Coral Reefs (2025) 44:1961–1976
https://doi.org/10.1007/s00338-025-02768-w

RESEARCH

Modernising sea cucumber surveys using remotely operated vehicles and aerial drones

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Received: 17 July 2025 / Accepted: 30 September 2025 / Published online: 9 October 2025

Abstract There is an urgent need for improved monitoring approaches to rapidly and accurately assess sea cucumber populations at ecologically relevant scales. Timely surveys are critical for informing effective fisheries management and decision-making. Traditional surveys, undertaken via snorkelling, manta tows, or SCUBA, are limited to shallow and accessible areas; however, sea cucumbers inhabit a broad range of depths, including areas beyond safe diving limits and exposed shallow waters inaccessible by boat. To overcome these limitations and increase the rapidity of field collection, we propose the use of remote sensing technologies to survey sea cucumber populations across a range of depths. Here, we evaluated the effectiveness of aerial drones and in-water remote operated vehicles (ROVs) for assessing sea cucumber species and abundances across various depth ranges (< 50 m) on the Great Barrier Reef, Australia. Aerial drone orthomosaics and ROV video footage were compared to more traditional snorkel and SCUBA-based assessments conducted at similar depths. The vast majority of pairwise comparisons between in-water ROV video counts and snorkel or SCUBA assessments found no significant differences in sea cucumber assemblages. Counts from aerial drone-derived orthomosaics, however, were significantly lower, counting approximately half as many sea cucumbers as snorkel counts. This was largely attributed to poor weather during the drone surveys. Remote methods were significantly faster in the field for surveying a given area than traditional methods. Given that towed ROVs can efficiently cover a broader depth range and aerial drones are effective for survey shallow areas under suitable weather conditions, we recommend using a combination of aerial drones and towed ROVs to survey sea cucumbers, with tool selection guided by prevailing weather conditions. This approach offers the advantages of collecting multiple types of data from a single data source, vastly increasing survey efficiency, and providing a historical record for future assessments. The methods have the potential to be used to survey other benthic–associated species.

Keywords Remote sensing · ROV · Holothurian · Trepang · Coral reef · Biodiversity

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Introduction

Sea cucumbers are ubiquitous organisms on coral reefs and one of the most diverse classes of benthic invertebrates (Slater and Chen 2015; Mercier et al. 2024). They are thought to play several key functional roles on reefs, such as removing organic matter from the sediments (e.g. Emiroğlu and Günay 2007), bioturbating and aerating sediments (e.g. Shiell and Knott 2010), releasing calcium carbonate and nutrients from sediments to the water column (e.g. Wolfe et al. 2018), enriching sediment microbiota (e.g. Yamazaki et al. 2019), and acting as hosts for other biota (e.g., Purcell et al. 2016). While debate remains as to the relative importance of their contribution to reef functioning, as discussed in Arnull et al. (2021), they are generally considered of high intrinsic value to marine ecosystems, particularly when their biomass is substantial. The crux of the debate about their contribution to ecosystem function sits with a lack of data on sea cucumber abundance and distribution on and across reefs, leading to an inability to understand their relative contributions to reef nutrient cycling. While eclectic and localised studies exist on the demographics of sea cucumbers, those at a reef to regional scale (e.g. Friedman et al. 2008, 2009, 2010; Pinca et al. 2009; Moore et al. 2017) and beyond are rarer due to the logistic challenges and financial costs of obtaining such data via traditional methods (Williamson et al. 2017).

In addition to their intrinsic value to reefs, sea cucumbers are a desired luxury food item and traditional medicine in many countries (Fabinyi 2011), and harvesting occurs in small-scale artisanal fisheries to large commercial enterprises (Bennett and Basurto 2018; Ru et al. 2019). Over 80 species of sea cucumber are wild harvested globally and target species range from low economic worth to high-value products for export (Purcell 2014; Purcell et al. 2023). Such enterprises can drive coastal economies (Toral-Granda et al. 2008) but can also lead to overharvesting (González-Wangüemert et al. 2014), with serial exploitation having the potential to deplete local fisheries (Rawson and Hoagland 2019). In addition to wild harvest, sea cucumber aquaculture is a burgeoning industry globally (Han et al. 2016; Purcell et al. 2012). As with wild harvesting (Friedman et al. 2011), the aquaculture industry relies on analysing patterns of broodstock source populations and their underlying processes for effective management (Eriksson et al. 2012; Hair et al. 2022). Sea cucumbers are also rich in collagen, which is in demand by the cosmetic industry (Li et al. 2020) and have other biological and pharmaceutical benefits (Hamel et al. 2024), further increasing their demand beyond that of a food resource.

Traditionally, sea cucumbers are surveyed by divers on snorkel or SCUBA via belt transects. Observers count individuals of a species within a set area or along transects. Based on depth and/or habitat type, the transect counts are routinely extrapolated to the area of interest due to the inhibitory costs of manually surveying the entire reef (e.g. Dissanayake and Stefansson 2010). While this method may be effective in aquaculture settings where sea cucumbers are maintained at high densities, spatial patchiness of wild populations can lead to high uncertainty around any extrapolations in the wild where the surveyed area is smaller than the spatial heterogeneity of the target organism (Morgan 2011). In-water person surveys can be broadened in area via manta tows; however, these can be limited in accuracy of identification and counts due to the speed of the tows, uneven distances to the sea floor, and the sizes of the animals (Fernandes 1990; Pakoa et al. 2014). Moreover, in-water person methods require substantial training (Miller and De'ath 1996), usually only record the number of individuals in the area covered and rarely produce datasets such as comprehensive photos or video transects that can be reassessed in the future.

Recent remote sensing tools such as aerial drones and remotely operated vehicles (ROVs) have enabled surveyors to greatly expand the area covered for quantitative and repetitive species assessments. For example, geotagged drone images with sufficient overlaps can be stitched together to remove distortions and generate georeferenced orthomosaics (Joyce et al. 2019). Williamson et al. (2021) used orthomosaics to count the sea cucumber *Holothuria atra* over an area of 27,000 m^2 and scaled these findings using classified satellite imagery to estimate the number of individuals across 19 km^2 of reef. They further calculated the amount of bioturbation attributed to *H. atra* in that system. Building on this work to reduce the amount of manual labour required in image analysis, Li et al. (2021) developed a deep learning workflow to detect a single sea cucumber species on a reef flat. Further developing these types of automated techniques becomes critical for broad-scale objective and repeatable stock assessments as our ability to capture large volumes of data from a variety of platforms grows.

Technological advances enable aerial drones to capture images with sub-centimetre ground sampling distances (GSD) suitable for detecting sea cucumbers when environmental and weather conditions allow (Li et al. 2021). The resolution of imagery from ROVs should surpass that of aerial drones given their closer proximity to the target while using similar camera payloads. While drones are extremely effective in acquiring data over shallow areas such as reef flats (<2 m depth), ROVs can operate in depths well beyond those safely and routinely accessible to SCUBA divers (Butcher et al. 2021; Hellmrich et al. 2023) and can be piloted or towed behind a vessel to increase the area covered within a given time frame (Raoult et al. 2025a). These remote sensing techniques have the added advantage of producing a permanent record of an area, which can then be reassessed or reused by other researchers for reassessment of additional information (e.g. coral cover). However, before they can become widely adopted and trusted methods for assessing sea cucumber stocks, rigorous testing and comparison with counts derived by traditional methods must be undertaken.

In this study, we compare traditional sea cucumber survey methods with counts derived from aerial drone and ROV imagery, conducted at four different water depths. At each depth, we address the following three key questions where possible: (1) Do the methods differ in the total number of sea cucumbers recorded along the transects? (2) Does the ability to identify individuals to species level vary across methods? and (3) Are there differences in the time taken to complete the field component of each survey method? We evaluate the strengths and weaknesses of each approach in this context and document our findings accordingly. Based on this evaluation and our prior expertise, we propose a standardised method for broad-scale sea cucumber assessments with consideration of constraints.

Materials and methods

Method comparisons were completed in Australia's Great Barrier Reef at Arlington Reef (146.03962; − 16.71155) and Michaelmas Reef (146.01980; − 16.58173) in March 2022; and Gould Reef (148.78581; − 19.41464) for the deeper comparison in October 2019 (Fig. 1). Similar species of sea cucumbers occurred and were assessed at the first two reefs. Only burrowing blackfish were assessed at Gould Reef due to their difference in habitat requirements and their abundances at greater depths. Testing of the different methods was done at four depth scenarios, with each methodology dependent on defined depths, as described below.

Depth 0–3 m: snorkel transects versus drone orthomosaics

Fieldwork occurred at Michaelmas Reef on the Great Barrier Reef. This reef is classified by the management authority as a "no-take" area where extractive activities such as fishing or collecting are not allowed without a special permit. Twenty in-water transects were completed on snorkel at high tide and compared to data from drone footage along the same transects. Representative areas of reef habitat likely to contain a mix of sea cucumber species were chosen for the transects. An area was considered representative if it contained a range of the types of available habitat (coral, sand, rubble, etc.) and was extensive enough to fit 100 m belt transects.

Once an area was chosen, 100 m of transect tape was deployed by a pair of snorkelers at high tide. Weights with buoys were attached to either end of the tape to ensure the transect remained in position and could be located from the surface. Another three transects were then run parallel to the first transect, with at least 20 m separating each transect to avoid overlap. If the tape encountered an obstacle (e.g. coral wall) or began to encounter deeper waters, the transect was oriented at intervals of 20 degrees to the right until the transect was 100 m in length, as per Raoult et al. (2020).

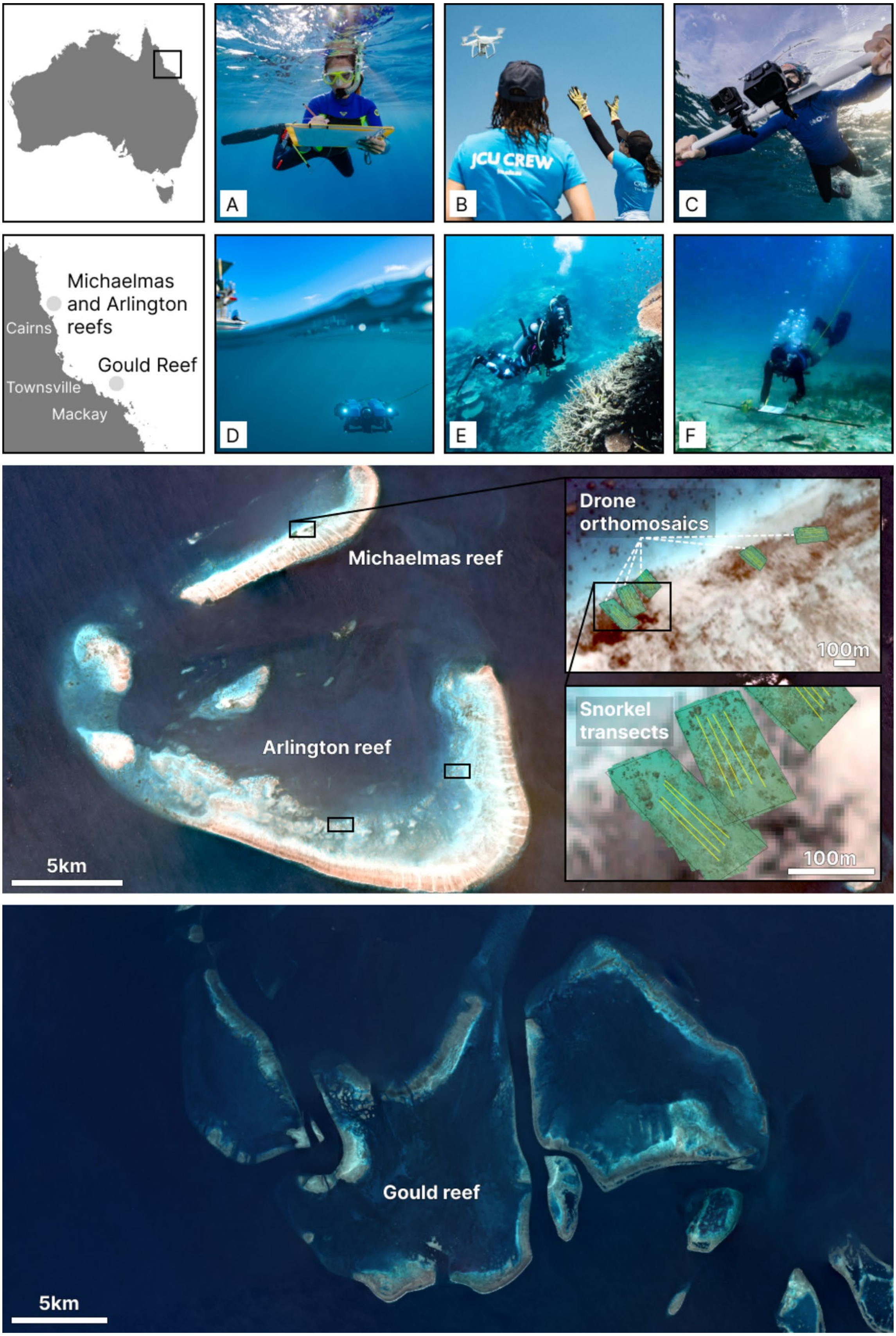
Once the set of four transects were laid, a pair of snorkelers swam each transect, independently identifying and counting sea cucumbers within 1 m of either side of the tape and recorded their *in situ* observations of sea cucumber on a dive slate (Fig. 1a). Each belt transect thus covered an area of 200 m^2 with a total of 4,000 m^2 covered at Michaelmas Reef. The first snorkeler swam the transect at a steady speed and, to ensure independence, the second snorkeler waited three minutes after the initial snorkeler had begun before swimming the transect. Both snorkelers recorded the start and end time of each survey to assess the transect sampling time, excluding tape deployment and retrieval time as this time was the same between methods.

Once the in-water surveys were complete, a Mavic 2 Pro drone with built-in RGB cameras was flown over the area containing the 20 transects (Fig. 1b). The drone was flown following planned mapping missions using a DJI GS Pro 2.0 (DJI Inc. 2021) with an overlap between images of 85% and sidelap between flight lines of 75%. The mission altitude was 20 m above takeoff level (approx. 24 m above sea level) to ensure the coverage of snorkel transect area and to achieve the spatial resolution (0.51 cm ground sampling distance) required to identify as many sea cucumbers as possible. Missions were executed after the snorkel transect GPS tracks were available to assist with planning, usually within 30 min and regardless of the weather and, where possible, at low tide in the afternoon to reduce sun glint and specular reflection at the water's surface (Joyce et al. 2019). All transects were still underwater at low tide.

Depth 1–4 m: snorkel transects versus ROV transects

Another 20 transects were set up and completed at Michaelmas Reef; a further eight transects were set up at Arlington Reef (a "take" zone where sea cucumber fishing is permitted), with a total area covered of 1,600 m^2 covered at the latter reef in addition to the 4,000 m^2 covered at Arlington Reef. All transects and snorkel assessments were completed at high tide as per the methods above, with the addition of a third snorkeler completing a video transect with a Paddy pole-mounted GoPro, described below. Data collected through direct counts recorded on slates were compared to counts derived from the GoPro footage captured by the third snorkeler. Both methods were also compared to data obtained from ROV footage, also described below.

Once the pair of snorkelers using dive slates had swum each transect and completed their surveys, a third snorkeler swam the transect with a handheld GNSS (Garmin eTrex 10) in tracking mode attached to a float. The third snorkeler had a GoPro 9 Black camera attached to a 30 mm diameter PVC pole ("Paddy" pole), which took video 1080 p at 60 frames per second in wide angle (110°) (Fig. 1c). The GoPro camera faced straight down (nadir) to cover an area approximately 2 m wide. A second GoPro on the pole faced obliquely forward and was used for another study.


A
B
JCU CREW
C
Michaelmas and Arlington reefs
Cairns
Gould Reef
Townsville
Mackay
D
E
F
Drone orthomosaics
Michaelmas reef
100m
Snorkel transects
Arlington reef
100m
5km
Gould reef
5km

◂**Fig. 1** Study sites, example survey transects, and survey methods: **A** snorkeler with slate; **B** drone; **C** snorkeler with video survey using downward facing camera; **D** Remotely Operated Vehicle (ROV); **E** SCUBA diver team with dive slates; and **F** hip chain method. Photo credits: Harriet Sparks (**A**,**B**,**C**); Patrick Burke (**D**); Joan Li (**E**); Matt Koopman/Adrian Flynn (**F**). Basemap imagery of Michaelmas, Arlington, and Gould Reefs was sourced from Planet's PlanetScope satellite data via the Allen Coral Atlas. Example drone imagery and snorkel transects are shown for Michaelmas Reef. Specific Survey locations on Gould Reef are withheld due to commercial confidentiality

Following assessment by the third snorkeler, a small vessel (6.5 m; 100 hp) towing a BlueRobotics BlueROV2 (ROV) equipped with a Heavy Lift kit and a ping sonar altimeter moved at a speed of 1–2 knots (idle forward) over each transect, also at high tide (Fig. 1d). Towing the ROV has the advantage of reducing current draw on the ROV and allowing longer deployments (Raoult et al. 2025a). The surface buoys at the start and end of each transect were used as reference points to orient the surface vessel. These ROVs are not designed for towing by default, so one was modified with a tow line anchor using 6 mm marine rope attached to the top half and front third of the frame. A 70 m tow line made of the same 6 mm marine grade, 600 kg break force rope was then attached to the towed ROV anchor with a stainless steel shackle, with the remaining two line stored in a hose reel.

The ROV operated at an optimal 'altitude' of 2.5 m above the substrate (as indicated by the ROV ping altimeter), or at the surface in shallower waters. This averaged a swath of ~ 3.8 m (measured using in-water reference marks) and gave a swept area of 380 m along each 100 m transect. The ROV was kept in 'depth hold flight mode' that uses the onboard inertial measurement unit (IMU) to automatically keep the ROV oriented in one direction, in a planar orientation, and maintain depth from the surface. If possible, the vessel ran the transect oriented into the wind and waves to lower the speed of the ROV relative to the substrate and provide more control to the boat pilot. At least double the operating depth of the ROV was released from the tow line spool (approximately 10 m) and attached to the transom of the vessel. Once an appropriate length of rope was available, all towing tension was placed on the tow line and the ROV's tether only served to provide signal to the surface. The ROV was also fitted with a GoPro 9 Black attached to the front of the vehicle that pointed straight down (nadir), recording 60 fps 1080 p video on wide angle setting, as per the third snorkeler video transects above.

The time taken to complete each transect via snorkel was assessed for each transect using a stopwatch, while the time to conduct each transect from the third snorkeler and ROV was determined by assessing video recording length.

Depth 5–10 m: SCUBA diver versus ROV video

Fieldwork occurred in March 2022 at Michaelmas Reef. Sites between 5 and 10 m deep (too deep for snorkel surveys) that contained representative habitat of the area were chosen to compare in-water counts using dive slates on SCUBA with those made via divers recording GoPro video and/or ROV video. Eight belt transects of 100 × 2 m were established. For each replicate, a team of three or four divers laid down the transect. The first diver recorded video along the transect using a Paddy pole as described above, while the other divers followed to identify and count the sea cucumbers in water, recording their sightings on dive slates (Fig. 1e). As with the snorkel transects, each diver waited three minutes after the previous diver had begun before swimming the transect to ensure independence.

Once all divers completed a transect, the ROV was immediately deployed from the vessel, again equipped with a GoPro as per the shallow transect surveys and in the same manner as described in the "Depth 1–4 m" section above. In this instance, however, the ROV was not towed but surveyed the transect under its own power at low-speed setting (25% gain), navigating 2 to 3 m above the substrate as indicated by the onboard depth sounder. This averaged a swath of ~ 3.8 m (measured using in-water reference marks) and a swept area of 380 m for each transect.

The time taken to complete each transect via each method was assessed as above.

Depth 13–27 m: hip chain method versus ROV transects

Of particular interest to the sea cucumber industry in eastern Australia are burrowing blackfish (*Actinopyga spinea*), which occur in abundance in deeper soft sediment habitat along the extent of the Great Barrier Reef (Koopman et al. 2019; Smart et al. 2024). As this species occurs in large clusters in habitat between reefs at 25 m (Smart et al. 2024), we used a survey of this species to test our remote methods at depth. Due to permit constraints, we were unable to directly sample using the same methods as above but were able to assess ROV footage run against commercial divers on surface-supplied breathing apparatus (SSBA) using the hip chain method of Leeworthy and Skewes (2007). This comparison was done at Gould Reef on the Great Barrier Reef and differed from the methods at the other depths in that the transects were assessed differently and the ROV did not cover the exact path of the divers.

Thirty-nine belt transects (200 × 2 m) were surveyed at Gould Reef in October 2019. Two highly trained commercial divers established and swam the transects and counted burrowing blackfish on a dive slate in-water using the method described in Leeworthy and Skewes (2007). Here, each diver laid a transect line as they swam, with the distance from the point of origin measured as the amount of transect laid (Fig. 1f). Transect start locations were randomly allocated using the “Random Points Inside Polygons” tool in QGIS. The direction of each transect was determined by current direction, with divers swimming in the same direction as the current. Divers counted burrowing blackfish 1 m either side of the transect using a 2 m pole attached perpendicular to the transect (similar to the Paddy pole), with the transect in the middle. Unlike the other scenarios, each transect was only surveyed by one diver.

Following the divers transects, a ROV was piloted (not towed) in the same area at ~ 1 m above the sea floor, as indicated by a depth sounder onboard a vessel above, travelling at a speed of 0.5–1 knots (0.26–0.51 m/s) for 100 m. In this instance, the HD ROV video camera onboard was used to collect all data rather than a GoPro. The ROV used lights due to the depth. It produced an average swath of 4.6 m (measured using in-water reference marks) and a swept area of 460 m. Time taken to collect the data was not assessed in this comparison.

Data analyses

Geotagged aerial drone images were uploaded to the GeoNadir portal for processing. Orthomosaics of the area that encompassed the transects at Michaelmas Reef were generated using the GeoNadir portal from the resultant photographs. Counts and identification of sea cucumbers were conducted by a trained expert who followed each belt transect, identifiable in the orthomosaics by the visibility of the buoys and transect tape and recording individuals as they appeared. The expert could zoom in and out of the orthomosaic as required. The data were then compared to sea cucumber counts recorded by snorkelers on dive slates. When identification was uncertain using either method, multiple still images of the individual were extracted from video footage and reviewed later by a team of experts.

A time comparison was not assessed for snorkeler and drone field comparisons or for post-processing imagery. Image post-processing can be highly variable depending on the focal species, habitat complexity (and the difficulty of separating the target species from this), and the frequency of items of interest, and such comparisons were beyond the scope of the current study, which assessed field methods only.

Video footage from the snorkelers, divers (SCUBA and SSBA), and ROV was reviewed by a trained expert, and each sea cucumber was counted and identified to species level. Any video footage was reviewed in 1 × real-time speed and paused at each sea cucumber to help with identification. Only burrowing blackfish were reported for the deeper area comparison. All analyses were conducted in R V4.2.2.

Correctly determining whether two methods are statistically different requires an understanding of the power of the analysis. As a result, prior to all statistical tests, power analyses were run using the ‘pwr’ package (Champely 2020) and the ‘pwrglm’ function designed to assess the statistical power of linear models. We tested the power of analyses using the corresponding degrees of freedom: a significance value of 0.05 and using ‘small’ (0.02), ‘medium’ (0.15), and ‘large’ (0.35) effect sizes, as per Cohen (1988). We assumed that a power > 0.8 was an appropriate level of sensitivity to detect differences between the methods.

To assess whether differences were observed between methods in the total number of sea cucumbers, we ran generalised linear mixed models with ‘transect’ as a random factor. The response variable (sea cucumber counts) was assessed through a Poisson link function. Pairwise tests were determined by using estimated marginal means with the emmeans package (Lenth et al. 2018). We also assessed any differences in sea cucumber species counts with a similar approach, but including an interaction between the method used and sea cucumber species.

Similarly, to test whether the different methodologies differed in the time taken to collect data, we ran generalised linear mixed models treating ‘transect’ as a random factor. The response variable (time) was analysed using a Poisson link function. Pairwise comparisons were done using estimated marginal means with the emmeans package.

To assess whether differences in identifying sea cucumbers to species between the different methods occurred, we used generalised linear models for multivariate abundance data (manyglm, Wang et al. 2012). Data for the more traditional methodologies were analysed against their remote sensing methodology separately. A negative binomial link function was used for better model fit. For the hip-and-chain method, burrowing blackfish densities were zero-inflated for both diver and ROV counts. As such, differences in counts were evaluated using a Wilcoxon signed-rank test on (log x + 1) transformed data.

Results

All methods successfully detected the presence of sea cucumbers, demonstrating their potential suitability for monitoring these benthic species across different survey approaches.

Depth 0–3 m: snorkel transects versus drone orthomosaics

Aerial drone and in-water snorkel surveys compared the same twenty 100 m × 2 m belt transects, covering a total of 4,000 m^2 of shallow area. The total orthomosaic area

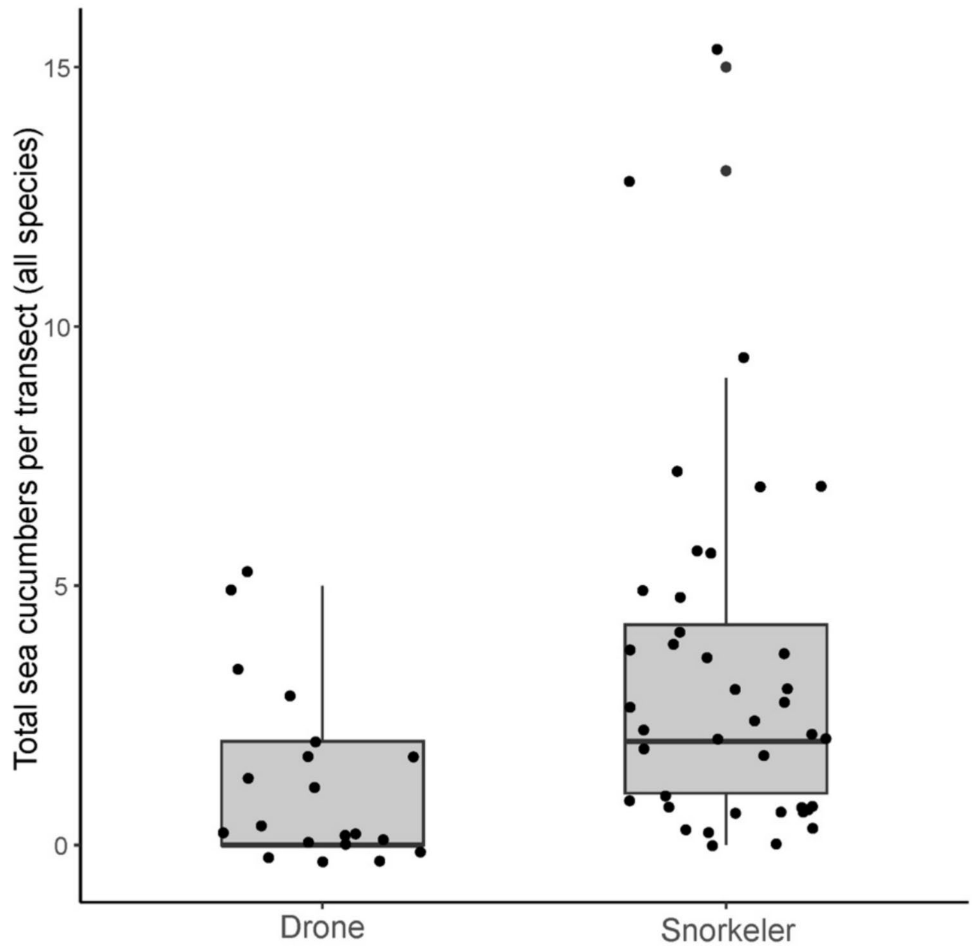


Fig. 2 Total number of sea cucumbers recorded at 20 shallow reef sites, shown using box plots comparing aerial drone survey methods with direct, in-water counts by snorkelers

covered by drone to ensure snorkel transects were within the bounds was 56,000 m^2. The original images and processed results are available via https://tinyurl.com/8rxhva77.

Power analysis suggested that there was sufficient power to detect large effect sizes (0.35) between the methods, with a power of 0.95, but only a power of 0.67 for moderate effect sizes (0.15).

Significantly fewer sea cucumbers were counted on the drone footage compared to the in-water snorkel counts ($df = 1, 58$; $p = 0.001$; Fig. 2). Similarly, a larger number of sea cucumber species were observed via in-water snorkel than by drone orthomosaics ($df = 1, 57$; $z = 4.75$, $p < 0.001$). On average, snorkelers recorded 2.1 more sea cucumbers per transect than were detected in the drone surveys. No time difference was recorded for this comparison.

Depth 1–4 m: snorkel transects versus ROV transects

In-water counts via snorkel, towed ROV, and in-water video surveys were each conducted across twenty-eight 100 m belt transects, covering a total area of 5,600 m^2 per treatment. Power analyses suggested that this study design had sufficient power to detect moderate effect sizes (0.15) with a power of 0.89, but not small effect sizes (0.02), with a power of 0.20.

Sea cucumber assemblages did not significantly differ at the species level between methods ($df = 2, 109$; $dev = 13.77$; $p = 0.72$). Significant differences in sea cucumber counts between these methods were observed at the 1–4 m depth (Chi-square: 12.258; $df = 2$; $p = 0.002$; Fig. 3a). The in-water snorkel method recorded significantly more sea cucumbers (mean 6.0 ± 0.8 SE) than were observed on either the ROV video (Tukey's pairwise test: $z = 3.13$; $p = 0.005$; mean 4.3 ± 0.82 SE) or snorkel video (Tukey's pairwise test: $z = 2.34$; $p = 0.047$; mean 4.7 ± 0.9 SE). However, these differences were only significant for one of the two snorkelers when compared to the ROV (Tukey's pairwise test: $z = 3.31$; $p < 0.01$ and $z = 2.23$; $p > 0.05$), and similarly for in-water snorkel video (Tukey's pairwise test: $z = 2.63$; $p = 0.04$; $p < 0.05$ and $z = 1.54$, $p > 0.05$).

Absolute and relative differences in sea cucumber counts between in-water snorkel and the two other video-based methods suggest the median difference between the two methods and in-water snorkel was − 1, with some outliers (especially for ROV transects), and a difference of up to − 5 sea cucumbers per transect. The mean relative difference of sea cucumber abundance between in-water snorkel and the

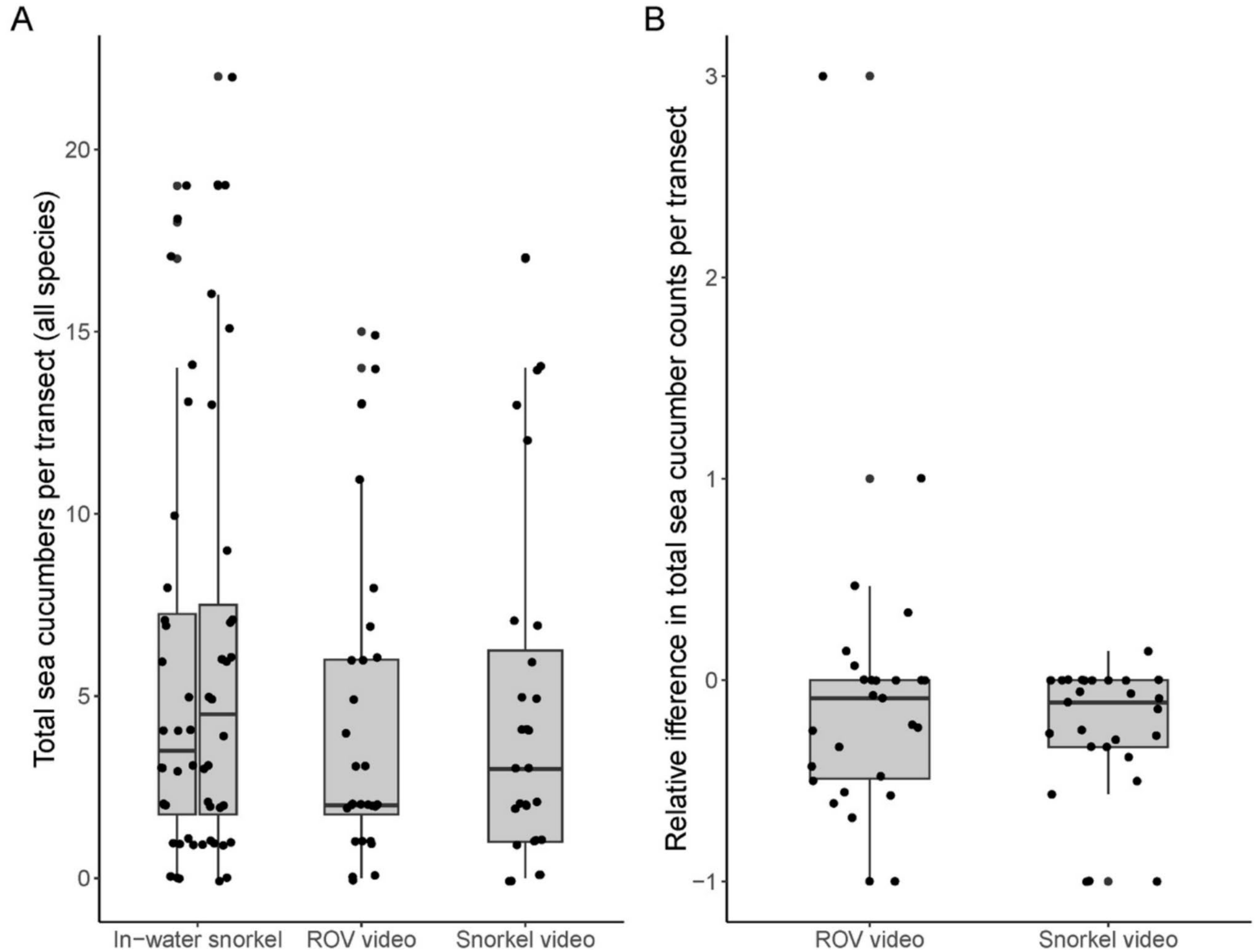


Fig. 3 **A** Total number of sea cucumbers counted per 100 m transect ($n = 28$) at the shallow reef sites using the three different methods. Results from the two in-water independent snorkel observers are shown as separate side-by-side box plots. **B** Relative differences in sea cucumber counts from ROV and snorkel video compared to in-water snorkel. Negative values indicate that fewer sea cucumbers were recorded than by in-water snorkel. Positive values indicate that more sea cucumbers were recorded, and zero indicates no difference between the method and in-water snorkel

two video-based methods was − 0.08 ± 0.76 SD relative to ROVs, and − 0.25 ± 0.32 SD for in-water video per transect. In some cases, the ROV video recorded one to three times more sea cucumbers than in-water snorkel averages between the two observers, whereas in-water video more closely resembled in-water snorkel with relative differences between − 1 to 0.25 (Fig. 3b).

Across all transects, some sea cucumber species were detected significantly more frequently than others, with *Holothuria atra* being the most common species observed across all transects (3.38 ± 0.36, mean ± SE across all methods; Chi-square = 643.97; df = 22; $p < 0.001$). We also detected significant differences between sea cucumber counts across methods (Chi-square = 31.65; df = 17; $p = 0.016$); however, no significant interaction was observed between method and species (Chi-square = 21.45; df = 24; $p = 0.61$; Fig. 4). Pairwise tests indicated that significant differences between methods occurred only in two cases: between both in-water snorkelers and ROV video for *Stichopus chloronotus* (Tukey's pairwise test: $z = 3.16$ and 2.74; $p = 0.008$ and 0.031, respectively), and between both snorkelers and snorkel video for *Holothuria edulis* (Tukey's pairwise test: $z = 3.23$ and 3.42; $p = 0.007$ and 0.003, respectively). It is also noted that the model failed to converge, likely due to the low detection rates of many observed species, which is common for sea cucumber communities.

In-water snorkel transects took significantly more time to complete (average 8 min) than the other methods, with the snorkel video method taking roughly half as long to travel the transects (4 min, Tukey's pairwise test: $z = 6.12$, $p < 0.001$), and ROV video taking half as long again (2 min, Tukey's pairwise test: $z = 9.38$, $p < 0.001$; Fig. 5a). The time

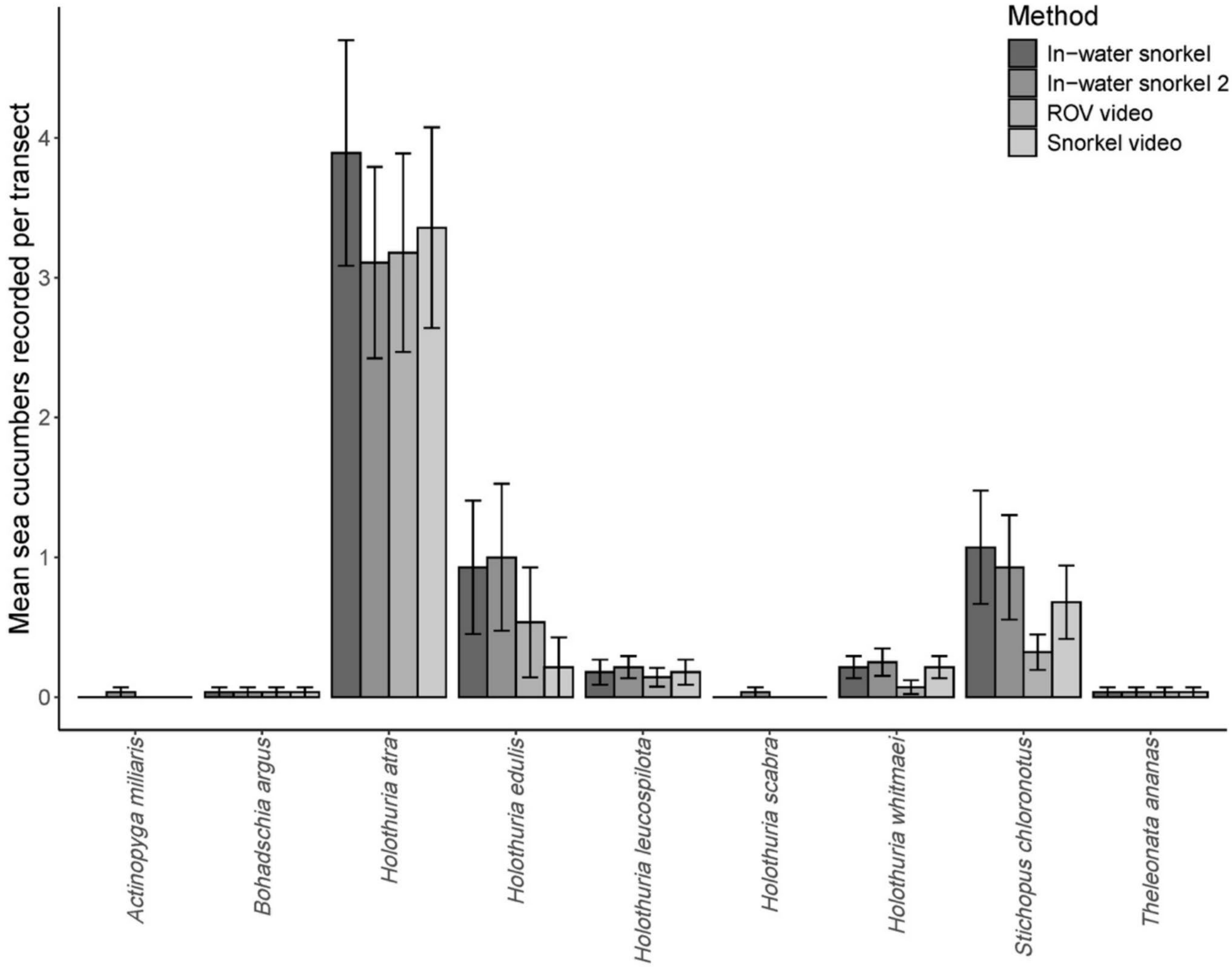


Fig. 4 Mean ± S.E. number of sea cucumbers per transect for each species across the three survey methods. Results from the two in-water snorkelers are shown separately to reflect independent observations

to conduct an in-water snorkel transect also had a higher coefficient of variation (38%) compared to video-based methods (29% for the ROV, 24% for in-water video; Fig. 5a).

Depth 5–10 m: SCUBA diver versus ROV video

The power of analysis for the SCUBA-based assessment was low, with a power of 0.69 for large effect sizes. This is not surprising considering the low number of replicates in the comparison and should be considered alongside the results. No significant difference was observed between the total sea cucumber counts recorded from video taken on SCUBA or via the ROV (df = 1; $F = 0.09$; $p > 0.05$; Fig. 6a). The total time taken to conduct surveys between SCUBA and ROV video was also not significantly different (df = 1, $F = 2.56$, $p > 0.05$; Fig. 6b). Some inter-individual variation in counts and time taken to conduct the surveys was observed between SCUBA divers; however, the small number of deep transects ($n = 8$) precluded any analysis.

Depth 13–27 m: hip chain method versus ROV transects

Approximately 15,600 m^2 total area was surveyed by the hip chain method and the ROV video. Densities of the target species of burrowing blackfish were variable, with areas of high densities interspersed with substantially lower densities observed by both divers and the ROV video (Koopman, unpublished data). Transformed (log x + 1) data were used. The power for this analysis was 0,81 for detecting moderate effects (0.15). A Wilcoxon signed-rank test revealed no significant difference in observations of burrowing blackfish densities between hip chain divers and ROV video ($W = 693$, $p > 0.05$; Fig. 7). Low and high densities of burrowing blackfish were observed by both the divers and from the ROV

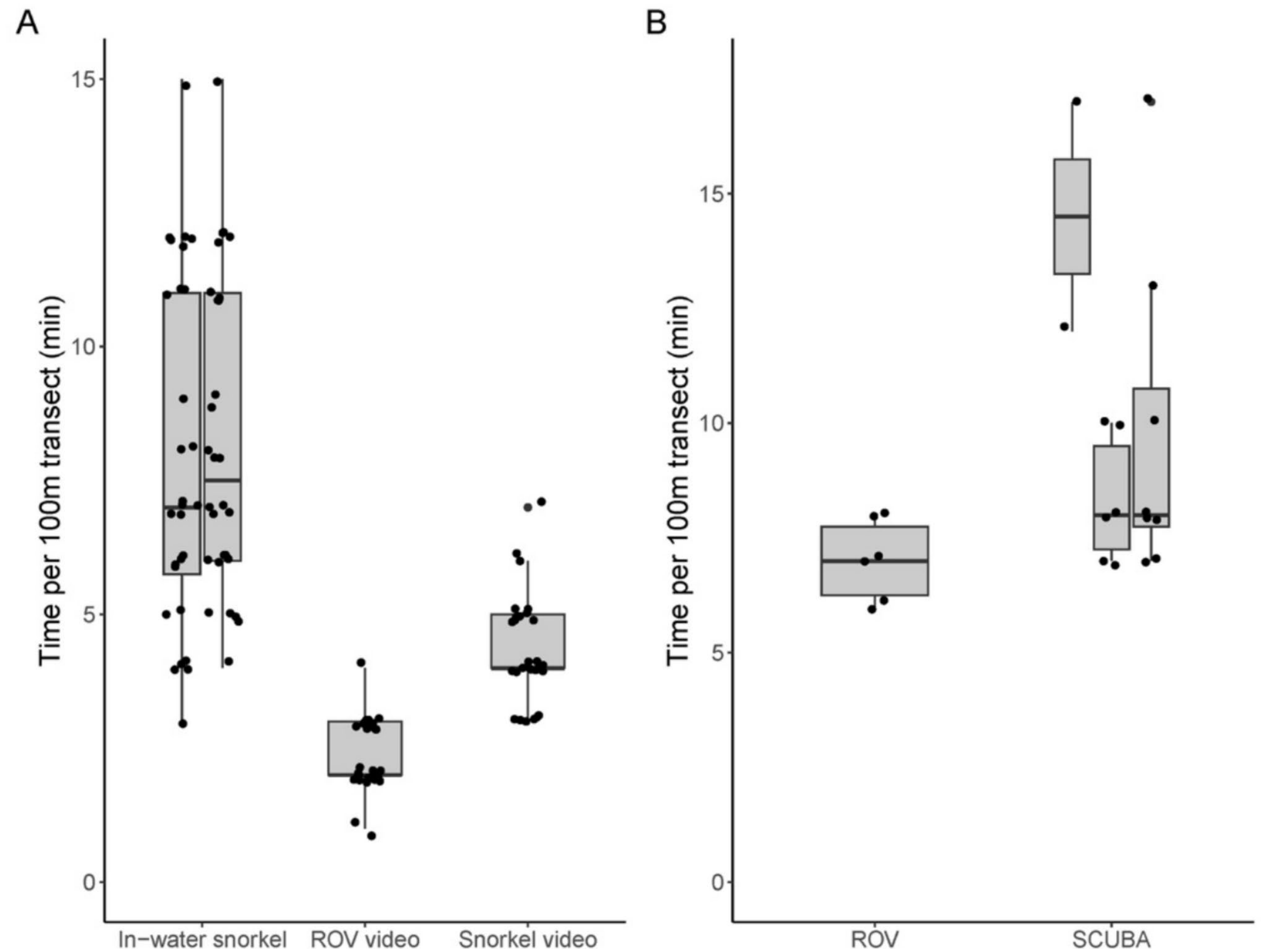


Fig. 5 **A** Field time required to survey the total number of sea cucumbers per 100 m transect ($n=28$) at the shallow reef sites using three different methods. Results for in-water snorkel are shown separately for two independent observers as two side-by-side box plots. **B** Field time taken to conduct surveys in deeper waters using the ROV compared to three SCUBA divers, with results from each independent diver shown as separate box plots. Note that the first SCUBA boxplot represents only two transects

video. The time taken for each of these field methods was not assessed for this method comparison.

Discussion

While traditional methods of direct in-water counts continue to be reliable for abundance and diversity assessments for sea cucumber surveys, our study demonstrated that remote methods, particularly in-water and ROV video surveys, can provide comparable results. The exception was aerial drones; however, our sampling methodology was biased against this technology, as discussed later. Snorkel-based in-water counts tended to detect more sea cucumbers than ROV video, but the assemblage composition was not different between the two methods, and differences in total abundance were only detected with one of the two snorkel observers, highlighting that in-water snorkel assessments can be impacted by observer bias. At the species level, ROV video surveys were largely consistent with direct snorkel assessments. Similarly, counts from SCUBA or hip chain SSBA surveys did not differ significantly from remote video-based approaches, although the comparison with SCUBA and ROV methods had a lower power of detecting a difference, and this needs to be taken into consideration. Habitat did not appear to influence our results as our ROVs regularly traversed both soft sediment habitats and complex coral reefs. For our shallow water (0–3 m) assessments, however, snorkel surveys recorded significantly higher sea cucumber abundance and diversity than assessment via the drone-based orthomosaics.

Where assessed, the time taken to complete field surveys differed between methods. For equivalent areas, data collection was significantly faster using remote sensing techniques than the in-water counts. At depths of one to four meters, our

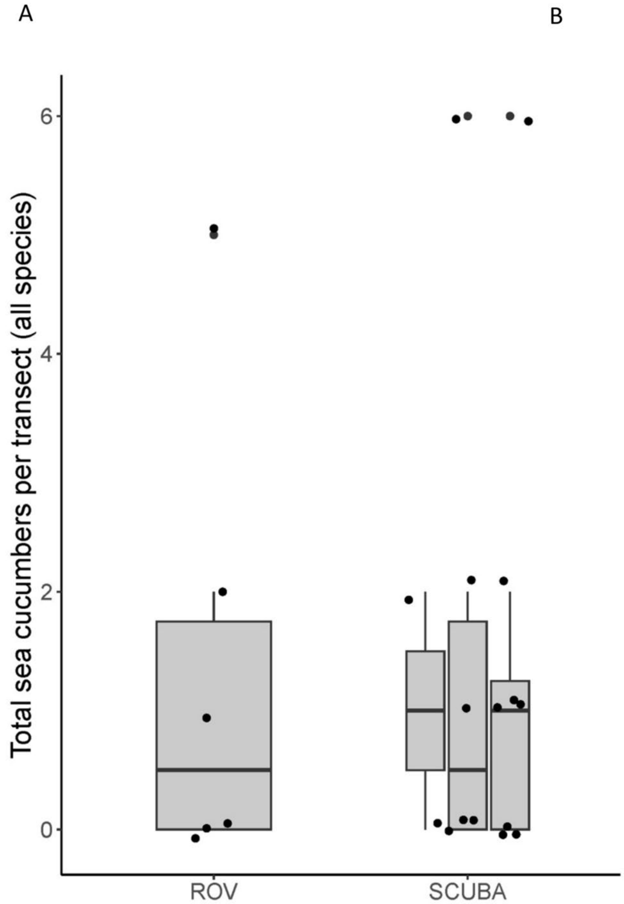


Fig. 6 Total number of sea cucumbers recorded per 100 m transect at eight shallow reef sites, comparing data extracted from video via ROV versus SCUBA-based counts. SCUBA results represent three independent divers, shown as separate box plots. SCUBA has results from three independent observers shown as three side-by-side box plots. Note that the first SCUBA box plot contains data from only two transects

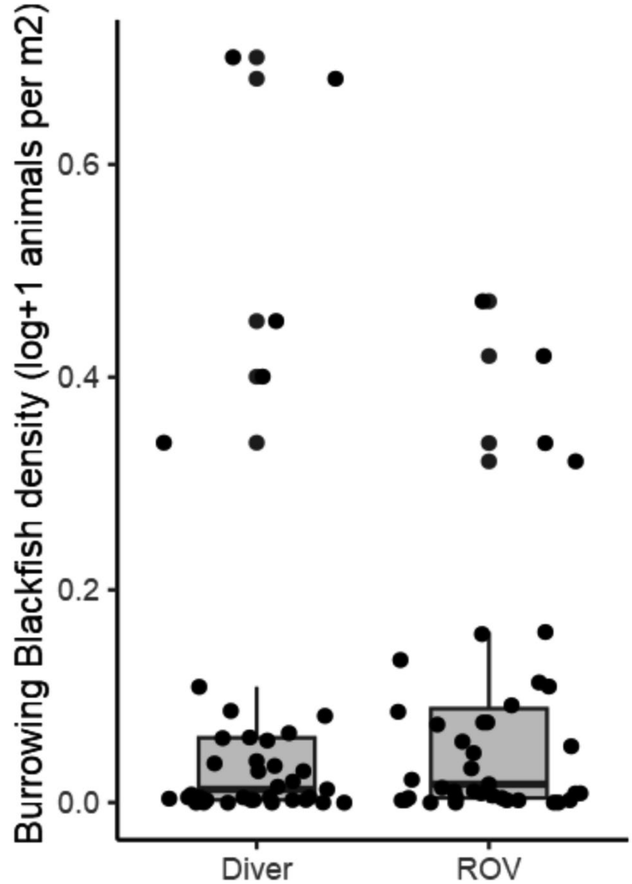


Fig. 7 Density (log x + 1; animals per m^2) of burrowing blackfish recorded by hip chain divers using SSBA and from ROV video at Gould Reef. Transect areas were 400 m^2 for the divers and 460 m^2 for the ROV

in-water snorkel counts took twice as long as snorkel video to complete, and four times longer than assessments via the towed ROV. Therefore, in general, our remote methods are generally equivalent to in-water counts but superior in the time taken to complete. Our results align with an earlier study that found no significant difference between echinoderm counts on ROV footage compared to in-water SCUBA counts in cooler waters off Washington State, USA (Carson et al. 2016). Both studies highlight the potential of remote sensing-based approaches as tools for enhancing the efficiency and statistical power of monitoring for sea cucumber fisheries and aquaculture. By reducing the time required for field surveys, our methods offer the possibility of covering larger areas within the same time commitment, thus improving cost efficiencies. Given the vast fishing grounds available to sea cucumber fisheries and the patchy nature of their distributions, expanding the survey area by orders of magnitude would greatly improve the reliability of stock assessments produced from these data.

Many survey operations may be hesitant to adopt new technologies like those presented here, often due to the assumption that eyes in the water yield superior results. Direct in-water assessments, however, introduce an additional layer of uncertainty that is not present in remote techniques. While they offer the advantage of immediate data availability after each survey, their accuracy depends heavily on observer skill as the data cannot be verified or reviewed after collection (Leujak and Ormond 2007). This was highlighted by remote methods differing in sea cucumber total abundance with just one of the two snorkelers in our study. If similar variations in counts occur in data collected using remote video methods, the footage can be reviewed to identify the cause of any inconsistencies. Our study revealed substantial differences in sea cucumber abundances, diversities, and survey duration among trained individuals conducting in-water counts, whether using snorkel or SCUBA. These observer-related variations could significantly influence survey outcomes and should be considered in such monitoring programs.

Observer training for all methods is key to reducing error and enhancing efficiencies. In this study, all observers were pre-trained in sea cucumber identification, minimising inter-individual variation attributable to learning competency deficiencies. Although inherent biases in observations may still occur, standardising observer differences should also be a routine part of any sampling design and field methods (Wilson et al. 2007). In this context, remote sampling has advantages over in-water counts because it relies on post-processing imagery that experts can review and count later, which helps reduce variation between observers (Raoult et al. 2016).

The remote sensing methods assessed in our study have the added advantage of producing images that can act as baseline data for future research for a range of researchers (Raoult et al. 2025a). Information captured by remote imagery can be mined for research not considered at the time of data collection (Butcher et al. 2021). For example, images obtained through routine monitoring of coral habitat over time can act as a historical 'before' baseline to a subsequent coral bleaching event. Remote imagery can also align the broader community to research by increasing the accessibility of the data through orthomosaics and photographs, thus increasing audience engagement in an alternate style (Christidou 2011; Li and Xie 2019; Bolick et al. 2022; Slater 2024).

Counts of sea cucumber abundances and the number of species via drone orthomosaics produced lower numbers of counts when compared to in-water counts in this study. This is not surprising considering the poor weather conditions faced during our surveys and our survey protocol that forced drone flying when such an activity would not usually occur. Drones produce excellent orthomosaics when the conditions are favourable, i.e. when drones are flown in winds below 10 kn, at low tide, in the early morning or late afternoon, and/or in overcast weather to minimise glint (Joyce et al. 2019). The conditions during our study were sub-optimal for drone work (15–20 kn winds, middle of a sunny day at mid tide) as the drone work had to fit in with all sampling techniques since each method ran immediately after the other to ensure a true comparison of sea cucumber metrics. When conditions are optimised for drone work, however, drone assessments and time efficiencies can be superior to direct counts of organisms (Corregidor-Castro et al. 2023) and comparable to in-water sea cucumber counts (Williamson et al. 2021). Additionally, the broader area coverage and enhanced habitat detail provided by drone images or orthomosaics can offer more comprehensive data than other methods (e.g. Hamad et al. 2022). For sea cucumber assessment, drones are less effective than in-water methods at detecting more cryptic species. Therefore, the suitability of drones as a preferred survey tool depends on the specific research question, the target species, and external factors such as weather conditions and local regulatory requirements, as discussed in Oleksyn et al. (2021). Thus, while weather conditions may preclude the exclusive use of drones for shallow sea cucumber surveys, their use is preferable if the conditions are optimal, and they should be an essential component of the sea cucumber survey toolkit.

As with aerial drones, the ROV (towed or tethered) also has the potential to produce footage substantially superior to those recorded in this study. Surveying benthic transects using a towed ROV at mid-water depths presented challenges, as the boat-based pilot often could not see the transect line and had to navigate opposing currents and wind to maintain the correct course. This likely means that some ROV transects did not precisely overlap with the snorkel transects. We suggest this largely explains the differences in *Stichopus chloronotus* counts compared to in-water snorkel surveys, particularly since this species is easily identified on video due to its high contrast appearance against the substrate. Such difficulties could be substantially reduced by completing transects that allow the ROV to travel with the currents and wind, and by tracking GPS coordinates rather than a physical transect line. The ROV in the SCUBA hip chain assessment did not follow a set transect and thus did not face the same difficulties as the shallower ROV routes, highlighting that on a survey scale the differences between approaches are negligible. Based on data collected using a towed ROV under the suggested conditions, this can greatly increase efficiency (Raoult et al. 2025a).

Remote sampling techniques used in this study have advantages over in-water counts for many sea cucumber species due to the increased area that they cover and the heterogeneous distribution of these species in space and time. Diurnal species may be more difficult to assess, and specific designs of the remote surveys will be required to ensure that the survey type and effort match the biological characteristics of the target species. For example, sandfish (*Holothuria scabra*) bury themselves at sunrise but generally reappear around midday to early afternoon, depending on the season (Hamel et al. 2001). Remote surveys targeting this species should thus be done in the early afternoon when the animals are visible. Nocturnal species also offer specific challenges that need consideration in design.

Each method assessed here has strengths and weaknesses for assessment of sea cucumber abundance and diversity (Table 1). Based on our research and on previous studies (see review by Yang et al. 2022), aerial drones are by far the most field time efficient approach as they can cover ~ 30,000 m^2 per 30 min flight in this habitat but are limited to shallower waters, optimal conditions, and flight time (although the latter is changing; see Kim et al. 2025). The ROV is the only method that can assess the entire depth range that we

Table 1 Comparison of capabilities and limitations of different sea cucumber survey methods, based on this study and others by the authors. In this table, more dots indicate a higher degree or requirement of a given factor. Similarly, more dollar signs represent higher relative costs. *Post-processing effort and water visibility were not directly assessed in this study but were evaluated based on the authors' collective experience with the field methods

	In-water counts	In-water video	ROV	Drone
Speed acquisition (time per 200 m^2)	7 min (density-dependent)	3 min	2 min	< 1 min
Image resolution	N/A	~ 1 mm/pixel	~ 1 mm/pixel	~ 1 cm/pixel
Learning curve	●●	●	●●●	●●●
Post-processing time*	Nil	●●●	●●●	●●●
Maximum wind	< 25 kn	< 25 kn	< 25 kn	< 10 kn
Depth	Snorkel < 5 m SCUBA < 30 m	Snorkel < 5 m SCUBA < 30 m	> 50 m	< 3 m
Rain	Yes	Yes	Equipment-dependent	No
Cost	$	$$	$$$$	$$$
Required minimum water visibility*	> 2 m	> 2 m	> 2 m	> 2 m

studied, although assessing the shallow areas where drones can survey requires using the ROV at high tide to allow boat travel. Due to its rapid acquisition time, ROVs are also able to cover a conservative ~ 8,000 m^2 per hour if towed (Raoult et al. 2025a). To streamline the process, we thus recommend that towed ROVs are routinely used for sea cucumber assessment, and drones are favoured for shallow waters when the conditions are optimal.

It is important to note that our study did not account for the time taken to review and count sea cucumbers in the video imagery or other post-processing activities, which can be considerable. The main restriction for surveys, however, is usually fieldwork time, which accounts for the largest part of operational budgets due to the cost of vessel operation. Field time is further constrained by suitable weather windows. As a result, the primary limitation to conducting more informative surveys is typically fieldwork efficiency rather than staff efficiency for post-processing data analysis. If rapid output is a higher priority that survey detail, traditional methods with immediate results may be preferable. Alternatively, video footage or imagery can be analysed in the field using suitable screen equipment, although this may increase fatigue for field teams.

The quantity of data produced by the remote sampling techniques used in this study lend themselves to automation via machine learning to reduce labour-intensive manual data processing, which would eliminate this post-processing issue. Machine learning models can be trained to expedite and streamline animal identification and classification. For example, deep learning applied to drone imagery has been successfully used to detect sea cucumbers on shallow coral reefs (Li et al. 2021) and to analyse their individual trajectories as an indirect measure of their feeding status and health (Li et al. 2019). Such opportunities in machine learning technologies offer a range of exciting avenues (Malde et al. 2019) and largely solve the inter-observer differences highlighted above and in post-processing challenges. Recently, artificial intelligence capable of automatically identifying sea cucumbers to species has been successfully developed, achieving species level detection accuracy of up to 89% (Williamson et al. 2024). Since its development, species assessments of sea cucumbers on Australia's Great Barrier Reef have increased substantially in time efficiency, and the model is expected to be adopted by commercial fishers in the near future (R Connolly, pers com). Data collected through these remote sampling methods can be further analysed to gain deeper insights into target species and their associated habitats (Habel et al. 2016). Moreover, by combining historical data with species populations, diversities, and environmental conditions, predictive models for future trends can be developed (Jurišić et al. 2022). Implementing remote sampling protocols, integrating machine learning models, and involving citizen science initiatives can greatly expand the scope and scale of data collection, thus augmenting datasets and improving geographic coverage.

Drones and ROVs are efficient and flexible remote sensing technologies that can enhance data collection for reef-associated animals, such as sea cucumbers. These technologies may also be highly effective for surveying other slow-moving or stationary, benthic-associated organisms such as clams, sea urchins, corals, and sea stars. While some preliminary work has begun (e.g. Decitre & Joyce 2024), we recommend that the methodologies proposed here be further tested on these taxa. While drones can be limited in use due to sub-optimal conditions, they also have the added advantage of being able to assess the demographics of more mobile organisms in shallow waters but from a greater height (e.g. sharks on coral reefs, Raoult et al. 2018) and in assessing large expanses of habitat (e.g. seagrass habitat, Duffy et al. 2018; coral habitat, Raoult et al. 2025b). With the addition of training and adherence to simple stepwise methodologies, commercial fishers and conservationists can collect comprehensive and reliable data using relatively inexpensive drones and ROVs. The resulting footage can be mined for habitat data and other variables in addition to the target survey, which can enhance our understanding of species and allow a "travel back in time" approach, providing georeferenced imagery that can act as historical records in the face of uncertainty and future perturbations. We propose that using our drone and ROV methodology outlined in this manuscript for assessing marine species, particularly slow mobile to immobile ones, will result in more accurate, more extensive, and more accountable assessments for those organisms.

Acknowledgements Many thanks to Nick Harris and Penny McCracken who assisted with the fieldwork for this research, and to members of the Marine Ecology Group at Macquarie University for their support. We thank the members of the Queensland Sea Cucumber Association including Ben Cochrane, Chauncey Hammond, Anton Krsinich, Rob Lowden, and Stirling McGregor, for their help during the burrowing blackfish section of the project, and for their advice on the practical aspects of conducting this deepwater survey. We thank divers Ben Cochrane and Ben Murray for assisting with the diving aspects of that survey. We acknowledge the traditional owners of the land and sea country on which these data were collected and analysed.

Author contributions JEW, KEJ, SD, TFG, and VR conceptualised the study; all authors contributed to data collection; JEW, KEJ, SD, MK, JYQL, and VR analysed the data; JEW wrote the initial draft of the manuscript; and all authors edited, reviewed, and finalised the manuscript for submission.

Funding Open Access funding enabled and organized by CAUL and its Member Institutions. This research was funded by Macquarie University and by the Great Barrier Reef Foundation for the Sea Cucumber Monitoring Project, as part of the Reef 2050 Integrated Monitoring and Reporting Program (RIMREP). The burrowing blackfish survey was funded by the Queensland Sea Cucumber Association.

Data availability Data are available on request, with the exception of the burrowing blackfish data, which are under a non-disclosure contract.

Declarations

Conflict of interests The authors declare no competing interests.

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