same species were observed in a single frame, this species was simply recorded as a "detection" in the frame. If multiple species were present in a frame, each one was recorded as a single "detection." Fishes may have occurred within a frame but were either hidden from view (e.g., concealed in a crevice or hole or were too successfully cryptic to detect) or may have fled the frame prior to arrival of the camera; thus, the use of the terms *detection* and *nondetection*.

Frequently, detections were not able to be identified to the species level. This varied considerably based on whether the species has many congeners (e.g., yellowtail rockfish and olive rockfish) or is rather distinctive (e.g., flag rockfish). Organism data were collected at multiple taxonomic levels (e.g., order, family, genus, and species), and analyses were conducted within a taxonomic level.

For each frame, the substrate of the seafloor was characterized using a primary/secondary scheme describing both the grain size and the relief. The primary grain size was determined by the most abundant grain size in a frame (encompassing ≥ 50% of the area), and the secondary grain size was established by the next most common grain size (encompassing ≥ 20% of the area) in the frame. If there is only one grain size present in a frame, it is recorded as both the primary and secondary grain size. This technique is a modification of the microhabitat classification system of Greene et al. (1999) and was also used by Tissot et al. (2006). The relief of both the primary and secondary grain sizes was recorded using a categorical system of high (>2 m), moderate (1–2 m), low (<1 m), and crested (Table 1).

For the fish-habitat association study, we also collected data on particular sessile invertebrates present in each frame to test if there was an association with biogenic habitats. Specifically, we focused on detections of structure forming invertebrate morphological groups such as sponges, gorgonians, and sea whips. Depending on the questions under review, other metrics such as percent cover or relief of biogenic structure could be collected.

In acknowledgement of assumptions for the modeling approaches described later, because nonuniform detection probability could potentially bias inferences about a fish's true habitat associations (as in "Scenario 2" from MacKenzie, 2006), we assumed that detection probability was essentially uniform. We recognize that the validity of these inferences is conditional on the validity of that assumption (see Auster et al., 2007; Stoner et al., 2008).

TABLE 1

Habitat categories and definitions: Substrate, grain size, and relief categories (adapted from Greene et al., 1999) and biogenic structure categories.

Substrate	Category	Description
Soft (S)	Mud (M)	Fine-grain soft sediment
	Sand (N)	Coarse-grain soft sediment
	Pebble/gravel (P)	Loose rocks < 2.5 cm
Hard (H)	Cobble (C)	Loose rocks = 2.5–24 cm
	Boulder (B)	Loose rock > 24 cm
	Rock (R)	Continuous rock (bed or ridge)
Relief	**Category**	**Description**
	Crested (CS)	Soft sediment with ripples or waves
	Low (LO)	<1 m above seafloor
	Moderate (MD)	1–2 m above seafloor
	High (HI)	>2 m above seafloor
Biogenic Structure	**Category**	**Description**
	Soft (BIO-S)	Sessile invertebrates > 5 cm in height on soft substrate (sea whips, e.g., *Halipteris* spp and *Stylatula* spp, and sea pens, e.g., *Ptilosarcus* spp)
	Hard (BIO-H)	Sessile invertebrates > 5 cm on hard substrate (gorgonians, e.g., *Swiftia* spp, and sponges)
	None (BIO-NO)	No invertebrates > 5 cm height

Method 3: Organism Inventory

To collect a detailed record of each organism observed, video was also viewed while recording the occurrence and identification of every organism of interest. The record of time for each organism was stored in a relational database (e.g., Microsoft Access) and referenced with the time code at the second of the observation. Each record is then linked to a variety of different data sets concurrently collected in the field (i.e., location, depth, temperature) or available through other sources (i.e., rugosity models, remote sensing data). This has been a common approach for monitoring and characterizing areas (Tissot, 2008), such that all species are identified and enumerated and that the data set can be mined for many types of questions across taxonomic levels.

Here, we use this approach to link observations of fishes or fish groups to positional data of the ship at the time of observation. Despite the offset of the ship and the sled, broad-scale fish distribution maps were created in

ArcGIS (ESRI v10.0; Redlands, CA) to show distribution trends across the entire study site.

Data Analyses

The variety of approaches to represent and analyze fish distributions and associations in seafloor imagery has included simple parametric (e.g., *t*-tests; Auster et al., 2003) and nonparametric tests (e.g., chi-squared; Laidig et al., 2009; Love & Yoklavich, 2008), visual representations of multivariate statistics (e.g., canonical correlation analysis; Anderson et al., 2009; Yoklavich et al., 2002), and model comparison approaches (e.g., generalized linear models [GLMs]; Chatfield et al., 2010; Young et al., 2010). Here, we have provided some examples of representations and analyses of the data collected with the towed camera sled, based on the methods for viewing the imagery described above.

Many types of imagery data are collected as consecutive points along (transect) lines and thus can potentially violate the assumption of independence in a random sample (spatial autocorrelation). We were able to test and compensate for this in the GLM comparison approach (Method 2, below), but it should be noted that the extent of spatial autocorrelation should be addressed in studies using quantitative approaches to analyze imagery data.

Method 1: RA and Taxonomic Distribution Plots

The RA method was used to create a taxonomic distribution (and abundance) plot (TDP or TDAP; Figures 4a and 4b, respectively). These plots provide a general "snapshot" of a given transect or multiple transects in an area. RA data were plotted to show their distribution across a transect (or any other desired sampling unit). The plot shows the heterogeneity (or homogeneity) in seafloor type and relief. By aligning the co-occurrence of fishes and invertebrates over these habitat data, the relationships between these elements become apparent. Incorporation of the abundance of each category (as in TDAPs) shows how the density of some groups changes over different habitats.

RA and TD(A)Ps were a simple way of visually representing a subset of the full imagery series. We have not, to date, used these data in statistical analyses or modeling methods due to their coarseness and broad coverage. Most of our research questions primarily consisted of relatively small-scale associations between fishes and their habitats. However, they could be used to test co-occurrences of general groups of organisms or to assess the strengths of the organism-habitat relationships.

Method 2: A "Frame-by-Frame" Approach, With Formal Statistical Inference

The distance between the sizing lasers (10 cm) was used to calculate frame width for each sample. To standardize the area encompassed in each frame, we limited imagery used in analyses to that which was collected at a similar altitude above the seafloor. Samples in which the frame width was less than 1.0 m or greater than 2.0 m or where the angle was such that the seafloor encompassed less than 75% of the view were eliminated from analysis.

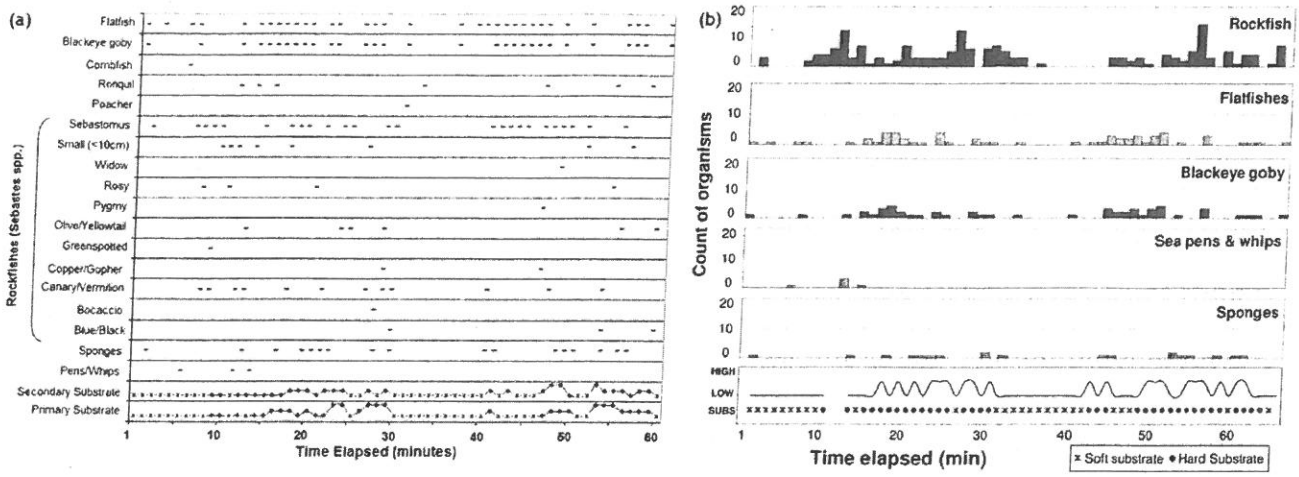
After elimination of frames that did not meet the criteria of 1- to 2-m width, the data set consisted of a list of frames (most of which were adjacent), each with the following data: a primary and secondary substrate type with corresponding relief, detection of any fishes, detection of particular structure-forming invertebrates, and depth. The following analyses were used to address the question, "how are different groups of fish distributed across different habitats?"

We used a set of GLMs to compare multiple hypotheses (models) relating species detection to different configurations of landscape habitats. The models were compared using information-theoretic methods based on Akaike's Information Criteria (AIC), as has recently become popular in marine ecology (e.g., Fenberg & Rivadeniera, 2011; Chittaro et al., 2009). This approach, contrasted to the traditional method of comparing one null hypothesis to all alternates, allows for improved interpretation of a more complicated and dynamic system (Burnham & Anderson, 2002). Inferences about the system structure were made from the model that best described the detected distribution of each fish group. Additionally, the relative importance (RI) of each habitat variable (substrate and biogenic habitat) was inferred by summing the total statistical support for all models containing that variable (Burnham & Anderson, 2002).

In the analyses of the data collected for the Piedras Blancas Study Site (see Knight, 2012, for the full approach), the AIC weights (AICw) of each model were compared. AICw represent the probability that a model is the best fit, given the other models in the set (Burnham & Anderson, 2002). From the AICw, evidence ratios (ERs) for the best-fit models were calculated. ERs compare two models: for our results, ER_o compares the null model to the one with the highest AICw, and ER_B compares the two highest AICw values to infer the degree to which one is the best fit. When any $\log_{10}$ ER between

FIGURE 4

(a) A TDP shows the presence of morphological groups (*y* axis) over elapsed time of a transect (*x* axis). There appear to be abrupt changes in fish presence when substrate and relief change (note the change in most groups and habitats at 30 min). (b) A TDAP shows the quantity of morphological groups (*y* axis) over the elapsed time of the transect (*x* axis).



the best-fit model and the next best model in the set was less than 0.5, the models were considered to be somewhat equivocal (*sensu*; Kass & Raftery, 1995). The RI for each variable was calculated as the sum of AICw for all models containing that variable.

To address the potential violation of independence due to spatial autocorrelation, we tested the residuals from each best-fit model using correlograms based on Moran's *I*. Model residuals were chosen as the basis for the correlograms, as opposed to raw observations, so as to quantify spatial autocorrelation in species response to habitat, as opposed to habitat itself.

We calculated Moran's *I* for each fish grouping at 50-m increments using custom R-code (R Core Development Team 2012; see Knight, 2012) that is equivalent to the correlation function in the "spatial" package in R. Our code was modified to sum a weighted Moran's *I* for each transect, in order to preserve the independence of each transect from the others. The correlograms were plotted in 10-m bins up to a maximum of 1,000 m. For fish species that showed spatial autocorrelation (a decreasing Moran's *I* with increasing distance), the raw responses were culled to remove frames that were within 5 m of each other. Residuals from models fit to the culled data were then reexamined and would be further culled if subsequent correlograms revealed persistent autocorrelation. Fish species that did not have a decreasing Moran's *I* with increasing distance were assumed not to be spatially autocorrelated (Figure 5).

Model comparison results were obtained at several taxonomic levels for a range of different ways of describing habitat. An example result was that we found substantial evidence that squarespot rockfish was positively associated with mixed and hard-bottom habitats in the deeper areas surveyed in the study ($\log_{10}$ ER = 0.74; Knight, 2014). Substrate type showed the strongest RI in predicted detections of squarespot rockfish, confirming observations at other deep reefs in Central California (Anderson & Yoklavich, 2007; Yoklavich et al., 2002).

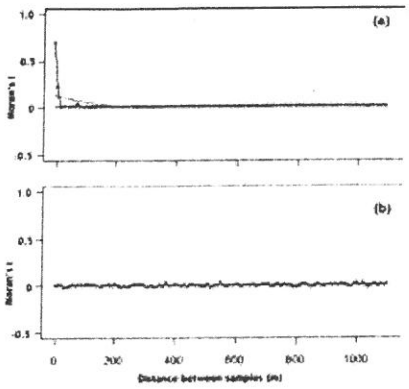
Method 3: Organism Inventory

Using each observation of a given organism, the distribution of a group of these organisms was represented on a map. By combining the organism identification (which has variable taxonomic resolution) with the position of the ship at the time the organism was observed, we could, with variable spatial resolution, display how different groups are using an area. We plotted the distribution of each fish grouping observed at the PBSMCA site (i.e., Figure 6) to see where fishes were distributed (in this case, the benthic habitats of the state MPA and the southern region of the MBNMS). Representation of the distribution of specific organisms across a given area has proved informative to managers and public audiences (i.e., IfAME-MBNMS, 2011).

The resolution of the geospatial positioning data, deriving from such factors as the location of the ship at

FIGURE 5

Example of Moran's *I* correlogram plot for spatially autocorrelated data. A relationship between distance between samples (*x* axis) and Moran's *I* (*y* axis) in plot (a) suggests a spatial correlation. Plot (b) shows no relationship and thus no spatial autocorrelation. The line indicates the best fit of the individual coordinate values.



the time of observation vs. the actual location of the towed camera sled, will drive the resolution of the analytical approach. For example, if the observation was confidently within 2–10 m of the location data (latitude/longitude) point, a multitude of habitat suitability models and spatial analyses could be conducted using equivalently scaled multibeam bathymetry and other fine-scale data sets (see Iampietro et al., 2008; Young et al., 2010). Where the error around any positional estimate increases, the accompanying resolution of the analyses will similarly be less precise.

Conclusion

Using imagery as a means to study and observe underwater resources is critical to understanding how fishes are distributed across seafloor types, an important element for determining the most effective way to establish and monitor protected areas. By providing imagery to these groups, more informed and comprehensive management decisions can be proposed. The ease of use, ease of access to, and affordability of a camera sled or similar devices as platforms for collecting imagery and conducting RAs allow managers to request surveys of specific areas of interest and, within a relatively short amount of time, have data to make decisions. More detailed data (i.e., the organism inventory) provide information for more specific management actions such as marine zoning decisions, designating essential fish habitat boundaries, or installing undersea cables.

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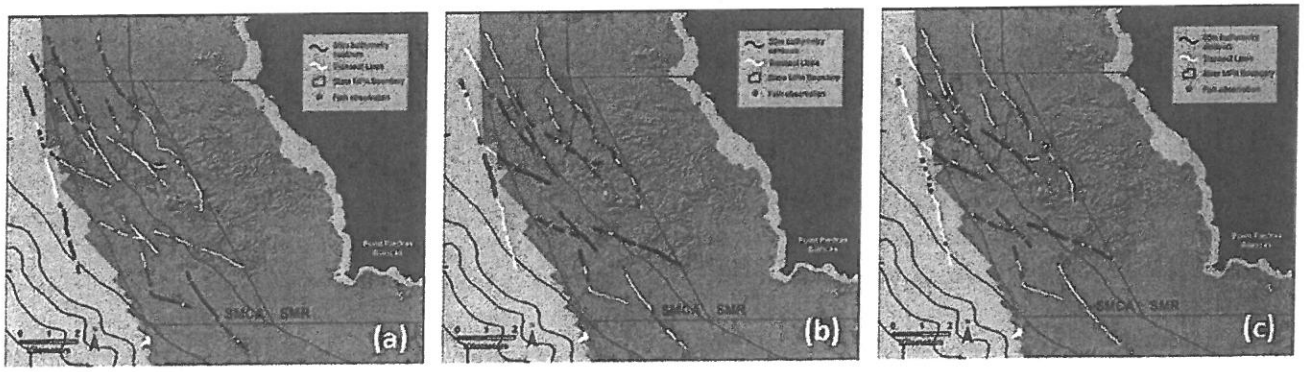
FIGURE 6

Distribution maps for fishes at multiple taxonomic levels: (a) family (pleuronectiform flatfishes), (b) genus (*Sebastes* spp., rockfishes), and (c) species (*Rhinogobiops nicholsi*, blackeye goby).



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