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BRITISH ECOLOGICAL SOCIETY Methods in Ecology and Evolution

PRACTICAL TOOLS

Benthic Observation Survey System (BOSS) for surveys of marine benthic habitats

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Abstract

1. Most platforms for collecting images to characterise marine benthic habitats involve a downward or forward-facing field of view that is relatively constrained (~70°), covering a relatively small area of benthos (downward ~1 m^2, forward ~25 m^2).
2. Here we propose the use of a four-camera platform having a wide combined field of view (~280°), covering a much greater area (up to 100 m^2). We also present a stereo-camera configuration that has the added benefit of being able to accurately measure sample area and dimensions of benthic biota. The design proposed is robust and self-righting, facilitating rapid deployment and retrieval from a range of vessels, depths and environments.
3. We present an exemplar workflow to generate a habitat map (~100 km^2) within a no-take National Park Zone within the South-west Corner Marine Park, Australia and demonstrate the benefit of increasing the field of view to estimate habitat heterogeneity.

For affiliations refer to page 8.

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4. The relatively broad sample unit of this wide-field drop camera is well suited to estimating coverage (e.g. of a seagrass bed) and habitat mapping. It is time-efficient in the field, enabling spatially balanced sampling designs to acquire ground-truthing data for medium- to large-scale habitat mapping projects. This platform is a practical tool to monitor change in marine environments and assess the environmental impact (e.g. sea bed alteration) of activities such as offshore energy or fishing gears.

KEYWORDS
benthic habitat, drop camera, environmental assessment, monitoring, population ecology, sampling, stereo-video, surveys

1 | INTRODUCTION

Marine benthic images are commonly used to quantify habitat composition, ground-truth remote data and predict the extent of habitat types (Holmes et al., 2008). Such imagery is now widely used to validate spatial analyses such as extent models, and change-over-time mapping (Mastrantonis, Radford, et al., 2024). Benthic images for habitat ground truthing captured by platforms such as divers, drop cameras, towed video, Remotely Operated Video (ROV), and Autonomous Underwater Video (AUV) are generally acquired from downward-facing cameras. These cameras typically have a field of view that is relatively constrained (~70° × ~40°) and covers a small area per sample unit (~1 m^2, Bennett et al., 2016; Sheehan et al., 2016). Horizontal-facing images, using the same field of view, have a larger area (~25 m^2) and are useful in a variety of situations and ecosystems, for example Bennett et al. (2016) demonstrated that downward-facing imagery is sensitive to detect change in horizontal growth forms (e.g. plate coral) or certain mobile invertebrates (e.g. sea urchins). Downward-facing images generally provide higher taxonomic resolution for sessile assemblages and sub-canopy species than horizontal-facing images, and improved estimates of mobile invertebrate numbers (Perkins et al., 2020). However, the larger area per sample unit of horizontal-facing images better aligns with spatial resolutions of remote sensing products such as bathymetric lidar (~25 m^2) and optical remote sensing platforms (~100 m^2). Obtaining ground-truthing data at a commensurate scale to remotely sensed products is an important consideration when modelling extent or community composition (Mastrantonis, Radford, et al., 2024). Horizontal-facing imagery is also more effective for monitoring the cover of erect habitats including canopy algae and corals (Bennett et al., 2016; Vergés et al., 2016), particularly if stereo images are captured allowing the dimensions of biota to be measured (Langlois et al., 2021). Stereo images further allow the sample unit to be standardised across varying visibility (Broad et al., 2023; McLean et al., 2016). The structural dimensions (i.e. height) of benthic biota can be an indicator of anthropogenic and environmental impacts. Imagery from Baited Remote Underwater stereo-Video (stereo-BRUV) surveys have been used to measure the recovery of soft-coral height after the cessation of trawling (Langlois et al., 2021), and the impacts of marine heat waves on macroalgal canopy height (Vergés et al., 2016). Typically, habitat characterisation from such platforms is only done to provide covariates for the interpretation of fish assemblage composition (Langlois et al., 2021; Merritt et al., 2011; Switzer et al., 2023) but not explicitly for habitat extent mapping.

Spatially balanced survey designs can increase sampling efficiency by evenly spreading samples in space and across the range of covariates of interest (e.g. depth and relief) (Mastrantonis, Langlois, et al., 2024; Robertson et al., 2013). Typical platforms for collecting benthic images (i.e. divers, towed video, ROV, and AUV) have logistical constraints (e.g. number of ascents, limited self-propulsion) that result in them generally being deployed along transects, or in discrete patches or mosaics (Sheehan et al., 2016). By contrast, drop cameras provide point samples, yielding a more spatially independent method of gathering benthic data (Robertson et al., 2013). Where rapid repeated deployments are possible, drop cameras are suited to ground-truthing relatively large spatial areas (Pelletier et al., 2020), and sites requiring validation can be chosen based on covariates of interest (Mastrantonis, Radford, et al., 2024). Transect-based sampling can also be used in a spatially balanced manner, but care must be taken to account for spatial dependence within transects and clusters of transects (Foster et al., 2020). Regardless, transect-based and locally dense sampling can introduce clusters of samples within similar environmental settings, or spatial bias, that can weaken subsequent statistical analyses (Mastrantonis, Langlois, et al., 2024; Robertson et al., 2013). Drop cameras have clear logistical and efficiency advantages for sampling larger areas, due mainly to the brevity of their deployments and relative ease of obtaining independent observation units. Untethered landers and swarms of AUVs are likely to be more appropriate for sampling in deeper water environments (>1000 m) than drop cameras, but these methods involve a substantial cost increase (Liu et al., 2023).

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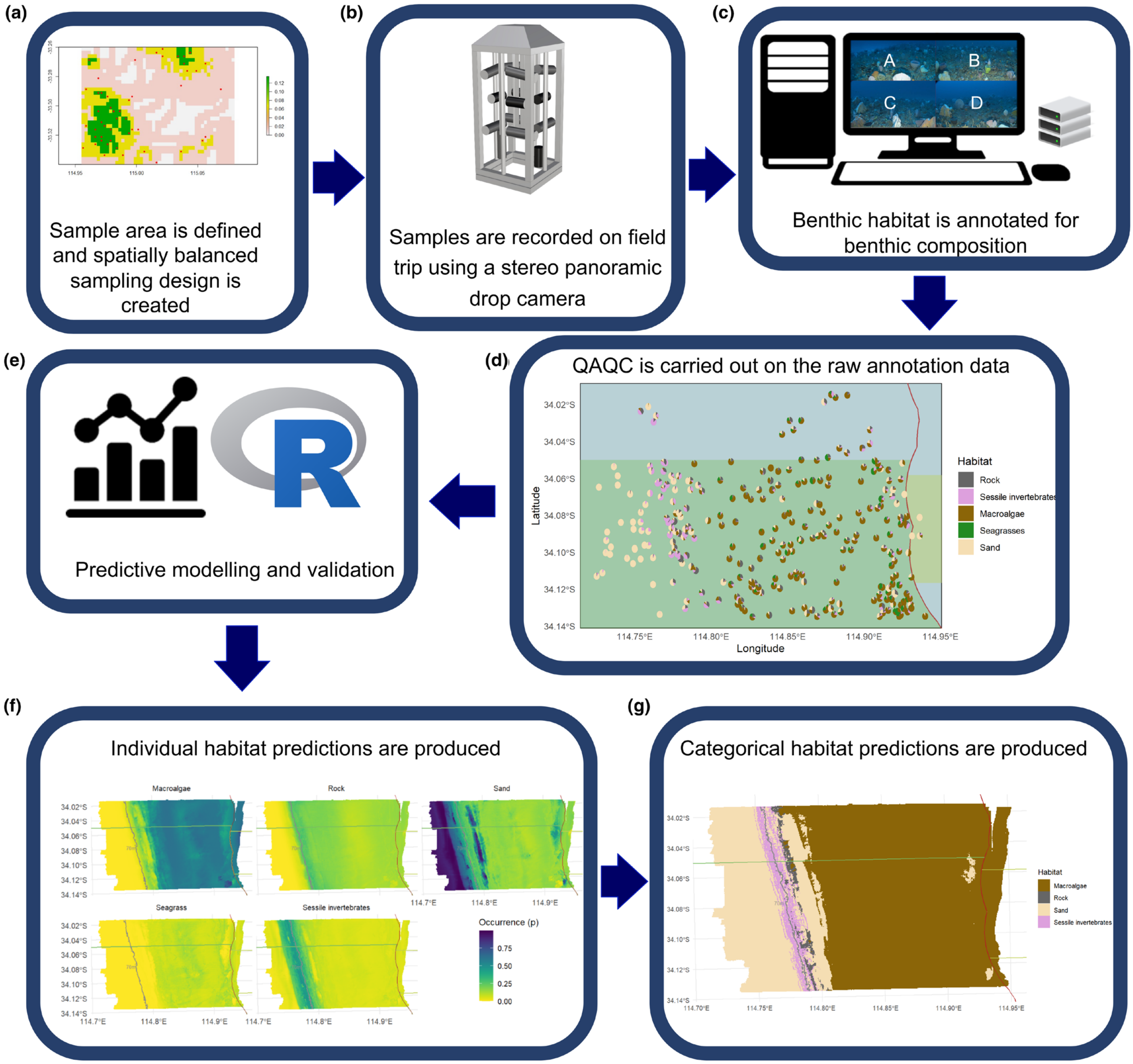

FIGURE 1 BOSS workflow for benthic composition ground truthing and production of predictive spatial models. (a) Spatially balanced design with inclusion probability, (b) drop camera, (c) imagery annotation, (d) quality control, (e) predictive modelling and validation to produce, (f) probabilities of occurrence for individual habitat classes and (g) categorical habitat predictions.

To overcome these challenges for mapping habitats across continental shelf waters, we have developed a remote wide-field drop camera system, called the Benthic Observation Survey System (BOSS), with a combined field of view of approximately 280° (Figures 1 and 2), amenable to stereo- or mono-camera configurations (Figure 3). The design originated from an integrated fibre-optic camera system developed by Rick Starr at Moss Landing Laboratories for sampling demersal fish assemblages, that developed from rotating stereo-video landers (Matthews et al., 2024). The system was adapted to be able to be rapidly deployed and retrieved from a variety of vessels into water depths of 2–200 m and is self-righting on the seabed (Figures 1–3). A single sample in 30 m of water takes just 8 min, including a 5-min bottom time to allow sediment to settle, with the remaining 3 min for deployment and retrieval. This platform was optimised for the collection of widespread georeferenced point samples, enabling the cost-effective sampling of broad areas using spatially balanced sampling designs, to produce benthic habitat coverage predictions (Figure 1) or inform other environmental assessments (i.e. benthic biota dimensions). We provide a standard operating protocol (SOP) for the BOSS with information on system

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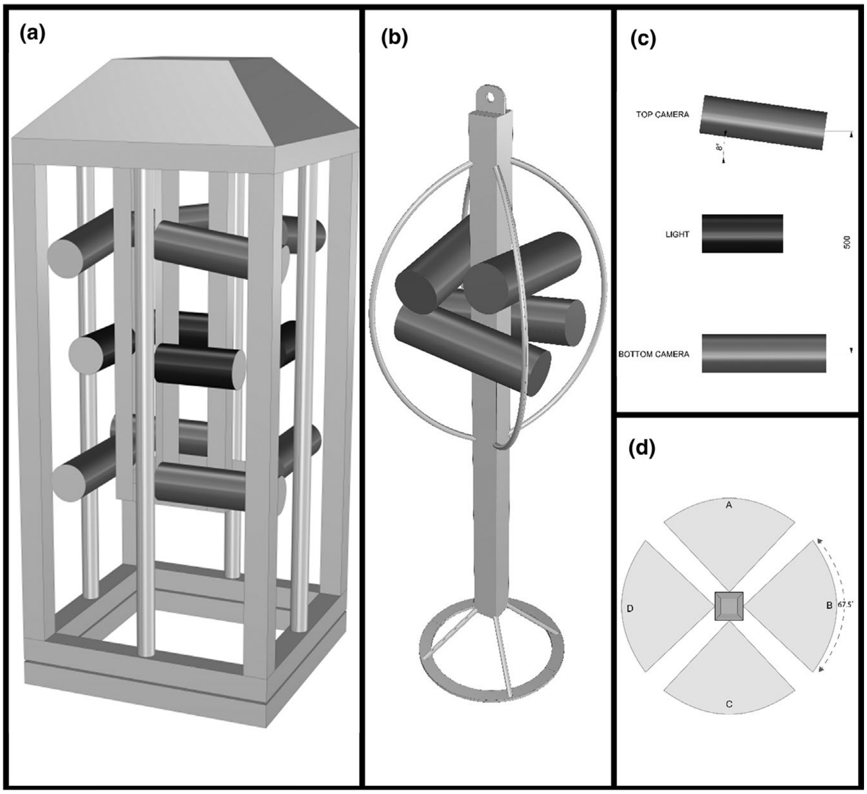

FIGURE 2 BOSS design. (a) stereo-configuration with camera pairs mounted on internal base bar cassette, showing camera housings (grey) and lights (black), (b) lighter weight mono-configuration, (c) specifications of the stereo-camera separation and angle of convergence and (d) overhead field of view showing the wide 280° field of view.

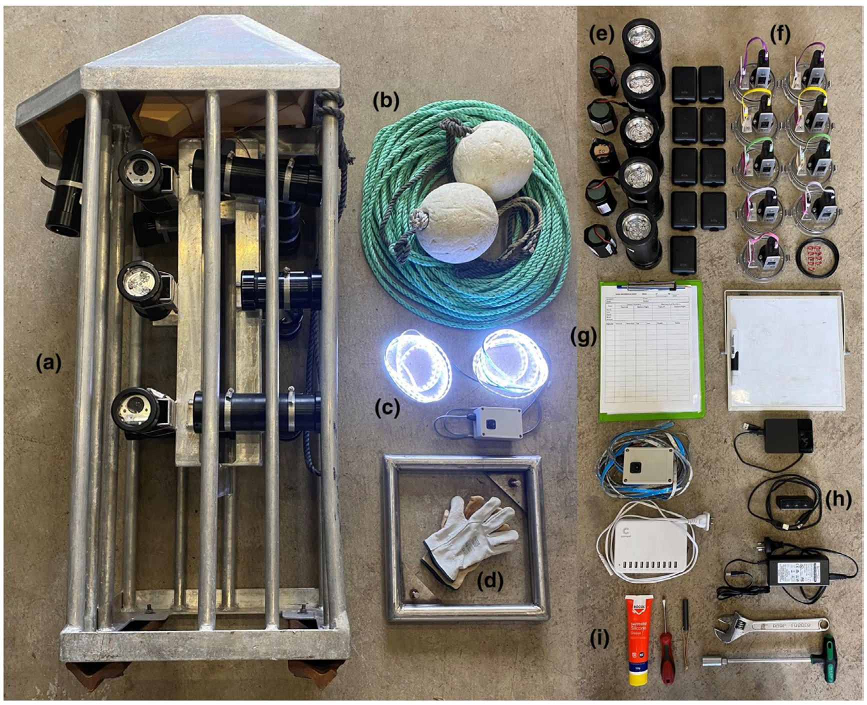

FIGURE 3 BOSS equipment required for deployment. (a) Stereo-camera frame with an additional downward-facing camera mounted in buoyancy compartment, (b) rope and floats, (c) synchronisation diodes, (d) detachable ballast and gloves, (e) lights and batteries, (f) cameras, battery packs, SD cards and spare O-rings, (g) field metadata sheet, whiteboard and marker, (h) charging equipment and downloading footage, and (i) tools including silicone grease.

design, field operation, image annotation, data validation, and examples of a workflow to generate a habitat map product (Figure 1). We highlight the benefits of using multiple horizontal fields of view to characterise benthic habitat heterogeneity but also suggest that future studies should investigate the potential of collecting demersal fish assemblage information building on Aston et al. (2024) and Matthews et al. (2024).

2 | DESIGN AND METHODS

2.1 | SOP development

The development of the SOP followed the approach described in Przeslawski et al. (2023). Experts and users in relevant marine imagery and habitat classification were invited to join a working

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group and contribute to the content of the SOP. The SOP will be maintained as part of a broader suite of sampling methods used for marine monitoring established by the Australian Government's National Environmental Science Program (marine-sampling-field-manual.github.io).

2.2 | System design

The BOSS has two variants: a stereo system with eight cameras (Figure 2a) and a lighter weight mono system with four cameras (Figure 2b). Both have cameras with standard ~70° field of view at 90° intervals providing a combined wide 280° field of view (Figure 2c). A 280° field of view was found to be more than adequate to variance in benthic habitats (Supporting Information S1) and the use of standard ~70° field of view avoids any issues with barrel distortion typical with photogrammetry using 360° cameras and four fields of view can be easily composited into a single image for annotation (Figure 1c). Both variants consist of a sturdy aluminium frame to secure and protect the camera equipment, a flotation compartment at the top and a bolt-on base weight. The buoyancy and weighting counteract to create a self-righting action, with flotation provided by compression-resistant syntactic foam or subsurface floats. The vertical profile, self-righting nature and tethering from the top surface of the system allows it to be deployed in very high relief topography and it has been successfully deployed and retrieved with no fouling amongst man-made offshore energy structures, unlike stereo-BRUV systems which due to their horizontal profile can become fouled in caves or amongst man-made structures (Langlois et al., 2020). In over 1000 BOSS deployments, from 2 to 200m, the system is also proving highly resistant to orbital water movement from surface wave action and in deeper waters with strong currents, where standard stereo-BRUV systems cannot operate. When weights are removed, either system can be safely carried by two people (i.e. <35kg). In the stereo system, each pair of cameras is separated by 500mm, with the top camera in each pair angled 8° downward and the bottom camera horizontal (Figure 2c) to provide adequate separations and overlap of imagery (Langlois et al., 2020). In the stereo version, eight horizontally facing cameras are secured to brackets aligned in four stereo pairs at 90° intervals (Figure 2d), and an optional downward-facing camera can be mounted within the buoyancy compartment to collect more traditional imagery (Figure 4 [left]). Four LED lights can be secured to brackets for sampling in low light conditions. In the stereo version, camera brackets are secured to a common central column (Figures 2a and 4 [left]) and removed from the outer frame to reduce the risk of any physical impacts on the outer frame compromising the stereo-calibration. Continuous filming for 12h can be achieved without opening the camera housings until the end of the day by using small-form action cameras with external battery packs and large capacity memory cards. This reduces risks to equipment, calibration stability, and substantially increases efficiency in the field. Further information on cameras and photogrammetry is provided in Supporting Information S1.

The BOSS design, of the stereo version in particular, is also suited to the inclusion of additional sensors. Thompson et al. (2024) has demonstrated how a suite of sensors can be integrated into a BOSS sampler, including CTD (Conductivity, Temperature and Depth), dissolved oxygen, Chl-a and turbidity, and Niskin bottles to collect water and eDNA. These sensors can be controlled to sample at the seabed using a standard oceanographic rosette control unit.

2.3 | Sampling design

Using sampling strategies appropriate for the study objectives will allow valid inferences, interpretations, and generalisation of resulting data (Robertson et al., 2013). For surveys of habitat composition to ground-truth remote sensed data or existing spatial predictive models, we recommend spatially balanced a priori stratification of survey locations as per Balanced Acceptance Sampling (BAS) or Generalised

FIGURE 4 Lighter weight mono-configuration wide-field drop camera system being deployed by hand (left) and stereo-configuration wide-field drop camera system deployed from a commercial fishing vessel fitted with a ‘pot tipper’ (right).

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Randomised Tessellation Structures (GRTS) (Robertson et al., 2013). BAS and GRTS approaches can be implemented using R packages 'MBHdesign' (Foster et al., 2020) or 'spsurvey' respectively (Kincaid et al., 2007). We provide an example sample design workflow (globalarchivemanual.github.io/CheckEM). Minimum separation distance is dependent on the spatial heterogeneity in the acquired data and should be tested during statistical analysis with spatial variograms, and any significant autocorrelation considered (Robertson et al., 2013). Balanced designs provide the optimal outcome between robustness and practicality. Furthermore, a direct comparison of mapping outcomes using preferential and spatially balanced survey designs conducted simultaneously and in the same area demonstrates that balanced designs lead to significantly higher map accuracy, even when using only half the number of samples compared to preferential surveys (Mastrantonis, Langlois, et al., 2024).

2.4 | Field logistics

We recommend the drop camera be deployed for a standard duration, with trials indicating 5 min bottom time allows any sediment suspended during the landing to settle, resulting in clear footage of the habitat. Shorter deployments may be sufficient for areas with limited sediment, and the ideal deployment length should be determined based on study objectives. Local fishing vessels fitted with trap retrieval equipment such as a swinging davit arm or a 'pot-tipper' and winch are ideal for deploying and retrieving both the stereo and mono-video systems, especially in deeper waters (Figure 3). These vessels are usually suited to the local sea conditions, and the involvement of experienced commercial skippers may provide valuable logistical and local knowledge. Due to the weight of the stereo-system with weights attached (~50 kg), we strongly encourage the engagement of commercial fishers and deckhands who are experienced at deploying weighted traps and their expertise will be beneficial and likely result in better Occupational Health and Safety outcomes. A field deployment checklist is provided in Supporting Information S2.

2.5 | Metadata collection

Metadata should be collected to ensure that imagery can be georeferenced and needs to be maintained throughout the planning, fieldwork, imagery download, and annotation phases to ensure data quality. Examples of metadata requirements are provided in Supporting Information S3.

2.6 | Image synchronisation, compositing, and stereo-calibration

To ensure that the imagery from each camera can be effectively composited to be viewed simultaneously, both the lightweight mono-video and the larger stereo-video drop camera systems require synchronisation. In particular, for stereo-video imagery, we recommend a minimum of four intermittent synchronisations should be done throughout the day. We propose the use of a flexible strip of waterproof LED lights, for synchronisation, to generate a simultaneous flash in the fields of view of all eight or four horizontally facing cameras (Figure 2c). We provide wiring diagrams for this synchronisation hardware in Supporting Information S4. Video from each set of four horizontally facing cameras must be synchronised and composited into a single video stream (Figure 5). We recommend using VidComp software which is freely available from seagis.com.au. For the stereo-video version of this platform, the use of a video composite is formed from standard fields of view, to minimise barrel distortion, rather than the typical 360° image which is formed using 'fish-eye' or 'omnidirectional' lenses. Standard lenses result in a less distorted image that is more suitable for stereo-calibration. For the stereo-video calibration procedures, we recommend the widely used and supported SeaGIS CAL (seagis.com.au/bundle.html) software and recommend calibrating cameras frequently, before and after each field campaign (e.g. every 2 weeks or 300 deployments). Frequent calibration will ensure against loss of stereo capability which could come from camera misalignment or swapping of cameras (i.e. optical properties vary within camera models).

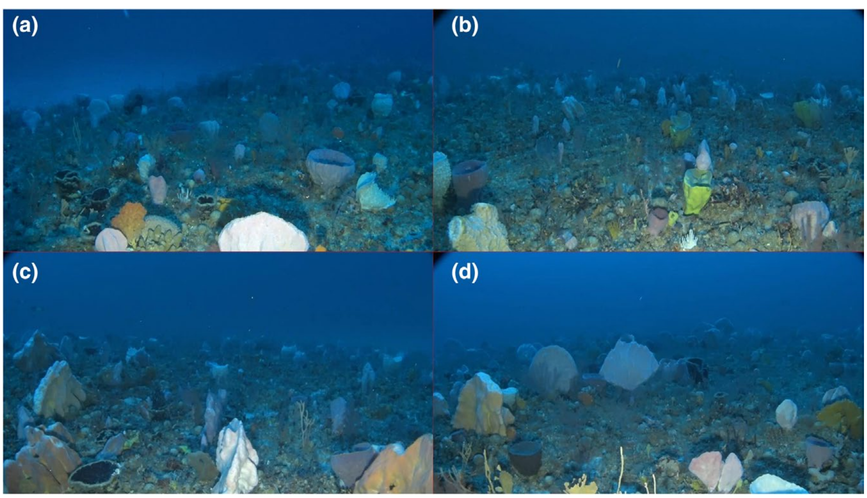

FIGURE 5 Synchronised and composited imagery from four horizontal cameras.

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2.7 | Image annotation

2.7.1 | Annotation software

There is a range of readily available image annotation software and platforms available such as TransectMeasure (seagis.com.au/transect.html), Squidle+ (squidle.org), CoralNet (coralnet.ucsd.edu), BenthoBox (benthobox.com), and ReefCloud (reefcloud.ai), all of which are suitable for mono-video annotation. For stereo-video annotation, we have used SeaGIS EventMeasure (seagis.com.au/event.html) and recommend this as a widely used and well-supported software workflow for stereo-annotation and measurement.

2.7.2 | Image annotation

For horizontally facing wide-field imagery, we recommend annotating 20 random points assigned to the lower 50% of each image. We provide example annotation and quality control workflows (globalarchivemanual.github.io/CheckEM/). A simulation study of point annotation of downward-facing imagery found that 20 points would provide an adequate estimate of variance in benthic assemblage composition whereas 80 points would provide a highly consistent estimate (Dumas et al., 2009). Similarly, for the horizontal-facing images collected by the BOSS, we explored the implication of annotating one field of view, using 20 points, to up to four fields of view, a total of 80 points, across multiple independent tropical, subtropical, and temperate locations (Supporting Information S5). We found generally more precise estimates of habitat composition using 40–80 points by annotating two to four fields of view, justifying our recommendation to annotate the combined field of view (~270°) of the four cameras to characterise benthic composition.

For annotation of benthic composition, we recommend the CATAMI (Althaus et al., 2015) as the base classification schema, which classifies organisms into standardised morphological groups. This schema is also recommended for similar marine sampling protocols for towed video, ROVs, AUVs (Przeslawski et al., 2023) and benthic composition from BRUV (Langlois et al., 2020). We provide a controlled extended repository of CATAMI formatted for use in TransectMeasure available at github.com/GlobalArchiveManual/CheckEM/tree/main/annotation-schema, which also includes species-specific annotation for certain common and easily identifiable taxa from the CAAB classification schema relevant to Australia (Rees et al., 1999). Also included is an annotation schema for visual estimates of structural complexity or relief (see Langlois et al., 2020).

2.8 | Quality control and data curation

Quality control and data curation workflows are vital to ensure data is findable, accessible, interoperable and reusable (FAIR, Wilkinson et al., 2016). All corrections should be made within the original annotation files to ensure data consistency over time. We recommend the following approaches to ensure quality control:

- Annotators should complete small identical 'training' image sets where habitat classes are known, to assess competency and benchmark accuracy.
- Quality assurance should be carried out by a senior analyst and involves a randomised review of 10% of annotated images and data within a project. If accuracy is below 95% for all identifications, imagery should be re-annotated.
- All annotators should meet periodically as a group to discuss image classification to ensure that consistency is maintained throughout the project.

We propose a series of simple visual quality control plots to identify outliers and provide examples of these in the annotation guide (globalarchivemanual.github.io/CheckEM/, Figure 1).

3 | CONCLUSION

The need for marine spatial planning and concerns about the environmental impacts of anthropogenic activities (including climate change, pollution and offshore industries) has led to a growing requirement for large-scale habitat characterisation to inform management, through mapping or environmental assessments. The drop camera system described here is robust, wide-field, and horizontal-facing, in either the stereo or mono-video variations. It is specifically designed for rapidly collecting benthic habitat composition and has been demonstrated to improve habitat quantification across a range of depths from 2 to 220 m. The system is ideal for collecting spatially balanced point samples over large areas. Other survey platform methods face logistical restrictions, such as long deployment times (e.g. stereo-BRUVs), a limited number of ascents (e.g. scuba) or the need to be tethered or supported along transects with a finite time underwater (e.g. ROV, AUV). These limitations typically lead to nested or spatially constrained sampling (Monk et al., 2018; Shortis et al., 2008). Around Australia, the application of this method is rapidly expanding, with large-scale deployments now visible at a national scale (i.e. Supporting Information S6), assisting with the creation of robust bio-regional scale habitat maps. The optional use of stereo-cameras enables the usable area of the image and range of observation to be quantified and included as an offset in analysis (e.g. when turbidity varies amongst sites, Broad et al., 2023). Photogrammetry of stereo images also enables the measurement of additional metrics such as algal canopy height or the dimension of benthic biota (Langlois et al., 2021; Vergés et al., 2016).

The potential contribution of the BOSS platform to marine ecology is large, the cost-effective in-situ acquisition of habitat data across large-scale areas is highly useful for medium to large-scale habitat mapping and monitoring (Ballantine et al., 1973; Kerr & Grace, 2005), ground truthing of remote sensing imagery (Mastrantonis, Radford, et al., 2024), detection of recovery in benthic

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biota after trawling (Langlois et al., 2021), and environmental impact assessments of man-made structure such as emerging industries including offshore renewables (LaFrance et al., 2014).

AUTHOR CONTRIBUTIONS

Tim Langlois, Rick Starr, John Fitzhardinge, Kingsley J Griffin, Claude Spencer and Brooke A Gibbons conceived the ideas and designed the methodology; Tim Langlois, John Fitzhardinge, Kingsley J Griffin, Claude Spencer, Brooke A Gibbons, Jacquomo Monk and Neville Barrett collected the data; Claude Spencer, Kingsley Griffin and Tim Langlois analysed the data; Tim Langlois, Claude Spencer and Jacquomo Monk led the writing of the manuscript. All authors contributed critically to the drafts and gave final approval for publication.

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DATA AVAILABILITY STATEMENT

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SUPPORTING INFORMATION

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

Data S1: Camera and photogrammetry.

Data S2: Field deployment checklist.

Data S3: Metadata format and file organisation.

Data S4: Synchronisation diode.

Data S5: Effect of increasing number of fields of view or annotation points on habitat observations and cost of data collection.

Data S6: Large-scale deployments in Seamap Australia.

Data S7: References used in Supporting Information.

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