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A review of the influence of marine habitat classification schemes on mapping studies: inherent assumptions, influence on end products and suggestions for future developments

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Abstract

The production of marine habitat maps typically relies on the use of Habitat Classification Schemes (HCSs). The choice of which HCS to use for a mapping study is often related to familiarity, established practice, and national desires. Despite a superficial similarity, HCS differ greatly across six key properties, namely, purpose, environmental and ecological scope, spatial scale, thematic resolution, structure and compatibility with mapping techniques. These properties impart specific strengths and weaknesses for each HCS, which are subsequently transferred to the habitat maps applying these schemes. This review has examined seven common HCSs, over the six properties, to understand their influence on marine habitat mapping. Recommendations are provided for improving HCSs for marine habitat mapping as well as for enhanced the working practices of mappers using habitat classification. It is hoped that implementation of these recommendations will lead to greater certainty and usage within mapping studies and more consistency between studies and adjoining maps. A review of six common HCSs has been conducted to highlight these issues, and to raise awareness of how these properties and assumptions are transferred into marine habitat maps. In addition, how mappers use HCSs also introduces additional uncertainties and biases into the final maps.

Keywords

Marine habitat mapping; habitat classification scheme;

1. Introduction

The pressing need for seabed inventory mapping, marine spatial planning, spatial estimates of anthropogenic impacts (as required by the Marine Strategy Framework Directive (Council Directive 2008/56/EC)) and the designation of seabed conservation features (as required by the Habitats Directive 92/43/EEC) has made the habitat map an indispensable item within marine management and research. The production, and ultimate presentation, of marine habitat maps typically rely on the use of a habitat classification scheme (HCS). Within mapping, HCSs categorise environmental and biological information (e.g., depth, topography, substratum, hydrodynamic energy, community composition) into distinct habitat classes. Each class is assumed to be associated with a distinctive abiotic condition and identifiable biological community, and therefore attempts to produce environmentally or ecologically meaningful units.

Habitat classification is an integral part of habitat map production, and as such, the HCS has a significant influence on how mapping information is: (i) interpreted during map production; (ii) displayed within the map; and (iii) interpreted by the end user. This review aims to examine explicitly how HCSs influence the production of marine habitat maps. A wider discussion will follow on what improvements can be made to HCSs, and how mappers should use these HCSs, to provide more consistent, accurate and useful products for end users. The specific objectives of this review are:

1. Introduce the principles of habitat classification for marine mapping;
2. Describe the properties common to most HCS;
3. Examine the variation in these common properties for seven, established HCSs, used for benthic habitat mapping;

4. Assess the influence of variations within these common properties on the production and representations of marine habitat maps;
5. Make recommendations for the development of HCSs in habitat mapping; and
6. Recommend best practice for marine habitat mappers when using HCSs.

2. Use of habitat classification schemes in marine mapping

Although HCSs are developed to support all sorts of environmental work, few activities are as intimately linked to the use of HCSs as habitat mapping. Many HCSs have been developed specifically for use in mapping studies, e.g., Potential Habitat Characterization Scheme (PHCS, Greene et al. 2005, 2007). This section introduces HCSs, as well as how and why they are incorporated into marine habitat mapping. The influence that HCSs have on habitat maps is also introduced, before being discussed in more detail at the end of the review.

2.1. Habitat classification schemes

Robinson and Levings (1995) defined a HCS as a set of instructions that identify, delimit and describe the habitats of distinct biological assemblages (communities or single species). The primary purposes of HCSs, summarised from Galparsoro et al. (2012) and Robinson and Levings (1995), are to:

- provide a structured framework for the efficient classification of habitats;
- provide common and easily understood concepts and language for the description of habitats;
- hold information in a relational structure that allows for the interrogation of information based on parameters collected by common survey methods;

- describe and standardise the physical, chemical and biological parameters that define habitat classes; and
- regulate the spatial and thematic scales and thresholds used for habitat classification, and thereby standardise the classification of habitats within and between studies.

The use of a HCS benefits marine habitat mapping in several ways. Most importantly, the HCS provides a structured framework for the integration of environmental and biological information (which have different spatial scales, units, and formats) into one, integrated product, via ecologically meaningful decision points along the classification pathway. Ultimately, HCSs facilitate the segmentation of discrete (e.g., categorical data such as substratum) and continuous variables into ecologically relevant spatial units.

2.2. The influence of habitat classification schemes on the outputs of habitat mapping

Although the benefits associated with the consistent classification of habitats during mapping are great, it must also be recognised that the use of a HCS also imposes certain constraints and limitations, which are inherent within the fundamental concepts of habitat classification. For example, many HCSs assume that individual habitats are discrete classes. When used in mapping, these classes form mutually exclusive patches when presented spatially, and therefore fail to capture the natural continuities (biocoenoses) and environmental gradients (ecotones) that perhaps better reflect the natural configuration and gradients between different habitat types.

The structure of an HCS has a marked effect on the production process for a habitat map, through dictating when different types of information are relevant during the classification pathway. The structure can, therefore, modify the relative importance of physical, chemical and biological variables in determining the final classification for a unit of habitat. The physical information is typically associated with the upper levels of the hierarchy and can sometimes be assigned based on existing, coarse-resolution data such as from hydrodynamic models and digital elevation models. Lower levels of classification (biotopes, communities and single-species distribution) often require biological data and are often applied at a more local scale. Due to insufficient biological data, or because it is not relevant for the specific scheme or level of classification, some HCSs are based purely on physical and environmental features of the seafloor environment, which are used as a proxy for habitats, on the assumption that there may be a correlation between the non-biological features and biological communities (Brown et al., 2011; Huang et al., 2011). Such assumptions are the basis for the use of distribution modelling techniques by employing full spatial coverage data of environmental variables to predict benthic spatial distribution patterns during the map production (Reiss et al., 2014).

Although it is a sensible aspiration that a single classification scheme is used for all marine habitat maps, multiple schemes have arisen to cater for the different applications, e.g., biological conservation, landscape ecology, environmental monitoring, marine spatial planning, fisheries management, and geomorphological descriptions, etc. The presence of several HCSs also reflects the fundamental difficulty of dividing natural continuities (biocoenoses) and environmental gradients (ecotones), into discrete and meaningful classes (McDougall et al., 2007). Furthermore, the number of HCSs is further inflated as individual schemes cater for specific biogeographic areas. Lund and Wibur (2007) and Greene *et al.* (2008) summarised 14 marine HCSs developed for North America and Europe alone. Interestingly, schemes differ substantially even though (i) the main physico-chemical variables that are known to define habitats are well-established, (ii) the majority of marine mapping studies record the same parameters and (iii) the predominantly physical nature of the majority of the classifications. The use of different HCSs for mapping can significantly influence the spatial representation of habitats in the final maps, which in turn can hinder the merging of adjoining maps as well as alter management outcomes based on these maps.

2.3. Variation and influence associated with six common properties of marine habitat classification schemes

An examination of the HCS suggests that they differ according to six properties, namely: (i) purpose of a HCS; (ii) environmental and ecological scope of a HCS; (iii) spatial scale covered by a HCS; (iv) thematic resolution covered by a HCS; (v) structure of a HCS; and (vi) compatibility of a HCS for habitat mapping. Variation in each property can influence the production, and representation, of a marine habitat map. The following section will: (i) introduce each property; (ii) examine seven common HCSs to highlight the variation within each property (these schemes are introduced in Table 1); and (iii) summarise the influence of variation, within each property, on habitat map production.

2.3.1. The purpose of a habitat classification scheme

A number of HCSs have been constructed for differing but specific purposes. For example, some schemes are designed to address the delineation of fisheries habitats, while others specifically include habitats of conservation importance. Most schemes are more generic classifications, which are more suitable for inventory mapping. The purpose of a HCS dictates the emphasis for separation between classes, and therefore the way in which observed variables are partitioned within the scheme. This structuring is reproduced within a habitat map when a specific HCS is used.

Variation in the purpose between habitat classification schemes

The majority of HCSs are generalist, descriptive schemes that potentially offer the greatest utility to the largest number of users. Maps produced using these schemes are most likely to be centrally collated and widely distributed. For instance, European policies, including the Habitats Directive (92/43/EEC), the Marine Strategy Framework Directive (MSFD; 2008/56/EC), the Infrastructure for Spatial Information in the European Community (INSPIRE; 2007/2/EC), and the Maritime Spatial Planning (Directive 2014/89/EU), aimed at marine mapping, assessment and reporting are increasingly using EUNIS and HELCOM Underwater Biotopes (HUB) (within the Baltic Sea) habitat categories and respective codes so as to guarantee a common shared path and technical terminology between Member States (Vasquez et al., 2015).

The Australian National Intertidal/Subtidal Benthic (NISB) scheme (Mount et al., 2007) and the Classification of Sublittoral Habitats (CSH) scheme (Valentine et al., 2005) are also broad enough to allow full coverage mapping and use for the environmental management of seafloor habitats (although NISB primarily focused on managing climate change related issues), as well as specifically providing a foundation for scientific research.

The primary purpose of Coastal and Marine Ecological Classification Standard (CMECS) is to be a national standard for the classification of habitats that ensures the consistency of state, national and international outputs (Madden *et al*., 2005). Unlike other schemes, CMECS is claimed to be relatively multipurpose in that it also caters for (i) fisheries management; (ii) the identification and administration of marine protected areas (Madden *et al*., 2005); and (iii) ecosystem-based management of marine resources. By contrast, the Potential Habitat Characterization Scheme (PHCS: Greene *et al*. 1999, 2005, 2007) has a clear geological emphasis, which is thought to provide a better basis for fisheries management, i.e., the identification of Essential Fish Habitat. Consequently, this scheme has been adopted for the contiguous western coast of the USA for rockfish habitat mapping (Greene *et al*., 2007).

Management purposes lie at the heart of the Hierarchical Framework of Marine Habitat Classification for Ecosystem-Based Management (HFMHC: Guarinello *et al*., 2010), which has been specifically designed for promoting ecosystem-based management (Guarinello *et al*., 2010). The framework incorporates the central concepts of ecosystem-based management - this ensures that the products of this HCS reflect the values and objectives of this style of management. The HELCOM HUB scheme has also been designed to align with a strategic plan to ensure ecosystem-based management (HELCOM Baltic Sea Action Plan) in the entire Baltic Sea region (HELCOM, 2013).

Summarising the influence of habitat classification scheme purpose on habitat maps

The majority of HCS are generic, inventory schemes that have subsequently been adopted for use in marine management. Several of the European systems were, however, designed initially for the ready identification of habitats of conservation importance. Other schemes are more specific, in either dealing with components of the habitat (e.g., ground fish), specific management topics (e.g., climate change, fisheries, conservation, ecosystem-based management). The purpose of an HCS will dictate the information that is required within the classification and, ultimately, how this information is partitioned and presented within a map. Most habitat mapping studies adopt just one HCS, and consequently limit the maps to a specific set of purposes. This restricts both the breadth of the maps for other purposes and how exhaustively the mapping data is used. It is likely that the greatest utility, accuracy, and confidence for a purpose can be obtained from a map classified using a scheme dedicated for that particular purpose.

2.3.2. The environmental and ecological scope of a habitat classification scheme

The scope of an HCS defines which (i) biogeographic region(s), (ii) biological realms (e.g., pelagic/benthos), and (iii) type of habitats included (e.g., coastal area, estuaries or hard substrata) are covered by the scheme. In some cases, a HCS will have been developed for a specific biological component, study or geographic location, and the resulting habitat types may not be applicable beyond that subject or area. In other cases, schemes have been developed using broad-scale data or using thresholds in ecologically relevant variables (Vasquez *et al*., 2015).

Variation in the scope of habitat classification shemes

The combined geographical scope of HELCOM HUB and the marine section of EUNIS is the marine waters off the European mainland, including offshore islands, and the archipelagos of the European Union Member States. Some regions are included in the scheme in principle, although knowledge from these areas is more limited, and their habitats descriptions are therefore poorly represented; e.g., the Black Sea and the Canary Islands. The HELCOM HUB and EUNIS schemes cover the entire seabed from the intertidal zone into deeper, subtidal areas (EUNIS also extends into the abyssal zone), as well as some broadscale pelagic habitats. Both schemes are heavily biased towards parts of Europe that have been well-studied and have existing HCSs (Galparsoro *et al*., 2012). Likewise, both the NISB and CMECS schemes are also designed for a broad set of habitats yet within specific geographic regions, i.e., NISB covers all of Australia's territorial waters between the high tide and out to the limit of the photic zone (depth of 50 – 70 m) and CMECS includes all estuarine, coastal and marine waters under U.S. jurisdiction in North America. Although initially developed for the Gulf of Maine region, the CSH scheme (Valentine *et al*., 2005) scheme is a generic classification and can, therefore, be applied to any continental shelf and shelf basin environment globally (excluding some low-latitude environments).

Other classifications have an even broader geographical scope. The PHCS was initially developed for use in specific deep-water habitats within North America (Greene *et al*., 1999, 2005, 2007). The PHCS has been expanded to include shallow water habitats, Arctic to tropical regions, including Antarctica (Vietti *et al*., 2001) and estuaries (Greene *et al*., 2007b). The upper levels of the HFMHC (Guarinello *et al*., 2010) was designed, from the beginning, to start with the global classification of large marine ecosystems (Sherman and Alexander, 1986). Subsequent levels include distinct ecosystem units, e.g., estuary, and broad, geological formations such as drowned river valley. The classification splits into three and covers the water column, benthos, and human activity/impacts. The flexibility to add user-defined classes at the lower levels of all three strands means the framework can be applied in any geographic location and is not limited by the methods used to observe any of the three classifiable components.

Summarising the influence of habitat classification scope on habitat maps

The sample of HCSs considered within this review span a range of habitats and geographical regions. Some schemes are broad in their scope from design, whereas others have grown to include new areas, such as the PHCS (Greene *et al*. 1999, 2005, 2007) and the CSH, Valentine *et al*., 2005). Classes in locally calibrated classification schemes are more likely to match the observations made in similar habitats or geographical areas. By contrast, classes within broader, generic schemes are likely to have to generalise class descriptions, thereby diminishing the ability of the scheme to reflect localised variation (reduced specificity) in habitats. However, habitat maps generated with broad-scale HCSs are more likely to be compatible with other maps and contribute to national and international mapping efforts.

Furthermore, the output format and classes of maps using broad-scale HCSs will be familiar, and hence more applicable, to more end-users that are already acquainted with the coding and purpose of the selected HCS.

2.3.3. The spatial scale covered by a habitat classification scheme

The seabed can be characterised and classified at different spatial scales ranging from the fine-scale, local environment (~1 – 10s metres), with factors affecting individual organisms, to landscapes and large-scale ecosystems (~100 – 1000s metres) where the substrates, terrain, and oceanographic settings influence biological communities and populations.

Variation in the spatial scale between habitat classification schemes

Progression through both the EUNIS and HELCOM HUB hierarchies results in finer thematic resolution as well as a finer spatial scale, e.g., a level 5 habitat is expected to cover a smaller area than its parent habitat at level 4. Helpfully, both schemes also provide an indication of the minimum spatial footprint for the finest units, e.g., as a working guide, biotope units extends over an area of at least 5 m x 5 m, but can also cover many square kilometres, such as for extensive offshore sediment plains. For minor habitats, such as rockpools and overhangs on the shore, this 'minimum size' can be split into several discrete patches at a site. The NISB scheme may be applied to fairly fine scales, while the upper tiers of the classification hierarchy, which has a reduced number of habitat classes, may be applied to broader, regional scales. The NISB scheme is particularly helpful in that it defines a ‘reference area’ of 9 m^2, for the assessment of habitat and biota dominance. Class modifiers applied to fine-scale features must be applied at the scale of the reference area as a minimum. This reference unit was deemed appropriate for a range of sensing techniques and a practical measure that can be easily made in the field with the current observation sensors and methods, such as videography and diver.

To allow for the varying scales of map production and use, the PHCS (Greene *et al*. 2005, 2007), recognises and defines four spatial scales. The macro- and micro-habitats can be nested within the smaller-scale mega- and meso-habitats. The appearance of specific habitat scales can, therefore, be linked to the scale of observation, thereby aiding the production and visual interpretation of the maps e.g. using dynamic segmentation methods such as those detailed by Nasby-Lucas *et al*. (2002). The tiers associated with the HFMHC scheme (Guarinello *et al*., 2010) are also associated with specific spatial scales, but no strict spatial constraints are set for any level, thereby allowing any project to be fitted within the framework. Equally, CMECS is designed to operate at multiple spatial scales and provides the specificity needed for local-scale applications. Like the previous two schemes, each level within CMECS is associated with a specific spatial scale, ranging from 10 – 1000 km^2 at the first 'regime' level, to 1 – 100 m^2 at the final 'biotope' level. As such, CMECS allows the aggregation and assessment of classified units across diverse systems at regional, national or global scales without loss of utility at local levels. These scales are useful in guiding the mapper during the interpretation of both survey observations and the classification scheme.

Summarising the influence of habitat classification schemes scale on habitat maps

The consideration of scale is relevant for several aspects of habitat classification, map production and usage. Firstly, the scale, and associated spatial resolution of a scheme determines which physical or ecological features can be represented on a map and what level of habitat heterogeneity can be captured. It is recognised by most mappers that many spatial units of classified habitat are mixed classes or mosaics. For simplicity, spatial units are typically labelled according to the dominant class and information regarding secondary habitats either removed or appended as a modifier. HCSs associated with finer spatial scales reduce the need to generalise mosaicked habitats and thereby better reflect heterogeneity at more scales. It should be noted that it is rarely stated within HCSs that units must be mutually exclusive i.e., multiple habitat codes can be attributed with either a proportion or probability and then allocated to a single, spatial unit.

Secondly, the scale of the HCS may also determine the type of mapping information, and therefore mapping methodology, required for the classification. For example, deep-water acoustic surveys may not have the required resolution for the identification of habitat classes with small footprints, whereby requiring the use of Autonomous Underwater Vehicles (AUVs)-mounted sonars for data collection. Furthermore, schemes that stipulate minimum mappable units and area thresholds for habitat classes also benefit the mapper and reduce the number of subjective decisions that might be needed during the production of maps. The final issue is that the scale addressed by the HCS also defines the type of management supported by the maps. For example, localized impact assessments will require maps with a sufficient resolution for the accurate prediction of impact.

2.3.4. The thematic resolution covered by a habitat classification scheme

The thematic resolution specifies how fine the increments are between classes within a parent habitat. For schemes with a high thematic resolution, one might expect a high number of classes, each separated by relatively small differences in environmental or biological variables. By contrast, low thematic resolution would entail a small number of coarser habitat classes.

Variation in the thematic resolution between habitat classification schemes

The most detailed levels in the EUNIS and HELCOM HUB classification schemes are predominantly defined by biotopes and therefore separates classes according to small, but significant, biological differences in otherwise similar habitats. In EUNIS, many of the biotopes at levels 5 and 6 originated from statistical clustering analysis and expert interpretation of data from diver surveys and intertidal surveys (rather than grab or remote video) in the EC Life Nature-funded BioMar project (Connor *et al*. 1997). Equally, level 5 biotopes in the HELCOM HUB scheme were defined by analysing more than 50,000 data observations (i.e., video data, diving observations, grab samples) using spatial and statistical methods as well as expert judgment.

The PHCS (Greene *et al*. 2005, 2007), CSH (Valentine *et al*., 2005) and the NISB scheme use modifiers to provide greater thematic resolution and flexibility for the finest classes present. The PHCS uses single letter modifiers that describe specific aspects of geology, biology, topography and seabed texture. These modifiers can be allocated to any of the six-letter habitat codes used by the scheme. There is no limit to the number of modifiers that can be attributed to each habitat code. Similarly, three themes within the CSH classification also provides modifiers that allow the user to describe 'biological' 'habitat association and usage' as well as short descriptors for 'community disturbance and recovery'.

Developing the use of modifiers further, the Hierarchical Framework of Marine Habitat Classification for Ecosystem-Based Management (Guarinello *et al*., 2010) scheme permits the use of user-generated classes (typically at the 'data analysis' level) and modifiers at most of the levels within the classification, which therefore allows for any type and level of thematic resolution. Units of information at the lowest levels of the framework can include a variety of relevant information such as absolute values of abundance, dietary composition for dominant species, rates for species-specific ecosystem functions and observed ranges for important physico-chemical characteristics.

Summarising the influence of thematic resolution on habitat maps

For the majority of the schemes, the finest classes are resolved according to biological characteristics of sessile benthic species. In some HCSs, more resolution is provided through the use of class modifiers rather than distinct classes. Such information displayed with classified habitats on the same map is likely to be valuable to a variety of map users. However, modifiers that unduly extend the basic classification of a habitat (i.e. 'what it is') are likely to complicate the habitat representation into maps, their interpretation by end users and reduce comparability between maps.

The greatest level of thematic resolution differs substantially between HCSs. This is due to either a shortage of information for the formation and validation of these most detailed classes or that the overall purpose and scope of the HCS does not concern itself with detailed biological information. Regardless of the HCS used, mappers must be aware of the level of the classification that can be safely supported by the survey data, e.g., what level of community classification can be supported by epibenthic video, and what the intended purpose of their map will be. Equally, to improve the compatibility of maps, attempts should be made not just to standardise the use of HCS (or suite of HCSs) for mapping but also to set the level of classification within a scheme for a specific mapping technique (matched to a specific purpose).

2.3.5. The structure of a habitat classification scheme

The structure of HCS can be either hierarchical or flat, as well as nested or un-nested (parallel hierarchies). For hierarchical structures, the highest tiers typically separate observations into coarse classes using broad physical and chemical variables. Lower tiers proceed to refine the classification based on more localised, physico-chemical variables, as well as biological information on the composition of the communities present. Flat classification structures do not nest classes under predefined physico-chemical pathways. As such, flat structures allow the user to combine physico-chemical classes with independent biological classes – such classifications may not be possible within hierarchical structures if the required biological class is not nested within the observed physico-chemical pathway. The restrictive nesting of classes within hierarchical structures is only a significant issue when the training data used to develop the HCS was not reflective of habitat conditions apparent throughout the intended area of application.

Variation in structure between habitat classification schemes

EUNIS, HELCOM HUB, and CMECS (substrate and biotic components only) are all hierarchical schemes with six levels of marine classification. For example, the first two levels of the CMECS scheme separate observations according to (i) salinity, geomorphology, and depth, and then (ii) by substrate type or water mass characteristics - additional levels sort observations by (iii) physical zones, (iv) macrohabitats (large and physically complex units containing several habitats), (v) habitats defined by physical and energy characteristics and finally, (vi) by characteristic biological composition. This structure is similar to both EUNIS and HELCOM HUB. For both systems, the structure of the hierarchy assumes that classes at the same level are mutually, and hence spatially, exclusive. Equally, specific communities and biotopes in the lower levels of the hierarchy are nested under specific physical conditions (defined by higher levels) and are not transferable between physical habitats. The NISB scheme is also hierarchical but with fewer levels. At the higher levels of the hierarchy, the NISB scheme assumes spatially exclusive habitats. The scheme uses ‘decision rules’ for attributing habitat classes and for allocating geomorphic, biological and environmental modifiers. These decision rules allow simple, unambiguous interpretation of survey data and facilitating the objective and consistent assignment of habitat classes. The decision rules are framed to be as sensor/method-independent as possible.

The PHCS is also hierarchical but has an un-nested structure. This scheme has separate attribution pathways for the classification of small-scale (megahabitats and mesohabitats) and large-scale (macrohabitats and microhabitats). The small-scale classification uses various environmental parameters to provide increasingly finer thematic classes. The large-scale pathway initially attributes the seafloor according to geological and coarse biological classes, and then followed again by textural attributes. Similarly, the lower levels of the HFMHC (Guarinello *et al*., 2010) scheme has three parallel (un-nested) ‘benthic’, ‘water column’ and ‘human’ hierarchies. The use of separate components within the framework avoids the difficulty of generating a single hierarchy for fundamentally different domains and the flexibility and structure of this framework allow for a broader storage of information. However, the interaction of the three hierarchies generates a large number of unique habitat classes.

The CSH (Valentine *et al*., 2005) scheme is quite different in structure to the other schemes considered, as it is structured round eight, non-hierarchical seabed ‘themes’ as the major subject elements of the classification. These themes are seabed topography, dynamics, texture, grain size, roughness, fauna and flora, habitat association and usage, and habitat recovery from disturbance. The themes all reside at the top level (i.e., are not hierarchical) and are applied to the classification of each site. Below the themes, a sequence of more hierarchical subclasses, categories, and attributes address habitat characteristics with increasing detail. This scheme was developed to be used exclusively for mapping purposes. As such, it was designed with a flexible structure to account for both data availability while maintaining a framework that is considered the best method of representing the habitats on maps based on the classification. The classification can accommodate new classes, subclasses, categories, and attributes, and it can easily be modified or expanded to address habitats of other regions.

Summarising the influence of habitat classification scheme structure on habitat maps

Most of the HCSs adopt a hierarchical structure, with the initial levels typically referring to broad-scale physical variables, biogeographic or domain regions. Classes within lower levels are either nested under higher level classes or are open and unrestrained by the high-level class. Hierarchical schemes allow habitats to be aggregated to a coarser level, thus allowing comparisons to be made between different studies using the same scheme, even when different levels of detailed information are available. These comparisons, however, are only possible if the HSC is interpreted consistently, and rests upon a thorough understanding of the scheme and how best to classify information using the scheme.

A nested structure will provide a smaller but more targeted number of possible classifications – this is likely to benefit consistency and compatibility between studies. However, Galparsoro *et al*. (2012) reported that for EUNIS, a nested hierarchy, some communities occur in different main branches of the hierarchy due to their variations in associated depth or sediment type, whereas in reality, they are very similar. Equally, some communities only occur in a single branch of the hierarchy because they are mainly associated with certain physical conditions; however, if the same community is observed with a different set of physical conditions, then it would not fit precisely in the existing category. Schemes with an open structure provide the user of the classification more flexibility to generate classes not previously documented during the development of the classification. Open, un-nested structures are perhaps best-suited for mapping in areas that may be poorly represented within more trained and structured classifications.

2.3.6. Compatibility of a habitat classification scheme for habitat mapping

Although several HCS have been designed specifically for mapping studies, this was not the intended purpose for all of the HCSs used in habitat mapping. As such, some of the decision points or environmental and ecological parameters that structure HCSs may not be routinely collected, or possible to observe, using the methods routinely deployed for marine habitat mapping. As such, the ease with which an HCS can be applied to mapping data can vary. HCSs that are designed specifically for mapping are more likely to be aligned to the commonly collected variables and include quantitative thresholds or decision points appropriate for these types of data and value ranges.

Variation in the compatibility of mapping techniques between habitat classification schemes

EUNIS has been used extensively for mapping and modelling (e.g., EUSeaMap, Vasquez *et al*., 2015; Populus et al., 2017) efforts and have collectively produced a pan-European habitat map for a coordinated approach to marine conservation, assessment of the status of marine waters and spatial planning. Until now, HELCOM HUB has been applied in national case studies only (e.g., Schiele *et al*. 2014, 2015). However, the use of the light penetration depth as a major structural variable in the HELCOM HUB scheme means that additional observations (not typically collected during marine habitat mapping) or external modelling outputs must be combined with the mapped variables to generate a classification. The same holds true for EUNIS regarding light availability and wave exposure at the seabed. The NISB scheme is interesting in that it provides an umbrella scheme that can adopt and amalgamate other classification schemes into its hierarchical system, i.e., the NISB scheme can be used to translate existing local habitat maps into a single, aligned product (Hilbert *et al*., 2007). The flexibility of this scheme allows old maps and mapping data to be translated into new and aligned products.

The EUNIS scheme has been criticised for incompatibilities between the information used to define classes and that typically collected during a mapping survey. Levels 5 and 6 of the hierarchy are based on data from a wide variety of sampling techniques; as a result, they describe different aspects of seabed habitats. For example, some biotopes describe infaunal communities, while others describe epifaunal communities. Robinson *et al*. (2009) argued that some biotopes can only be identified if the method used during survey work is the same as the method used to originally define that biotope. For example, the characteristic species defining the level 5 biotope "*Hesionura elongata* and *Microphthalmus similis* with other interstitial polychaetes in infralittoral mobile coarse sand" are tiny polychaetes that would be grossly under-sampled using all but the finer meshes for sieving sediment. The 1 mm sieve used as standard on offshore surveys would not retain meiofauna such as these polychaetes (Parry, 2014).

The classes within the PHCS of Greene *et al*. (1999, 2005, 2007) are mostly defined by their geological character. As such, the scheme is well suited for the detection of habitats using acoustic remote sensing and thereby increases the confidence in the resulting classification. However, the biological classes are coarse, exclusively epifaunal and taxonomically distinct, which is perhaps unreflective of the typical composition of many seafloor communities and means that seafloor biota only have a fairly minor influence on the overall classification. The CMECS scheme is designed to be compatible with a range of sampling methods, e.g., cameras and certain acoustic devices can be used to identify the higher classification levels, while traditional point sampling methods, such as sediment sampling using grabs, can be used for the lower levels of classification. Equally, the sediment classes within CMECS are aligned to the Folk (1954) sediment classification, which is an established scheme in marine habitat mapping. This differs from the EUNIS classification which is underpinned by a 'modified' (simplified) Folk classification.

Summarising the influence of habitat classification scheme compatibility on habitat maps

The ease with which habitat mappers can integrate HCSs is based on the compatibility of the scheme's classifying variables with survey outputs. For example, in the PHCS presented by Greene *et al*. (2005, 2007) several of the classification attributes are generated specifically from common acoustic parameters such as depth (for bathymetric zones, slope, and rugosity) and backscatter (for hardness). Most of the geomorphological classes for other attributes are easily identifiable from full coverage bathymetric surfaces. However, it is clear that the ease and accuracy of classification also varies between habitat types. For example, it may be relatively straightforward to distinguish rock from muddy habitat in multibeam echosounder backscatter data, while there may be no clear boundary between coarse and mixed sediment. At the more detailed levels, many of the differences in the communities cannot be distinguished in acoustic data and therefore they are difficult to map.

Difficulties in finding an appropriate class can be further compounded when HCSs are biased towards the habitats used in the initial development of the classification. For example, the marine component of EUNIS is primarily based on the British-Irish BioMar scheme, which was originally developed largely using UK near-shore data, primarily from grab sampling and, to a lesser extent, diver surveys (Connor *et al*., 2004). This means that EUNIS is less well-developed for offshore habitats, particularly those occurring on hard substrates. Furthermore, EUNIS is arguably less well developed for interpretation of data from remote video techniques which sample different parts of a biological community than divers or grab samples, and at a different scale, therefore posing difficulties in matching the communities from video/photographic techniques to the statistically driven clusters from grab sample and diver surveys. Similarly, certain classifications have been developed to use certain data types, e.g., schemes developed for the interpretation of satellite imagery (e.g., Mumby and Harborne 1999), and may therefore not apply to data obtained from other sources.

3. Recommendations for the use of marine habitat classification schemes in marine mapping

This review will firstly summarise the most influential aspects of HCSs in marine habitat mapping and consider how this influence can be accounted for, or reduced, in habitat mapping. Some of the common limitations associated with the use of HCS in habitat mapping are often propagated by how habitat mappers use HCSs rather than being issues implicit within the schemes themselves – these issues are also discussed below and recommendations are provided.

Defining 'actual' and 'potential' habitats within mapping

Many habitat maps present an unspecified mixture of 'realised' and 'potential' habitats when using HCSs. For example, the upper classification levels of many HCSs divide areas by geomorphology and rely on acoustic survey data to achieve this delineation. Continuous bathymetric surfaces can, therefore, confirm the presence of large, physical features from observations. Observations of biotopes are only provided by point (e.g., grab or photographic still) or line (e.g., video transect) sampling during ground truthing. The continuous distribution of the biotopes is then predicted using geo-spatial modelling or expert judgment, meaning that the resulting distribution is an extrapolated product not fully supported by direct observation (unless one is mapping a biogenic biotope with a detectable structure). The predictor variables typically used to model the distribution of these biotopes also fail to represent influential biological processes such as competition, predation, and dispersal (Brown *et al*., 2011). As such, one is modelling 'potential' habitat for that biotope, which may or may not be occupied by the species constituting that biotope. The distinction between features that are realised versus potential habitat is rarely explicitly expressed when presenting mapped habitat classes. A lack of specificity may contribute to inaccurate assessments of the confidence of habitat maps by end-users, uncertain assessments of extent, and ambiguity about the relevant management action for sites and feature. It is therefore recommended that maps label habitats and biotopes with potential (modelled and potentially not occupied) and realised (delineated by direct observation) habitat labels or modifiers.

Improvements to the consistency of habitat classifications

The use of habitat classification involves accepting some of the inherent assumptions associated with HCSs. An assumption common to all schemes is that all habitats can be classified into distinct and identifiable classes. It is often the case that observations, collected during habitat mapping surveys, fail to fall neatly into classes within a scheme. The presence of ecotones and mosaics of heterogeneous habitat reduces the clarity of class membership, and hence the ability to accurately reflect conditions on the seabed.

The difficulty in classifying a continuous variable into a discrete class is further complicated when HCSs lack a quantitative definition, or clear 'decision rules' for each class. Also, as habitat mapping became heavily based upon physical measurements in the past 15 years (e.g., Al-Hamdani and Reker, 2007; Cameron and Askew, 2012, Vasquez *et al*., 2015, Galparsoro et al., 2015), there came an increasing demand for quantitative definitions. Without this information, qualitative classifications are often open to subjective interpretation and inconsistencies between studies or adjoining maps.

Common schemes, such as EUNIS and CMECS (Federal Geographic Data Committee, 2012), lack quantitative definitions that could define classes. For EUNIS, the absence of these definitions is a result of it being constructed from several classification schemes, making it difficult to achieve consensus on what those definitions should be. The large part of the scheme that originated in Connor *et al*. (2004) was designed primarily as a biological classification system, with the physical descriptions at the higher levels being convenient groupings that did not necessarily need to adhere strictly to any definitions.

HELCOM HUB provides quantitative delineation and classification rules within each of the classification levels. As an example, the system differentiates between soft and hard bottom substrata (Level 3), by a spatial coverage percentage of hard substrates within a given area (HELCOM, 2013). The latter also holds true for the delineation between infaunal and epifaunal dominated biotopes (Level 4), and between epifaunal communities (Level 5) and dominating species (Level 6).

Other HCSs also incorporate quantitative thresholds, for example, the Australian NISB habitat classification also uses decision rules (such as quantitative measures, percentage cover thresholds, and particle size bands) at all levels of the hierarchy and for the class modifiers. The PHC scheme uses objective methods to calculate specific attributes, such as rugosity and slope, to reduce subjective attribution and delineation, and clear thresholds that separate classes e.g., depth ranges for megahabitats or particle size for substrata. However, some attribute classes lack quantitative definitions which could lead to subjectivity, and hence variation, during the manual delineation of features. The use of quantitative attribution will also provide a more robust basis for: (i) initial classification of habitats; (ii) the estimation of how well the observation fits the assigned class; and (iii) greater certainty about the detection of change over time during repeat mapping. Quantitative thresholds and class definitions should not be specific to certain sampling devices or biased towards the survey techniques that were used to initially define classes. Ideally, the class or biotope description should include an indication of how the biotope may appear using a variety of survey techniques.

The influence of the structure of a classification scheme on a habitat map

HCSs designed for habitat mapping, and aligned to the types of information typically collected, are likely to be easier to use, reduce subjectivity during the classification of seabed information and generate more accurate maps. A single, nested hierarchical structure probably generates the most consistent classification between studies, but typically provide less breadth and flexibility during the classification process. It is recommended that rigid, hierarchical systems need to have a good system for updating either their structure or classified units as new delineations are required.

Modifiers are an extremely useful structural component for appending additional information onto a class without necessarily complicating the production or display of habitat maps. For example, modifiers could be used to represent: (i) observations on the condition of habitats; (ii) evidence of anthropogenic pressures (e.g. litter, physical alteration); (iii) labels for habitats that are hard to classify (e.g. fall between classes or units containing a mosaic of classes); or (iv) associations with other biological features not covered by the HCS such as large shoals of fish. To ensure their consistent application of modifiers, HSCs should once again provide detail on when and how to apply modifiers.

Contextual attribution of habitat codes within habitat classification schemes

A scheme name or code for a habitat provides a unique and brief title for the classified feature. Habitat classes are typically supported by a fuller description that many contain, for example, the identity and relative abundance of characterising species as well as the prevailing physico-chemical conditions present. However, this supporting information is typically detached from the map and just the class names are presented. It is recommended that all HCSs be available on an online vocabulary server and that digital maps include a unique resource identifier for each habitat class. Although essential, the name of a particular habitat may not necessarily be the most informative or valuable attribution for a map feature. It is likely that additional attribution providing details, for example, on class sensitivity, rarity, or ecosystem services provided (e.g., Salomidi *et al*., 2012; Galparsoro *et al*., 2014) may be of greater interest to the end user. It is also recommended that HCSs provide a broader array of attribution with each class. This will make it easier for maps to display alternative types of information as well as more contextual information for the class name.

Providing multi-purpose marine habitat maps

Habitat mapping is conducted for a multitude of purposes and this is reflected in the number and variety of HCSs available. Classification schemes can be either specialised or generic. Generic classifications are best suited for baseline data, inventory mapping and marine spatial planning. Specialised classifications provide greater specificity, and therefore applicability, for specific topics or management issues (e.g., climate change, fisheries, conservation).

Management outcomes are presumed to be more effective when based on specialised HCS aligned to the topic of interest. Despite this, most mapping studies tend to produce just one map, or set of maps, based on just one adopted HCS scheme. Based on the cost and effort required to gather the data used for habitat mapping, the practice of producing just one map, based on one HCS per study, is potentially inefficient and narrows greatly the breath of the mapping exercise. Each use or purpose should be linked to the most informative and appropriate classification scheme. It is therefore recommended that habitat mappers use several HCSs to generate multiple map products, each with a dedicated purpose. For example, a suite of maps that offers the greatest utility might include, among others,: (i) a generic, descriptive map for inventory purposes, (ii) a map attributed according to representativity, rarity or conservation value for the protection of species and habitats (design of Marine Protected Areas networks), (iii) sensitivity maps for supporting marine spatial planning and management, (iv) a map of ecosystem services for regional valuations and assessments, (v) maps of essential fish habitat for fisheries management, and (vi) geomorphological and surficial sediment maps for sediment dynamics, extraction and mining.

The production of a suite of map products does not hamper our ability to standardise or merge maps within a thematic area, nor does it necessarily represent a significant additional workload for mappers. The ability of mappers to produce multiple maps, based on several classification schemes, can be simplified if translation tables (tables that map classes of one HCS to units of another HCS) are made available. It is therefore recommended that mappers use multiple HCSs to produce a suite of maps and that this activity is supported by the development of translation tables (e.g. JNCC, 2018).

4. Conclusions

Marine HCSs differ greatly within six key properties, due in part to their initially intended application and structure (i.e. whether they follow a strictly hierarchical approach to classification and how readily they incorporate modifiers for the incorporation of greater detail). Consequently, each HCS has specific strengths and weaknesses. These strengths and weaknesses, along with the inherent assumptions associated with the classification process, modify the final representation of habitats when mapped. It is important for mappers to be aware of how these properties and assumptions are transferred into marine habitat maps, and whether these constrain their subsequent use for a wider variety of applications. Equally, decisions on how mappers use HCSs within the mapping process, which is independent of the properties associated with the HCS, also introduces additional artefacts and biases. Having identified all of these issues, recommendations have been provided for improving HCSs for marine mapping as well as enhanced working practices for mappers using these schemes. For example, limiting interpretation of data to fit only one HSC compromises the information we can communicate through our maps and limits their use to a wider range of stakeholders. It is hoped that implementation of these recommendations will lead to: (i) greater certainty and usage within mapping studies; (ii) more consistency between studies and adjoining maps; and (iii) increased use of mapped products by a greater diversity of end users.

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Table 1. Marine (benthic) habitat classification schemes used to document the variation in the six scheme properties considered.

Habitat Classification Scheme	**Description**	**Examples of usage**
European Nature Information System (EUNIS) - Davies *et al*. (2004) http://eunis.eea.europa.eu/	EUNIS is a pan-European habitat classification scheme developed between 1996 and 2001 by the European Environment Agency (EEA) (Davies *et al*., 2004). It considers both marine and terrestrial habitats in Europe. The geographical scope of the EUNIS marine scheme is the marine waters off the European mainland, including offshore islands (British Isles, Cyprus, Iceland, but not Greenland), and the archipelagos of the European Union Member States (Canary Islands, Madeira, and the Azores). EUNIS marine scheme covers the entire seabed from the intertidal zone to the abyss, and also includes a section of pelagic habitats. In the marine sector, it is based on the Joint Nature Conservation Committee (JNCC) Marine Habitat Classification for Britain and Ireland (Connor *et al*., 2004) and habitat types developed by the Barcelona and Helcom marine conventions (Barcelona Convention, 1998; Helsinki Commission, 1998).	EUNIS supports inventory mapping (EMODnet), ecosystem-based management (Andersen et al., 2018) and policy implementation Marine Strategy Framework Directive (Council Directive 2008/56/EC).
HELCOM Underwater Biotope and Habitat classification system (HELCOM HUB) – HELCOM (2013) http://www.helcom.fi/baltic-sea-trends/biodiversity/helcom-hub	HELCOM HUB was developed to be a comprehensive classification system for marine biotopes of the Baltic Sea (HELCOM, 2013). Its origins go back to the HELCOM EC-NATURE Red List Project (HELCOM, 1998) which was a first Baltic Sea wide classification scheme based on substrate type and bathymetry. Its classification rules mainly relied on expert judgment and biological classification criteria were not included. In 2007, the goal was set to renew the Red List Classification system by a HELCOM Red List Biotope Expert Group. Previous attempts had been made to apply EUNIS to the Baltic Sea region but the system was recognized to poorly represent its biotic and abiotic characteristics (Galparsoro *et al*., 2012). Nevertheless, HELCOM HUB was to be compatible with EUNIS and account for available biological information on	Supports the national implementation of the Marine Strategy Framework Directive (Council Directive 2008/56/EC).

	marine biotopes from the Baltic Sea. HELCOM HUB is primarily focused on benthic habitats/biotopes - the pelagic environment is only dealt with in the upper part of the classification system. As one major improvement, HELCOM HUB provides clear quantitative classification rules for both abiotic and biological criteria. It was therefore used as a basis for the development of the national classification system of the German Red List of Threatened Habitat Types for both the North and the Baltic Sea (Finck et al. 2017).	
Potential Habitat Characterization Scheme (PHCS) - Greene *et al.* (1999, 2005, 2007)	This classification covers deep-water habitats within North America and has been expanded to include shallow water habitats, arctic to tropical regions, including Antarctica (Vietti *et al.*, 2001) and estuaries (Greene *et al.*, 2007b). This scheme has been specifically developed for seafloor mapping and uses common mapping information such as multibeam echosounder data, video, photographs taken with still cameras and seafloor samples from grabs. The attributions used to classify the seafloor are mainly based on physical parameters and features and therefore, has a 'bottom-up' structure. The classification scheme is unusual in that it recognises four spatial scales. The first three scales can be defined with acoustic methods whereas the finest scale habitats can only be delineated with direct observation (via video, photographic still imagery, diver observations or seafloor sampling) Greene *et al.* (2005, 2007).	Fisheries management (Greene *et al.*, 2005, 2007)
Hierarchical Framework of Marine Habitat Classification for Ecosystem-Based Management (HFMHC) - Guarinello *et al.* (2010)	This classification framework is specifically designed for promoting ecosystem-based management. The upper levels of the scheme start with the global classification of large marine ecosystems. Subsequent levels include recognizable ecosystem units; e.g. estuary, and broad, geological formations such as drowned river valley. The flexibility to add user-defined classes at the lower levels of all three strands means the framework can be applied in any geographic location and is not limited by the methods used to observe any of the three strands. The framework incorporates the central concepts of ecosystem-	Ecosystem-based management (Guarinello *et al.*, 2010)

	based management within the structure of the framework. This ensures that the products of this HCS reflect the values and objectives of ecosystem-based management.	
Classification of Sublittoral Habitats (CSH) - Valentine *et al*. (2005)	This classification scheme was designed to describe and classify habitats in terms of geological, biological and oceanographic attributes. It is unusual in that the scheme also captures information on the effects of natural and anthropogenic processes on habitats. The purpose of the classification is to provide a foundation for scientific research and environmental management of seafloor habitats across a relatively large, regional area. Although initially developed for the Gulf of Maine region (an area that reaches depths of approximately 400 m but also has submarine canyon heads that incise the continental shelf and reach depths of up to 800 m), the scheme is a generic classification and can therefore by applied to any continental shelf and shelf basin environment globally (excluding some low-latitude environments).	Fisheries management (Valentine *et al*., 2005)
Australian National Intertidal/Subtidal Benthic Habitat Classification Scheme (NISB) http://lwa.gov.au/products/pn21267	The NISB scheme was developed to identify a "uniform definition of communities, habitats and ecosystems" at both state and national scales, and spatial information that is informative for assessing critical climate change issues and the detecting change or loss of habitats or communities. The proposed scheme covers all of Australia's territorial waters between the high tide and the approximate outer limit of the photic zone (depth of 50 – 70 m).	Inventory mapping of ecoregions (bioregional subregions)
Coastal and Marine Ecological Classification Standard (CMECS) - Madden *et al*. (2005) https://www.cmecscatalog.org/cmecs/	CMECS was developed by the National Oceanic and Atmospheric Administration (NOAA) and NatureServe. The scheme is founded on existing schemes (e.g. Cowardin *et al*. (1979), Dethier (1992), Greene *et al*. (1999), Allee *et al*. (2000), Zacharias and Roff (2000) and Connor (2004)). CMECS includes all estuarine, coastal and marine waters under U.S. jurisdiction in North America. This includes wetlands, the intertidal zone, coastal and deep-water habitats (including the Great Lakes) as well as the pelagic realm.	Inventory mapping (Madden *et al*., 2005)