Improving the “chain and tape” method: A combined topography index for marine fish ecology studies

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A B S T R A C T

The “chain and tape” method is used to quantify topographic complexity in reef ecology studies, consisting of the ratio of the linear distance between the start and end points of a chain moulded to the surface of the substrate to its stretched length, a measure known as the substrate rugosity (SR) index. This measure has several advantages in the field when compared to other methods, but some weaknesses have been pointed out. However, it is still one of the most frequently used topography measures in reef fish ecology. The present study proposes a combined topography index (CTI) that uses the “chain and tape” method in the field, with results that can match more complex methods, outperforming the traditional SR index. The CTI is structured as a weighted sum of 3 topographic features: SR index, number of corrugations (NC) and maximum vertical relief (MVR), where NC and MVR are given weight coefficients ranging from 0 to 1. In order to establish weight coefficients, fish assemblages were sampled at 6 training sites, representing a topographic complexity gradient. A series of candidate weight combinations were then selected so that CTI was optimally correlated with each one of several fish assemblage parameters. The list of possible solutions was then applied to nine previously published schematic profiles and compared with other methods. The final index was established as: CTI = (1 – SR) × NC/25 + MVR/25. Ultimately, the predictive performance of CTI and SR was tested by applying them to 11 new sites as predictors of species abundances in distance-based models. The CTI outperformed SR when added to 3 previously fitted variables (depth, percent cover of sand, percent cover of cobble), explaining 5.6% additional variation when using all species and 8.1% when using only cryptobenthic species, whereas SR showed no significant additional effects.

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1. Introduction

The quantification of environmental parameters that drive the abundance and distribution of species in an ecosystem is a major part of both fundamental ecological studies and environmental monitoring (Costello, 2009). In marine reef ecology, one of the most important parameters is the structural complexity of the underlying substrate, which can ultimately determine the number of niches available when considering substrate alone.

To this day, many measurements of structural complexity have been applied in reef ecology, such as the diversity of shapes or “growth forms” (e.g. Luckhurst and Luckhurst, 1978), the diversity of substrate types and boulder sizes (e.g. García-Charton and Pérez-Ruzafa, 2001) or the calculation of complexity indices that are known a priori for a number of substrates (e.g. Brokovich et al., 2006; Roberts and Ormond, 1987). These measures are often used to complement a measure of surface topography that quantifies the complexity of the underlying substrate (McCormick, 1994; Underwood and Chapman, 1989), and the most common choice is the application of cost-effective small-scale field methods by SCUBA divers, who can accomplish enough detail with minimum cost, when compared to more expensive technology (Costello, 2009; Johnson et al., 2012).

In a study published in 1994, a series of performance tests were applied to a number of these methods using both real and schematic reef profiles (McCormick, 1994). Most of the methods tested required the use of a field profile gauge, an apparatus with eleven 1 m long graduated needles placed 10 cm apart, which are able to move vertically on a frame when placed over the substrate. The only method tested that did not require a field profile gauge was an adaptation of Risk’s “chain and tape” method (Luckhurst and Luckhurst, 1978; Risk, 1972), where a chain is moulded to the surface of the substrate, and its length is compared to the horizontal distance covered. This method usually leads to the calculation

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Abbreviations: CHD, consecutive height differences; CTI, combined topography index; MVR, maximum vertical relief; NC, number of corrugations; SASS, substrate angle standard deviation; SR, substrate rugosity; VSD, vectors standard deviation.

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of a substrate rugosity index (SR) that has two variations. In Risk's index, a variable chain length is used to cover a fixed horizontal distance (“tape”), leading to the calculation of a chain:tape ratio, which is mainly used for smaller scales (1 m²). On larger scales (100 m²), due to practical field constraints, many researchers rely on a fixed chain length and invert the index to a tape:chain ratio, so that the index maintains a linear response, decreasing as the horizontal distance covered decreases (with increasing rugosity) (e.g. Grigg, 1994; Óhman and Rajasuriya, 1998).

McCormick (1994) pointed out several weaknesses of the SR index, demonstrating that it could not distinguish among substrata with very different profiles, especially between a single large corrugation and a series of small corrugations. Nevertheless, the “chain and tape” method is still one of the most frequently applied in marine fish ecology studies (e.g. Brokovich et al., 2006; Ferreira et al., 2001; García-Charton and Pérez-Ruzafa, 2001; Óhman and Rajasuriya, 1998), most likely due to its advantages in the field: (1) there is no need to invest in or build a calibrated apparatus that is difficult to carry underwater; (2) the “chain” can be replaced by a thin leaded rope and either of them can be carried on a reel, along with a measuring tape for the linear distance, while performing other tasks; (3) the length of the “chain” can be adjusted to cover smaller (e.g. quadrats) or larger areas (e.g. transects).

The common practice of introducing other variables to complement the weaknesses of SR in modelling approaches can lead to variable correlation problems. Moreover, having two or more variables to describe topography can be seen as an unnecessary increase in dimensionality that adds to model complexity (Raudys and Jain, 1991). With this in mind, and taking into account that the main drawbacks of the SR index are related to the number and height of corrugations, the present study aims to incorporate these parameters into a combined topography index (CTI) that uses the “chain and tape” method in the field, with results that outperform the traditional SR index.

2. Materials and methods

2.1. Study area

In order to study the relationship between topographic features and fish communities, 6 sites were chosen along a 7 km stretch of coast located off Cascais, Portugal, an area sheltered from the prevailing north winds and representing a topographic complexity gradient (henceforth referred to as “training sites”). In order to test the index, an additional 11 test sites along a 250 km stretch of the Portuguese coast were sampled (Table 1).

2.2. Fish sampling method

Fish were sampled during daytime hours using visual censuses obtained by SCUBA-diving along 50 m strip transects (Harmelin-Vivien et al., 1985). In order to sample both demersal and cryptobenthic species, each transect was travelled twice for each replicate (De Girolamo and Mazzoldi, 2001), with a first pass for demersal species (50 m × 2 m) and a second for cryptobenthic species (50 m × 1 m). In order to minimise the disturbance on fish behaviour, transects were deployed while performing the first pass, with cryptobenthic fish sampled while reeling the transect, by searching in crevices and under cobbles ≤20 cm in diameter.

A total of 3 transects per site, per season were performed, starting each time at a random point and allocated to predetermined depth intervals (3–6 m and 8–11 m), according to each site's characteristics. On cryptobenthic transects, only the families Blenniidae, Bothidae, Batrachoididae, Callionymidae, Congridae, Gadidae (subfamilies Lotininae and Phycinae), Gobiesocidae, Gobiidae, Muraenidae, Scorpaenidae, Scophthalmidae, Soleidae, Syngnathidae and Tripterygiidae and the species Ctenolabrus rupestris (L.) and Labrus mixtus L. were counted. Due to ontogenic variations in behaviour, fish smaller than 5 cm TL from the genus Symphodus were also counted on cryptobenthic transects (but not considered cryptobenthic species). All others were counted on demersal transects.

Since topographic complexity remains similar yearlong, fish at the training sites were sampled in winter, spring and summer, in order to account for seasonal variation (autumn was not sampled due to turbulent sea conditions). For the test sites, an effort was made to cover a wide array of conditions (i.e. depth, exposure, latitude), while maximising the potential of each site by sampling fish assemblages during summer, which is close to the spawning season for many species (Almada et al., 1999).

2.3. Topography sampling method

In the proposed method, the aim is to sample an area in the same period of time it takes to apply the usual “chain and tape” method, while recording additional features to improve the final index value. Due to the relatively large scale covered by fish transects (50 m × 2 m), a fixed chain length of 25 m was adopted and the substrate rugosity (SR) index was calculated as the ratio of the horizontal distance covered by the contoured chain to its stretched length (Grigg, 1994). For this purpose, a reel with a 25 m long leaded rope was used, along with a 25 m reeled measuring tape. Both the leaded rope and the measuring tape are anchored at the starting point, randomly placed for each replicate. Then, one diver carrying a depth gauge (e.g. in a dive computer) unreels the leaded rope, while making sure it closely follows the contours of the substrate in a fixed direction. A second diver follows behind, unreeling the measuring tape while maintaining linear tension.

The diver carrying the measuring tape must count the number of significant height variations (≥0.5 m was adopted in this study) as they appear, recording the total number of upwards (N_u) and downwards (N_d) elevation changes along the profile. This is used
to calculate an approximation of the number of corrugations (NC), defined as

$$NC = \frac{N_t + N_d}{2}. \quad (1)$$

The linear distance \((Ld)\) given by the measuring tape from the anchor point to the end of the ledged rope is measured and the substrate rugosity index (SR) calculated as

$$SR = \frac{Ld}{Lc}. \quad (2)$$

where \(Lc\) is the stretched length of the “chain”, or ledged rope (25 m). The diver with the ledged rope then records the depth (in metres) at the deepest \((D_d)\) and shallowest \((D_s)\) points on the profile to permit calculation of the maximum vertical relief (MVR) for that replicate:

$$MVR = D_d - D_s. \quad (3)$$

Additionally, the diver with the measuring tape records the total distance travelled over several types of substrate (rock, sand, cobbles). The percentage of tape length covered by each substrate provides an approximate measure of substrate heterogeneity without much additional effort. Three replicates were performed per site, placed 3 m apart and following the direction of highest complexity within the defined depth ranges. However, due to the random placement of transects and the mobility of fish assemblages, no direct comparison between topography and fish replicates can be made. Thus, results were averaged across the fish transects and values were assumed representative of each site (Table 1).

2.4. Building and testing the index

A linear combination was chosen in order to merge the rugosity index (SR), the number of corrugations (NC) and the maximum vertical relief (MVR) into a single final index. This was accomplished through a weighted sum of these components.

Since SR decreases linearly from a maximum value of 1 as rugosity increases (Grigg, 1994; McCormick, 1994), while NC and MVR tend to increase with complexity, the variation of the rugosity term was inverted by changing it to \(1 - SR\), which in practice represents the proportion of measuring tape that is left after reaching the end of the “chain” (Öhman and Rajasirija, 1998).

The final form of the combined topography index (CTI) is therefore

$$CTI = (1 - SR) + W_{NC} \cdot NC + W_{MVR} \cdot MVR. \quad (4)$$

where SR is the rugosity index (Eq. (2)), NC is the number of corrugations (Eq. (1)), MVR is the maximum vertical relief in metres (Eq. (3)) and \(W_{NC}\) and \(W_{MVR}\) are the weight coefficients for NC and MVR, respectively.

The calculation of weight coefficients for the CTI was approached as an optimisation problem, with McCormick’s tests as performance goals. As a starting point, all 9 fish transects per training site (3 per season) were used to establish an initial list of 4 possible solutions, by setting \(W_{NC}\) and \(W_{MVR}\) to values ranging from 0 to 1, so that the final index value had an optimal Pearson’s correlation with each one of 4 fish assemblage parameters (Table 2). The list of parameters with expected positive correlations with topographic complexity was adapted from McCormick (1994) and the solution for each parameter was found using the optimisation algorithm in Microsoft Excel Solver (Fylstra et al., 1998).

In order to allow direct performance comparisons with McCormick’s approach, the list of possible weight combinations was tested by calculating the CTI for the exact same schematic profiles (Fig. 1). These theoretical profiles, although originally based on coral reefs, cover a wide range of shapes, slopes and heights that are transversal to tropical and temperate reefs, even if we consider a larger scale. Profile 1 can represent any transition from a large flat block to sand on a lower level, or to bedrock; profile 2 represents a tall hill; profile 3 is found on temperate reefs where a large rock is eroded at the base due to wave action, sand and boulders, while the top is unaffected; profiles 4 and 5 represent any surface with medium hills or blocks; profile 6 can be found when a large block is detached from a cliff and some smaller blocks fall near it; profiles 7–9 can represent several different shapes of wave-eroded tilted rock layers.

Contour length was measured using image analysis software, by laying a “chain” of fixed length (equal to the horizontal distance of the profiles) 3 times over each profile. Once the chain ended, the horizontal distance covered was measured and no further corrugations were counted. In order to cover the whole profile, one chain was laid from the leftmost point in the profiles, one at a random point in the centre and another from the rightmost point. Both the SR and all versions of the CTI were then calculated for each of the three measurements and the final index values were averaged to represent each profile.

<table>
<thead>
<tr>
<th>Fish assemblage parameters</th>
<th>CTI weight solutions</th>
<th>Separate terms</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CTI_{S1}</td>
<td>CTI_{S2}</td>
</tr>
<tr>
<td>(W_{NC})</td>
<td>0.00</td>
<td>0.04</td>
</tr>
<tr>
<td>(W_{MVR})</td>
<td>0.00</td>
<td>0.04</td>
</tr>
<tr>
<td>1. Total number of species</td>
<td><strong>0.094</strong></td>
<td>−0.006</td>
</tr>
<tr>
<td>2. Total density (fish m(^{-3}))</td>
<td>0.388</td>
<td><strong>0.414</strong></td>
</tr>
<tr>
<td>3. Density of cryptic individuals (fish m(^{-3}))</td>
<td>0.357</td>
<td>0.393</td>
</tr>
<tr>
<td>4. Density of rock residents (fish m(^{-3}))</td>
<td>0.366</td>
<td>0.379</td>
</tr>
<tr>
<td>Mean (standard deviation)(^a)</td>
<td>0.371 (0.016)</td>
<td>0.395 (0.040)</td>
</tr>
<tr>
<td>No. of correlated species(^b)</td>
<td>7</td>
<td>8</td>
</tr>
<tr>
<td>No. of correlated cryptic species(^b)</td>
<td>3</td>
<td>3</td>
</tr>
</tbody>
</table>

CTI – combined topography index; SR – substrate rugosity index; NC – number of corrugations; MVR – maximum vertical relief; \(W_{NC}\) – weight coefficient for the number of corrugations; \(W_{MVR}\) – weight coefficient for maximum vertical relief.

\(^a\) Mean correlations did not take into account parameter 1, due to non-significant results.

\(^b\) Number of significant correlations out of a total of 48 species, 14 of which are cryptobenthic.
Candidate weight combinations and the SR index were compared according to the order of complexity among the 9 profiles, by analysing Kendall’s rank correlations with the three best performing profile gauge methods, namely the sum of consecutive needle height differences (CHD), vectors standard deviation (VSD) and substratum angle standard deviation (SASD) (McCormick, 1994). Finally, the individual performance of indices on the profiles was graphically analysed.

After selecting the weight coefficients based on training sites and schematic profiles, the predictive performances of the proposed CTI and the original SR index were compared, by using them separately as predictor variables to model Bray–Curtis dissimilarity matrices of square-root transformed species densities at the test sites. This was accomplished by using distance-based linear models (DISTLM), a routine that attempts to model a multivariate data cloud described by any distance measure of choice, by partitioning variation according to a regression model (Legendre and Anderson, 1999). P-Values for the pseudo- $F$ ratios were calculated through 9999 permutations and considered significant at $P < 0.05$.

### 3. Results and discussion

The present study proposes a combined topography index that merges three topographic features to improve the performance of the traditional SR index. Of the four candidate weight combinations in Table 2, the one that maximised the correlation with the total number of species, $\text{CTI}_{14}$, is redundant with $1 - \text{SR}$, as it gives zero weight to both NC and MVR, and was therefore discarded.

Unlike the results found by McCormick (1994) in the Great Barrier Reef, no solution was able to find a significant correlation with the total number of species. In fact, conclusions regarding the influence of topography on fish species richness are highly variable (e.g. Gratwicke and Speight, 2005; Luckhurst and Luckhurst, 1978), even on different substrates in the same region (Ohman and Rajasurija, 1998). This is probably related to the erratic behaviour of this parameter, as counting rarer species can be unrelated to habitat features (Pooe and Jackson, 2012). The remaining parameters showed significant correlations with substrate complexity, with the three CTI configurations performing better than the individual terms. The effect of vertical relief in the training sites is evident, with MVR dominating $\text{CTI}_{14}$ and showing significant correlations with a larger number of species.

Despite having significant correlations with assemblage parameters, the three candidate solutions are likely to respond differently to changes in the shape of substrate profiles. This is best observed when applied to the schematic profiles proposed by McCormick (1994), which vary in complexity and shape (Fig. 1). In fact, the results of Kendall’s correlation in Table 3 lead to the decision of discarding $\text{CTI}_{14}$, since the order of complexity of the nine profiles according to this index was the least correlated with the order achieved using the best profile gauge methods. The fact that NC was not taken into account in this configuration and that excessive weight was given to MVR result in higher values for profiles with higher peaks, regardless of their shape.

The two remaining configurations, $\text{CTI}_{12}$ and $\text{CTI}_{13}$, had similar results and the traditional SR index also showed equivalent performance in terms of the order of complexity, although it was different from the substratum angles standard deviation (SASD). This index varies with the angular standard deviation of the angles formed by lines joining two consecutive needles in a profile gauge and vertical, while vectors standard deviation (VSD) depends on the angles formed by vectors perpendicular to these lines, making SASD much more sensitive to variations in height, to which SR is not very sensitive (McCormick, 1994). However, these results refer to ranks only, and thus do not take into account how different indices distinguish among different topographic features. Therefore, the final decision can only be made when graphically comparing the relative values

**Table 3**

Kendall rank correlations between several index values obtained for 9 schematic profiles adapted from McCormick (1994). All values were significant at $\alpha = 0.05$.

<table>
<thead>
<tr>
<th></th>
<th>CHD</th>
<th>VSD</th>
<th>SASD</th>
</tr>
</thead>
<tbody>
<tr>
<td>$1 - \text{SR}$</td>
<td>0.719</td>
<td>0.764</td>
<td>0.689</td>
</tr>
<tr>
<td>$\text{CTI}_{12}$</td>
<td>0.764</td>
<td>0.719</td>
<td>0.733</td>
</tr>
<tr>
<td>$\text{CTI}_{13}$</td>
<td>0.764</td>
<td>0.719</td>
<td>0.733</td>
</tr>
<tr>
<td>$\text{CTI}_{14}$</td>
<td>0.719</td>
<td>0.629</td>
<td>0.733</td>
</tr>
</tbody>
</table>

$\text{CTI}_{2-54}$ – combined topography index according to the configurations proposed in Table 2; SR – substrate rugosity index; CHD – consecutive height differences; VSD – vectors standard deviation; SASD – substratum angle standard deviation.
obtained when using CTI$_{52}$, CTI$_{53}$, the SR index and McCormick’s CHD (Fig. 2).

The weaknesses of the SR index applied to these profiles have already been pointed out by McCormick (1994) and were the motivation for this study, but Fig. 2 clearly shows its lack of sensitivity to tall and highly corrugated structures, since it only focuses on the perimeter of the shapes regardless of their number or height, giving too much importance to the tabulate outcrop in profile 3. What is accomplished by introducing sensitivity to height and the number of corrugations in the CTI is a small increase in the response to the number of corrugations and a clear valorisation of higher structures, which is evident in the increased values of profiles 2, 4 and 6 and the reduced importance given to the perimeter of the tabulate outcrop when compared to the SR index. Moreover, it is clear that the weight given to vertical relief in CTI$_{53}$ is too high, since the complexity of higher profiles is always overestimated regardless of shape, so the distinction of the more complex tabulate outcrop from its neighbours becomes less pronounced. Considering this, CTI$_{52}$ was considered the best configuration for the index, achieving a better balance between corrugations and vertical relief. Therefore, with $W_{NC} = W_{MVR} = 0.04 = 1/25$, the final configuration of the combined topography index becomes CTI = (1 – SR) + NC/25 + MVR/25 (MVR in metres$^1$).

It is also evident that no single index has an ideal response regarding the perceived complexity by itself, with the CHD method failing to quantify the complexity of the tabulate outcrop and the CTI approximating profiles 3 and 6, which have different configurations. This behaviour of the CTI, however, is because the relative weights of rugosity and vertical relief have been tuned to maximise total abundance (CTI$_{52}$ in Table 2). In fact, the CTI gives a high value to profile 3, since larger caves and indentations can provide shelter to more fish and cave-dwelling species, and the large corrugation in profile 6 can also provide shelter for more juveniles and adults and therefore increase the carrying capacity of a habitat in terms of total abundance, while protecting the fish from predators and wave action (García-Charton and Pérez-Ruzafa, 2001; Henríques and Almada, 1998).

Although the linear correlation with assemblage parameters has been optimised, and taking into account oscillations due to seasonal patterns, this does not mean causality or good performance in a modelling context. For this purpose, distance-based linear models (DISTLM) were used to test the CTI and the SR index (Table 4) in new, independent test sites covering a wide variety of conditions (Table 1). This approach resulted in 2.8% (whole assemblage) and 4.5% (cryptobenthic only) more variation explained with the CTI, when compared to the SR in marginal tests. However, to better understand the explanatory capabilities of the topography indices in a context of intricate effects and interactions, they were fitted into a model after fitting three potentially confounding variables (depth and percent cover of sand and cobble). This way, by using type I (sequential) sums of squares, the effects of a new variable are calculated over and above the effects of the previously fitted variables (Anderson et al., 2008). Fitting the CTI to this model achieved a significant gain in 5.6% more variation explained for the whole model using the complete assemblage and 8.1% using only cryptobenthic species, whereas the SR index had no significant additional effects. The main advantage is that this was achieved only through index configuration and not by adding dimensions to the model, something that is often undesirable, due to added complexity (Raudys and Jain, 1991).

This behaviour optimisation of the index was not intended as a tailor-made approach to fit our data, and care was taken to use independent data to test its performance. Instead, it was a way of looking at topography “through the eyes of fish”, since habitat classifications are highly dependent upon the organisms of interest and the existence of a universal measure is unlikely (Costello, 2009). Overall, the CTI showed promising results, at a time where there is a need to detect and act upon anthropogenic impacts to marine ecosystems, by isolating them from natural variation (Henríques et al., 2008). Further developments should go into applying the index in other areas, especially in highly diverse tropical reefs, as well as optimising weight coefficients to other biological elements, such as sessile macroinvertebrates.

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1 For units in feet, use CTI = (1 – SR) + NC/25 + MVR/82.

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Table 4

<table>
<thead>
<tr>
<th>Performance of the substrate rugosity index and the combined topography index in distance-based linear models (DISTLM), when modelling Bray–Curtis dissimilarity matrices of square-root transformed species densities. Indices were used alone in marginal tests and then introduced in a model with 3 previously fitted variables (depth, percentage cover of sand and percentage cover of cobble). Both the additional proportion of variation explained by fitting the indices and the cumulative variation explained by the whole model are shown. P-Values are italicised when non-significant.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Marginal tests</strong></td>
</tr>
<tr>
<td>All species</td>
</tr>
<tr>
<td>SR</td>
</tr>
<tr>
<td>Cryptobenthic species</td>
</tr>
<tr>
<td>CTI</td>
</tr>
<tr>
<td><strong>Whole model</strong></td>
</tr>
<tr>
<td>All species</td>
</tr>
<tr>
<td>SR</td>
</tr>
<tr>
<td>Cryptobenthic species</td>
</tr>
<tr>
<td>CTI</td>
</tr>
</tbody>
</table>

| SR – substrate rugosity index; CTI – combined topography index. |
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References


