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ORIGINAL RESEARCH

Red List for British seaweeds: evaluating the IUCN methodology for non-standard marine organisms

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Abstract
The IUCN Red List of Threatened Species is an authoritative tool in biodiversity conservation. Whilst IUCN criteria have been applied successfully to groups such as birds and mammals, a Red List assessment of British seaweeds in 2021 revealed that the categories to which seaweed species were assigned were dependent on how the criteria were applied. Here, this seaweed assessment is used as a case study with which to evaluate the IUCN methodology for use with 'non-standard' groups of organisms. A data-driven assessment of red (Rhodophyta), green (Chlorophyta) and brown (Phaeophyceae) seaweeds, which applied three (A, B and D) of the five IUCN criteria (A–E), categorized 13% of 617 British species as threatened. Following peer review, only 7% of species were categorized as threatened (1% Critically Endangered—CR, 3% Endangered—EN, 3% Vulnerable—VU), and 55% as Data Deficient. This reduction in species categorized as threatened suggests that strict application of the IUCN criteria may, at least for the seaweeds, over-estimate threat. As a result of this assessment, recommendations include the need for a more unified monitoring system and a review of the suitability for/application of the IUCN assessment criteria to some types of organisms. For example, in clonal populations, it is not possible to count individuals, and complex life histories cause additional complications. IUCN criteria must be applicable to a wide range of organisms, including seaweeds.

Keywords Climate change · Clonal populations · Generation time · Peer review · Seaweeds · Species extinction

Introduction

The IUCN (International Union for Conservation of Nature) Red List of Threatened Species aims to evaluate the extinction risk for species using explicit, objective, comparable and revisable criteria and is a powerful tool in biodiversity conservation (IUCN 2001, 2019; Mace and Baille 2010; Mace et al. 2008). Originally intended for global assessments,

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it was meant to be applicable to all species except microorganisms (Rodrigues et al. 2006; Zamin et al. 2010). The Red List assessment has been applied successfully to some groups, notably mammals, birds and reef-building corals (Brooks et al. 2015), but it has not been applied or applied only in a very limited way to most other groups of organisms. Consequently, critical groups of organisms are not included in policy or conservation management decisions at regional or national levels (Dahlberg and Mueller 2011). Reasons for the lack of Red Lists are various, including limited resources, cultural constraints, biases, or logistical difficulties, but scarcity in the lists of many non-standard groups of organisms suggests that applying a 'one size fits all' set of criteria to cover all life may not be appropriate. For example, Bergamini et al. (2019) reported difficulties in applying the criteria to bryophytes and other clonal and colonial organisms. They also discussed how to deal with concepts of generation time, mature individuals and severe fragmentation of distribution under the narrow Red List criteria, and provided pragmatic recommendations for applying the IUCN criteria to bryophytes, which could be applied to other clonal organisms. Another major obstacle is the massive data requirements of the Red List process to adequately address established criteria, which is a reason why the current Red List is biased towards organisms with large data collections, often over large temporal and spatial scales, such as for birds and mammals. However, evidence that this may be changing includes attempts to apply Red List criteria to organisms in challenging marine environments, such as hydrothermal vents (Thomas et al. 2021).

Although the Red List is intended to be global, there is scope for specific geographical or politically defined Red Lists. It has been applied at the national and regional level with explicit adaptations to the criteria (Brito et al. 2010), and the IUCN hosts a National Red List database (https://www.nationalredlist.org/). The IUCN considers such lists to be important in informing national reporting in relation to international biodiversity targets, such as the Convention on Biological Diversity (CBD) and Sustainable Development Goals (SDGs).

In this paper, the IUCN criteria are used to evaluate British seaweeds for the Red List and tested to determine whether the criteria are universally suitable for application to non-model organisms. Many seaweed characteristics do not fit the Red List criteria and, despite their global importance and the many threats they face, seaweeds have received little attention from the IUCN Red List. Although Zaloumis (2008) investigated the applicability of Red List criteria to South African seaweeds and concluded that "Overall the IUCN evaluation process should not need to adapt for seaweed species and that [sic] evaluations have the potential to be used as indicators of ecosystem change for a region", seaweed Red List engagement remains low.

It is estimated that there are c. 24,000 seaweed species globally, of which approximately 12,000 have been described (Guiry 2012). Globally, only 75 seaweed Red List assessments have been made, focussed on endemic species in Hawaii and Galapagos (https://www.iucnredlist.org/ accessed on 5th March 2021). National assessments examine only distributions within a targeted jurisdiction (rather than the global distribution) and there are 423 seaweed species documented with Red List criteria on the national IUCN Red List database (https://www.nationalredlist.org/ accessed 4th May 2021). These entries need to be treated with caution because a number of species listed do not occur in the regions from which they were reported (J. Brodie pers. obs.).

In 2021, we undertook an IUCN Red List assessment of British seaweeds. A provisional Red List assessment for British seaweeds (Brodie and Wilbraham 2013) provided a basis for the 2021 Red List project. Seaweeds recorded from the seas around Britain represent about 7% of the world's known species and are a key component of British biodiversity

(Brodie et al. 2016). Increasing evidence demonstrates change in the seaweed flora linked to climate change, both globally, with an estimated 30% loss of kelp forests (Smale 2020), and regionally (Brodie et al. 2014; Yesson et al. 2015). Concurrently, there are increasing human pressures from harvesting and foraging, loss of habitat and increases in the arrival of non-native species (Clubbe et al. 2020).

During the 2021 Red List assessment, it rapidly became apparent that, depending on how the criteria were applied, the category to which species were assigned varied considerably. The seaweeds did not 'fit' a number of the assumptions inherent in the assessment. The aim of this paper is to use the Red List assessment of British seaweeds to review the application of IUCN criteria as an example of a non-standard group.

Methods

Creating the species list

A species list was created (Supplementary Table 1) based on "A revised check-list of the seaweeds of Britain" (Brodie et al. 2016). Taxonomic and nomenclatural changes and species additions, including new reports of non-native species, were updated based on current literature and personal observations (JB). The names used for the list followed Guiry and Guiry (2021). Non-native species were excluded from the Red List assessment (Supplementary Table 2).

Distribution data

The geographic scope of this assessment covered England, Scotland, Wales, the Channel Islands and Isle of Man. Species distribution was assessed by cross-referencing all names from the species list (and their recent synonyms) with publicly accessible and other sources of distribution data (Supplementary Table 3). This cross-referencing required an exact name match. Data were accessed during January and February 2021.

For quality control, only records with a valid collection date and a valid spatial coordinate (within Britain) with spatial uncertainty < 2 km (the width of a tetrad) were included in the data set.

Nine datasets covering c. 0.5 million observations were used for the assessment. Data from the National Biodiversity Network Atlas (NBN) represented 58% of all observations and 99% of observations with abundance information (N = 85,424). GBIF and OBIS provided the next largest datasets (16% and 15% respectively). These datasets overlapped in their content, but de-duplication was not required for Red List evaluation (details below).

Observations date back to 1668, but half of all observations were from 2000 onwards and 30% within the default assessment period (2009–2018). Fifty-five taxa had no records, while 29 were represented in only a single tetrad.

Red List assessment criteria

The Red List process has a variety of spatial and temporal criteria to assess and classify threat levels based on knowledge of species distributions and abundance (IUCN Guidelines Version 14, IUCN 2019). The categories relevant to this study are: CR = Critically

Endangered, EN = Endangered, VU = Vulnerable, NT = Near Threatened, LC = Least Concern, DD = Data Deficient. Some of these categories are amenable to a provisional automated assessment based on observations (assuming that available species data are a reliable representation of their distribution).

The Red List assessment process [Criteria A (subcriterion A2c), B and D] employs two spatial metrics to examine a species' distribution (IUCN 2019): Area of Occupancy (AOO) and Extent of Occurrence (EOO). AOO is the area of occupied grids of a dimension appropriate to the taxon; here, we have followed the IUCN recommended grid size of 2 km × 2 km (a tetrad). EOO is defined as "the area contained within the shortest continuous imaginary boundary which can be drawn to encompass all the known, inferred or projected sites of present occurrence of a taxon" (IUCN 2019). In practice, this is calculated by fitting a minimum convex polygon around species' occurrence observations.

Criterion A2 is based on observed population reductions assessed over 10 years or three 'generations' (IUCN definition of generation—IUCN 2019). For the application of this criterion, an assessment was made of generation times for all species based on available literature. A conservative approach was taken to identifying long-lived species, only including species with reliable evidence of longevity. For the rest, it was assumed that there would be at least 3 generations covered during the default 10-year assessment period.

Sub-criterion A2b is based on "an index of abundance appropriate to the taxon". In this assessment we have used the commonly employed "SACFOR" abundance scheme (Crisp and Southward 1958; Yesson et al. 2015; S = Superabundant, A = Abundant, C = Common, F = Frequent, O = Occasional, R = Rare). The SACFOR (or SACFOR<u>N</u> where N = not observed) scheme is used by a variety of recording schemes and available through the NBN atlas. Although 99% of the abundance observations come from the NBN data, only 25% of NBN records contain abundance data. These data have been used to assess declines in British seaweeds (Yesson et al. 2015). Observations within the assessment time-frame were grouped by monad (1 km × 1 km grid cell) and a trend for each monad was calculated by regression of ranked SACFOR category (S = 6, A = 5, C = 4, F = 3, O = 2, R = 1, N = 0) with year of observation (trend being quantified as slope of the regression of ranked category against year). Each species was assessed based on the median change in SACFOR category (following Yesson et al. 2015). Thus, a median trend of − 0.1 is the equivalent of a single category decline over a decade (Fig. 1). The SACFOR scheme is a semi-logarithmic scale designed so that each categorical step represents an order of magnitude change in cover or abundance. The UK Biological Records Centre guidance recommends using different SACFOR schemes based on the size and habit of species. For example, a crust form of seaweed or small sized organism would be categorized as S when > 80% or > 1 per 0.001 m^2 but the abundance criteria would shift down with fleshy seaweeds or larger sized organisms. The scheme for turfing species is based on percentage cover, and each categorical change represents a doubling/halving of cover. The schemes for "small" and "large" seaweeds are based on abundance (individuals per m^2) and each category represents a 10-fold change (https://mhc.jncc.gov.uk/media/1009/sacfor.pdf; Hiscock 1996; Strong and Johnson 2020). Unfortunately, the NBN database does not record which of the SAFCOR schemes was used for any observation. Rather than guess the scheme selected, we have adopted a conservative approach, interpreting each categorical change as a doubling/halving. Therefore, we interpret a single category per decade decline as a 50% reduction, which is interpreted (with sufficient sampling) as "Endangered" under criterion A2b (see Fig. 1). Category change is converted to percentage change (p) based on the formula $p = 100 \times \mathrm{sign}(T) \times (1 - 0.5^{|T|})$ where T is the median category change (based on the numeric rankings) over the assessment period, and sign(T) = 1 if T is positive and − 1 if T is negative.

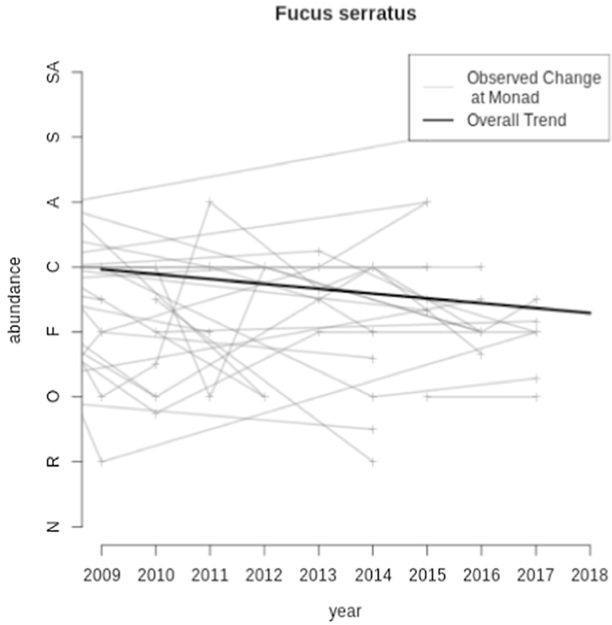

Fig. 1 Sub-criterion A2b application for *Fucus serratus*. Observed changes in SACFOR category are assessed for each monad (1 km^2) over the 10 year period. The rate of change for each monad is calculated (slope of grey lines). The overall trend is calculated as the median of all slopes (black line). Average categorical change is calculated for the assessment period (10 years). In this case the change represents a decline of slightly less than one category over the assessment period from C to F (0.74 of a whole category or ~13 years per category decline). Each category drop is interpreted as a 50% decline, so the observed trend represents a $100 \times -1 \times (1 - 0.5^{0.74}) = 40\%$ decline over the assessment period, which is categorised as Vulnerable

Species without abundance data within the evaluation period are automatically classified as data deficient.

Sub-criterion A2c is based on an observed decline in AOO or EOO over the assessment period (IUCN 2019). AOO and EOO were calculated for each year of the assessment, and a regression was fitted of the form Area against Year (Fig. 2). Species showing a significant decline (negative trend with $p < 0.05$) were assessed for the scale of decline. Total AOO and EOO values for the start and end of the assessment period were calculated based on the regression model and the percentage change between the start and end period was used to calculate the scale of decline, with this derived value used to assign a threat category: 80+% = Critical CR, 50+% = Endangered EN, 30+%=Vulnerable VU, 25+% = Near threatened NT, Decline < 25%/Stable/Increase = Least concern LC. Additionally, insignificant regressions ($p > 0.05$) with declines greater than or equal to the VU threshold (30%) were classified as NT, and all other insignificant trends were classified as LC. Species without data within the evaluation period are automatically classified as data deficient.

Criterion B is based on geographic range, with area thresholds (AOO or EOO) determining each category. This criterion is useful for classifying rarer taxa (with more limited distributions), which lack sufficient data to employ the data-hungry criteria A2b and A2c. Under such circumstances, we have chosen to employ Criterion B2 based on AOO rather than B1 based on EOO, which can fluctuate dramatically with the addition of a single observation. The area thresholds of the B2 criterion are only applicable if other conditions are met, i.e. evidence of decline and limited number of locations. We have defined the area of decline by comparing total AOO for the assessment period (henceforth 'recent AOO') with total AOO observed over all time (henceforth 'all-time AOO'). Any taxon for which recent AOO is less than half of all-time AOO is determined to have shown a decline. The other B2 condition assessed was number of locations. The IUCN definition of location can be a difficult concept to assess, requiring populations to be grouped by the presence of a shared threat (IUCN 2019). These data

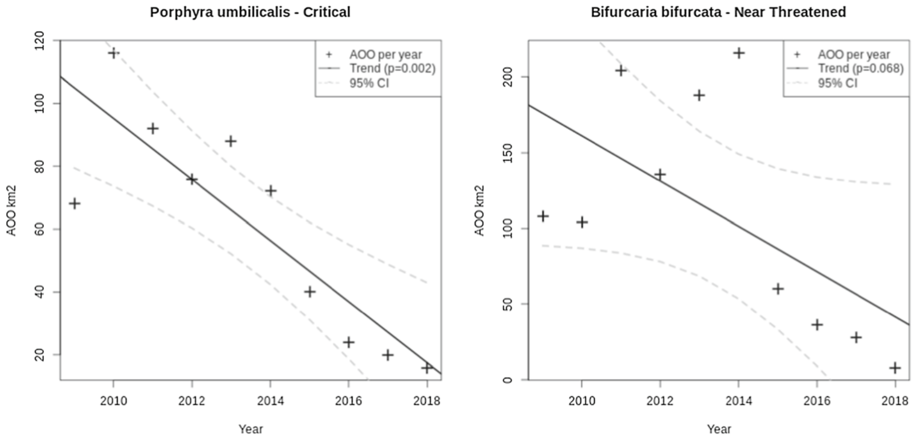

Fig. 2 Example implementations of Criterion A2c: decline in AOO. Annual AOO values for each species are plotted for the assessment period (2009–2018). The regression line for both species shows a negative trend. The trend for *Porphyra umbilicalis* (left) is significant ($p < 0.05$), so the proportional difference between the start and end modelled AOO is used to calculate the decline (83%), which fits the Critically Endangered threshold. *Bifurcaria bifurcata* (right) shows a steep declining trend (77%), but the regression is insignificant ($p > 0.05$), so the evidence of decline is not clear and the category of Near Threatened is selected. NB: the example presented does not reflect the final categorisation of *B. bifurcata* which is ultimately classified as Endangered (EN; Table 4)

were not available for this report, so we have taken a conservative approach, assuming that the number of tetrads where a species occurs is greater than or equal to the number of locations. A tetrad (2 km × 2 km) is unlikely to contain multiple locations (i.e. multiple populations each with distinct threats), while conversely a single location, e.g. a large bay, is likely to encompass multiple tetrads. As with Criterion D2, species identified as being data poor due to difficulties of identification (requiring microscopic examination or DNA verification) were not evaluated in this category, as there is a risk of misinterpreting under-reporting as vulnerability.

Criterion C is based on counts of individuals within populations. These data are not available for any seaweeds, so we have not applied this criterion.

Criterion D2 classifies species as Vulnerable based on a restricted AOO. We have used the recommended threshold of under 20 km^2. Therefore, species with distribution data covering fewer than 5 tetrads (2 km × 2 km square = area 4 km^2) were provisionally automatically assessed as Vulnerable, subject to expert confirmation and identification of “a plausible future threat that could drive the taxon to Critical or Extinct in a very short time” (IUCN 2019). We have identified two types of threat: climate change and habitat loss. Firstly, increasing sea surface temperatures due to climate change has a dramatic impact on many marine species. In the northern hemisphere many species are contracting their southern range as these areas become too warm (Mieszkowska et al. 2006; Brodie et al. 2014). Climate change was classified as a threat for all species where Britain is at the southern limit of their distribution. Secondly, decline and/or degradation in kelp and maerl habitats and gravel beds around Britain are well-documented (Hall-Spencer et al. 2010; Krumhansl et al. 2016; Yesson et al. 2015). We have classified all seaweeds dependent on these habitats as under threat of habitat loss. The D2 criterion was assessed using all records for the species over all time. Species identified as being data poor due to difficulties of identification (requiring microscopic examination or DNA verification) were not evaluated in this category, since there is a risk of misinterpreting under-reporting as vulnerability.

Criterion E—As for C, we do not have these data available to calculate extinction probability for any seaweeds, so we have not applied this criterion.

All spatial points were projected onto the Ordnance Survey Grid of Great Britain (EPSG:27700) for spatial assessment using the function 'project' in the R package PROJ4 (https://cran.r-project.org/package=proj4). These points were used for calculation of EOO and AOO. EOO was calculated using the gConvexHull and gArea functions in the R package RGEOS (https://cran.r-project.org/package=rgeos). AOO was calculated by tallying the number of occupied tetrads and multiplying by 4 (area of each tetrad is 4 km^2). A reference layer of British tetrads was constructed using the FSC QGIS plugin (https://www.fscbiodiversity.uk/fsc-plugin-qgis-v3).

Most species were assessed over the default 10-year time period (but see section on generation times below). After examination of available data, the period 2009–2018 was selected as the most recent 10-year stretch with consistent data coverage (Supplementary Fig. 1). There is a notable drop-off in data for more recent years, consistent with a time lag between observations and deposition of records into databases.

All assessments were assigned using a bespoke R script, which is available at https://github.com/cyesson/RedListEvaluation, following the criteria outlined below.

Determining the proportion of intertidal and subtidal species records

To determine whether there was a bias towards more intertidal than subtidal records, depths and location of the data were analysed. Approximately 30% of observations reported a depth, the majority using a narrative reporting style: "− 5 to 5 m". These were converted into a minimum and maximum depth, from which the mean was calculated to represent the observation. Of these observations, c. 25% were deeper than 10 m, and 50% deeper than 5 m. However, as 70% of records had no observer-reported depth, record depths (or elevations) were inferred by spatially cross-referencing the observation localities with a high-resolution digital elevation model (https://portal.emodnet-hydrography.eu/), which reports depth relative to chart datum.

Biogeographic analysis

Geographic distribution of species was examined in relation to the "biogeographic boundaries" implemented by the Joint Nature Conservation Committee's regional seas project (Connor et al. 2004). Presence of each species within the seven regions around Britain was determined from the distribution data using the point.in.polygon function from the R package "sp" (https://cran.r-project.org/package=sp).

Expert evaluation and revision

The results of the automated process (Supplementary Table 1, column D) were presented as provisional assessments to a group of phycological experts with extensive experience conducting surveys around Britain (Supplementary Table 4) at a workshop on 28th June 2021. The experts reviewed the lists and provided feedback. Every species designated VU, EN or CR was discussed which resulted in the revision of some assessments (Supplementary

Table 1, column D), mostly reclassifying the species in question as data deficient due to uncertainty over the quantity and quality of data available. For several species only certain criteria were reclassified as data deficient, resulting in other criteria being used for the final assessment. The agreed criteria were used to derive the final assessment categories (Supplementary Tables 5–7).

Results

Species list and dataset

The species list was composed of 656 taxa, predominantly species but including one ecad, two varieties and two subspecies (189 brown seaweeds–Phaeophyceae, 112 green seaweeds–Chlorophyta, and 355 red seaweeds–Rhodophyta). It included 39 non-native species (Supplementary Table 2), which were not Red List assessed, leaving 617 species for assessment.

The dataset had 566,381 observations collected from 9 data sources (Supplementary Table 3), with a median of 66 observations amongst the 554 names with observations and the most widely observed species (*Saccharina latissima*) having 32,211 observations.

Determining the proportion of intertidal and subtidal species records

The depth (or elevation) of observations (inferred from spatial coordinates) is presented in Supplementary Fig. 2. 38% of all analysed seaweed observations were from water deeper than 5 m (22% deeper than 10 m), representing a substantial number of subtidal observations.

Generation time

Generation time for the seaweed species was assumed to be three 'generations' over the 10-year assessment period, 2009–2018, for the majority of species, but complex life histories and a lack of knowledge about particular species raised doubts over this assumption. The results are influenced by the difficulty of identifying minute epiphytic and endophytic species that require specialist identification techniques.

Of the species assessed for generation time, only 12 were identified as having a generation time of more than three years (Table 1). For the rest, it was assumed that there were at least 3 generations over the 10-year assessment period. Life histories are complex in all groups of seaweeds and in general, research indicates a range of different modes of reproduction but with little or no real indication of generation time (e.g. Lee 2018). Some species or some populations within a species only reproduce vegetatively. Other species undergo an alternation of sexual and asexual phases where one life history phase (e.g. crustose asexual phase) might live for many years, whereas the other phase (e.g. upright sexual phase) may be seasonal and short-lived. Other species may reproduce from an annual blade and overwinter as a basal crust, rhizoids or endophytically as a few cells just below the host surface.

Table 1 Species with generation times of more than 3 years

	Source
RED	
Ahnfeltia plicata	https://www.marlin.ac.uk/species (Rayment 2004)
Furcellaria lumbricalis	Dixon and Irvine (1977)
Lithothamnion corallioides	Irvine and Chamberlain (1994)
Lithothamnion erinaceum	Melbourne et al. (2017)
Lithothamnion glaciale	Irvine and Chamberlain (1994); Gunnarsson (pers. comm.)
Phyllophora crispa	Dixon and Irvine (1977)
Phyllophora pseudoceranoides	Dixon and Irvine (1977)
Phymatolithon calcareum	Irvine and Chamberlain (1994)
GREEN	
Codium adhaerens (?)	Thought to be perennial (Brodie et al. 2007) but see Gaspar et al. (2017)
Codium bursa	Geertz-Hansen et al. (1994)
BROWN	
Ascophyllum nodosum[a]	Bush et al. (2013) and refs therein
Laminaria hyperborea	Bush et al. (2013) and refs therein

[a]Includes *Ascophyllum nodosum* ecad *mackayi*

Criteria used in evaluations

Most evaluations were based on criterion A2c (N = 214), but most assessments of threatened species were based on criterion B2ab (ii) (N = 11) (Table 2). The provisional automated assessment placed 13% in threatened categories and 46% as data deficient (DD) (Table 3). Expert revision resulted in a reduction to 43 (7%) species being placed in threatened categories and 338 (55%) being classed as DD (Table 3; Supplementary Fig. 3).

Assessment after peer review evaluation

The percentages of brown, green and red seaweeds in each category are summarized in Supplementary Fig. 3. The categories for all the species assessed along with AOO and EOO areas, earliest and latest dates of records are shown in Supplementary Table 1. Species assessed as Critically Endangered, Endangered and Vulnerable are shown in Supplementary Tables 6–8.

Overall, 7% of the seaweed species fell into the threatened categories Critically Endangered (CR), Endangered (EN) and Vulnerable (VU). Only red species were assessed as CR. Some red, green and brown species were assessed as EN but only reds and browns were assessed as VU. Just over half (55%) of all seaweed species were classified as Data Deficient (DD), although this was slightly higher for the greens (66%) and browns (62%) than for the reds (47%).

The species lists for CR, EN and VU after peer review evaluation are shown in Table 4. Five red species were classified as CR. For the species assessed as EN, the majority were red and most rare. Two green species were in this category, of which

Table 2 Criteria used to determine categories

Criterion	All categories			Threatened categories		
	Provisional	Final	Change	Provisional	Final	Change
None (DD)	281	338	57	–	–	–
A2b	57	51	− 6	17	7	− 10
A2c	258	214	− 44	24	5	− 19
B2ab(ii)	112	124	12	38	29	− 9
D2	3	2	− 1	3	2	− 1

Note that column sums do not equal total taxa evaluated as final categorisation can be based on multiple criteria

Lychaete pygmaea is inconspicuous and confined to maerl, and *Codium bursa* is considered to be extinct on mainland Britain. There are five brown species, of which three, *Acrothrix gracilis*, *Spermatochnus paradoxus* and *Tilopteris mertensii*, are rarely recorded summer annuals, *Alaria esculenta* is common and *Ericaria selaginoides* is locally common. The majority of the reds assessed as VU are rare and although there are many old records, very few recent records exist. Of the browns, *Fucus distichus* and *Halosiphon tomentosus* are boreal species, with the former confined to the far north of Britain. *Desmarestia aculeata* is restricted in habitat. *Porphyropsis coccinea*, also listed as VU, is a common red epiphyte on *D. aculeata*. *Fucus cottonii* encompasses several brown species, dwarf forms of which are confined to some saltmarshes (Neiva et al. 2012).

Comparison of the Red List assessment made in 2013

A comparison of the Red List species classification in the provisional UK assessment (Brodie and Wilbraham 2013) with the current assessment (Table 5) showed that two species categorized as threatened in 2013 are still considered threatened. Those previously assessed are almost all in the Data Deficient category, while those categorised as threatened in this assessment were mostly previously classed as Least Concern. This reflects differences in methodology between the purely data-driven approach of the current assessment and the expert assessment of the previous report. The former assessed trends in distribution, abundance and cover and depended upon substantial data being available to identify declines, whereas the latter focussed on identifying species with restricted ranges. The absolute number of non-native species has increased since Brodie et al. (2016), but the proportion remains stable as there has also been an increase in the number of native species observed.

Biogeographic analysis

The highest proportion of species that were assessed as threatened for the different biogeographic regions (sensu Connor et al. 2004) was for reds in the Scottish Continental Shelf (31%) and the lowest was for greens (8%) in the Northern North Sea (Supplementary Table 9).

Table 3 Changes in the numbers of species in each Red List category based on provisional (automated) assessment and the final assessment agreed at the expert workshop

Provisional category	Final category						Total (%)
	CR	EN	VU	NT	LC	DD	
CR	5	0	0	0	11	8	24 (4)
EN	0	20	0	0	10	2	32 (5)
VU	0	0	18	0	5	3	26 (4)
NT	0	0	0	57	25	44	126 (20)
LC	0	0	0	0	127	0	127 (21)
DD	0	0	0	0	1	281	282 (46)
Total	5 (1%)	20 (3%)	18 (3%)	57 (9%)	179 (29%)	338 (55%)	617 (100)

Discussion

This is one of the first Red Lists for a non-standard group of species. Two overall outcomes of applying the IUCN criteria stand out. Firstly, how the criteria are applied affects the category to which species are assigned, and, secondly, the peer review evaluation has a considerable impact on the final category assigned to the species. These results highlight the inherent difficulty in applying the current criteria, which are not designed to take into account the nature of individual species and the range in the quality of knowledge associated with them and may be responsible for the low take-up of the Red List for non-standard groups.

Evaluation of the criteria applied

Both the need in the application of Criterion A2b for sufficient abundance data with which to make a reliable assessment over the (mostly) ten-year assessment period and knowledge of the generation time of the species assessed present challenges in the case of seaweeds. The result is that only 13% of taxa (n = 84) can be assessed with this criterion, with one-sixth classified as CR and EN. The majority of species that can be classified under this criterion are the larger more abundant species (where abundance or cover data is recorded). The nature of the SACFOR abundance/percentage cover categories means that a change between categories is on average a halving of cover (or a 10-fold reduction in abundance), but at any site a single category decline could represent a reduction of ~ 1–99% (depending on where the actual abundance/cover value falls within the range of the two categories). The re-interpretation of the SACFOR scale back into percentages is not an exact process but has been shown to produce reliable results (Strong and Johnson 2020). The assessments rely on the assumption that, with the exception of the 14 species with longer generation times (Table 1), all other species probably have at least 3 generations (sensu IUCN 2019) within the 10-year period.

Generation time is a difficult concept to apply to species with complex life histories or clonal organisms. As demographic patterns are linked to stage-specific survival (Hernández-Yáñez et al. 2022), and stressors on different life history stages may vary, Red List classification might need to be considered as an initial formal assessment in order to

Table 4 Critically Endangered (CR), Endangered (EN) and Vulnerable (VU) seaweed species with assessment code

Critically endangered (CR)	Code	Endangered (EN)	Code	Vulnerable (VU)	Code
RED		RED		RED	
Dasya corymbifera	B2ab(ii)	*Atractophora hypnoides*	B2ab(ii)	*Ahnfeltiopsis devoniensis*	B2ab(ii)
Helminthocladia calvadosii	B2ab(ii)	*Bornetia secundiflora*	B2ab(ii)	*Apoglossum ruscifolium*	A2b
Lithothamnion glaciale	A2c	*Coccotylus truncatus*	B2ab(ii)	*Delesseria sanguinea*	A2b
Porphyra umbilicalis	A2c	*Dasya ocellata*	B2ab(ii)	*Erythrodermis traillii*	B2ab(ii)
Schmitzia neapolitana	B2ab(ii)	*Dermocorynus dichotomus*	B2ab(ii)	*Gymnogongrus griffithsiae*	B2ab(ii)
		Dermocorynus montagnei	B2ab(ii)	*Nemalion multifidum*	D2
		Gloiosiphonia capillaris	B2ab(ii)	*Nesoia latifolia*	D2
		Halurus equisetifolius	A2b	*Porphyropsis coccinea*	A2b
		Jania squamata	B2ab(ii)	*Rhodomela lycopodioides*	B2ab(ii)
		Mastocarpus stellatus	A2b	*Rhodymenia delicatula*	B2ab(ii)
		Schmitzia hiscockiana	B2ab(ii)	BROWN	
		Vertebrata reptabunda	B2ab(ii)	*Desmarestia aculeata*	A2b
		Xiphosiphonia pennata	A2c	*Eudesme virescens*	B2ab(ii)
		GREEN		*Fucus cottonii*	B2ab(ii)
		Codium bursa	B2ab(ii)	*Fucus distichus*	B2ab(ii)
		Lychaete pygmaea	B2ab(ii)	*Halosiphon tomentosus*	B2ab(ii)
		BROWN		*Laminaria digitata*	A2b
		Acrothrix gracilis	B2ab(ii)	*Punctaria latifolia*	B2ab(ii)
		Alaria esculenta	A2c	*Punctaria plantaginea*	B2ab(ii)
		Ericaria selaginoides	A2c		
		Spermatochnus paradoxus	B2ab(ii)		
		Tilopteris mertensii	B2ab(ii)		

highlight threats (Jacoby et al. 2015). Similar difficulties for clonal and colonial bryophytes are what led Bergamini et al. (2019) to their pragmatic and effective way of using Red List criteria for this group. To deal with definitions of generation time, mature individuals and severe fragmentation, bryophyte species are categorised into short-lived, medium-lived, long-lived and those that have no means of asexual reproduction. Such an approach has the potential to be adapted for use with seaweeds and warrants further study.

The majority of all NT species were identified as such under Criterion A2c. The advantage of this criterion is that it is straightforward to measure AOO and EOO, although this assumes that the survey data are consistent over time. The data used in this study are relatively consistent over the 10-year assessment period, in terms of tetrads visited and species observed each year (Fig. 1), but there is a 20% 'churn' of observation locations between years (i.e. for tetrads with observations in year N, typically only 80% of these have observations in year N + 1). Therefore, the variability in yearly observations for some taxa could lead to mistaken interpretations of decline (or increase). Over the course of the 10(+) year assessment period, it is unlikely that this variability will result in a statistically significant decline, although this does not exclude the possibility of some form of systematic bias in the observation data that might lead to a misinterpretation of decline (for example, a concerted sampling effort for a particular species at the start of the assessment period could lead to an inflation of AOO that tails off at the end of the assessment due to a discontinued sampling effort). However, the finding that Near Threatened species include many common and conspicuous species and that local declines may well be occurring flags up again the need for careful monitoring.

The application of Criterion B2 was heavily constrained by the assumption that the number of locations is equal to the number of tetrads. This very conservative assumption means that only taxa with 10 or fewer tetrads can be classified as threatened. A more comprehensive (and time consuming) examination of locations (*sensu* IUCN) would lead to more taxa being assessed as threatened under this criterion as our current implementation of criterion B2 always has location thresholds stricter than the area thresholds (e.g., there is a 10 location threshold for assigning a vulnerable category, but 10 tetrads give an AOO of 40 km^2, which qualifies for endangered under the area threshold).

Evaluation using Criterion D2, where species are automatically assigned as VU based on their presence in ≤5 locations (tetrads), would lead to a large number of vulnerable classifications without the filter of identifying a threat. Critical to the application of this criterion is whether there is "a plausible threat that could drive the Taxon to CR or EX in a very short time" (IUCN 2019). The evidence points to the impact of increasing sea surface temperatures as a major threat to these seaweed populations, particularly if they are on the edge of their range or in areas where warming is most rapid (Brodie et al. 2014; Yesson et al. 2015).

Despite application of these criteria, we were unable to classify a threat status for almost half of all taxa. While it may be possible to treat those with limited or no records under criterion VU D2 based on a restricted range, the majority of data deficient taxa are those present in 5 or more tetrads (the threshold for VU D2 categorisation), but with insufficient data during the assessment period to permit application of the A2 criteria. Our 46% data deficient rate compares unfavourably with 14% of DD for all Red List assessments and c. 7% for all plants (https://www.iucnredlist.org/search) and stresses the need for further work to improve this rate of assessment.

Red List outcome for British seaweeds

The classification of 9% as Critically Endangered, Endangered or Vulnerable and a further 7% classified as Near Threatened is indicative of changes in the seaweed flora that are consistent with recent reports of decreasing seaweed populations (Smale 2020; Yesson et al. 2015). However, the reduction to 6% of species assessed as threatened and recognition of 9% as DD following peer review evaluation means that the results from the purely data-driven assessment need to be treated with caution.

This list is important, as Britain is located at the centre of the northeast Atlantic distribution for many of the habitat-forming large brown species, including *Laminaria hyperborea*, the main kelp forest species (Yesson et al. 2015).

Reasons for threatened species

There are several reasons why a species might be assessed as threatened. Some species are rarely observed or may be present as a crust but the gametophytes are rarely seen (e.g. *Helminthocladia calvadosii*), or geographically restricted, occur in restricted habitats, or are logistically difficult to study (Yesson et al. 2015; Brodie et al. 2018). Species may be common but under-recorded, e.g. the sublittoral fringe which is only accessible from the shore on extremely low tides and difficult for scuba divers to access due to the shallow depth and/or wave action.

The impact of increasing temperatures is causing loss or decline of some species on the edge of their range and is another reason for species to be assessed as threatened. For example, populations of the brown seaweed *Alaria esculenta* have been lost from south-west England (Mieszkowska et al. 2006), close to the species southern limit in northern France. Epiphytic species may decline as they are associated with a declining host.

Species extinction may be cited as another reason. For the seaweeds, the only example deemed by a formal Red List assessment to have become extinct is *Vanvoorstia bennettiana* from Australia (Brodie et al. 2009). In the case of *Codium bursa*, the only seaweed considered to be extinct on the British mainland, large numbers of specimens in the Natural History Museum algal herbarium (BM) and regional herbaria suggest that over-picking

Table 5 Comparison of threat categories for taxa assessed in both 2013 and 2021 Red Lists.

2013	2021						Total
	CR	EN	VU	NT	LC	DD	
CR	1	*1*	*0*	*0*	*0*	*0*	2
EN	**0**	0	*0*	*0*	*0*	*0*	0
VU	**1**	**1**	0	*1*	*2*	*25*	30
NT	**0**	**0**	**0**	0	*0*	*0*	0
LC	**2**	**10**	**14**	**36**	136	*119*	317
DD	**1**	**1**	**2**	**13**	**12**	145	174
n/a	0	7	2	7	29	49	94
Total	5	13	16	50	150	289	617

Italic values represent a reduction in threat assessment level, while bold values indicate a higher threat categorisation in the more recent assessment. n/a indicates species assessed in the current study but not assessed in 2013 by 19th century collectors may have contributed to this loss. Species which have not been observed for many years might be considered extinct. For example, 36 species of British seaweeds have not been observed in the last 50 years (Supplementary Table 5), all of which are classified as Data Deficient, but could potentially be considered extinct in Britain. The majority of these are microscopic epiphytes or endophytes which require identification by specialists. A concerted effort should be made to search for such species at the country level, as failure to locate them should lead to their classification as regionally extinct.

Another reason why species may be categorised as threatened relates to the impact of molecular phylogenetic analysis on taxonomic re-evaluations (e.g. Díaz-Tapia et al. 2017) which has led to new species, or discovery of cryptic species, including unrecognised non-natives (Robba et al. 2006), with a consequent growth in name changes in recent years. For example, *Corallina caespitosa* (LC A2c; B2ab(ii), which was described within the 10-year Red List period (Walker et al. 2009), closely resembles *C. officinalis* (NT A2b), records of which will have included both species until recently.

As highlighted by the species aggregate *Fucus cottonii*, another challenge is applying Red List criteria to taxonomically problematic species—should they be included in Red List assessments and if so, how?

Causes of data deficiency

The problems of species identification can be a major cause of data deficiency. Recording might be undertaken by a wide range of individuals and groups, from specialist research scientists and professionals to citizen/community scientists but a lack of consistency in how and what people record, including species, dates and locations, and whether there is any indication of abundance, can also limit the value of, or invalidate, observations. For example, misidentification of species in the Big Seaweed Search citizen science project could be as high as 90% (Brodie et al. 2022).

The availability of data is another limitation. In this study, primary data sources used were publicly accessible but this is not always the case for regional datasets The time of year when recording takes place may be another factor in data deficiency. Recording might take place at one time of year but many seaweed species have a marked seasonality. They might only be present for certain periods of the year, e.g. summer annuals, or be more conspicuous at others. For example, coralline crusts tend to be more obvious in the winter when not covered by summer growth of fleshy algae. Recording seasonality/phenology is problematic for many groups of organisms. Whilst long-term datasets exist for mammals and birds, this is typically not the case for non-standard organisms (e.g. Chambers et al. 2013).

Evaluation of results

As a result of this Red List assessment, several recommendations are proposed to improve the process and therefore the outcome. A review needs to be undertaken of the suitability/application of IUCN assessment criteria for non-standard species such as seaweeds where populations are clonal, single individuals cannot always be counted and where species have complex life histories. We propose the following recommendations, in this case for seaweeds, but with applicability to other non-standard species groups.

Holding a series of workshops would enable an evaluation of the seaweed Red Data List in relation to exploring regional floras, developing and training in a unified approach for recording and targeting species for intensive searching and recording.

A review of current approaches to recording and data sharing needs to be undertaken, with a move towards a more unified method. This should include consideration and improvement of the mechanisms by which seaweed records are captured, assessed for accuracy and centralised in NBN, including direct engagement with regional recorders.

To develop a more robust/optimised data set for Red List analysis in ten years time, there needs to be a strategic approach to data collection. This should include rarities, those not seen for 50 years from the start of the assessment period and those deemed to be common and widespread but which have been classified as threatened or near threatened in this assessment. Fieldwork should be promoted/undertaken to collect data for more strategic purposes such as for monitoring change. Annual surveys should be undertaken to provide long-term time-series of the abundance and distribution of seaweeds for the species of interest.

For the best use of available resources, repeated surveys should be undertaken at a few key locations for the species of interest. Regional species lists should be compiled, ensuring those with restricted geographical distribution are monitored. There should be targeted recording of species in under-recorded habitats, including the sublittoral fringe, shallow subtidal, and subtidal gravel beds. Taxonomic and nomenclatural work should be ongoing in order to gain a more precise description of seaweed biodiversity. Red List assessment should be extended more widely, e.g. the wider Northeast Atlantic region, and involve a wider network of seaweed specialists.

Finally, it is proposed that an IUCN Species Survival Commission Group on Seaweeds is set up and international partners engaged to enable the development of a global approach to seaweed Red Listing.

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Author contributions JB, JW and CY conceived and designed the study, wrote the text and prepared the tables and figures. CY undertook the Red List data analysis. CAM, LB, FB, NM, CS, IT and MW undertook peer review of the results. All authors edited the manuscript.

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Data availability The datasets analysed during the current study are freely available online. Further information can be obtaibed from the corresponding author on reasonable request. R-scripts to perform evaluations are available through the R-package "RedListEvaluation" at https://github.com/cyesson/RedListEvaluation.

Declarations

Competing interests The authors declare no competing interests.

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References

Bergamini A, Bisang I, Hodgetts N, Lockhart N, van Rooy J, Hallingbäck T (2019) Recommendations for the use of critical terms when applying IUCN red listing criteria to bryophytes. Lindbergia 42:1–6. https://doi.org/10.25227/linbg.01117

Brito D, Ambal RG, Brooks T, De Silva N, Foster M, Hao W, Hilton-Taylor C, Paglia A, Rodríguez JP, Rodríguez JV (2010) How similar are national red lists and the IUCN Red List? Biol Cons 143:1154–1158

Brodie J, Wilbraham J (2013) A provisional Red Data List for UK seaweeds. Report for John Spedan Lewis Foundation. Natural History Museum, London

Brodie J, Maggs CA, John DM (eds.) (2007) Green seaweeds of Britain and Ireland. Printed for the British Phycological Society by Dataplus Print & Design, Northern Ireland

Brodie J, Andersen R, Kawachi M, Millar A (2009) Endangered algal species and how to protect them. Phycologia 48:423–438. https://doi.org/10.2216/09-21.1

Brodie J, Williamson CJ, Smale DA, Kamenos NA, Mieszkowska N, Santos R, Cunliffe M, Steinke M, Yesson Y, Anderson KM, Asnaghi V, Brownlee C, Burdett HL, Burrows M, Collins S, Donohughe P, Harvey B, Foggo A, Noisette F, Nunes J, Raggazola F, Raven JA, Schmidt DN, Suggett D, Teichberg M, Hall-Spencer JM (2014) The future of the northeast Atlantic benthic flora in a high CO_2 world. Ecol Evol 4:2787–2798. https://doi.org/10.1002/ece3.1105

Brodie J, Wilbraham J, Pottas J, Guiry MD (2016) A revised check-list of the seaweeds of Britain. J Mar Biol Assoc 96:1005–1029. https://doi.org/10.1017/S0025315415001484

Brodie J, Ash LV, Tittley I, Yesson C (2018) A comparison of multispectral aerial and satellite imagery for mapping intertidal seaweed communities. Aquat Conserv 28:872–881. https://doi.org/10.1002/aqc.2905

Brodie J, Kunzig S, Agate J, Yesson C, Robinson L (2022) The big seaweed search: evaluating a citizen science project for a difficult to identify group of organisms. Aquat Conserv 33:44–55. https://doi.org/10.1002/aqc.3903

Brooks TM, Butchart SHM, Cox NA, Heath M, Hilton-Taylor C, Hoffmann M, Kingston N, Rodríguez JP, Stuart SN, Smart J (2015) Harnessing biodiversity and conservation knowledge products to track the Aichi targets and sustainable development goals. Biodiversity 16:2–3. https://doi.org/10.1080/14888386.2015.1075903

Bush L, Davies A, Maggs CA, Yesson C, Brodie JA (2013) Review of evidence for the loss of large brown macroalgae. A review for The Crown Estate. https://macroalgalresearchgroupcom.files.wordpress.com/2017/03/bush_2013_reviewofloss.pdf. Accessed July 2013

Chambers LE, Altwegg R, Barbraud C, Barnard P, Beaumont LJ, Crawford RJM et al (2013) Phenological changes in the Southern Hemisphere. PLoS ONE 8(10):e75514. https://doi.org/10.1371/journal.pone.0075514

Clubbe C, Ainsworth M, Bárrios S, Bensusan K, Brodie J, Cannon P, Chapman T, Copeland AI, Corcoran M, Sanchez MD, David JC, Dines T, Gardiner L, Hamilton MA, Heller T, Hollingsworth PM, Hutchinson N, Llewelyn T, Forrest LL, Macdonald I, McGinn K, Miles S, Woodfield-Pascoe N, Rich TCG, Rumsey F, Sharrock S, Sim J, Smith SR, Spence N, Stanworth A, Stroh P, Taylor I, Trivedi C, Twyford A, Viruel J, Walker K, Wilbraham J, Woodman J, Fay MF (2020) Current knowledge, status and future for plant and fungal diversity in Great Britain and the UK Overseas Territories. Plants People Planet 2:557–579. https://doi.org/10.1002/ppp3.10142

Connor DW, Allen JH, Golding N, Howell KL, Lieberknecht LM, Northen KO, Reker JB (2004) The Marine Habitat Classification for Britain and Ireland Version 04.05. In: JNCC (2015) The Marine Habitat Classification for Britain and Ireland Version 15.03. https://mhc.jncc.gov.uk/resources#version0405. Accessed 24 Mar 2021

Crisp D, Southward A (1958) The distribution of intertidal organisms along the coasts of the English Channel. J Mar Biol Assoc 37:157–203

Dahlberg A, Mueller GM (2011) Applying IUCN red-listing criteria for assessing and reporting on the conservation status of fungal species. Fungal Ecol 4:147–162. https://doi.org/10.1016/j.funeco.2010.11.001

Díaz-Tapia P, McIvor L, Freshwater D, Verbruggen W, Wynne H, Maggs MJ, CA, (2017) The genera Melanothamnus Bornet & Falkenberg and Vertebrata SF Gray constitute well-defined clades of the red algal tribe Polysiphonieae (Rhodomelaceae, Ceramiales). Eur J Phycol 52:1–30

Dixon PS, Irvine LM (1977) Seaweeds of the British Isles: part 1. Introduction, Nemaliales, Gigartinales. Rhodophyta, vol 1. British Museum (Natural History), London

Gaspar R, Pereira L, Neto JM (2017) Intertidal zonation and latitudinal gradients on macroalgal assemblages: species, functional groups and thallus morphology approaches. Ecol Indic 81:90–103. https://doi.org/10.1016/j.ecolind.2017.05.060

Geertz-Hansen O, Enríquez S, Duarte CM, Agusti S, Vaqué D, Vidondo B (1994) Functional implications of the form of Codium bursa, a balloon-like Mediterranean macroalga 1994. Mar Ecol Prog Ser 108:153–160

Guiry MD (2012) How many species of algae are there? J Phycol 48:1057–1063. https://doi.org/10.1111/j.1529-8817.2012.01222.x

Guiry MD, Guiry GM (2021) AlgaeBase. World-wide electronic publication, National University of Ireland, Galway. https://www.algaebase.org. Accessed 16 March 2021

Hall-Spencer JM, Kelly J, Maggs CA (2010) Assessment of maerl beds in the OSPAR area and the development of a monitoring program. Report prepared for the Department of the Environment, Heritage & Local Government (DEHLG). Ireland (Ospar Report)

Hernández-Yáñez H, Kim SY, Che-Castaldo JP (2022) Demographic and life history traits explain patterns in species vulnerability to extinction. PLoS ONE 17(2):e0263504

Hiscock K (1996) Marine nature conservation review: rationale and methods. Coasts and seas of the United Kingdom. Joint Nature Conservation Committee, Peterborough

Irvine LM, Chamberlain YM (1994) Seaweeds of the British Isles volume 1 Rhodophyta part 2B Corallinales, Hildenbrandiales. HMSO, London

IUCN (2001) IUCN Red List categories and criteria: Version 3.1. IUCN Species Survival Commission IUCN Gland, Switzerland

IUCN Standards and Petitions Committee (2019) Guidelines for using the IUCN Red List categories and criteria. Version 14. Standards and Petitions Committee, Switzerland

Jacoby DMP, Casselman JM, Crook V, DeLucia M-V, Ahn H, Kaifu K, Kurwie T, Sasal P, Silfvergrip AMC, Smith KG, Uchida K, Walker AM, Gollock MJ (2015) Synergistic patterns of threat and the challenges facing global anguillid eel conservation. Glob Ecol Conserv 4:321–333. https://doi.org/10.1016/j.gecco.2015.07.009

Krumhansl KA, Okamoto DK, Rassweiler A, Novak M, Bolton JJ, Cavanaugh KC et al (2016) Global patterns of kelp forest change over the past half-century. Proc Natl Acad Sci USA 113:13785–13790

Lee RE (2018) Phycology, 5th edn. Cambridge University Press, Cambridge

Mace GM, Baillie EM (2010) The 2010 biodiversity indicators: challenges for science. Conserv Biol 21:1406–1413

Mace GM, Collar NJ, Gaston KJ, Hilton-Taylor C, Akçakaya HR, Leader-Williams N, Milner-Gulland EJ, Stuart SN (2008) Quantification of extinction risk: IUCN's system for classifying threatened species. Conserv Biol 22:424–1442

Melbourne LA, Hernández-Kantún JJ, Russell S, Brodie J (2017) There is more to maerl than meets the eye: DNA barcoding reveals a new species in Britain, *Lithothamnion erinaceum* sp. nov. (Hapalidiales, Rhodophyta). Eur J Phycol 52:66–178

Mieszkowska N, Kendall MA, Hawkins SJ, Leaper R, Williamson P, Hardman-Mountford NJ, Southward AJ (2006) Changes in the range of some common rocky shore species in Britain—a response to climate change? In: Marine biodiversity. Developments in hydrobiology. Springer, Dordrecht, pp 241–251. https://doi.org/10.1007/1-4020-4697-9_20

Neiva J, Hansen GI, Person GA, Van de Vliet MS, Maggs CA, Serraõ EA (2012) *Fucus cottonii* (Fucales, Phaeophyceae) is not a single genetic entity but a convergent salt-marsh morphotype with multiple independent origins. Eur J Phycol 47:461–468. https://doi.org/10.1080/09670262.2012.736536

Rayment WJ (2004) *Ahnfeltia plicata* A red seaweed. In: Tyler-Walters H, Hiscock K (eds) Marine life information network: biology and sensitivity key information reviews. Marine Biological Association of the United Kingdom, Plymouth. https://doi.org/10.17031/marlinsp.1656.1

Robba L, Russell SJ, Barker GL, Brodie J (2006) Assessing the use of the mitochondrial *cox1* marker for use in DNA barcoding of red algae (Rhodophyta). Am J Bot 93:1101–1108. https://doi.org/10.3732/ajb.93.8.1101

Rodrigues AS, Pilgrim JD, Lamoreux JF, Hoffmann M, Brooks TM (2006) The value of the IUCN Red List for conservation. TREE 21:71–76. https://doi.org/10.1016/j.tree.2005.10.010

Smale D (2020) Impacts of ocean warming on kelp forest ecosystems. New Phytol 225:1447–1454

Strong JA, Johnson M (2020) Converting SACFOR data for statistical analysis: validation, demonstration and further possibilities. Mar Biodivers Rec 13:2. https://doi.org/10.1186/s41200-020-0184-3

Thomas EA, Böhm M, Pollock C, Chen C, Seddon M, Sigwart JD (2021) Assessing the extinction risk of insular, understudied marine species. Conserv Biol 36(2):e13854.https://doi.org/10.1111/cobi.13854

Walker RH, Brodie J, Russell S, Irvine LM (2009) Biodiversity of coralline algae in the northeastern Atlantic including: *Corallina caespitosa* sp. nov. (Corallinoideae, Rhodophyta). J Phycol 45:287–297. https://doi.org/10.1111/j.1529-8817.2008.00637.x

Yesson C, Bush LE, Davies AJ, Maggs CA, Brodie J (2015) Large brown seaweeds of the British Isles: evidence of changes in abundance over four decades. Estuar Coast Shelf Sci 155:167–175. https://doi.org/10.1016/j.ecss.2015.01.008

Zaloumis NP (2008) IUCN Red Listing of Marine Macroalgal Species: A South African Case Study. PhD Thesis, University of Cape Town, South Africa. http://hdl.handle.net/11427/25983. Accessed 24 Oct 2022

Zamin TJ, Baillie JEM, Miller RM, Rodriguez J, Ardid A, Collen B (2010) National Red Listing beyond the 2010 target. Conserv Biol 24(4):1012e1020

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