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ARTICLE

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Investigating human impacts on rocky reefs using measures of complexity and relief from 3D photogrammetry

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Abstract

The structural complexity of a habitat is linked with the health and biodiversity of the ecosystem. Computational methods analyzing 3D representations of the environment allow for accurate measurement; however, rocky reef environments that feature gullies, arches, stacks, and ledges may be inaccurately represented using standard measures of complexity. This article presents a novel assessment of structural complexity through relief calculated from 3D reconstructions of marine environments, tailored for rocky reefs with vertical features. This method is tested in two case studies: a tropical coral reef in Indonesia and a rocky (chalk) reef in the United Kingdom. Chalk reef relief was not correlated with vector dispersion or fractal dimension and was weakly correlated with rugosity ($r = 0.3781$); however, in two comparison tropical reef datasets, relief correlated moderately with vector dispersion on both coral reefs ($r = 0.4657$, $r = 0.4934$) and moderately-strongly with rugosity ($r = 0.4023$, $r = 0.6703$). On the chalk reef, tailored complexity metrics confirmed the previous finding that catch-size *Cancer pagurus* abundance ($\geq$115 mm) was correlated with fractal dimension ($r = 0.4499$), indicating that adults preferred elevated, complex reefs. Analysis showed correlations between relief and low-severity chalk damage ($r = 0.3931$) and between relief and abrasion damage ($r = 0.4109$), whereas previous research had indicated that damage was not correlated with complexity (assessed computationally with rugosity, fractal dimension, and vector dispersion). Surveying marine environments with multicamera arrays and 3D photogrammetry can drastically reduce the time and cost of fieldwork surveys and provide accurate measures of complexity across survey sites. Adapting complexity metrics to habitat-specific topography provides valuable insight (in this case, into rocky reef marine habitats). Findings from the UK case study support the continued monitoring of the Cromer Shoal Chalk Bed Marine Conservation Zone (MCZ).

KEYWORDS
3D photogrammetry, chalk reef, complexity, coral reef, fisheries, human impact, relief, rocky reef

INTRODUCTION

Substrate complexity and ecosystem health

Substrate complexity has a well-established relationship with ecosystem health (Graham & Nash, 2013; Price et al., 2019; Richardson et al., 2017); however, the methods for these assessments are often time-consuming and limited in scale. Even with the advancement of 3D technologies and remote sensing, there are limits to the size of areas that can be assessed within pragmatic timescales (such as the duration of a SCUBA dive). The efficiency of surveying methods for projects with a limited budget that monitor marine systems repetitively should be a priority in marine conservation.

As complexity is intrinsically linked with ecosystem health and biodiversity, metrics that can integrate substrate morphology and organism interaction, or the potential thereof, are becoming more prevalent, particularly computational methods that allow for accurate measurement to be carried out. One such method, fractal dimension (*D*), relates the complexity of an ecosystem to its ability to be utilized by organisms of a defined size (Kostylev et al., 2005; Young et al., 2017).

The complexity of marine reefs is in decline (Morais et al., 2020). Monitoring these systems can track structural change, but often cannot trace the cause, so assessments should additionally measure defined substrate damage, tailored to either the ecosystem type (e.g., coral reefs, rocky reefs, sand banks), the specific region of interest, or both. Any proposed method for substrate monitoring needs to not only be rapid and robust but also be as cost-effective as possible (Young et al., 2017). It also needs to include metrics that can relate to past data, or the monitoring risks becoming obsolete and may suffer from shifting baselines.

Natural complexity of reefs

The two important types of reef habitats are coral reefs and rocky reefs. Both feature submerged outcrops of hard substrate that provide a foundation and refuge to support an ecosystem.

Coral reef systems, the most prevalent and commonly thought of reef type, are those predominantly composed of scleractinian corals, although the term can be used to describe systems that have later degraded and lost their coral dominance. The secretion of calcium carbonate layering on the coral surface increases both the size and structural complexity, growing and adapting to environmental conditions. The intricate morphology of scleractinian corals supports a wide range of ecological niches, creating a diverse and robust system (Graham & Nash, 2013). As such, reefs dominated by complex coral types support a greater number of niches than their less complex counterparts (Richardson et al., 2017).

The structural complexity of rocky reef systems is created by geological features and erosion over time. Harder rock formations provide a stable habitat, but rocky reefs of softer rock such as chalk are more susceptible to change.

Chalk bed habitats (classified as rocky reefs) are relatively rare. They are formed through deposition from calcareous ooze and calcite shells that build up into stretches of chalk reef with different characteristics (Savrda, 2012). The complex structures formed by the erosion of chalk give habitat variations that allow for a wide range of organisms to thrive. They provide refuge from predation and for spawning, grazing, and hunting grounds and a range of environmental conditions that suit different environmental niches. The complexity of the chalk is due to layering deposits over millennia (Buatois et al., 2003) and is easily damaged due to its softness (Ziogos et al., 2016). Any damage done, either naturally or anthropogenically, is permanent, and prolonged destruction of the system could lead to a dramatic ecological change to the system.

The layered deposition of chalk and continuous water movement creates a gradually changing structure, with transitions between high and low areas characterized by the presence of gullies, arches, stacks, and ledges (Moffat et al., 2019). This contrasts with the topography of a coral reef that has organically developed over time and may limit the appropriateness of established complexity assessment metrics, as they are often tailored for small changes to a system, such as branching corals on tropical reefs, rather than shifts in topography of a rocky seabed.

Height, relief, and other metrics in ecology

In marine monitoring, substrate height encompasses a wide range of reef metrics and meanings. Several height measurements were developed by McCormick (1994) relating to height that showed varying success in plotting changes in height, separating substrate types, and correlating with fish abundances.

Elevation is usually used to describe the height of something above sea level or a given point. In ecology, it has been linked to species abundance for a number of fauna, for example, amphibians in the Himalayas declined in abundance with greater elevation but grew in body size (Khatiwada et al., 2019) and arthropod abundance varied across elevations depending on latitude, with greater latitude showing stronger correlations between higher elevation and abundance (Supriya et al., 2019).

Relief measures the height difference between two points that may not necessarily be directly vertical (as with height) nor do they need to be set (as in elevation). Relief has been found to correlate with an abundance of reef-associated fish on a rocky reef area in Sweden (Wilhelmsson et al., 2006), experimentally tested through constructed, high-profile structures.

Slope and *gradient* are also common measures used in ecology that may refer to the same value in some cases. Gradient is measured as the ratio of the vertical to horizontal distance between two points. Slope refers to either this measurement or the angle of the horizontal to vertical points, with the horizontal being 0°. Reef gradient is also used in coral reef ecology to refer to the different areas of a coral reef (i.e., crest, slope) without using any quantitative measurement.

Damage to ecosystems from human impacts

Humans have become a leading cause of damage to many ecosystems, by pollution, anthropogenically exacerbated climate change, fishing impacts, recreational and tourist activities, and other direct and indirect action (Burke et al., 2011; Cesar et al., 2013).

In the United Kingdom, fishing impacts, in particular, are an increasingly important topic legislatively with the departure from the European Union and there is need for up-to-date policies. Prior research into crustacean fisheries has investigated the effects on epifauna rather than on the structural complexity of the system itself (Gall et al., 2020; Rees et al., 2018). Understanding the impact of the fishery on habitat features is crucial for the management and conservation of reef systems. The management of small-scale fisheries must incorporate conservation of ecosystems and socioeconomic factors into policies for the betterment of the environment and those that rely on it for food and income (Vaughan, 2017).

With shellfish fisheries being the second largest in the United Kingdom, and potting being a common approach, reducing any associated damage to benthic organisms and physical structure is essential for conservation efforts. Pots are known to cause damage due to contact with the seabed, through abrasions caused by water movement, and when they are set and removed (Rees et al., 2018). The use of single pots as opposed to a series of pots on a rope (called shanks) has been tested experimentally. Single pots' heavier weight had a more damaging impact when being deployed and in water, but a lesser impact when being hauled in, as pots were not dragged along the seabed (Stephenson et al., 2017).

Research aims

The focus of this article is to review commonly used complexity metrics for different types of reef topography. We propose a novel measurement of relief through 3D reconstructions of marine environments to represent topographical changes that complexity metrics do not adequately measure in rocky reef systems. Specifically,

1. Do changes in relief correlate with other metrics of complexity in coral and chalk reefs?
2. Do changes in relief correlate with measures of species abundance on chalk reefs?
3. Do changes in relief correlate with observed human impacts on chalk reefs?

MATERIALS AND METHODS

Study sites

Surveying was conducted on a chalk reef in the United Kingdom in 2019, and on two coral reefs in Indonesia in 2018.

Cromer Shoal MCZ, Norfolk, UK (rocky chalk reef)

The Cromer Shoal Chalk Bed was designated as an MCZ in January 2016. This classifies it as a site of "nationally important, rare or threatened habitat," with the objective of maintaining the system of designated features (UK Ministerial Orders, 2016). The MCZ stretches from Weybourne southeastward to Happisburgh. It begins 200 m offshore (of mean low water) and extends 5–10 km seaward, covering a total of 320.5 km^2.

The crustacean fishery on the chalk reef follows the minimum landing sizes set by the Eastern Inshore Fisheries and Conservation Agency (EIFCA) region: 115-mm carapace width for *Cancer pagurus* and 87-mm carapace length for *Homarus gammarus* (Eastern Inshore Fisheries and Conservation Authority, 2019). This is smaller than other UK regions (Tibbitt et al., 2020).

Four randomly selected shanks were surveyed across the accessible regions of the Cromer Shoal Chalk Bed MCZ chalk reef: two at West Sheringham (WS1 and WS2), one at West Runton (WR), and one at East Runton (ER). The GPS locations of the study sites have not been released as per agreement with the fishing industry. Each shank was approximately 200 m and had 10 pots each (up to 5 of which were used as surveying sites [4-m^2 quadrats] per dive). The sites had unique features that presented different areas of interest:

WS1	A flat area of flint, sand, gravel, and chalk cobbles with no areas of exposed chalk bed.
WS2	A region of reef predominantly covered in a thin algae layer with 2-m high ridges and gullies between 5 and 10 m wide composed of flat chalk and sand. There were minimal regions of cobbles.
WR	A similar area to WS2 with smaller ridges of approx. 1 m high and less well-defined gullies of sand, chalk, and cobbles.
ER	An area of small ridges approx. 0.5 m high with ill-defined chalk bed, rubble, cobble, and sand regions.

Wakatobi National Park, Indonesia (coral reef)

Pulau Hoga and Sampela are located in the Wakatobi National Park, Indonesia, in the Coral Triangle—an area known as the center of marine biodiversity. They are close together, but represent two distinct reef habitats.

Hoga's reef is a fringing reef with a range of microhabitats across it. It has few direct stressors, although they may have been subject to blast fishing, leading to increased rubble load on the reef (Gouraguine et al., 2019) and decreasing complexity.

Sampela reef has been heavily impacted by extreme levels of fishing and high sedimentation. The decrease in herbivorous fish has led to increased algae and sponge cover, with subsequent coral loss reflected in a low-complexity region (Crabbe & Smith, 2005).

Four sites were selected at each reef. Each of these contained six adjacent 4-m^2 quadrats, forming a 4×6 m rectangle. Sites on the same reef all had the same characteristics, but each reef was highly distinct from the other.

Pak Kasims	A fringing reef beginning 350 km offshore, with a shallow crest and flat (5 m) moving to a 40°–70° slope, which descends to sand flats at 50 m (05°27.569 S, 123°45.179 E).
Sampela	A lagoon reef, cresting at 1–5 m and sloping to sand flats at 10–15 m interspersed with coral bommies along one side and sparse reef on the other (05°29.300 S, 123°45.100 E).

In situ assessment and data collection

In situ chalk reef data and models were obtained from the Natural England investigation in September 2019 (conducted in collaboration with the authors of this article) (Tibbitt et al., 2020).

Five SJCAM action cameras were attached to a plastic frame facing outward at an oblique angle and an additional GoPro camera was set facing directly down. All were set to video mode and still frames were extracted in post-processing. Although image capture provides higher quality data for 3D reconstruction, the extraction of lower quality stills from video footage was more beneficial due to the logistical difficulty of surveying the reef.

A team of four in-water divers worked along one shank per dive, split into an imaging and a biological team (two divers per team). The imaging team used the camera rig to gather topographical and damage data. The biological team collected abundance and habitat assessment data.

The imaging team filmed each shank. Each diver had a multicamera array and swam along one side of the shank (~2 m apart with the shank between them) at ~1 m above the substrate. One diver also placed an A4 control marker a random number of fin kicks after each pot during the filming of the shank.

The biological assessment divers carried out a visual habitat characterization survey, which is standard for Natural England assessments (Tibbitt et al., 2020), and then followed the shank after the imaging divers, with one diver on each side of the rope. When they encountered a pot or control marker, they recorded a count of all commercial crustaceans (*C. pagurus* and *H. gammarus*) as well as their age (juvenile or adult, determined by catch limit sizes) within a 4-m^2 quadrat directly ahead of the pot/marker. Control markers were removed as they were passed.

Coral reef images were collected over a 2-month period, through July and August 2018, and models were generated using Agisoft Photoscan (now Metashape). Sites were dived before surveying and metal pins were placed into rocks on the reef to mark the bounds of each

4-m^2 quadrat, ensuring that placement was accurate across repeated dives. Each quadrat was filmed using a single GoPro camera, as described by Young et al. (2017). Metal pins were removed after all surveying was complete.

Ex situ assessment

The same chalk reef models were analyzed here as in the Natural England investigation, and data for rugosity, R, and vector dispersion, $\frac{1}{k}$, were that previously found in the Natural England investigation (Tibbitt et al., 2020). Rugosity can be simply defined as the ratio of linear to contoured distance over a straight line. It is most commonly assessed by draping a chain over a substrate (Graham & Nash, 2013). Vector dispersion was described by Carleton and Sammarco (1987) as an "estimate of vector variance for all vectors normal to the individual planar surfaces considered."

Two complexity metrics were evaluated and added to those previously reported:

1. *Relief* was determined as a variation on verticality, where instead of the height difference per an interval on a linear line, the total height difference across an area was calculated (Figure 1). All models were checked for size to determine the largest scale area that could be consistently used, and then a closed object was created—in this case, a 64-m^3 cube to be greater than the largest relief of all models. The object was placed to intersect with the model mesh and encompass the area, then was split across the intersection to provide halves ending in the contour or inverse contour of the reef surface.

$$\text{Relief} = |a - b|, \tag{1}$$

where a is the height of split object with surface contour, and b is the height of split object with inverse surface contour.

2. *Fractal dimension* (D) links complexity to size categories by demonstrating changes in 3D structure across given spatial scales (Bradbury & Reichelt, 1983). Size categories were adjusted to suit the carapace width of *C. pagurus* catch size: D_{catch} for D between 345 and 115 mm; and $D_{\text{non-catch}}$ for D between 115 and 28.75 mm. Sizes for *H. gammarus* were not incorporated as there were so few seen and they were excluded from the analysis. *C. pagurus* abundance was grouped into

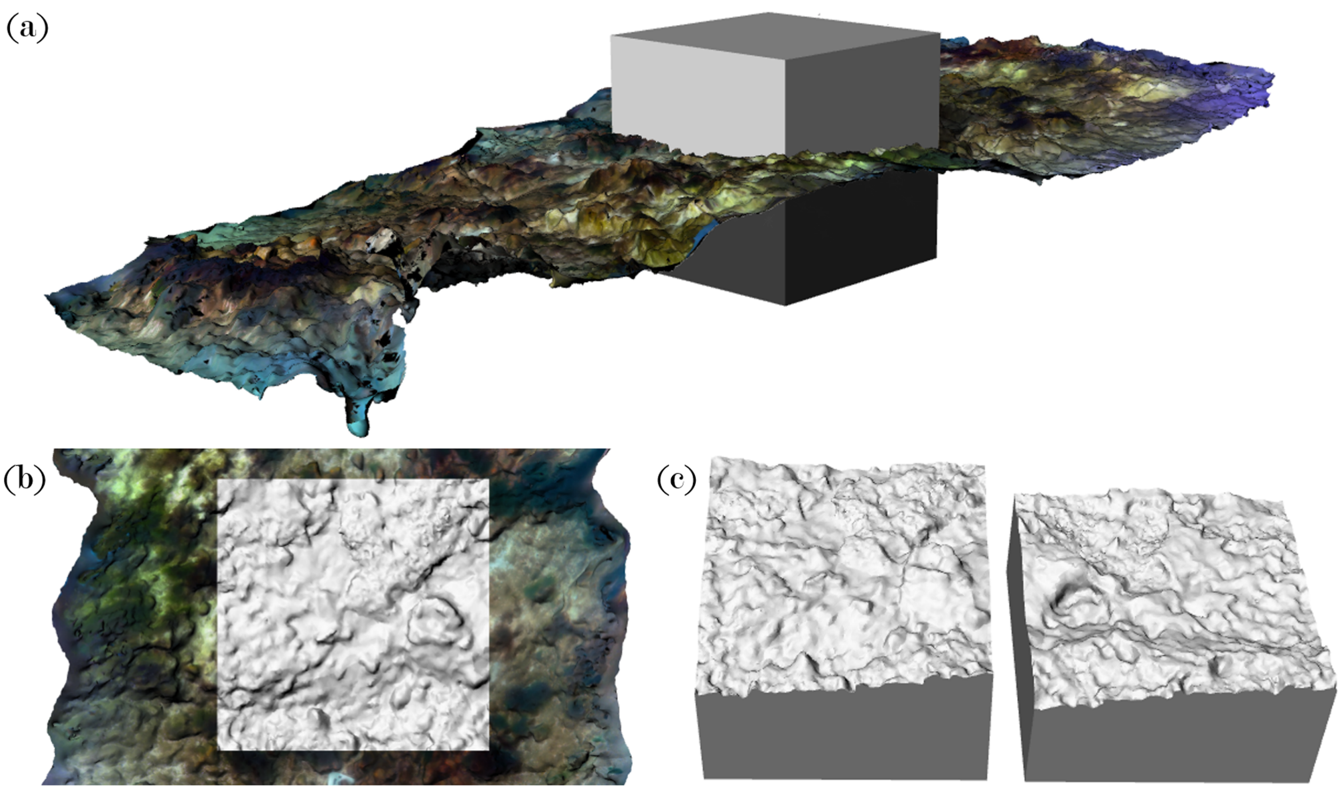

FIGURE 1 Relief assessment of an area of reef. (a) A solid box scaled to be greater than the largest relief across all models was intersected with the model mesh. (b) The box was then split across the intersection, matching the contour of the model mesh. (c) The box was separated to show the contour of the substrate and the inverse of it. The height of one split was then subtracted from the height of the other and the absolute value was the relief of the area.

catch and non-catch, determined by size as per adjusted *D* categories.

$$D_{x_1-x_2} = \frac{\log\left(\frac{N(x_1)}{N(x_2)}\right)}{\log\left(\frac{x_2}{x_1}\right)}, \quad (2)$$

where x_1 is size 1, x_2 is size 2, and N is the number of times x is required to cover the substrate surface. The higher the value of D, the greater the complexity.

All coral models were evaluated for complexity per the specifications of Young et al. (2017), as well as with the relief assessment described above. Damage categories, severity (Table 1), and counts remained as originally determined (Tibbitt et al., 2020). Reanalysis of the videos allowed for approximate position of damage to be accounted for. Time before surveying was removed and any pauses in surveying to place markers were accounted for and removed from the time to minimize any impact on damage position. Assuming a constant swimming speed, total surveying time was divided evenly by the shank distance (200 m) to provide a damage point as well as category.

Statistical analysis

Abundance data were combined into catch and non-catch crabs, determined by local minimum catch size, and lobster counts were excluded due to their low occurrence. All ER quadrats and 2 WS1 quadrats were excluded from the analysis as no counts were carried out due to diving restrictions. WS1 was removed from damage analysis as there were no incidences observed and it was not on the chalk reef.

Per Tibbitt et al. (2020), Pearson's correlations were used to assess any relationship between complexity metrics. ANOVA tests were used to assess any difference in fractal dimension, *D*, and relief between sites.

For the damage assessment, only damage observed in the first 100 m was used, as all pot and control quadrats were within this area. Damage was grouped into severity levels for analysis (Table 1). *T* tests were used to determine any difference in damage between pot and control quadrats. ANOVA tests then assessed damage incidence between sites. Pearson's correlations were calculated to show the relationship between damage incidence and complexity.

TABLE 1 Damage categories observed on the chalk bed.

Damage type	Damage label	Damage severity	Damage description
Lift	LIF	High	Shattered chalk at edges with one edge lifted out.
Grating	GRA	High	Rubbed epifauna and chalk of nonhorizontal areas creating uneven grooves and chalk debris below the site.
Rubble	RUB	High	Angular chalk cobbles that indicate disturbance but with no clear cause.
Saw	SAW	High	Broken angular rubble in a line as a result of continued vertical burns.
Cut	CUT	High	Single line of horizontal indentation of approximate equal width.
Level shear	LSH	High	Horizontal and flat area of exposed chalk as a result of a complete cut.
Unlevel shear	USH	High	Flat (but not horizontal or level) area of exposed chalk from an incomplete cut or a large amount of chalk disturbance in one impact.
Strike	STR	Medium	A vertical strike with a visible impact site and shattered chalk in edged pieces.
Drag	DRA	Low	Single lines of chalk indentations of unequal width.
Abrasion	ABR	Low	Rubbed epifauna and chalk forming a flattened horizontal plane.
Burn	BUR	Low	Single line of vertical indentation of approximate equal width.

Note: Low severity was classed as damage that only removed the surface chalk layer, medium severity caused broken chalk structure without removal of chalk, and high severity caused broken and removed chalk (Tibbitt et al., 2020).

Annotator agreement by video analysis for assessment of damage occurrence was calculated as a percentage agreement, and for agreement of damage category with Cohen's kappa.

RESULTS

Relief and metrics of complexity in coral and chalk reefs

Relief had a weak–moderate correlation with rugosity ($r = 0.3781$, $t_{34} = 2.3817$, $p < 0.05$, Pearson's correlation), but not with vector dispersion, D_{catch} or $D_{non\text{-}catch}$ ($p > 0.05$, Pearson's correlation) on the chalk reef (Figure 2c). Pak Kasims coral reef site showed a moderate correlation between vector dispersion and relief ($r = 0.4657$, $t_{22} = 2.4685$, $p < 0.05$, Pearson's correlation), and moderate correlation between rugosity and relief ($r = 0.4023, t_{22} = 2.0608, p = 0.051$, Pearson's correlation) (Figure 2a). Sampela coral reef also showed a moderate correlation between vector dispersion and relief ($r = 0.4934$, $t_{22} = 2.6609$, $p < 0.05$, Pearson's correlation) and a moderate–strong correlation between relief and rugosity ($r = 0.6703$, $t_{22} = 4.2361$, $p < 0.0005$, Pearson's correlation) (Figure 2b).

Relief and species abundance on chalk reefs

A replication of tests with generalized *D* size categories (Tibbitt et al., 2020) was performed with those tailored to *C. pagurus* and relief (Table 2). No difference was found in *D* or relief between pot and control sites ($p < 0.05$, *t* test).

D_{catch} showed variation ($F_{3,32} = 4.461$, $p < 0.01$, ANOVA) across the sites: WS1, the non-chalk site, was less complex than WS2 ($p < 0.05$) and WR ($p < 0.01$). $D_{non\text{-}catch}$ did not differ ($p > 0.05$). Relief followed the same trend as D_{catch} between sites ($F_{3,32} = 4.606$, $p < 0.01$, ANOVA): WS1 and WS2 ($p < 0.01$), and WS1 and WR ($p < 0.05$).

When considering tailored fractal dimension, adult crab (115 mm and above, catch) abundance correlated with fractals at the larger size scale and not the smaller one. Juvenile crabs (115 mm and below, non-catch) did not correlate with either sizing, supporting the original

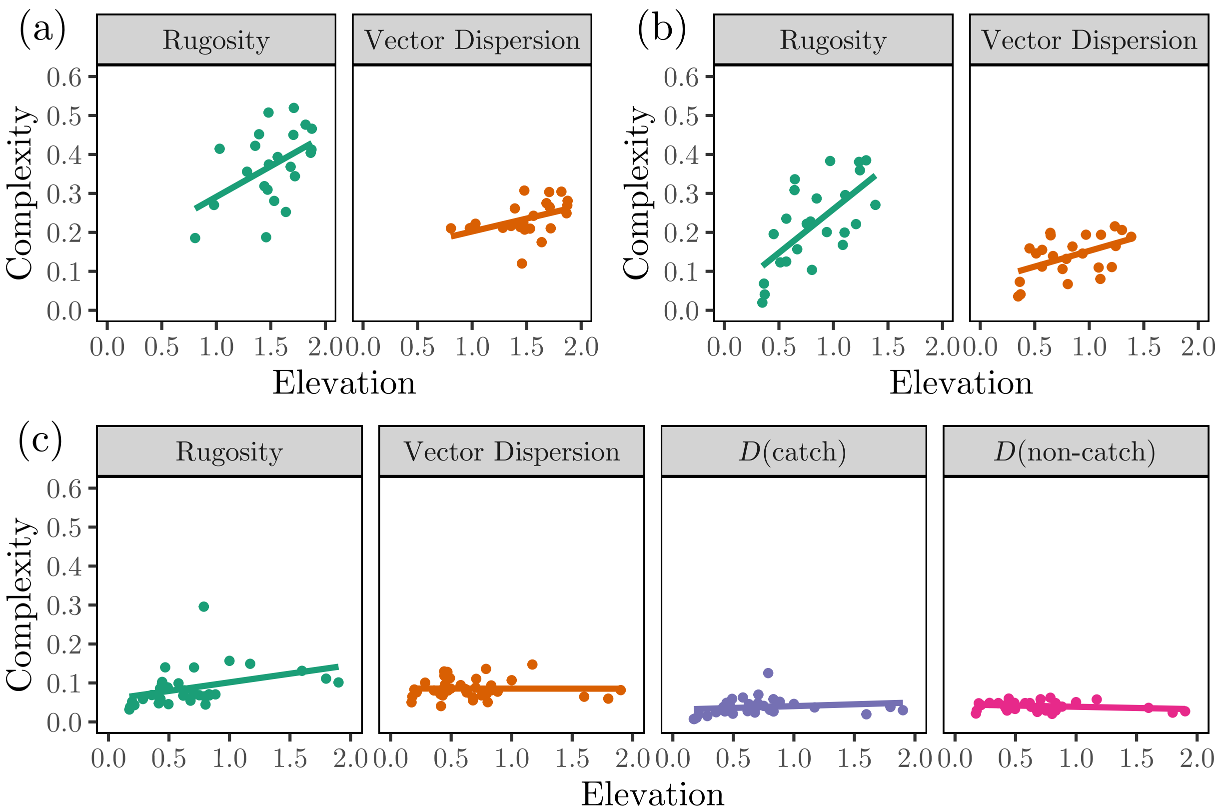

FIGURE 2 Linear correlations between relief and other complexity metrics (rugosity, vector dispersion, and fractal dimensions—D_{catch} for fractal dimension between 345 and 115 mm, and $D_{non\text{-}catch}$ for fractal dimension between 115 and 28.75 mm) at (a) Pak Kasims and (b) Sampela coral reef sites, and (c) Cromer chalk reef.

TABLE 2 Summary statistics at each site with fractal dimension size groups of 345–115 mm (D_{catch}) and 115–28.75 mm ($D_{non\text{-}catch}$), and for relief (with the values for relief in meters).

Fractal	Site	*n*	Mean	Median	SD	Min.	Max.
D_{catch}	WS1	6	2.0142	2.0128	0.0071	2.0073	2.0248
	WS2	10	2.0416	2.0381	0.0161	2.0210	2.0701
	WR	10	2.0485	2.0391	0.0286	2.0267	2.1253
	ER	10	2.0363	2.0354	0.0113	2.0196	2.0592
$D_{non\text{-}catch}$	WS1	6	2.0398	2.0455	0.0117	2.0214	2.0488
	WS2	10	2.0392	2.0380	0.0107	2.0238	2.0582
	WR	10	2.0400	2.0356	0.0160	2.0206	2.0620
	ER	10	2.0441	2.0454	0.0077	2.0292	2.0558
Relief	WS1	6	0.2343	0.2055	0.0728	0.1730	0.3580
	WS2	10	0.8869	0.6925	0.5420	0.4100	1.9010
	WR	10	0.7796	0.7910	0.1791	0.4440	1.1710
	ER	10	0.6024	0.4710	0.3577	0.4260	1.5990

Abbreviations: ER, East Runton; WR, West Runton; WS, West Sheringham.

TABLE 3 Correlations between crab abundance and fractal dimension, and crab abundance and relief at different size groups.

Metric	Abundance	*r*	r^2	*T*	*p*
D_{catch}	Total	0.0552	0.0030	0.2594	0.7977
	Adult	0.4499	0.2024	2.3629	**0.0274**
	Juvenile	−0.0280	0.0008	−0.1314	0.8967
$D_{non\text{-}catch}$	Total	−0.0492	0.0024	−0.2314	0.8191
	Adult	0.2676	0.0716	1.3027	0.2061
	Juvenile	−0.0975	0.0095	−0.4595	0.6504
Relief	Total	−0.0629	$3.9554e^{-3}$	−0.2956	0.7703
	Adult	0.1466	0.0215	0.6950	0.4943
	Juvenile	−0.0887	$7.8757e^{-3}$	−0.4179	0.6801

Note: Bold text indicates significant correlation.

findings that juveniles do not rely on complexity in their distribution, but adult crabs prefer more complex areas (Table 3). Relief did not correlate with crab abundance overall or by age group.

Relief and observed human impacts on chalk reefs

WS1 was excluded from damage analysis as it was not a chalk reef site. WS2 had 83 instances of damage, WR had 37, and ER had 72 across each category (Figure 3). WS2 had more low-severity damage than any other category (53), whereas ER had mostly high-severity damage (48) (Figure 3).

Due to the modeled complexity and species abundance data available, analysis of damage incidence was only carried out for the first 100 m of damage (Table 4).

Damage totals and severity did not vary between pot and control quadrats ($p > 0.05$, t test); however, control sites had more than double the incidence of abrasion than pot sites ($t_{23.106} = 2.4676$, $p < 0.05$, t test). Damage did not correlate with crab abundance at either size category.

Damage incidence was different at each site ($F_{2,27} = 6.453$, $p < 0.01$, ANOVA), with WR having significantly less damage than both WS2 ($p < 0.05$) and ER ($p < 0.01$). High-severity damage varied between sites ($F_{2,27} = 6.205$, $p < 0.01$, ANOVA), with significantly more at ER than at WR ($p < 0.005$).

This is similar to the variation in rubble ($F_{2,27} = 8.789$, $p < 0.005$, ANOVA), as ER had more than both WR ($p < 0.01$) and WS2 ($p < 0.01$) (Figure 3). Medium-severity damage was significantly greater ($F_{2,27} = 4.778$, $p < 0.05$, ANOVA) at ER than at WR ($p < 0.05$). This can be attributed to strike damage as the only category at this severity level. There was more

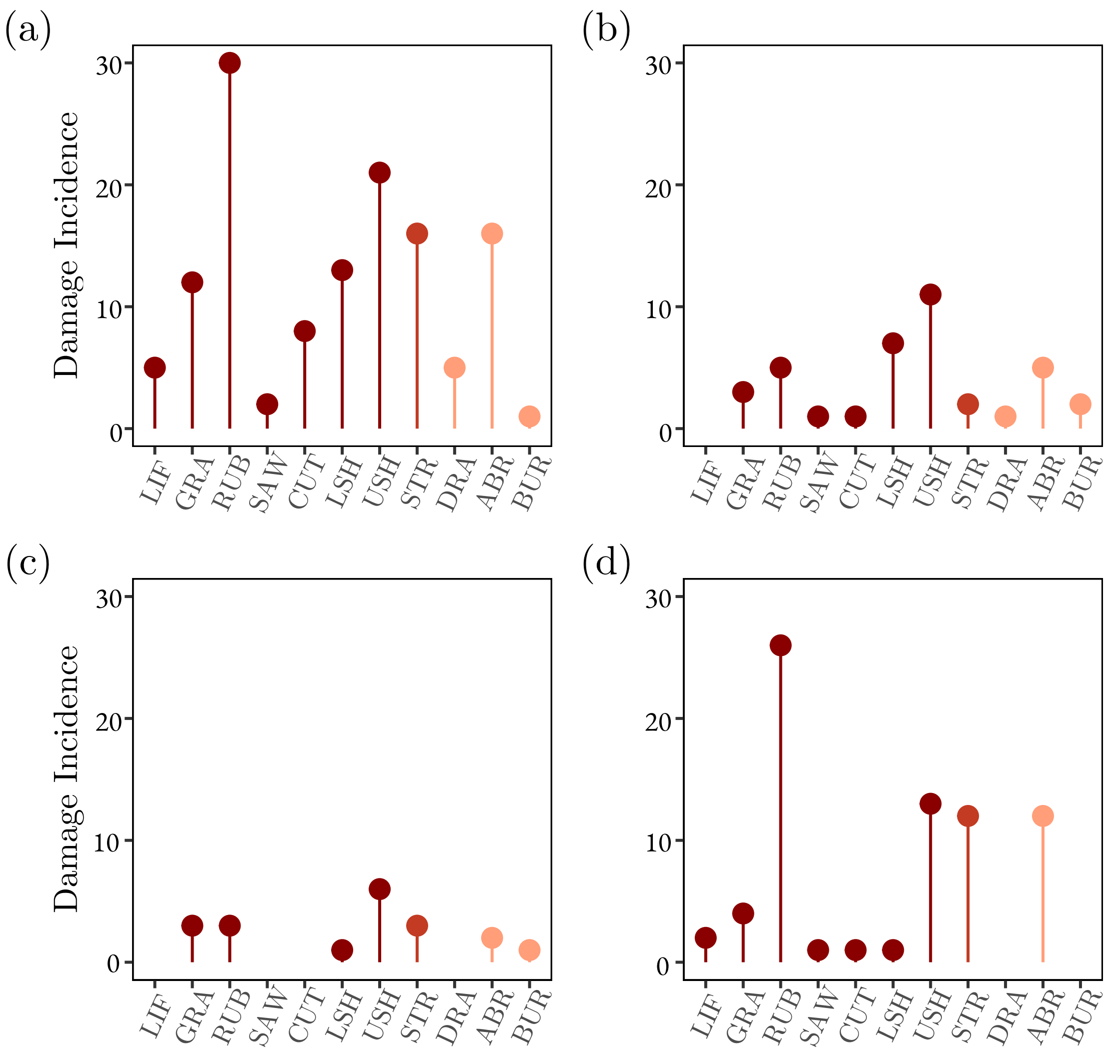

FIGURE 3 Incidence of high-severity (dark red), medium-severity (red), and low-severity (pink) damage for (a) all sites, (b) WS2 ($n = 83$), (c) WR ($n = 37$), and (d) ER ($n = 72$). ER, East Runton; WR, West Runton; WS, West Sheringham.

TABLE 4 Incidence of damage by severity level in the first 100 m of each transect.

Site	All	High	Medium	Low
WS2	49	18	2	29
WR	18	8	1	9
ER	55	36	8	11

Abbreviations: ER, East Runton; WR, West Runton; WS, West Sheringham.

low-severity damage ($F_{2,27} = 5.953$, $p < 0.01$, ANOVA) at WS2 than at WR ($p < 0.01$) or at ER ($p < 0.05$). This is reflective of the high incidence of abrasion ($F_{2,27} = 7.122$, $p < 0.005$, ANOVA) at WS2 versus that at WR ($p < 0.005$) and ER ($p < 0.05$).

When correlating damage incidence with complexity, no relationship was found with R, $\frac{1}{k}$ or D_{catch} (Figure 4). Medium-severity (strike) damage correlated with $D_{\text{non-catch}}$ ($r = 0.3751$, $t_{28} = 2.1412$, $p < 0.05$, Pearson's correlation). Relief correlated with low-severity damage ($r = 0.3931$, $t_{28} = 2.2625$, $p < 0.05$, Pearson's correlation), specifically with abrasion ($r = 0.4109$, $t_{28} = 2.3849$, $p < 0.05$, Pearson's correlation).

Damage classification and annotator agreement

Video analysis of footage was performed by two annotators independently after training, and the results were then consolidated to a final decision (Tibbitt et al., 2020). Analysis of initial annotator agreement found 47.76% agreement of damage incidence across all sites, with 65.13% agreement at WS2, 46.88% agreement at WR, and 28.24% agreement at ER. Using Cohen's kappa, κ, good agreement was found between annotators for damage categories across all sites ($\kappa = 0.6160$, $p < 0.001$). Broken down per site, WS2 had good agreement

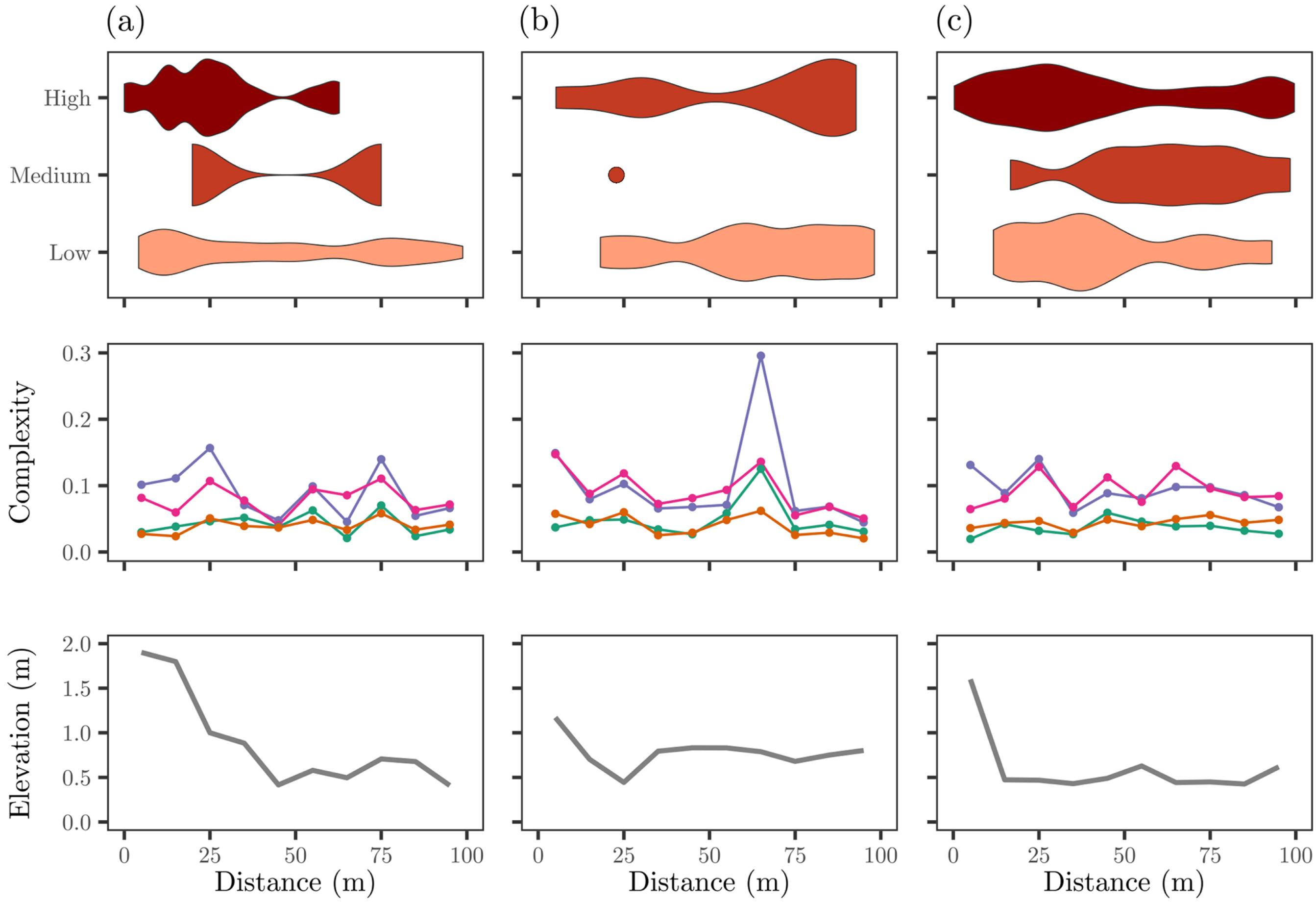

FIGURE 4 Damage distribution per severity (high—dark red, medium—red, and low—pink), complexity, and highest relief across the first 100 m of (a) WS2, (b) WR, and (c) ER. As WS2 only had two instances of medium-severity damage, it could not be plotted in this manner. Complexity plots show R (purple), $\frac{1}{k}$ (pink), $2-D_{\text{catch}}$ (green), and $2-D_{\text{non-catch}}$ (orange). D was transformed for ease of visual comparison. ER, East Runton; WR, West Runton; WS, West Sheringham.

($\kappa = 0.5900$, $p < 0.001$), WR had good agreement ($\kappa = 0.6670$, $p < 0.01$), and ER had no significant agreement of damage categories ($\kappa = 0.3750$, $p > 0.05$).

DISCUSSION

Complexity and relief on chalk reefs and coral reefs

Cromer reef pot and control sites showed no difference in any complexity variable, which is likely due to the similarity of conditions across each sample site, and shanks being dropped in roughly, but not exactly, the same location repeatedly. This would spread any impact on the reef across the entire fished area rather than in dedicated "pot spots."

Cromer site variation showed, as previously reported (Tibbitt et al., 2020), that WS1 was less complex than WS2 and WR. This indicates that the chalk substrate present along parts of the North Norfolk coast provided complexity to the region that cannot be attributed to sandy and stone-covered substratum. ER was not dissimilar to any region, likely as its mixed substratum provided areas of raised chalk and flat sand and stone grounds similar to other sites.

Here, relief is taken as the absolute vertical increase in a substrate within a given area. This took the linear assessment of verticality/slope (Oakley-Cogan et al., 2020) and applied it to a surface area for a more interactive view on how the changing substratum could interact with organisms and objects introduced.

The difference in all summary statistics of relief on the Cromer Shoal Chalk Bed strongly suggests that the relief of the reef is provided by the chalk, as the elevated sites were those of chalk substrate, and the flatter site was that of cobbles, sand, and gravel (Table 2). The lack of correlation with vector dispersion and fractal dimension showed that relief focuses on medium-scale complexity than the small scales used in those metrics. The slight correlation with rugosity is likely due to the gullies and ridges captured in both relief and rugosity factoring into the calculation of each metric.

Rugosity had moderate to strong correlations with relief, and vector dispersion had moderate correlations with relief at both coral reef sites. Pak Kasims was a sloping site with raised and settled substrate, whereas Sampela had coral bommies, but both would provide elevation. Therefore, relief at both sites also led to more intricate complexities in rugosity and vector dispersion on the coral reefs.

Relief provides information for both coral and rocky reefs. Coral reef relief could highlight areas providing both medium- and small-scale complexities, such as bommies and raised substrate that allows for more settlement of complex organisms. For rocky reefs, relief provides a different view to other common complexity metrics across a 3D area of reef, one that may better represent the complexity of other medium-scale rocky reef features.

Here, the relief of chalk may also associate with the abundance of catchable crustaceans on the chalk reef with more data, as fishers often prefer to place their pots on "rough ground," their term for visibly (seen on an echo sounder) complex chalk bed.

The extraction of relief data would benefit from vertical reference in each modeled area, such as a float (Young et al., 2017), as the models here used visually assessed alignments from video footage.

C. pagurus preferences in habitat complexity

Adapting the size categories of fractal dimension to suit the target species, *C. pagurus*, confirmed the overall findings of the previous study (Tibbitt et al., 2020). The distinction in complexity and species abundance with regard to D was more reflective of real-world separation in *C. pagurus* individuals here than those in the previous study, which found correlations between the two only at scales above the minimum landing size (starting at 15 cm and upward) (Tibbitt et al., 2020). The adjusted metric applies context for species targeted by fishing and may be a more viable foundation for policy changes and supporting research.

When considering relief, the most complex site shifted from WR to WS2, matching with in situ visual observations. WS2 was also the most varied site, with large shifts in relief consistently, compared with the occasional higher area in other sites followed by generally consistent relief. WS1 was the most uniform of the sites assessed in terms of relief, likely as the lack of chalk and layering prevents much of the shifting topography indicative of the other sites.

The relief metric suited this study more than assessments of rugosity and vector dispersion as it was selected for the environment itself, to detect medium-scale changes in structure, compared with other common metrics used in other studies with similar aims (McCormick, 1994; Oakley-Cogan et al., 2020; Young et al., 2017). Relief had a weak correlation with R that is likely reflective of R's ability to track the changing height of the substrate if it is constant in one direction, that is, an increase is not matched by a decrease in the same measurement.

The finer scale of R is made finer still when considering $\frac{1}{k}$, which did not correlate with relief likely because of this difference in resolution. Neither category of D correlated with relief, likely as the metrics are focused on entirely different factors.

The increased D_{catch} at the more visibly complex chalk sites indicates a preferential environment for catch-size *C. pagurus* that is not reflected in flatter environments or with non-catch, smaller individuals. This is supported by the correlation between D_{catch} and adult crab abundance, and the lack of correlation with $D_{non\text{-}catch}$ or juvenile crab at either complexity. The lack of apparent habitat preference with juvenile crab could be due to all sites having the same $D_{non\text{-}catch}$, indicating that complexity preference for juvenile crabs was the same across the study, or because of the territorial nature of adults, particularly male, *C. pagurus* causing smaller individuals to be pushed out of their preferred environment (Vogan et al., 1999). Relief was also not correlated with species' abundance overall or by age/size. This is likely as the smaller intricacies of complexity favored by *C. pagurus* are not detected by the medium-scale assessment of relief performed here.

Monitoring human impacts on chalk reefs

The difficulty in the analysis of chalk damage on the site limits the conclusions that can be drawn. We know how human objects impact the substrate (Tibbitt et al., 2020) but not the extent across the site, partly because of the mixture of substrates and complexity and partly because fishing pressures are unevenly distributed across the MCZ due to the location of shore launching sites and nomadic fishing boats. Increasing the data collected may bring out patterns already appearing to emerge in the damage observations. The clustering of damage along the survey sites (Figure 4) is a potential avenue for further investigation to determine whether particular chalk features and characteristics are more at risk of certain types of damage. Further surveys along shanks, or alternatively reference areas of reef, could provide greater insight into this when combined with both complexity assessments, visual descriptions of the site and hardness measurements of the chalk itself.

Areas of higher relief showed increased levels of low-severity damage and abrasion damage, showing that more elevated sites are more susceptible to pots scraping down chalk to settle below, abrading the substrate, and to ropes dragging across them to scrape off surface algae and score into the chalk. The correlation between the metrics used in the present study and damage, when compared with the lack of correlations seen in the original report (Tibbitt et al., 2020), highlights the need for tailoring complexity metrics to the environment.

The types and occurrences of damage at different sites, with different topographies, substrates, and ecological functions need more surveying to explain (e.g., higher rates of damage at WS2 and ER compared with WR). Visual assessment at WR indicated an algae layer as with WS2, and this may offer protection from some impacts. For ER, when also considering its higher instances of rubble and strike damage, this could indicate a chalk composition and/or structure that is more susceptible to breaking than at the other sites. A more refined method for testing chalk hardness than used in the Natural England report (Tibbitt et al., 2020) could be used. Greater incidence of low-severity damage at WS2 than at the other sites appears entirely reflective of abrasion damage (Figure 3). This could be due to varied relief of the site as indicated in visual characterization and in the changes measured (Figure 4). This supports the correlation of low-severity damage, specifically abrasion, with greater relief.

Damage analysis showed varying agreement between annotators of damage incidence across all sites. The variation could be for any number of reasons, including video quality, turbidity, experience of the site conditions, experience of video annotation, etc. The good-to-strong agreement found for damage categories overall, at WS2, and at WR shows the capability of similar assessments in producing robust data, but there is always a need for annotator training and a consolidation stage to resolve disagreement. In this project, data were consolidated and agreed upon by the annotators after independent assessment.

CONCLUSIONS

Tailoring complexity metrics to target environments or species is a key step in gaining insight into community interactions within a habitat. The study of rocky reef environments that feature gullies, arches, stacks, and ledges would benefit from an analysis of relief and a novel method to capture and assess relief is presented in this article. Surveying marine environments with multicamera arrays and 3D photogrammetry can drastically reduce the cost and time of fieldwork surveys and provide accurate measures of complexity across survey sites.

The investigation into the human impacts on the Cromer Shoal Chalk Bed MCZ highlights the need for urgent action and more data are vital for accurate assessments of interactions between structural complexity and the species communities that make use of niches. Future work with Natural England, EIFCA, conservation groups, and the fishing industry aims to address these challenges through adaptive risk management.

AUTHOR CONTRIBUTIONS

Jessica Wright and Jon Chamberlain conceived the ideas and designed the methodology. Jon Chamberlain collected the UK data and Jessica Wright collected the data from Indonesia. Jessica Wright and Jon Chamberlain analyzed the data. Jessica Wright led the writing of the manuscript. All authors contributed critically to the drafts and gave final approval for publication.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

Code (Wright & Chamberlain, 2024) is available from Zenodo: https://doi.org/10.5281/zenodo.10401738.

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