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Extracting ecological metrics from archeological surveys of shipwrecks using submersible video and laser-line scanning

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Abstract. Ecological metrics derived from habitat surveys can provide information necessary to understand population, community, and ecosystem processes. Here, we present a case study on the feasibility of extracting ecological metrics from archeological studies of shipwrecks. Even though shipwrecks that are the focus of archeological surveys also form habitat for diverse flora and fauna, shipwrecks are often studied separately by archeologists and ecologists. Conducting joint archeological and ecological surveys promises to maximize research resources and outputs, yet this cross-disciplinary approach is rare. Here, we test the feasibility of extracting ecological metrics from archeological surveys of two historically significant and deep (200 m) shipwrecks, the German U-boat U-*576* and the Nicaraguan freighter SS *Bluefields*, which sank in close proximity to one another on the continental shelf of North Carolina, USA during World War II. First, we assessed fish density, community composition, behavior, and spatial distribution on these shipwrecks using video and laser-line scanning data collected from human-occupied submersibles during archeological surveys. Second, we examined the ecological benefits and biases of pairing laser-line scanning and video surveys designed for archeological specifications. Our approach allowed us to pinpoint locations of fish around the shipwrecks and to identify these fish to fine taxonomic levels. The extracted ecological data revealed that both shipwrecks hosted high densities (U-*576* 38.2 ± 4.0; SS *Bluefields* 32.0 ± 18.0 per along-ship transect) of demersal fishes, including grouper species, and that fish concentrated around high-relief shipwreck features. More broadly, our findings demonstrate the utility and benefits of collecting multipurpose and cross-disciplinary data and provide a proof-of-concept for conducting joint archeological and ecological studies.

Key words: archeology; deep reefs; fish community; grouper; human-occupied submersible; interdisciplinary research; laser-line scanning; shipwreck.

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Introduction

A fundamental goal of ecology is to understand relationships between species and their habitats (Huffaker 1958, MacArthur and MacArthur 1961, Simberloff and Wilson 1968). Ecological metrics that describe species-habitat relationships can provide data necessary for untangling population, community, or ecosystem processes. In systems that are remote or difficult to access, however, it can be challenging to collect sufficient data to derive or estimate these ecological metrics. One approach toward overcoming this challenge is to combine survey efforts across disciplines (Lubchenco et al. 1991, Daily and Ehrlich 1999, Martínez et al. 2006). Interdisciplinary collaborations are common between ecologists and economists (Peters 1992, Farber et al. 2006, Loucks 2006, Polasky and Segerson 2009), ecologists and politicians (McCully 1996, Benjaminsen et al. 2010, Goldman et al. 2018), and ecologists and psychologists (Sheridan and Gutkin 2000, Nettle and Penke 2010, Worthman 2010), for example. Ecologists and anthropologists also collaborate on research topics ranging from deforestation to fishing communities (McCay 1978, Sussman 1994). Archeology is a subfield of anthropology (Lyman 2007), yet interdisciplinary ecological and archeological studies are rare. Ecologists can likely benefit from combining efforts with archeologists to conduct joint surveys because this collaboration may maximize research outputs while simultaneously addressing ecological and archeological research objectives.

Underwater Cultural Heritage (UCH) represents remnants of human activity deposited in submerged environments. These resources range from ancient cities and ports to sacred sites, inundated shoreline structures, and shipwrecks. Archeological surveys of these resources serve to identify, document, and gather information through a variety of methods, including visual observation, photographic documentation, application of remote sensing technologies, and excavation. While studies of such cultural resources can provide new information that informs archeological interpretation and expands our understanding of the past, these cultural resources also form important habitats for diverse flora and fauna. This occurs both on land and in underwater contexts. For example, plant species have been found occupying ancient Egyptian tombs (Day 2013), while species including macroalgae, invertebrates, fishes, and top predators use shipwrecks and other submerged human-made structures for habitat (Paxton et al. 2017). Given that diverse species use submerged maritime resources as their habitat, conducting joint archeological and ecological surveys promises to maximize research resources and outputs.

Despite the promise of joint archeological and ecological surveys, ecological studies of species and their habitats are often undertaken separately from archeological investigations, and archeological investigations utilizing environmental and ecological information often solely rely on this information as a means to understand past human activity. Within the sub-discipline of environmental archeology, for example, the environmental or ecological patterns revealed by analyzing pollen and climate records have been used by archeologists to understand how past societies interacted with the environment (Guiot et al. 1989). And, within the sub-discipline of battlefield archeology (Scott et al. 2006), elements of the physical environment and natural features that could influence human activity have been used by archeologists to study and interpret World War II shipwrecks (Bright et al. 2012). Ecological indicators have also been used to study archeological site formation processes, for example, investigating microbial action and resident biota to measure site preservation and potential impacts to shipwrecks from exposure to oil spills (Mugge et al. 2019). In contrast, ecologists can use artifacts discovered during archeological investigations to provide information on species and the age and colonization of habitats by attached or associated biota. For example, ancient art has been used to compare sizes and populations of dusky grouper (*Epinephelus marginatus*) depicted in early Etruscan, Greek, and Roman murals to current species metrics inside marine protected areas (Guidetti and Micheli 2011). And, ecological assessments of fossilized abalone shells from archeological sites on the Channel Islands off the coast of California, USA, have provided historical data on sea otter (*Enhydra lutris*) populations (Erlandson and Rick 2010). Remotely-operated vehicle (ROV) video and photographic imagery of archeological sites has been used to conduct ecological surveys, such the analysis of ROV videography to study the ecological communicates associated with WWII shipwrecks in the Gulf of Mexico (Church et al. 2007).

While these examples provide evidence for archeologists using ecological patterns and ecologists using archeological information to answer questions within their respective disciplines, the case study that we present here highlights that there are opportunities to further collaborative archeological and ecological investigations using methods that advance both disciplines. Here, we evaluate the feasibility of collecting archeological and ecological data simultaneously using advanced technologies. Specifically, we test the practicability of extracting ecological data from both video survey and laser-line scanning acquired from human-occupied submersibles during archeologically designed surveys of two historic shipwrecks. Laser-line scanning is a method that emits laser beams of light in a fixed-angle band toward structures on the seafloor. The reflected light is absorbed by a sensor to measure precise range to structure and can be used to form point cloud digital elevation models (Amend et al. 2007). Video and laser-line scanning surveys have been used independently for archeology and ecology but not for a cross-disciplinary approach. For example, video has been used to search a section of the continental shelf off the north coast of Turkey, a now-submerged paleoshoreline, for evidence of humans from more than 7000 yr ago (Coleman et al. 2000). Also for archeological purposes, laser-line scanning was used to model the shipwreck of the RMS *Titanic* (Ludvigsen et al. 2007). Ecologically, video from submersibles and laser-line scanning have been used together to assess marine habitats and fish populations. Yoklavich et al. (2003) and Amend et al. (2007) collected videos and laser-line scanning from remotely operated vehicles to document benthic reef fish habitats and populations, but not shipwrecks. For ecological assessments of shipwrecks, combining video surveys with laser-line scanning surveys allow us to count, identify, and measure fish species, as well as to document spatial relationships between these species and shipwrecks.

We focused our surveys on two World War II shipwrecks: the U-*576* and the SS *Bluefields*. These ships sank during a naval battle on 15 July 1942, when the German U-boat U-*576* attacked the KS-520 convoy, a fleet of 19 allied merchant vessels and five escorts headed south from Hampton Roads, Virginia to Key West, Florida (Bright et al. 2012). The U-*576* fired four torpedoes and struck three merchant ships, incapacitating the *Chilore* and *J.A. Mowinckel*, and sinking the Nicaraguan freighter SS *Bluefields*. The U-*576* was also damaged during the battle, reportedly sustaining damage from an armed guard crew aboard SS *Unicoi*, and concurrently straddled by aerial depth charges from two U.S. Navy *Kingfsher* aircraft. Today, the 67-m long U-*576* rests 241 m apart from the 76-m long SS *Bluefields*, in 210 and 245 m of water, respectively. Since this is the only naval battlefield of World War II on the east coast of the United States where both the victim and aggressor sank in the same vicinity, the resting place of these two shipwrecks remains important historically and archeologically (Bright et al. 2012). These shipwrecks also provide habitat for fish species and benthic invertebrates.

Our main objective was to document fish communities on two deep shipwrecks: the U-*576* and SS *Bluefields*, providing a case study in using archeological data to extract ecological metrics. We utilized data from video and laser-line scanning surveys conducted from human-occupied submersibles to ask three ecological questions: (1) What is the fish community composition and abundance on each shipwreck? (2) What are the behaviors displayed by fish near the submersibles? and (3) How are fish spatially distributed on and around each shipwreck? In pairing video and laser-line scanning technologies, we can obtain ecological metrics for fish communities associated with shipwrecks from archeological data.

Methods

Study sites

Archeological surveys of two shipwrecks, the German submarine U-*576* and the Nicaraguan freighter SS *Bluefields*, were conducted on 24–26 August and on 28 August 2016 during daytime hours. These ships sank on 15 July 1942 during the same World War II battle on the continental shelf of North Carolina, USA (Fig. 1).

Data collection

Both shipwrecks were surveyed from two human-occupied submersibles (Triton 1000/2) deployed from the R/V *Baseline Explorer*. One of the submersibles, which we refer to as the laser-line scanning submersible, was equipped with a laser-line scanning system (2G Robotics ULS-500) and a high-definition video camera. The second submersible, which we refer to as the photo-video submersible, was equipped with an ultra high-definition video camera (Red Dragon Cinema Camera) and still camera (Sub C Imaging 1 Cam Alpha +) intended to collect imagery for documentation and photogrammetry. The video camera footage was illuminated by lights on the submersible. The laser-line scanning system uses lasers to acquire a point cloud of shipwreck features with accuracy <1 mm, enabled by a long-baseline navigation system and an array of six acoustic beacons mounted on tripods with acoustic releases and float collars. These beacons were placed in a large circle encompassing both wrecks sites approximately 200 m apart and with line of sight to at least two other beacons in the array.

During shipwreck assessments, the laser-line scanning submersible surveyed first and was followed by the photo-video submersible. There was a one- to two-hour delay between launch of the laser-line scanning submersible and the photo-video submersible because of the time necessary to launch each submersible. Although the data streams from the two submersibles were not collected simultaneously, the collected data are

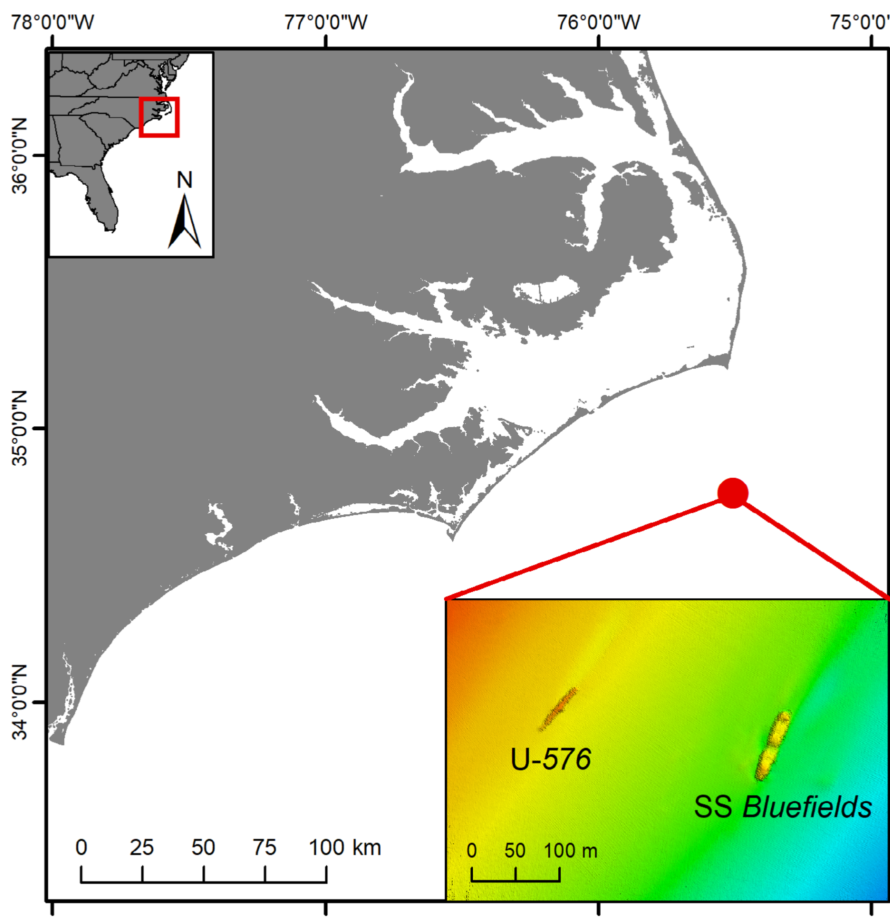

Fig. 1. Location of shipwrecks U-*576* and SS *Bluefields* on the continental shelf of North Carolina, USA. Insert in lower right shows multibeam bathymetry of the two shipwrecks, where warmer colors indicate shallower depths.

comparable both spatially and temporally (Fig. 2). The submersibles generally traversed from the bow to the stern of the wrecks or vice versa multiple times until laser and video imagery had been collected over the entire wreck. While the field of view was consistent across transects, the two shipwrecks were different lengths, and therefore, the associated transects were also of different lengths. Because current was minimal, we were able to look at both sides of the shipwrecks. The laser-line scanning submersible often resurveyed parts of the shipwreck that were specific archeological targets to acquire optimal imagery to compile into a three-dimensional model. Similarly, the submersible collecting video often approached specific targets on the shipwrecks to acquire close-up footage of the targets (Fig. 2).

Since the human-occupied submersibles collected video and conducted laser-line scanning continuously when performing archeological site assessments, we divided the continuous video and laser-line scanning footage into discrete transects demarcated by changes in the travel direction of the submersible (Appendix S1: Table S1). For example, when the submersible traveled from the stern to the bow collecting continuous video footage, this was a full transect. When the video cut to new footage looking at the bow and drove toward the stern, this was an additional full transect. Due to the high variability of conditions over transects, fish abundance was not averaged over all transects from a wreck, but instead, the most comparable video and laser-line scan transect on each wreck were used to assess fish metrics extracted from the two techniques. The most comparable transect for each wreck was chosen based on which video and laser-line transects followed the closest path, spatially. Some surveys did not fully traverse from the bow to the stern of the vessels, and we did not analyze these partial transects due to uncertainty in search area and lack of spatial reference. In total, four full video transects were conducted on the U-*576* and two on the SS *Bluefields* (Appendix S1: Table S1).

Video data processing

For each transect delineated from the continuous video, we counted and identified fish to the lowest taxonomic level possible. Most fish were identified to species level; however, some

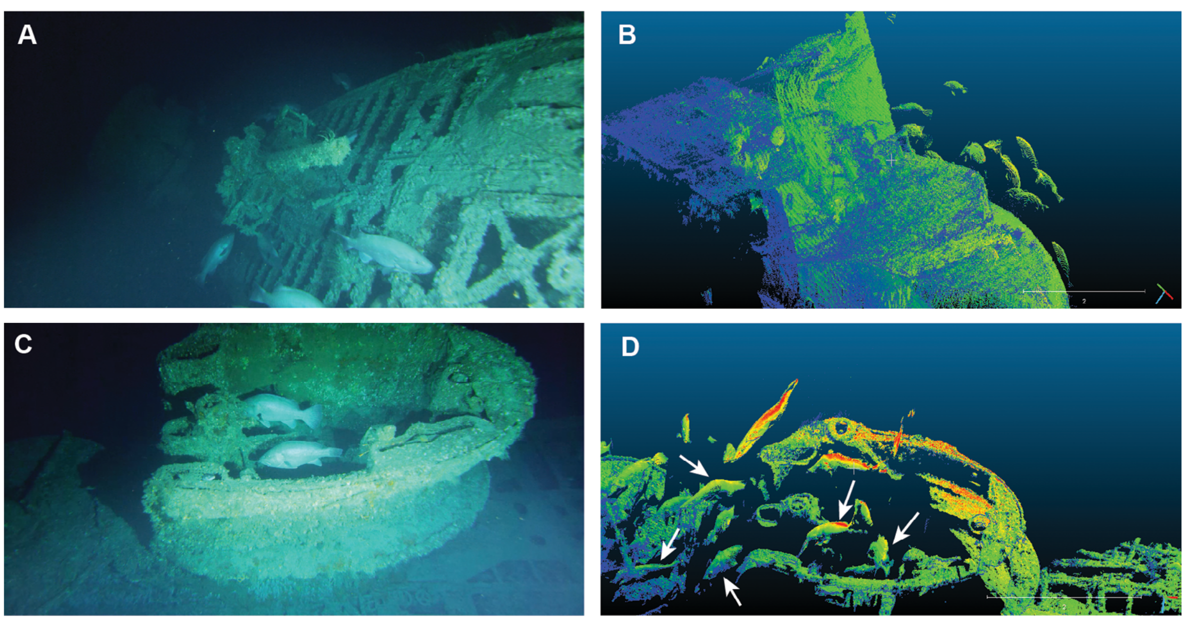

Fig. 2. Human-occupied submersible video and laser-line scanning imagery for two prominent features on the U-*576*: deck gun (A, video; B, laser-line scanning) and conning tower (C, video; D, laser-line scanning). White arrows in panel (D) highlight fish that are more difficult to see.

fish were identified to the genus level, largely when we were unable to distinguish among grouper species. We recorded the time when each fish was first observed in the video, as well as the location of the fish on the shipwreck (e.g., port, starboard, stern bow, conning tower, deck gun). Fish behavior, such as resting, swimming, stationary, changing direction, and following, was also noted. Fish were classified as resting when the fish and its fins were motionless, usually close to the bottom (Gerlai et al. 1990). If a fish was moving from one place to another using all or most of its fins, then it was deemed swimming (Gerlai et al. 1990). When a fish continuously moved its caudal and pectoral fins but did not change location, it was classified as stationary (Bolgan et al. 2016). When a fish moved its caudal fin quickly resulting in modification of its trajectory toward a different direction, it was categorized as changing direction (Bolgan et al. 2016). When one fish swam behind another in the same direction, it was classified as following. We recounted the fish multiple times over each transect to help avoid double counting fish that were moving. Most swimming fish moved more slowly than the submersible or sought refuge in the wreck structure, which helped us avoid double counting, yet although unlikely, we acknowledge that double counting could have occurred. We could not measure the fish length using video data because the photo-video submersible lacked a calibrated stereo-system, as well as set-distance lasers.

For each transect, we also recorded qualitative information about the transect direction (e.g., transect from bow to stern and transect from stern to bow). Submersible behavior was recorded as either crabbing (moving forwards and sideways simultaneously), zooming in toward a target feature, ascending, descending, sustaining a close-up look, etc. For example, when the submersible drove down the side of the wreck simultaneously looking at the hull and the area off the hull, this was considered crabbing. Zooming in was the action of moving closer, while a close-up look was footage once the vehicle was already close to a target feature. We used these supplemental classifications mainly as a means of auditing and creating a reproducible video processing protocol.

Laser-line scan data processing

The data points recorded during laser-line scanning were post-processed to incorporate navigation data so that the resulting three-dimensional models were geo-rectified. This was accomplished by Sonardyne technicians and required manually referencing time stamps from the long-baseline navigation data to the laser data. The point clouds were then imported into CloudCompare Edition 2.10.2. Similar to the video data, the laser-line scanning data were split within CloudCompare into transects, and fish were counted separately for each transect. When a fish was observed, the point picking tool was used to click on the center of the fish body. This tool provided x, y, and z coordinates of the fish. Using the point picking tool, the total length (m) from the tip of the caudal fin to the front of the mouth was measured. When a fish was in close proximity to another fish or the wreck, the point picking tool sometimes selected points that were not part of the fish in question. Because of this, we confirmed that the points chosen when measuring the length of the fish were points that composed the target fish, not the surrounding fish or structure. For each fish, the x, y, z coordinates, and total length were recorded. Some fish were behind a part of the wreck or partially outside of the field of view so did not have a fully visible body. When this occurred, the point picking tool was used to choose the best estimate of the center of the fish. Sometimes, laser-line scanning revealed imagery of parts of fish, rather than whole fish. The partial fish were excluded from transect abundance values and later analyses to focus on measured fish. For each of the observed individual fish, the fish type (e.g., large-bodied fish like grouper and wreckfish) was deduced based on length and shape of the fish. Because laser-line scanning was conducted at a similar time as the video, the video helped verify which species and families may have been imaged during laser-line scanning. Even though the laser-line scanning imagery is a still three-dimensional model of points, we could classify fish behavior as stationary, swimming, or changing direction. For example, some fish had distorted bodies or elongated tails indicating they moved quickly (swimming) as the lasers hit them. All fish that were distorted were classified as swimming while the fish that were still during the laser burst were categorized as stationary. Other fish were visibly changing direction during laser detection. With many of the partial fish, there was no way to determine behavior. General fish location was noted in accordance with the video data (e.g., port, starboard, bow, stern, and conning tower).

Data analysis

Data were analyzed and visualized using R version 3.5.3 (R Core Team 2019). We limited our analyses to simple numerical assessments for several reasons. First, as our goal was to see how laser-line scanning and video surveys could provide complementary information, quantitative comparisons were not warranted. Second, we did not compare estimates of fish abundance between shipwrecks since the shipwrecks and associated transects were of different lengths. Third, this case study contains low replication of transects over which fish abundances can be highly variable. Partial video and laser-line scanning transects were not included in the numerical assessments, rather we used four full video transects and three laser-line scanning transects for the U-*576*. Of these, we selected one video and one laser-line scanning transect that were the most spatially and temporally coincident and used them to determine how the two survey methods complement each other. We refer to these as the coincident transects. For the *Bluefields*, we obtained two full video and two full laser-line scanning transects and again examined one of each transect type directly.

Demersal fishes were detectable in laser-line scanning, as well as videos, whereas schooling fishes were detected only in videos. Because one of our objectives was to assess video and laser-line scanning survey methods, we focused our analyses on demersal fishes. The fish classified as demersal were fish that associated with the bottom or structural components of the wrecks. There were water-column species present that were not included in the analyses due to their transient nature. We classified the following species as demersal: snowy grouper (*Hyporthodus niveatus*), warsaw grouper (*Hyporthodus nigritus*), yellowedge grouper (*Hyporthodus flavolimbatus*), and wreckfish (*Polyprion americanus*). We excluded conger eel (*Conger oceanicus*) from demersal fishes despite their strong association with the shipwreck structure because they often hide in crevices of the wreck so are difficult to detect using either survey method. We qualitatively assessed demersal fish abundance among all transects on each shipwreck. We also examined demersal fish counts from the two survey methods using the coincident video and laser-line scanning transects from each shipwreck. We then examined numerical patterns in fish behavior on the coincident video and laser-line scanning transects.

For the coincident laser-line scanning transect on each wreck, we determined demersal fish spatial distributions and size distributions. To investigate the spatial distribution on each shipwreck, the x, y, and z coordinates were used to plot the three-dimensional locations of each fish relative to shipwreck structures. These visualizations allowed us to qualitatively assess whether fish distributions concentrated on particular portions of the shipwrecks, such as the bow, stern, or other distinguishing features. From the laser-line scanning data, we also extracted fish lengths. We binned fish into 10 cm wide size classes ranging from 40 cm to 110 cm. We then calculated the percent frequency of fish of particular size bins on each shipwreck.

Results

Fish communities

Video surveys revealed that the fish community on the U-*576* included two grouper species: snowy grouper and warsaw grouper, as well as demersal wreckfish (Table 1). Fish more transiently associated with the shipwreck structure included Darwin's slimeheads (*Gephyroberyx darwinii*) and barrel fish (*Hyperoglyphe perciformis*). Barrel fish were only observed off transects so were not included in analyses or visualizations. Conger eel, *Anthiinae*, and other unidentified small fish were observed close to the structure. The SS *Bluefields* also hosted snowy grouper and warsaw grouper (Table 1). Another species of grouper, yellow-edge grouper, occurred on the SS *Bluefields* but not the U-*576*. Fishes, such as wreckfish, Darwin's slimeheads, *Anthiinae*, conger eel, and other unidentified small fish, observed on the U-*576* were likewise observed on the SS *Bluefields*.

On the U-*576*, an average of 38.2 $\pm$ 4.0 demersal fish was observed across the four video

Table 1. Fish abundance for (A) video transects and (B) laser-line scanning transects on the U-*576* and SS *Bluefields*.

		U-*576*				SS *Bluefields*	
Fish species	Common name	Transect 1	Transect 2	Transect 3	Transect 4	Transect 1	Transect 2
(A) Video							
Anthiinae (subfamily)	Anthiinae	56	0	0	0	4	0
Conger oceanicus	Conger eel	1	0	1	0	3	0
Hyporthodus flavolimbatus	**Yellow-edge grouper**	0	0	0	0	0	1
Hyporthodus nigritus	**Warsaw grouper**	3	5	2	0	3	0
Hyporthodus niveatus	**Snowy grouper**	11	19	30	9	32	5
***Hyporthodus* sp.**	**Unknown grouper**	17	10	18	28	14	8
Gephyroberyx darwinii	Darwin's slimehead	2	1	3	0	5	1
Polyprion americanus	**Wreckfish**	1	0	0	0	1	0
Unknown small fish	Unknown small fish	0	0	144	0	386	0
Total fish		91	35	198	37	448	15
Demersal fish		32	34	50	37	50	14
(B) Laser-line scanning							
Demersal fish		20	23	35		19	65

Notes: For video transects, species-specific abundance, as well as demersal fish abundance (bold text), and total fish abundance are provided. For laser-line scanning, species identification was not possible, so aggregated demersal fish abundance is provided. On the U-*576*, the most spatially coincident transects were video transect 2 and laser-line scanning transect 3. On the SS *Bluefields*, the most spatially coincident transects were video transect 1 and laser-line scanning transect 2.

transects (Fig. 3A). Abundances varied among transects with observations ranging from 32 to 50 fishes per transect. Laser-line scanning revealed a lower mean demersal fish abundance than the video transects (26.0 ± 4.6) across three transects. Fish abundance from different laser-line scanning transects was also variable, ranging from 20 to 35 fish per transect (Fig. 3A). When we examined one video and one laser-line scanning transect for the U-*576* chosen to be spatially and temporally coincident, a similar number of demersal fish were counted in the video (34 fish) and laser-line scanning transects (35 fish; Figs. 3A, 4). Of the 34 fish observed in the video, the majority (19) were snowy grouper, 5 were warsaw grouper, and 10 were unspecified grouper of the genus *Hyporthodus* (Fig. 4B). From the laser-line scanning transect, we learned that the 35 fish detected from laser-line scanning had a mean length of 76.8 ± 3.2 cm (Fig. 5A).

On the SS *Bluefields*, the average number of fish observed across the two video transects was 32.0 ± 18.0. Abundance, however, was highly variable between the two transects, as 50 demersal fish were counted on the first video transect and 14 on the second (Fig. 3B). Fish abundance enumerated from the laser-line scanning transects was variable, as well, with observations of 19 demersal fish on the first and 65 on the second transect, resulting in a mean fish abundance of 42.0 ± 23.0 (Fig. 3B), which was higher than the abundance estimated from the video transects. For the single video and single laser-line scanning transects that we assessed due to their high spatial and temporal overlap, the video detected 50 demersal fish, whereas 65 demersal fish were detected with the laser-line scanning data (Figs. 3B, 4). The 50 demersal fish from the coincident video transect included mainly snowy grouper (32) but also 3 warsaw grouper, 14 unspecified grouper of the genus *Hyporthodus*, and 1 wreckfish (Fig. 4D). The mean length of the 65 fish detected with laser-line scanning was 78.1 ± 2.57 cm (Fig. 5B).

Behavior

Video and laser-line scanning imagery provided different resolutions for fish behavior classification. Across all video transects, we observed demersal fish exhibiting five behaviors: resting, swimming, stationary, changing direction, and following in the video data. From the laser-line scanning data, we were able to classify fish behavior more coarsely as stationary,

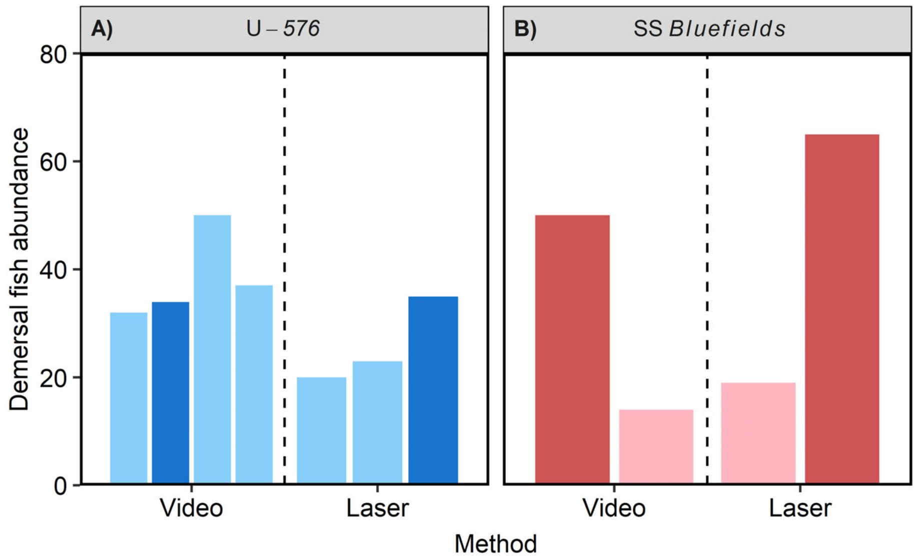

Fig. 3. Demersal fish abundance observed during video vs. laser-line scanning transects for (A) U-*576* and (B) SS *Bluefields*. Dark bars are the most spatially coincident transects for video and laser-line scanning on each individual shipwreck, since these transects cover nearly the same area of each shipwreck.

swimming, and changing direction. Because the laser-line scan is a still image made from a beam of lasers, resting and following behaviors were undistinguishable from stationary behavior. The coincident U-*576* video transect was mainly composed of swimming (31) fish but also included 3 stationary fish (Table 2). In the U-*576* laser-line scan, the majority of the fish (33) were stationary, rather than swimming, since their body shapes showed no signs of distortion (Table 2). There were only 2 demersal fish whose bodies were distorted, indicating that they were swimming (Table 2). Similarly, on the SS *Bluefields* video transect, the majority of fish were swimming (49) and only one was stationary (Table 2). And, like in the U-*576*, the SS *Bluefields* laser-line scanning showed the opposite pattern to the video—of mostly stationary fish (62) vs. only several (3) swimming (Table 2).

Spatial distribution

Fish were largely located in four locations on the U-*576*: stern, conning tower, deck gun, and bow. The coincident video and laser-line scanning transects indicated that there were 34 detected demersal fish using the video data and 35 detected fish using the laser data (Fig. 3A). In the video data, the majority of the fish occurred on the conning tower (13 fish), followed by the deck gun (11 fish) and the bow of the shipwreck (10; Fig. 4B). No fish occurred toward the stern of the vessel. In the laser-line scanning survey, the highest number of fish occurred around the conning tower (26) with several around the deck gun (four fish; Fig. 4A). In contrast to the video data, no fish were detected on the bow, but several (five fish) were detected on the stern of the U-*576*.

On the SS *Bluefields*, the fish were classified as located on the stern, midship, or bow. The video and laser-line scan transects that were coincident showed that of the 50 demersal fish from the video, most fish occupied the midship region (24 fish), whereas fewer fish occupied the stern (11 fish) and bow (15 fish; Fig. 4D). Similarly, of the 65 fish in the laser-line scanning transect, the highest number of fish occurred near midship (43 fish) with fewer near the stern (seven fish) and bow (15 fish; Fig. 4C).

Discussion

We successfully extracted fish community metrics from archeological surveys of two deep shipwrecks. Specifically, joint video and laser-line scanning surveys revealed abundances of demersal fishes on both shipwrecks and that these fish concentrated around high-relief shipwreck features. Fish often swam away from the submersible collecting video footage but remained more stationary during laser-line scanning. Here, we discuss the type of information learned from video and laser-line scanning and then place our observations on fish abundance, spatial distributions, and behavior into a broader ecological context.

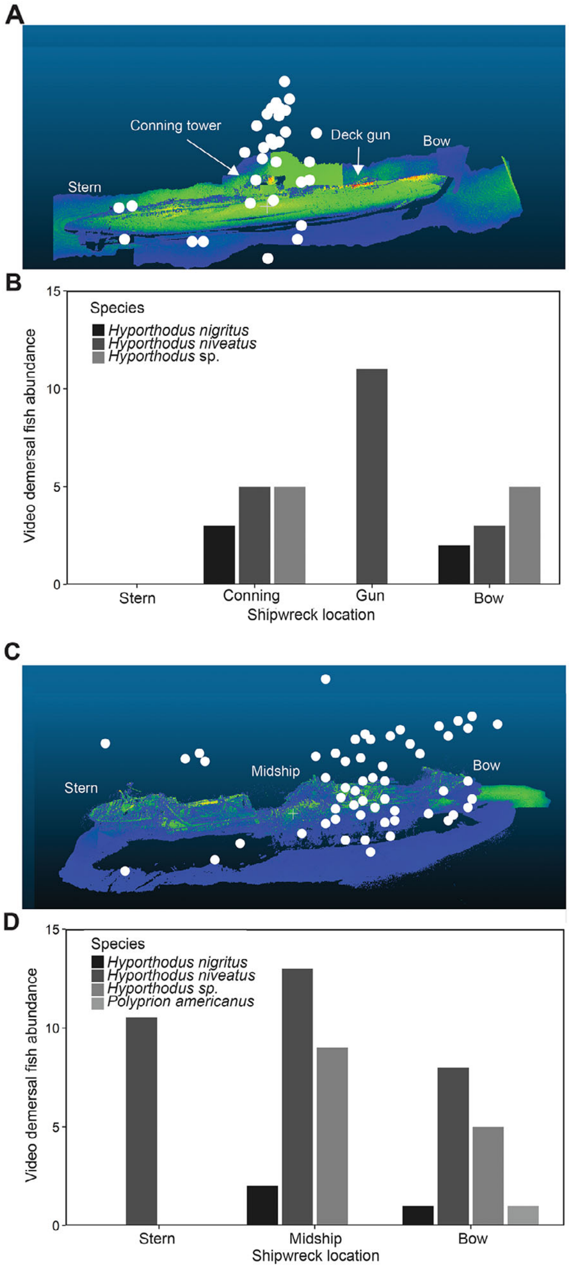

Fig. 4. Three-dimensional models of shipwrecks and corresponding fish spatial distributions for (A, B) U-*576* and (C, D) SS *Bluefields*. (A, C) Locations of individual demersal fish (white points) relative to laser-

Extracting fish metrics from video and laser-line scanning data worked well, largely because the types of data collected by the two methods complemented each other. Video data were better at identifying fish to fine taxonomic levels and describing fish behavior, whereas laser-line scanning data were better at documenting spatial distributions and measuring fish sizes. We do note, however, that coupling video with dual, static lasers could have provided accurate fish size measurements, as well. Both video and laser-line scanning provided abundance estimates, yet these estimates often differed from each other because of differing fields of view. On one shipwreck (U-*576*), we counted nearly identical numbers of fish in video and laser-line scanning, whereas on the other shipwreck (SS *Bluefields*), we counted fewer fish in the video than laser-line scanning. Different estimates of fish abundance from video and laser-line scanning have also been shown on natural reef habitats, likely because of differences in how these methods distinguish fish from the surrounding seafloor structures (Yoklavich et al. 2003). For example, one of the shipwrecks that we surveyed, the U-*576*, lists toward port, so fish hiding underneath the port side were obscured from the video and laser-line scanning data unless the human-occupied submersible was close to the sand at an angle enabling visualization of these fish. Additionally, since video surveys often paused to investigate specific archeological targets of interest, this could affect abundance estimates by providing a different perspective than

Fig. 4. *Continued*
line scanning models of shipwrecks. Relative locations of fish to one another are to scale. Fish locations in the z-dimension have been translated above the wreck to improve the ability to see the fish locations in the x and y dimensions, and thus do not represent actual altitude off the wrecks. (B, D) Species-specific abundances of demersal fish associated with key shipwreck features as seen from video footage.

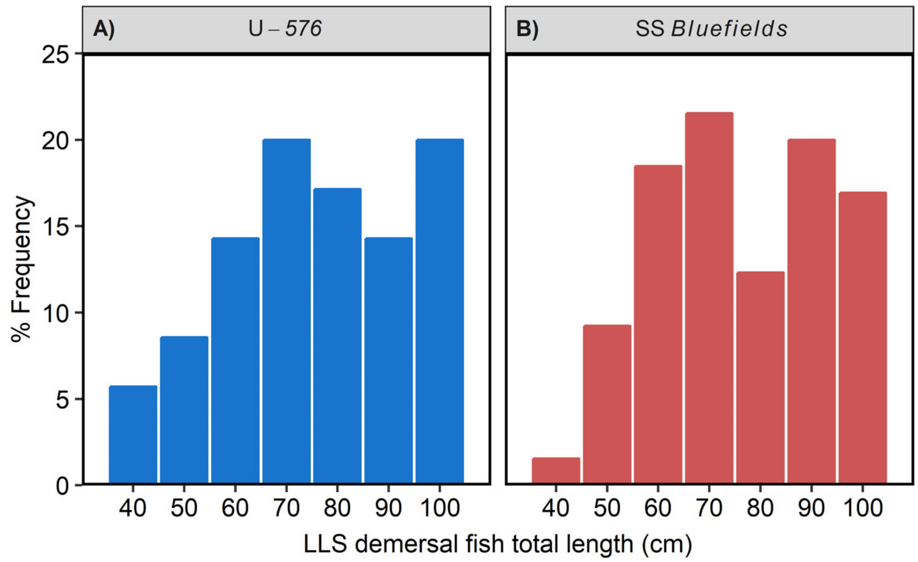

Fig. 5. Percent frequency of demersal fish observed by total length (cm) from laser-line scanning data collected on one transect for each shipwreck: (A) U-*576* (n = 35, transect 3) and (B) SS *Bluefields* (n = 65; transect 2).

Table 2. Demersal fish behavior from coincident video and laser-line scanning transects on the U-*576* and SS *Bluefields*.

Behavior	Video	Laser-line scanning
(A) U-*576*		
Swimming	31	2
Stationary	3	33
Total	34	35
(B) SS *Bluefields*		
Swimming	49	3
Stationary	1	62
Total	50	65

seen in the laser-line scanning data. Likewise, since the amount of time required for video vs. laser-line scanning surveys differs, this could affect abundance estimates.

Demersal fishes on both shipwrecks that we surveyed clustered around structures of high relief, such as the conning tower and deck gun on the U-*576*. This pattern of fish concentrating around defined seafloor structures has also been demonstrated around rocky hard-bottom reefs. For example, on rocky reefs on the continental shelf of the southeast United States, grouper tend to aggregate around structures of high relief (Harter et al. 2009). On the shipwrecks that we studied, the midship of both the U-*576* and SS *Bluefields* have many areas of high relief (e.g., U-*576* conning tower and deck gun or SS *Bluefields* deck winches and rubble) relative to other parts of the shipwrecks, where the grouper tended to congregate. Demersal fishes also aggregated on the port side of both vessels. Incidentally, the port sides face the same direction because the bows of both shipwrecks point toward the southwest. We hypothesize that water current direction and magnitude could influence spatial distributions of the demersal fish around shipwrecks and that these fish likely aggregated on the port side of the vessel because it was upstream. Although we do not have water current data from either shipwreck during our surveys, we do know that on shallower shipwrecks also on the US continental shelf, fish tended to concentrate on the upstream side of shipwrecks (Paxton et al. 2019).

Fish exhibited behavioral changes when approached by the submersible collecting video imagery with lights to illuminate the shipwreck structure. This avoidance response is consistent with prior observations that groupers can hide in or around structures, making them difficult to observe from human-occupied submersibles (Campbell et al., *unpublished manuscript*) and that Acadian redfish (*Sebastes fasciatus*) seek refuge near the seafloor when approached by survey vehicles (Stoner et al. 2008). Interestingly, demersal fish did not exhibit a pronounced behavioral change when approached by the submersible conducting laser-line scanning. Since light from video surveys often produces an avoidance behavior in fish (Ryer et al. 2009), we hypothesize that light emitted during video collection elicited a swimming response from fish. In contrast, the laser-line scanning submersible only emitted quick bursts of lasers toward the shipwreck and fish, perhaps encouraging the fish to remain more stationary. With this being said, the laser-line scan lacks the ability to detect the level of fine motion that the video can capture.

Many other shipwrecks rest along the southeastern U.S. continental shelf, as well as on seafloors worldwide, that provide habitat for marine species. While video surveys have been conducted on many shipwrecks, laser-line scanning is rarely conducted. Of the shipwreck laser-line scans that have been conducted, to our knowledge, none have been used for ecological data extraction. Coupling video and laser-line scanning surveys offers the ability to simultaneously accomplish archeological and ecological objectives so could be applied to additional shipwrecks. Ecologically, video data identify fish to fine taxonomic levels and describe their behavior, whereas laser-line scanning documents fish spatial distributions and fish sizes. In addition to shipwrecks, many other types of artificial structures, such as artificial reefs and energy extraction infrastructure, rest on the seafloor and could be assessed using this hybrid approach of video combined with laser-line scanning to extract ecological metrics that could become meaningful for diverse applications, such as habitat enhancement initiatives and fisheries management. Both video and laser-line scanning are well suited for small targets, such as artificial structures. Scaling these methods up, however, to broader reefs or regions is likely impractical because of the high time investment and associated expenses.

By pairing video and laser-line scanning technologies, we were able to successfully extract fish community metrics from archeological surveys of two deep shipwrecks. Our research provides a proof-of-concept that conducting joint archeological and ecological studies offers mutual benefits for these often separate disciplines. For cross-disciplinary surveys to remain beneficial for both disciplines, archeologists and ecologists must plan surveys according to both archeological and ecological objectives and ensure transparency and collaboration in data collection and processing. Combining archeological and ecological surveys, especially in ecosystems that are remote or harder to access, can facilitate productive research missions and maximize research outputs while paving the way for future cross-disciplinary collaborations.

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Literature Cited

Amend, M. R., M. M. Yoklavich, Y. Rzhanov, C. B. Grimes, and W. W. Wakefield. 2007. Mosaics of benthic habitats using laser line scan technology. Pages 61–69. Special Paper, Geological Association of Canada, St John's, Newfoundland, Canada.

Benjaminsen, T. A., J. B. Aune, and D. Sidibé. 2010. A critical political ecology of cotton and soil fertility in Mali. Geoforum 41:647–656.

Bolgan, M., J. O'Brien, and M. Gammell. 2016. The behavioural repertoire of Arctic charr (*Salvelinus alpinus* (L.)) in captivity: a case study for testing ethogram completeness and reducing observer effects. Ecology of Freshwater Fish 25:318–328.

Bright, J., N. Richards, J. Hoyt, J. Wagner, and T. Allen. 2012. The battle of the Atlantic expedition 2011: the battle of convoy KS-520 North Carolina, 15 July 1942. American Battlefield Protection Program, National Parks Service, Washington, D.C., USA.

Church, R., D. Warren, R. Cullimore, L. Johnston, W. Schroeder, W. Patterson, T. Shirley, M. Kilgour, N. Morris, and J. Moore. 2007. Archaeological and biological analysis of World War II shipwrecks in the Gulf of Mexico: artificial reef effect in deep water. U.S. Department of the Interior, Minerals Management Service, Gulf of Mexico OCS Region, New Orleans, Louisiana, USA. OCS Study MMS 2007-015. 387 pp.

Coleman, D. F., J. B. Newman, and R. D. Ballard. 2000. Design and implementation of advanced underwater imaging systems for deep sea marine archaeological surveys. Oceans Conference Record (IEEE) 1:661–665.

Daily, G. C., and P. R. Ehrlich. 1999. Managing earth's ecosystems: an interdisciplinary challenge. Ecosystems 2:277–280.

Day, J. 2013. Botany meets archaeology: people and plants in the past. Journal of Experimental Botany 64:5805–5816.

Erlandson, J. M., and T. C. Rick. 2010. Archaeology meets marine ecology: the antiquity of maritime cultures and human impacts on marine fisheries and ecosystems. Annual Review of Marine Science 2:231–251.

Farber, S., R. Costanza, D. L. Childers, J. Erickson, K. Gross, M. Grove, C. S. Hopkinson, J. Kahn, S. Pincetl, A. Troy, P. Warren, and M. Wilson. 2006. linking ecology and economics for ecosystem management. BioScience 56:121–133.

Gerlai, R., W. E. Crusio, and V. Csányi. 1990. Inheritance of species-specific behaviors in the paradise fish (*Macropodus opercularis*): a diallel study. Behavior Genetics 20:487–498.

Goldman, M. J., M. D. Turner, and M. Daly. 2018. A critical political ecology of human dimensions of climate change: epistemology, ontology, and ethics. Wiley Interdisciplinary Reviews: Climate Change 9:e526.

Guidetti, P., and F. Micheli. 2011. Ancient art serving marine conservation. Frontiers in Ecology and the Environment 9:374–375.

Guiot, J., A. Pons, J. L. De Beaulieu, and M. Reille. 1989. A 140,000-year continental climate reconstruction from two European pollen records. Nature 338:309–313.

Harter, S. L., M. M. Ribera, A. N. Shepard, and J. K. Reed. 2009. Assessment of fish populations and habitat on Oculina bank, a deep-sea coral marine protected area off eastern Florida. Fishery Bulletin 107:195–206.

Huffaker, C. B. 1958. Experimental studies on predation: dispersion factors and predator-prey oscillations. Hilgardia 27:343–383.

Loucks, D. P. 2006. Modeling and managing the interactions between hydrology, ecology and economics. Journal of Hydrology 328:408–416.

Lubchenco, J., et al. 1991. The sustainable biosphere initiative: an ecological research agenda: a report from the Ecological Society of America. Ecology 72:371–412.

Ludvigsen, M., B. Sortland, G. Johnsen, and H. Singh. 2007. Applications of Geo-referenced underwater photo mosaics in marine biology and archaeology. Oceanography 20:140–149.

Lyman, R. L. 2007. Archaeology's quest for a seat at the high table of anthropology. Journal of Anthropological Archaeology 26:133–149.

MacArthur, R. H., and J. W. MacArthur. 1961. On bird species diversity. Ecology 42:594–598.

Martínez, M. L., R. H. Manson, P. Balvanera, R. Dirzo, J. Soberón, L. García-Barrios, M. Martínez-Ramos, P. Moreno-Casasola, R. Rosenzweig, and J. Sarukhán. 2006. The evolution of ecology in Mexico: facing challenges and preparing for the future. Frontiers in Ecology & the Environment 4:259–267.

McCay, B. J. 1978. Systems ecology, people ecology, and the anthropology of fishing communities. Human Ecology 6:397–422.

McCully, P. 1996. Silenced rivers: the ecology and politics of large dams. University of Michigan, Ann Arbor, Michigan, USA. 350 pp.

Mugge, R. L., M. L. Brock, J. L. Salerno, M. Damour, R. A. Church, J. S. Lee, and L. J. Hamdan. 2019. Deep-sea biofilms, historic shipwreck preservation, and the deepwater horizon spill. Frontiers in Marine Science 6:48.

Nettle, D., and L. Penke. 2010. Personality: bridging the literatures from human psychology and behavioural ecology. Philosophical Transactions of the Royal Society B: Biological Sciences 365: 4043–4050.

Paxton, A. B., et al. 2019. Citizen science reveals female sand tiger sharks (*Carcharias taurus*) exhibit signs of site fidelity on shipwrecks. Ecology 100:e02687.

Paxton, A. B., E. A. Pickering, A. M. Adler, J. C. Taylor, and C. H. Peterson. 2017. Flat and complex temperate reefs provide similar support for fish: evidence for a unimodal species-habitat relationship. PLOS ONE 12:e0183906.

Peters, C. M. 1992. The ecology and economics of oligarchic forests. Non-timber Products from Tropical Forests9:15–22.

Polasky, S., and K. Segerson. 2009. Integrating ecology and economics in the study of ecosystem services: some lessons learned. Annual Review of Resource Economics 1:409–434.

R Core Team. 2019. R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.

Ryer, C. H., A. W. Stoner, P. J. Iseri, and M. L. Spencer. 2009. Effects of simulated underwater vehicle lighting on fish behavior. Marine Ecology Progress Series 391:97–106.

Scott, D., L. Babbits, and C. Haecker. 2006. Fields of conflict: battlefield archaeology from the Roman Empire to the Korean War. Praeger, Westport, Connecticut, USA.

Sheridan, S. M., and T. B. Gutkin. 2000. The ecology of school psychology: examining and changing our paradigm for the 21st century. School Psychology Review 29:485–502.

Simberloff, D. S., and E. O. Wilson. 1968. Experimental zoogeography of islands: the colonization of empty islands. Ecology 50:278–296.

Stoner, A. W., C. H. Ryer, S. J. Parker, P. J. Auster, and W. W. Wakefield. 2008. Evaluating the role of fish behavior in surveys conducted with underwater vehicles. Canadian Journal of Fisheries and Aquatic Sciences 65:1230–1243.

Sussman, R. W., G. M. Green, and L. K. Sussman. 1994. Satellite imagery, human ecology, anthropology, and deforestation in Madagascar. Human Ecology 22:333–354.

Worthman, C. M. 2010. The ecology of human development: evolving models for cultural psychology. Journal of Cross-Cultural Psychology 41:546–562.

Yoklavich, M. M., C. B. Grimes, and W. W. Wakefield. 2003. Using laser line scan imaging technology to assess deepwater seafloor habitats in the Monterey Bay national marine sanctuary. Marine Technology Society Journal 37:1238.

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