Methods in Ecology and Evolution
July 2016, Volume 7, Issue 7, Pages 843-852
http://dx.doi.org/10.1111/2041-210X.12540
http://archimer.ifremer.fr/doc/00319/42984/

An experimental comparison of three Towed Underwater Video Systems using species metrics, benthic impact and performance

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Abstract :

1. Managing ecological systems, which operate over large spatial scales, is inherently difficult and often requires sourcing data from different countries and organizations. The assumption might be made that data collected using similar methodologies are comparable, but this is rarely tested. Here, benthic video data recorded using different towed underwater video systems (TUVSs) were experimentally compared.

2. Three technically different TUVSs were compared on different seabed types (rocky, mixed ground and sandy) in Kingmere Marine Conservation Zone, off the south coast of England. For each TUVS, species metrics (forward facing camera), seabed impact (backward facing camera) and operational performance (strengths and limitations of equipment and video footage) were compared with the aim of providing recommendations on their future use and comparability of data between different systems.

3. Statistically significant differences between species richness, density, cover and assemblage composition were detected amongst devices and were believed to be mostly due to their optical specifications. As a result of their high image definition and large field of vision both the benthic contacting heavy and benthic tending TUVS provided good quality footage and ecological measurements. However, the heaviest TUVS proved difficult to operate on irregular ground and was found to cause the most impact to the seabed. The lightest TUVS (benthic contacting light) struggled to maintain contact with the seabed. The benthic tending TUVS was able to fly over variable seabed relief and was comparably the least destructive.

4. Results from this study highlight that particular care should be given to sled and optic specifications when developing a medium- or long-term marine protected area monitoring programme. Furthermore, when using data gathered from multiple sources to test ecological questions, different equipment specifications may confound observed ecological differences.

5. A benthic tending TUVS is recommended for benthic surveys over variable habitat types, particularly in sensitive areas, such as marine protected areas.

Keywords : environmental management, marine protected area, meta-analyses, sampling impact, towed video, underwater imagery

Introduction

The health of marine ecosystems that deliver resources and services is now of international concern as a result of increasing pressure from human activities (Halpern et al. 2008). Governments from different countries and management organisations bordering shared water bodies often need to work together to manage the marine environment. For the purpose of understanding and managing systems over large scales, data from different sources need to be utilised for studies relating to e.g. marine renewables, fishing impacts and marine protected areas (MPAs) (Inger et al. 2009; Collie et al. 2000; Worm et al. 2006; Stewart et al. 2007). The assumption might be made that data collected using similar methodologies are comparable but this is rarely tested. An experimental trial was therefore undertaken to assess the comparability of data recorded using different Towed Underwater Video Systems (TUVSs), and to make monitoring recommendations for future users.

Preservation of MPAs that exclude destructive and economically lucrative activities requires justification of their effectiveness to stakeholders and governments. This can be achieved by monitoring and reporting any resulting changes in ecosystem processes and services (Rees et al. 2013). In recent years, the number, size and coverage of MPAs has increased rapidly as governments around the world strive to meet international targets to protect the world‟s oceans (Spalding et al. 2013; Singleton & Roberts, 2014). As a consequence of the growing size and coverage of MPAs, monitoring the features within such vast areas, and collecting meaningful data to assess changes over time, poses both financial and logistical constraints. Limited budgets to survey MPAs (Ehler, 2003) require survey methods to be cost effective and provide robust data that can have multiple uses and users (i.e. uses: assess local habitat recovery and contribute to national ecosystem service assessment; users: organisations, such as universities, consultancies or government agencies; regions and countries).

Analysis of underwater imagery is used to enumerate species abundance, diversity and behaviour (Machan & Fedra, 1975; Hughes & Atkinson, 1997) and characterize habitats to help managers identify and manage vulnerable communities (Larocque & Thorne, 2012; Fabri et al. 2013). Cost-effective MPA video monitoring programmes have been developed to detect management effectiveness on seabed habitats (Sheehan et al. 2013 a & b) and on fish abundance and size (Assis et al. 2007, Tessier et al. 2013), helping managers to evaluate and adapt their policies (Stevens et al. 2013).

To capture benthic footage, video can be deployed in numerous ways, including: "drop cameras" for stationary imaging of multiple small areas; Remotely Operated Vehicles (ROV); Autonomous Underwater Vehicles (AUV); manned submersibles (Fabri et al. 2013) or Towed Underwater Video System (TUVSs) with continuous video recording along a transect (all systems are reviewed in Rooper, 2008).

The most commonly used design for TUVSs is a weighted system using skids or runners that contact the seabed ("benthic contacting"; Machan & Fedra, 1975; Hughes & Atkinson, 1997; Spencer et al. 2005; Stoner et al. 2007). The platform stability of such TUVSs provides a fixed field of view from the video camera; however, these TUVSs are limited to fairly homogenous seabed types as they are prone to snagging on rocks and can damage the seabed (Sheehan et al. 2010).

An alternative TUVS design is a "benthic tending" design (for example see Sheehan et al. 2010). Such a TUVS is suspended above the seabed by the counterbalance of weight and buoyancy, with a ground chain providing the only seabed contact to achieve a stable specified altitude. The sled is typically towed at slow speed or allowed to drift with prevailing currents. The advantage of this type of system is that it can be designed to work over rugged ground, theoretically having less impact than benthic contacting sleds. Successful operation of these systems, however, is technically more challenging resulting from the need to achieve neutral buoyancy and constant height above the seabed in variable conditions (Rooper, 2008).

Three technically different TUVSs were tested together at one location where three habitat types could be sampled: rocky, mixed ground and sandy. The following criteria were assessed: Data comparability of species metrics (Number of taxa, Density, Cover and Assemblage composition), Impact of sled and Performance (operation and video).

Methods

Study site and experimental design

TUVSs were compared in Kingmere Marine Conservation Zone (MCZ, designated under the UK Marine and Coastal Access Act 2009), a 48 km^2 MPA in 20 m water depth, 5 km off the south coast of England (Fig. 1). Sampling was undertaken from 2nd - 13th September 2013 using an 18 m vessel (owned and skippered by Sussex IFCA).

To compare species metrics derived from the video, the impact of each TUVS, and TUVS performance over different habitats, three habitat types were selected using a broad scale habitat map, echo-sounder and local knowledge of the IFCA skipper: (1) rock and chalk outcropping reef “Rock”, (2) boulders, cobbles and stones on sediment “Mixed”, and (3) sandy habitats “Sand”. For each habitat type, two areas within the MCZ were selected (Fig. 1), though only one area was identified for “Sand”. In each area, for each TUVS three 200 m video tows were recorded. The skipper used the echo-sounder to ensure that tows were positioned on the correct habitat type. Tows were haphazardly interspersed between TUVSs to ensure that comparable benthic habitats were assessed. Tows were located a minimum distance of 350 m apart to ensure that replicates did not overlap each other.

Species data comparability was assessed using footage from forward facing cameras. To assess benthic “Impact” on the seabed and associated fauna, a backwards facing HD Hero2 GoPro camera was mounted on each TUVS.

“Performance” (operation and video) was assessed throughout the field trial and subsequent video analysis. Equipment specifications (camera, lights, lasers, CTD (Conductivity/Temperature/Depth), frame, connection to hardware on the boat, power supply, sled dimensions, weight and cost), Operational performance (no. of tows per day, potential deployment in wind and tide, deployment requirements and operator skill required) and Video performance (speed, camera angle, image quality, information on screen and field of view) were assessed using the following scale : 1. Room for improvement (criteria were identified that should be amended for future benthic video survey), 2. Fit for purpose (criteria were suitable for good quality benthic video survey or 3. Recommended (criteria were suitable for excellent quality benthic video survey).

TUVS specification and deployment procedures

Two benthic contacting sleds, one heavy “BCH” and one light “BCL”, and one benthic tending sled “BT” were compared. Both benthic contacting sleds had two runners while the benthic tending sled had one ground chain (Fig. 2).

Cameras were positioned forward facing at an oblique angle to the seabed (BCH: 35°, BCL:50°, BT:30° to the horizontal) to optimise mega- and macro epi-benthic species identification while maximising the field of view. All TUVSs were fitted with lights set to illuminate the field of view and two laser pointers were mounted on each TUVS as a scale to quantify the field of view (see Appendices Table 1).

Benthic Contacting Heavy (BCH): This TUVS was developed for opportunistic deployment on existing stock assessment surveys. It was designed to withstand all types of sea conditions, currents and depth ranges on the European continental shelf (i.e. down to 600 m depth), and to be easily operated by non-specialist staff. The TUVS comprises a large stainless steel sled (Length: 1500 mm, Width: 1100 mm, Height: 740 mm, Weight: 290 kg, Total cost: €14,000). There is no cable connection of this TUVS and so sensors are set before deployment. Sensors include a 600 m depth rated anodised aluminium housing able to contain any off the shelf camcorder (here, a Panasonic HC-V700 High Definition 1920 x 1080 p -50 fps, with a 32 GB SD card recording up to 3 hours); two LED lights (underwater LED SeaLite® Sphere, SLS 5100, 20/36 V, 80 W, 5000 Lumens) were fixed to the sled on each side of the camera; Two laser pointers (SeaLasers® 100 Dualmount, wavelength 532 nm Green) set 100 mm apart; two subCtech Li-Ion PowerPacks to power lights and lasers (25Ah, 24V, ~4h autonomy). The weight of this TUVS meant that a winch and three personnel were required to deploy it.

Benthic Contacting Light (BCL): This small TUVS was designed for inshore MPA monitoring within shallower waters (<50m depth). An umbilical was connected to a RovTech system topbox comprising a power supply, light control, recording facility and GPS feed. This enabled real time footage to be viewed from the surface. The BCL TUVS comprises a small stainless steel sled (Length: 820 mm, Width: 495 mm, Height: 430 mm, Weight: 9 kg, Total cost: €12,000). Mounted on the sled was a Seacam ultra wide-angle colour camera, one LED light and lasers set 200 mm apart. This TUVS represents a relatively cheap method of surveying the seabed for authorities, which may just need to e.g. ground truth habitat, and therefore, do not require a HD camera, and the associated fibre optic cable and expensive lights. Deployment of this TUVS was simple and required minimal personnel (one to deploy the sled and one to monitor the video) and training.

Benthic Tending (BT): This TUVS was designed to fly above heterogenous seabed to monitor sensitive habitats. The umbilical used here was 250 m, which limits it to 150m. The umbilical was connected to a Bowtech System control unit, which allows control of the camera (Surveyor-HD-J12 colour zoom titanium camera, 6000 m depth rated, 720 p) focus, zoom and aperture, the intensity of three lights fixed to the array in front of the camera (Bowtech Products limited, LED-1600-13, 1600 Lumen underwater LED) and a mini CTD profiler (Valeport Ltd). Two battery powered laser pointers (wavelength 532 nm Green) set 300 mm apart were also mounted either side of the camera. The frame was made from aluminium with high strength plastic ballast tubes and ground chain (Sled: Length: 700 mm, Width: 700 mm, Height: 400 mm, Weight: 30 kg; Ballast tubes: Length: 130 mm, Depth: 100 mm; Chain: L: 3150 mm, W: 33 mm, Weight: 10 kg, Total cost: €35,000). The system floats above the seabed and altitude is controlled using a drop-weight between the boat and the sled, and a length of rope that acts as a weak-link between the sled and the ground chain. A tow rope was used to reduce strain on the cable (detailed methods are described in Sheehan et al. 2010). The BT TUVS is easy to deploy, though perhaps more technical to tow than the benthic contacting TUVSs to achieve good quality video. New skippers often need to practice in shallow sheltered habitats before attempting more extreme conditions. The BT TUVS is best retrieved using a winch or pot hauler due to the heavy drop-weight.

Video analysis

Data comparability: To eliminate observer bias contributing to differences between datasets, the same person analyzed the video from all three TUVSs. To analyze the video, frame grabs were extracted at five second intervals and a digital quadrat overlaid (5x5 matrix) (Cybertronix frame extractor). The file format from the BCH TUVS was not compatible with the frame extracting software and so frame grabs were extracted manually at 5 second intervals. Frame grabs were discarded if they were not in focus, overlapped each other, or were not on the appropriate habitat. After this process, 10 randomly selected frame grabs were analysed for each transect.

All organisms present were identified to the lowest taxonomic level possible and their abundance recorded. Taxonomically similar species, which could not be distinguished with confidence, were grouped. Such groups included: *Inachus* spp. (Weber, 1795) and *Cerianthus* spp. (Delle Chiaje, 1830) (identified to genus level); Gobies; Hydroids and Branching sponges. It was concluded that hydroids could not be accurately counted for each TUVS and so were excluded from the density analysis. The category "Turf" incorporated hydroids and bryozoans that were <1 cm high. Individual or discrete colonial organisms were expressed as densities (individuals m^{-2}). Densities were calculated using the laser scaling on each TUVS (BCH: 100 mm, BCL: 200 mm, BT: 300 mm). The BC TUVS have a fixed field of view per frame grab as the camera is at a set distance from the seabed. The BT TUVS has a variable altitude and consequently variable field of view; hence the frame area was calculated per frame grab (See Appendices Table 2.). Cover-forming colonial taxa and Turf were quantified as percent cover using the number of dots from the overlay that each taxon covered. As the camera angle on the BCL was set at 50° a proportion of the frame was open water. To account for this, the mean frame area of open water from the 10 frame grabs for each tow was used to correct the percent cover data so that values were not underestimated.

Impact: To assess impact of each TUVS on the seabed, footage from the backward facing HD Hero2 GoPro was analysed by a single analyst using a bespoke ordinal scale. Where 0 = no impact, 1 = fine sediments disturbed, 2 = stones disturbed, 3 = cobbles disturbed and sediments re-suspended (Fig. 3). Grain size was modified after the Wentworth Scale (Irving, 2009). Scores 2-3 were cumulative, e.g. if score 3 is awarded for cobbles being disturbed, this suggests that stones were also disturbed. Five 1 minute observations were made, haphazardly selected throughout each tow, and scored based on visual assessment of the seabed disturbance.

Data analysis

Data comparability: For each habitat type, two areas were identified (only one was identified for sand) and three transects were recorded for each TUVS, giving 6 replicates per TUVS within each Habitat. A replicate constituted the average of data from 10 frame grabs for each transect. After examination of data distribution number of taxa and density were left untransformed, while the cover data were transformed using arcsine transformation ($y' = arcsin\sqrt{y}$) (Legendre & Legendre, 2012). Permutation Analysis of Variance was preferred as it is deemed a distribution-free non parametric test (Anderson, 2001). For univariate response variables, we used two-way permutation ANOVAs between two fixed factors that both had three levels: TUVS (BCH, BCL and BT) and Habitat type (Rock, Mixed and Sand). The significance level for this statistic was set at p-values ≤0.001 with 9999 permutations. Permutation ANOVA tests were completed by computing effect size values from Generalised Linear Models (Nakagawa & Cuthill, 2007) corresponding to TUVS and habitat types multiplicative effects. Poisson and quasi-poisson distributions were chosen for number of taxa and density response GLMs respectively while Gaussian distribution was applied to arcsine-transformed cover data. Mean and confidence intervals for each effect were computed and marked effects were compared to the statistical significance levels obtained in permutation ANOVA in R. These univariate analyses were implemented in R (R-3.2.1, 2015) using the vegan (Oksanen et al. 2015) and effects (Fox, 2003) packages.

For each metric raw values, the mean (SD) were reported and data distribution were plotted as a function of habitat and TUVS type by the mean of standard boxplot.

Permutational Multivariate Analysis of Variance in PRIMER 6 (PERMANOVA, Anderson, 2001; Clarke & Warwick, 2001) was used to test for differences in multivariate response variable (Assemblage composition) between the same factors as above. Multivariate data (Assemblage composition) were square root transformed and based on the Bray Curtis similarity index (Bray & Curtis, 1957).

Impact: Ordinal scale scores were averaged for each transect. Mean scores ± standard deviation (SD) were plotted on the y axis of a histogram. To account for the different sized footprint of each TUVS, the width of histogram bars represented the width of each TUVS benthic contact point (BCH 2 x 0.12 m runners = 0.24 m, BCL 2 x 0.05 m runners = 0.1 m, BT 1 x 0.033 m chain). The corrected scale reported (mean and SD) is the original score multiplied by the total width of contact for each TUVS.

Results

All three TUVSs surveyed all habitat areas within Kingmere MCZ (Fig. 1). A total of 80 taxa from nine different phyla were recorded. Common taxa on sand included hydroids and the sand mason worm *Lanice conchilega* (Pallas 1766). *L. conchilega* was also common on mixed ground along with the calcareous tube worm *Spirobranchus triqueter* (Linnaeus, 1758) and dead man's fingers *Alcyonium digitatum* Linnaeus, 1758. *A. digitatum* was also recorded on rock habitat, along with several algae and bryozoan species such as *Phyllophora crispa* (Hudson) P.S Dixon, 1964 and *Cellaria fistulosa* (Linnaeus, 1758).

Data comparability

Number of taxa

Trends in the number of taxa differed between TUVSs and Habitat (Fig. 4a; Table 1). On Rock, the BCL TUVS recorded statistically significantly less taxa than the other two TUVSs (BCH 6 (1.5) m^{-2}; BCL 3.3 (1.9) m^{-2}; BT 6.6 (1.7) m^{-2}). On Mixed ground, the number of taxa for the BCH and BT TUVSs were similar and both were greater than the number of taxa observed using the BCL TUVS (BCH 4.2 (1.9) m^{-2} ; BCL 1.3 (1.2) m^{-2}; BT 4.6 (1.9) m^{-2}). On Sand, however, the number of taxa observed was similar for all three TUVSs (BCH 3.1 (1.1) m^{-2}; BCL 2.3 (1.3) m^{-2}; BT 2.1 (1.5) m^{-2}). These results were comparable to those obtained from effect size value comparison that also highlighted the lower performances of BCL on rock and mixed sediment habitats (Appendices Table 1A).

Density

Trends in the mean density mostly differed between habitat types (Fig. 4b; Table 1). Density was greater on the Rock habitat than Mixed and Sand for all TUVSs (Rock: BCH 68.7 (33.5) nb.m^{-2} ; BCL 52.0 (46.1) nb.m^{-2}; BT 67.1 (48.8) nb.m^{-2}; Mixed: BCH 30.1 (31.6) nb.m^{-2}; BCL 12.5 (18.3) nb.m^{-2}; BT 23.3 (24.6) nb.m^{-2}; Sand: BCH 43.2 (29.0) nb.m^{-2}; BCL 13.3 (15.0) nb.m^{-2}; BT 19.8 (25.0) nb.m^{-2}). Pairwise analyses, however revealed that the BCH TUVS generally yielded statistically significantly higher densities on mixed and sand grounds. Effect size value comparison also confirmed these results (Appendices Table 1B).

Cover

Trends in the surface cover of colonial organisms observed differed between TUVS and Habitat (Fig. 4c; Table 1). On Rock and Mixed ground, the mean percent cover recorded by the BCH and BT TUVSs was similar and both were greater than the mean cover observed using the BCL TUVS (Rock: BCH 36.4 (13.8) %.m^{-2}; BCL 6.8 (13.7) %.m^{-2}; BT 41.8 (17.3) %.m^{-2}. Mixed: BCH 15 (10.2) %.m^{-2}; BCL 3.2 m^{-2} (7.1) %.m^{-2}; BT 21.6 (14.0) %.m^{-2}). On Sand, however, while the BCH TUVS recorded the greatest mean cover, no statistical difference was detected (BCH 2.5 (4.2) %.m^{-2}; BCL 0.3 (1.7) %.m^{-2}; BT 1.0 (2.9) %.m^{-2}). Here again the analysis of the effect size value confirmed the lower performance of the BCL on rock and mixed grounds (Appendices Table 1C).

Assemblage composition

The assemblage composition observed at each habitat and TUVS was statistically significantly different (Fig. 5; Table 1), however, data from the BCH and the BT TUVSs were more similar to each other than to the BCL TUVS (see nMDS plot Fig. 5).

Impact

BCH: Visually assessing the damage impact of this TUVS proved difficult as the sediment plume was often so large that the seabed was obscured from view. The rocky ground in Kingmere MCZ had large boulders and fragile associated sessile benthos. Consequently, it was decided that this TUVS was too damaging and prone to snagging to complete the planned transects. Due to this, the BCH TUVS only completed 2 replicates on rock rather than the 6 originally planned. When the TUVS did come into contact with large cobbles, the size and weight of the TUVS dislodged encrusting and sessile species (such as sponges); thus, it received a mean (standard deviation) score of 0.96 (0) on the corrected impact scale for rock. Mixed ground was the best habitat type for this TUVS and visibility was better than on sand, but overall it was still difficult to assess damage impact. Where visibility was clear, tracks were noticeable from the runners - overall the TUVS scored a mean corrected impact value of 0.9 (0.1) for mixed ground. On sand, it was very difficult to see any damage impact as the plumes caused from disturbed sediments clouded the field of view. This TUVS scored a mean corrected impact score of 0.48 (0) for this habitat (Fig. 3 & 4d).

BCL: As this TUVS was light, the damage impact from this sled was relatively low. On rock, this sled was not heavy enough to maintain contact with large boulders, and as a result it flew through the water column and did not spend much time on the seabed. Occasionally, it would collide with large cobbles, which caused damage to some sponge species and ross coral *Pentapora foliacea* (Ellis & Solander, 1786). However, because of the weight of the TUVS, it rarely disturbed large cobbles - hence was awarded a mean corrected impact score of 0.33 (0.05) for rock. On mixed ground, this TUVS generally ran across the top of stones, only dislodging them occasionally – resulting in a mean corrected impact score of 0.24 (0.07) for this habitat. On sand, it received a mean corrected impact score of 0.2 (0) as it disturbed fine sediments, but only created small plumes (Fig. 3 & 4d).

BT: This TUVS was the most consistent on all habitat types. The advantage of the BT TUVS is that it had only one point of contact with the seabed. This TUVS flew better over the rock habitat than the other TUVS, consistently staying on the seabed. Occasionally, this sled disturbed large cobbles when the chain became stuck, but this was rare and generally large cobbles were undisturbed. The chain itself caused some disturbance, dislodging some sponges and ross coral, resulting in a mean corrected impact score of 0.11 (0.02) for rock habitat, 0.10 (0) and for mixed. The impact of this TUVS on sand was relatively low, with a corrected mean score of 0.07 (0) as it disturbed fine sediments creating relatively small plumes (Fig. 3 & 4d).

Performance (operation and video)

Below is a summary of the equipment specification and performance for operation and video. The complete breakdown of the scores is shown in Appendices Table 2.

Equipment specification scores out of 27: BCH (24), BCL (19), BT (25)

The quality of the HD cameras and lighting on both the BCH and the BT were of a high enough standard to recommend to future users while the BCL was not HD, which made a difference to the image quality for analysis (Fig. 6). The main difference of equipment between the three TUVS was that the BT surface connection allowed real time viewing with remote adjustment of the camera focus, zoom and lighting intensity, this allowed the quality of the footage to be maximised as conditions and habitat changed throughout a transect and any obstacles to be avoided.

Operational performance scores out of 15: BCH (12), BCL (10), BT (11)

All three TUVS scored similarly on operational performance, with variability in the scores related to potential deployment in wind and tide and the level of operator skill required to work the equipment. BCH was the most labour intensive to deploy, due to its size and weight, but this allowed it to have a greater potential for deployment in greater depth, wind and tide conditions. The BCL was the simplest to deploy as this could be done by hand, but it required constant attention throughout the transect in rocky areas to avoid getting snagged. The BT was relatively straightforward to deploy, but inexperienced users required some familiarisation with the bridle set up and the hardware prior to deployment.

Video performance scores out of 15: BCH (14), BCL (5), BT (13)

The BCH had a better image quality and camera positioning whilst filming thus resulting in a large exploitable field of view. However the quality of images of both BCH and BCL TUVSs could be affected by irregular towing speed during the transects as uncontrolled fast speed resulted in blurred images. In contrast the BT tended to maintain a constant speed as a result of the skipper‟s ability to monitor the video screen. The light weight of the BCL frame resulted in the sled rarely being flat on the seabed, particularly when towed at speed. This resulted in the camera frequently pointing outwards rather than towards the seabed, making identification of benthic fauna difficult.

Discussion

Data comparability

The results of this experimental trial demonstrated that, despite the three TUVSs recording transects from comparable habitats, statistically significant differences in benthic metrics were recorded. The BCL TUVS recorded consistently lower values for each univariate metric compared to the other TUVSs across all habitat types. These differences were not statistically significant on Sand, however, where the three TUVS performed most similarly, presumably as a result of Sand being the most homogenous habitat. Likewise, in a study comparing different habitats and image resolutions, results from „Simple‟ sandy habitats were found to be more similar than those from „complex‟ reef (Coggan et al. 2007). The BCL

TUVS was the only non HD camera and so it was expected to not perform as well as other systems as analog cameras have lower image quality (Harvey et al. 2010). The weight of the BCL also meant that on complex habitat, the sled spent little time on the seabed and often was pointing up into the water column. Combined with the difference in resolution from a HD camera, data users of remote cameras should be aware that lower quality footage is likely to yield relatively lower species metrics than those with greater video quality and operational performance.

More encouragingly, the BT and BCH TUVS tended to record similar and higher values for univariate metrics across the different habitat types, indicating that data collected from these two systems were more comparable and valuable for ecological measurements. The BCL sled also recorded a markedly different assemblage composition than BCH and BT TUVS. This further indicated that the BCH and BT TUVSs were most comparable for sharing survey data. Even after standardisation, species richness is known to be related to the area sampled (Gotelli & Colwell, 2001), therefore, differences in the average field of view and image resolution of the different TUVS could explain the observed differences.

Differences observed in benthic metrics between video transects recorded using three different TUVS has therefore highlighted a potential issue when combining data from different video equipment to compare species metrics between treatments, places or times.

Impact

Despite similarities in the data collected between the two largest TUVSs, the Impact of the gear on the seabed was markedly different. Across habitat types the BCH TUVS caused more damage than the other two TUVSs, while the BT had the least impact. While heavy benthic contacting TUVSs can still be suitable within areas where demersal trawling generally occurs (most of the shelf area), monitoring rocky reefs (boulders over 1m) requires benthic tending systems (or drop down). Benthic tending systems would be particularly more appropriate for operation in sensitive habitats such as MPAs where any damage to the seabed needs to be avoided and to monitor habitat recovery.

Performance (operation and video)

Deployment ease was often related to the weight of the TUVS. The lighter TUVS was easily deployed and recovered, but the heavier TUVS was found to be more stable on the seabed, and would be suitable for deployment during more severe weather conditions and larger tides. The benefit of the BCH TUVS was that the height above the seabed was constant and the technology and power was housed on the sled so there are few surface requirements, other than ensuring appropriate speed was maintained and that crew were alert to the potential of the gear snagging. While this sled was large, it could be modified to be lighter by adding floats, and therefore cause less impact, while maintaining constant contact with the seabed still collecting cost effective, high quality data. The main disadvantage of this TUVS was that the footage quality was unknown until the data were recovered and the risk of snagging over complex habitats was high. Benthic contacting TUVSs were not found to be operational on high rock boulders unless used only as drop down devices.

On the other hand, the BT TUVS proved to be extremely adaptable over a range of habitat types, and can be deployed over a range of weather and tide conditions. If the ground chain was to be snagged on wreckage or rocks, the weak link would ensure that it is only the chain that is lost while the expensive kit returns to the surface. If the seas were large or the tidal flow was strong, the equipment can be stabilised by adding to the drop-weight or chain. If the visibility is poor, the BT can be flown closer to the seabed. However, the BT sled was also the most expensive and complex system to set up. It is essential that benthic tending TUVSs are connected viewing hardware on the research vessel as they require constant monitoring to ensure that the height above seabed is appropriate, the camera is focused and that the camera does not snag on ghost fishing gear or rocks (Sheehan et al. 2010). This requires specialised staff that further increases the cost of deployment of this type of TUVS.

Conclusions

TUVSs provide a valuable, relatively non-destructive method to monitor habitat, biodiversity and human impact. TUVSs are cost-effective, simple to operate and survey, deployment and analysis protocols may be easily adapted. Archiving of videos allows for sharing and re-analyses of data whenever required (e.g. change in scope or methodology); however, not all TUVSs function the same and statistically significant differences in the measured benthic metrics were highlighted between each of the three gear types investigated. Rocky or sensitive seabed types were best surveyed using a benthic tending TUVS, where stable footage with relatively low impact can be achieved. On soft sediment areas, bottom contacting TUVS constitute a more cost-effective alternative assuming deployment and analysis costs are similar. Particular care should be given to sled and optics specifications when developing a middle or long term monitoring programme. Considering their significant impact on the data extracted from the video footage, it is not recommended to change the gear specifications over the monitoring period if the purpose of the study is to detect trends over time. For the purpose of combination of videos obtained from different TUVS specification, we recommend only using HD resolution and steady TUVS to enable unbiased comparison.

Acknowledgements

We would like to thank INTERREG IV A France-England cross-border European cooperation programme, co-financed by the European Regional Development Fund for funding this as part of the Protected Area Network Across the Channel (PANACHE) project. We would also like to thank Sussex IFCA crew, Ian Jones, Richard Larocque, Dr Anthony Bicknell, Dr David Rodriguez-Rodriguez and the anonymous reviewers for their help and contribution to the project.

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Table 1. Results of permutation ANOVA to test the differences in Number of taxa: Density (excluding hydroids) and Cover; between Habitat type and TUVS. Pairwise tests were used to examine statistically *significant interactions. Bold values indicate* statistically *significant differences (p<=0.001).*

Source	*df*	*Variance*	*F*	*P*	*Pair-wise comparison*	*F*	*P*	*F*	*P*	*F*	*P*
Number of taxa											
TUVS (TU)	2	1.23	87.58	**0.001**	*TUVS x Ha*	*Rock*		*Mixed*		*Sand*	
Habitat (Ha)	2	1.17	83.30	**0.001**	BCL, BCH	29.5	**0.001**	88.9	**0.001**	8.59	0.008
TU × Ha	4	0.36	12.89	**0.001**	BCL, BT	100.7	**0.001**	108.7	**0.001**	0.21	0.70
Residual	388	1.72			BCH, BT	1.54	0.23	0.98	0.38	10.0	0.003
Total	394										
Density											
TUVS (TU)	2	24.9	4.31	0.016	*TUVS x Ha*	*Rock*		*Mixed*		*Sand*	
Habitat (Ha)	2	358	61.87	**0.001**	BCL, BCH	*1.94*	0.162	12.04	***0.001***	25.0	**0.001**
TU × Ha	4	10.8	0.93	0.451	BCL, BT	3.04	0.082	6.60	*0.008*	1.48	0.238
Residual	388	1121			BCH, BT	0.0159	0.904	1.72	0.193	11.2	0.002
Total	394										
Cover											
TUVS (TU)	2	0.026	170	**0.001**	*TUVS x Ha*	*Rock*		*Mixed*		*Sand*	
Habitat (Ha)	2	0.024	156	**0.001**	BCL, BCH	63.8	**0.001**	72.7	**0.001**	7.90	0.009
TU × Ha	4	0.007	24.1	**0.001**	BCL, BT	185	**0.001**	141	**0.001**	1.70	0.281
Residual	388	0.030			BCH, BT	1.06	0.31	10.4	0.003	2.55	0.128
Total	394										

Table 2. Results of PERMANOVA to test the differences in Assemblage composition; between Habitat type and TUVS. Pairwise tests were used to examine statistically significant interactions. Bold values indicate statistically significant differences.

Source	*df*	*MS*	*F*	*P*	*Pair-wise comparison*	*F*	*P*		*F*	*P*
Assemblage					TUVS			Habitat		
TUVS (TU)	2	10097	7.14	**0.00**	BCL, BCH	2.65	**0.00**	Mixed, Rock	2.97	**0.00**
Habitat (Ha)	2	13007	9.2	**0.00**	BCL, BT	3.29	**0.00**	Mixed, Sand	2.93	**0.00**
TU × Ha	4	1871.6	1.32	0.08	BCH, BT	1.58	**0.01**	Rock, Sand	3.25	**0.00**
Residual	31	1413.8								
Total	39									

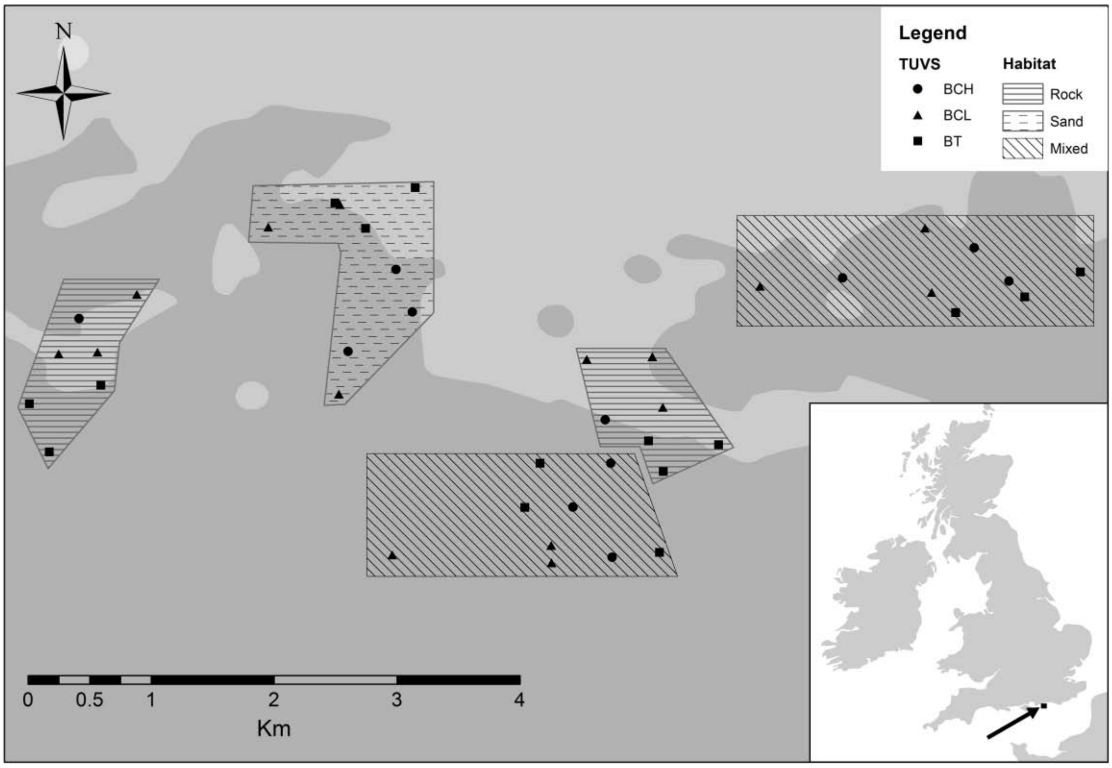
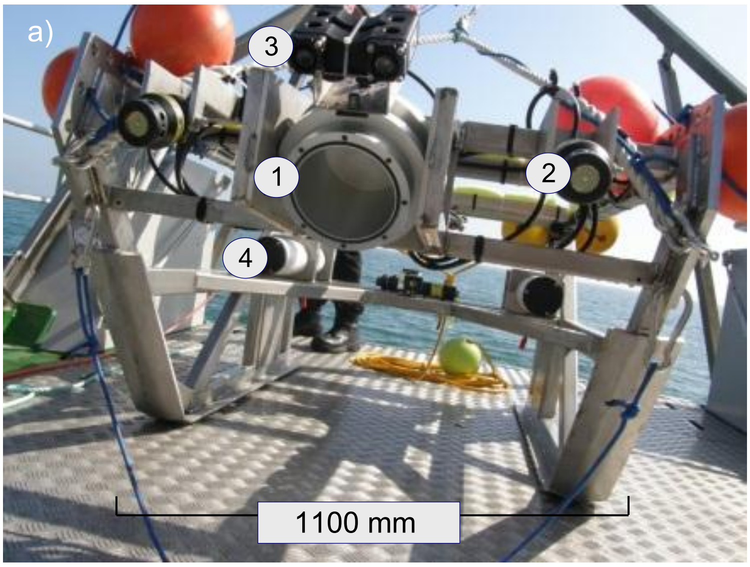
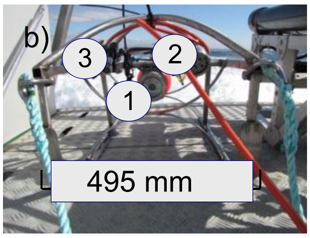


Fig. 1. Location of sites within the Kingmere MCZ. Southern England. TUVS = Towed Underwater Video System; BCH = Benthic Contacting Heavy; BCL = Benthic Contacting Light; BT = Benthic Tending.





1 = Video Camera
2 = LED Lights
3 = Laser scaling
4 = Power pack
5 = CTD

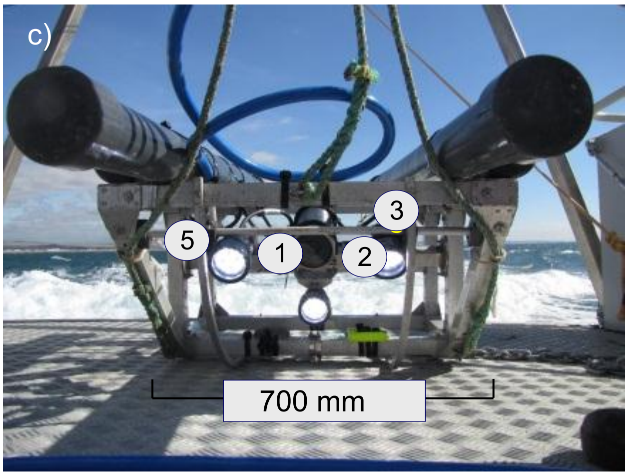


Fig. 2. Images to depict proportional sizes of the Towed Underwater Video Systems: a) Benthic Contacting Heavy (BCH), b) Benthic Contacting Light (BCL) and c) Benthic Tending (BT) See Sheehan et al. (2010) for deployment schematic. Actual widths are shown below each TUVS.

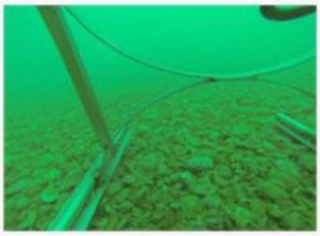
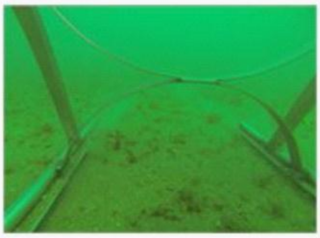
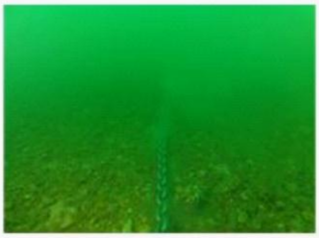
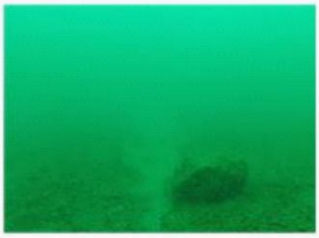
Scale	Image of disturbance
0 No disturbance	
1 Fine sediments disturbed	
2 Stones disturbed	
3 Cobbles disturbed and sediments re-suspended	

Fig. 3. Ordinal scale of impact. Images from backward facing HD Hero2 GoPro camera.

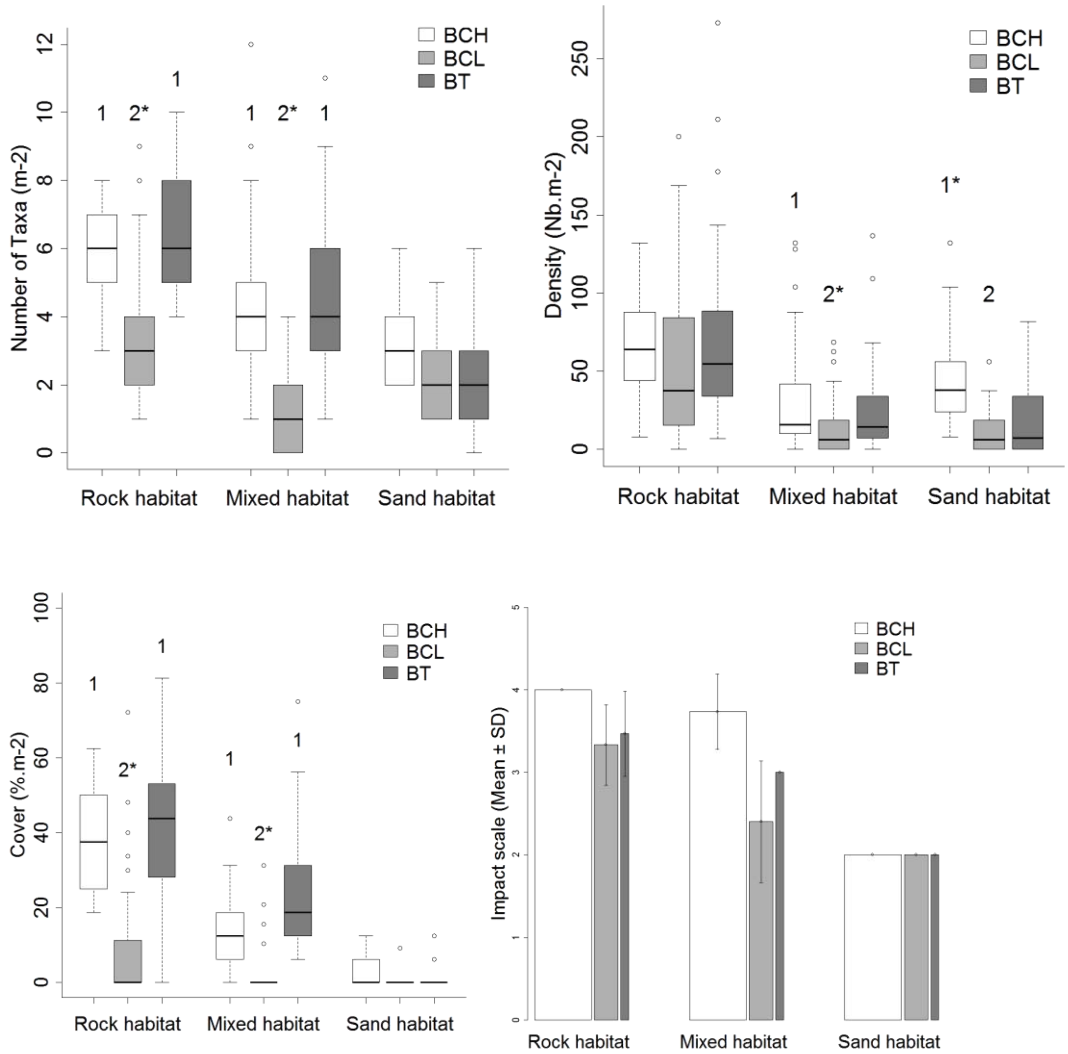


Fig. 4. Boxplot (box ranging from first to third quartile and showing median value, whiskers extending to values equal to 1.5 the interquartile distance, and circles highlighting outliers) of a) Number of taxa; b) Density (excluding hydroids); c) Cover between each TUVS on different habitat types. For a) and c) Results from the pairwise tests used to interpret a significant interaction are shown, where different numbers indicate that P<0.001 between TUVS within each Habitat and * indicate no overlap in the confidence intervals in the effect size values; d) Barplot (Mean ± SD) of damage impact based on an ordinal scale (Fig. 3), width of bars indicate width of contact point of each TUVS.

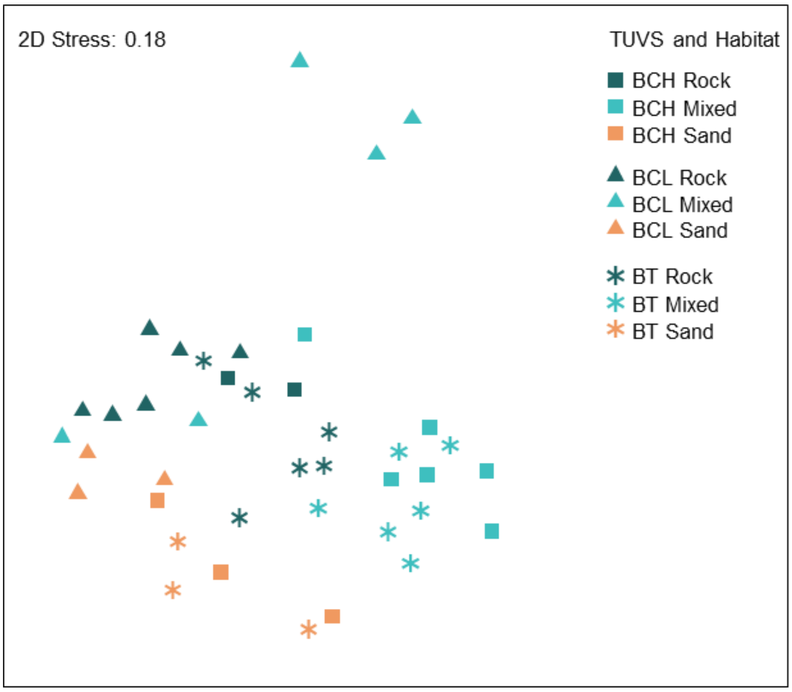
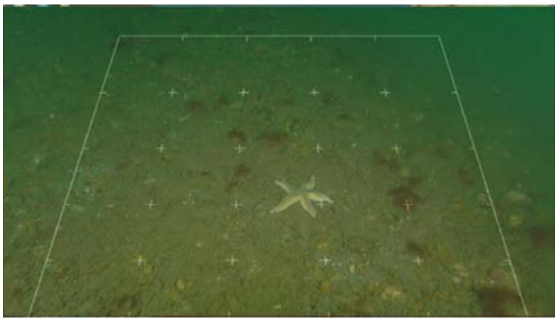
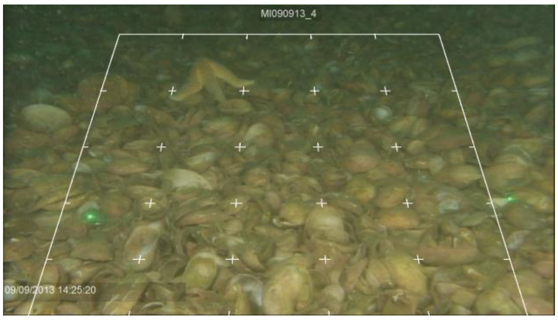


Fig. 5. nMDS ordination illustrating similarities in Assemblage Composition between TUVS and Habitat types (as displayed on the key). TUVS codes as shown in Figure 2.


Benthic Contacting Heavy

Benthic Contacting Light



Benthic Tending

Fig. 6. Example frame grabs from the three TUVSs.

Appendices

Table 1. Effect size value estimated from GLM analyses (marked differences between TUVs are highlighted in grey)

A) GLM Formula = NbTaxa ~ TUVS + Habitat + TUVS:Habitat

Family = Poisson $R^2 =$ 0.50

Coefficient	Estimate	SE	z value	Pr(>|z|)		MIXED		ROCK		SAND	
					Effects : Mean (95% Confidence Interval)						
(Intercept)	0.2311	0.126	1.834	0.067	BCL	1.26	(0.98- 1.61)	3.28	(2.86- 3.78)	2.27	(1.79- 2.87)
BCH	1.2079	0.1408	8.579	>0.001	BCH	4.22	(3.73- 4.77)	6.00	(4.94- 7.29)	3.17	(2.59- 3.87)
BT	1.2877	0.1397	9.216	<0.001	BT	4.57	(4.06- 5.14)	6.57	(5.95- 7.25)	2.10	(1.64- 2.69)
ROCK	0.9577	0.1447	6.617	<0.001							
SAND	0.5872	0.1749	3.358	0.001							
BVH:ROCK	-0.605	0.1863	-3.248	0.001							
BT:ROCK	-0.5945	0.1647	-3.609	<0.001							
BVH:SAND	-0.8736	0.2123	-4.115	<0.001							
BT:SAND	-1.364	0.2238	-6.094	<0.001							

B) GLM Formula = Density ~ TUVS + Habitat + TUVS:Habitat

Family = Quasipoisson $R^2 =$ 0.26

Coefficient	Estimate	SE	z value	Pr(>|z|)		MIXED		ROCK		SAND	
					Effects : Mean (95% Confidence Interval)						
(Intercept)	2.5257	0.2182	11.575	<0.001	BCL	12.5	(8.1- 19.2)	52.0	(42.9- 63.0)	13.3	(7.8- 22.8)
BCH	0.8777	0.2532	3.467	<0.001	BCH	30.1	(23.4- 38.7)	68.7	(50.2- 94.0)	43.2	(32.1- 58.2)
BT	0.6222	0.2625	2.370	0.018	BT	23.3	(17.5- 31.0)	67.1	(56.7- 79.5)	19.8	(12.8- 30.8)
ROCK	1.4251	0.2391	5.961	<0.001							
SAND	0.0645	0.3493	0.185	0.854							
BVH:ROCK	-0.5987	0.3148	-1.902	0.058							
BT:ROCK	-0.3667	0.2930	-1.252	0.211							

BVH:SAND	0.2979	0.4018	0.741	0.459
BT:SAND	-0.2258	0.4397	-0.514	0.608

C) GLM Formula = Cover* ~ TUVS + Habitat + TUVS:Habitat, *arcsine-transformed values

Family = Gaussian $R^2 =$ 0.26

Coefficient	Estimate	SE	t value	Pr(>|z|)	Effects : Mean (95% Confidence Interval)	MIXED	ROCK	SAND
(Intercept)	0.0815	0.0248	3.289	0.001	BCL	0.08 (0.03- 0.13)	0.15 (0.10- 0.19)	0.01 (0.00- 0.07)
BCH	0.2822	0.0336	8.411	<0.001	BCH	0.36 (0.32- 0.41)	0.64 (0.56- 0.73)	0.09 (0.02- 0.15)
BT	0.3840	0.0336	11.44	<0.001	BT	0.46 (0.42- 0.51)	0.69 (0.65- 0.74)	0.04 (0.00- 0.10)
ROCK	0.0655	0.0336	1.953	0.051				
SAND	-0.0712	0.0405	-1.759	0.079				
BVH:ROCK	0.2124	0.0587	3.620	<0.001				
BT:ROCK	0.1636	0.0464	3.528	<0.001				
BVH:SAND	-0.2058	0.0563	-3.654	<0.001				
BT:SAND	-0.3569	0.0563	-6.338	<0.001				

Appendices

Table 2. Equipment specification, Operational and Video performance of the three TUVSs. Criteria is scored 1-3: 1. Room for improvement; 2. Fit for purpose; 3. Recommended.

Criteria	Benthic Contacting Heavy		Benthic Contacting Light		Benthic Tending	
Equipment specification						
Camera	3	Panasonic HC-V700 HD (1080p). M ax depth: 600m	1	RovTech RSL portable camera system. Seacam (480p) wide angle. Max depth: 150m	3	Bowtech Surveyor HD set to 720p zoom and focus controllable at surface. Max depth: 6000m
Lights	3	2 x Projectuer LED Sealite® Sphere de Deep Sea Power and Light Corps. Max depth: 6000m	1	1 x RovTech Seabeam Ultra LED light. Max depth: 150m	3	3 x Bowtech LED lamps with light intensity controllable from the surface. Max depth: 3000m
Lasers	3	2 x SeaLaser® 100-5 (green), 532nm <5mW. Max depth: 2000m	2	2 x Trident SCUBA lasers (red). Max depth: 50m	2	2 x Z-Bolt SCUBA - (green). Max depth: 60m
CTD	-	None	-	None	-	Valeport mini CTD rated to 500m
Frame	3	Stainless steel sled with anodised aluminium housing. Contact with seabed: 2 runners	3	Stainless steel sled based on Salacia Marine/ Seafish design. Contact with seabed: 2 runners	3	40 mm box section aluminium, with ballast tubes to lift from the seabed. Contact with seabed: 1 central chain
Connection to viewing hardware	1	No connection	2	90m umbilical; Bowtech system top box with a Sony DVD recorder; recorder; GPS feed; and light control	3	200m umbilical; Bowtech System which allows control of camera focus, zoom, aperture, and intensity of lights
Power supply	3	SubCtech Li-Ion Powerpacks (25Ah 24V, ~3h autonomy) powering lights	3	Boat mains electrical supply or generator (see BT example)	3	Boat mains if electrical supplies clean electricity to power a computer or a

		and lasers				2KVA Honda generator through a 1000VA with a UPS (Uninterrupted power supply
Dimensions	3	L= 1500mm, W=1100mm, H=740mm	3	L=820mm, W=495mm, H=430mm	3	Frame: L=700mm, W=700mm, H=400mm. Ballast tubes: L=130mm, D=100mm. Chain: L=3.15M, W=33mm
Total weight: Fit for purpose	2	290kg	1	9kg	3	Frame=30kg, Chain=10kg. Total=40kg
Cost	3	€14,000	3	€12,000	2	€35,000
Subtotal (27)	**24**		**19**		**25**	
Operational performance						
Average No. of 200m tows per 8 hour day	2	6-8	3	8-10	3	8-10
Potential deployment in wind and tide	3	Force 7 No current restriction	1	Force 2 ⩽ 1 knot tide	2	Force 6 ⩽ 2.5 knot tide
Max deployment depth	3	600m	1	Depending on umbilical (here ~30m)	2	Depending on umbilical (here ~70m)
Deployment requirements	1	Requires two winches capable of lifting 300kg and 2 personnel under all	3	Deployed by hand. Can be deployed by 1 person, though 2 personnel	2	Can be deployed by hand in shallow waters, requiring a winch or pot-hauler in deeper waters. 3 personnel required

		scenarios		optimal for cable management		for optimal deployment
Operator skill required	3	Technician to deploy kit and a technician to operate camera	2	Technician to deploy kit and a Research assistant to operate camera	2	Technician to deploy kit and a Research assistant to operate camera
Subtotal (/15)	**12**		**10**		**11**	
Video performance						
Speed	2	Dependent on boat speed. Fast in places as not possible to monitor	1	Fast in places as it was light and left seabed easily	3	Constant and steady as long as the boat was controlled
Camera angle	3	35° to the horizontal. Good angle to the seabed to observe benthos	1	50° to the horizontal. Angle often pointed outwards to the water column	3	30° to the horizontal. Good angle to seabed to observe benthos
Image quality	3	Excellent when sled was at a steady speed	1	Low resolution of camera produced low quality images, difficult to ID some taxa	2	Consistently good, able to identify most taxa
Information on screen	3	No information on screen to insure maximum visibility . Time could be added if required.	1	Too much information, obscured image for analysis	3	Time and sample label
Field of view	3	Altitude 55cm; low camera inclination, giving a FOV of approximately 1.3 m^2	1	Altitude 30cm; giving a FOV of approximately 0.16m^2	2	Altitude 30 cm – 70 cm; giving FOV range of 0.074 m^2 to 0.387m^2
Subtotal (/15)	**14**		**5**		**13**	

Total score (/57)	**50**		**34**		**49**	