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Review

Use of macroalgae to biomonitor pollutants in coastal waters: Optimization of the methodology

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ABSTRACT

Although native macroalgae have been used for biomonitoring purposes since the 1950s, a standardized protocol that would enable widespread implementation of the technique has not yet been developed. The aim of this review study, in which 445 articles were consulted, was to evaluate the monitoring methods applied in coastal environments worldwide and to assess the degree of standardization of the techniques used. Finally, on the basis of the conclusions reached, we propose a standardized protocol for implementing the method.

1. Introduction

Human activities such as agriculture, aquaculture, mining and numerous industrial processes involve the uncontrolled discharge of waste containing heavy metals, excess nutrients and organic compounds, thus seriously threatening the quality of coastal aquatic ecosystems (Islam and Tanaka, 2004; Halpern et al., 2008).

Marine organisms (e.g. macroalgae, fish and crustaceans) have been used as monitors to provide information about concentrations of pollutants in the surrounding environment, as an alternative to the analysis of water or sediment (Phillips, 1977, 1990, 1994; Zhou et al., 2008). The biomonitoring technique has significant advantages over traditional analytical techniques, in which the sampling must be carried out at pre-established times (Conti et al., 2002). Biomonitors are able to reflect the bioavailable fraction of pollutants in the water and to integrate the temporal variability, thus providing a more stable measure of pollution.

Macroalgae are the most important primary producers in marine coastal waters and thus play a key role in accumulating pollutants, which then enter aquatic food chains and threaten animal and human health as a result of biomagnification (Conti et al., 2007; Conti and Finoia, 2010). Biomonitoring with macroalgae (passive biomonitoring) was first introduced in the early 1950s (Bryan et al., 1980; 1985; Rainbow and Phillips, 1993) and is still widely used to assess the state of the environment (Gubelit et al., 2016; Olivares et al., 2016). At the early stage of development of the technique, use of macroalgae to monitor metal pollution in coastal environments was mainly restricted to the UK (Black and Mitchell, 1952; Fuge and James, 1973) and Canada (Wort, 1955; Bohn, 1975). However, the technique is now used worldwide with either native (passive biomonitoring) or transplanted species (active biomonitoring) (Fig. 1). Macroalgae can be used to indicate pollution in both estuarine and coastal waters because they combine different characteristics that make them ideal biomonitors (see e.g. Haug et al., 1974; Phillips, 1990): (i) most of them are sessile; (ii) they are widely distributed and available all year round; (iii) they tolerate wide ranges of salinity, turbidity and high levels of pollutants; (iv) they are easy to sample and process; (v) and they can be maintained in laboratory conditions.

Reviews concerning the bioaccumulation patterns of pollutants (i.e. heavy metals and organic pollutants) in the marine environment are numerous and generally involve different types of marine organisms (e.g. Rainbow and Phillips, 1993; Sánchez-Quiles et al., 2017), with few specifically concerning the use of macroalgae to monitor coastal waters (e.g. Topçuoğlu et al., 2004; Malea and Kevrekidis, 2014).

2. Status of passive biomonitoring coastal environments with macroalgae

For this literature review, we consulted a total of 445 articles concerning the use of macroalgae for the passive biomonitoring of pollutants in coastal environments. The aims of the review were to establish the status of the method, identify the degree of standardization of the techniques applied and propose a standardized protocol. We selected articles published worldwide in English, in journals to which we had

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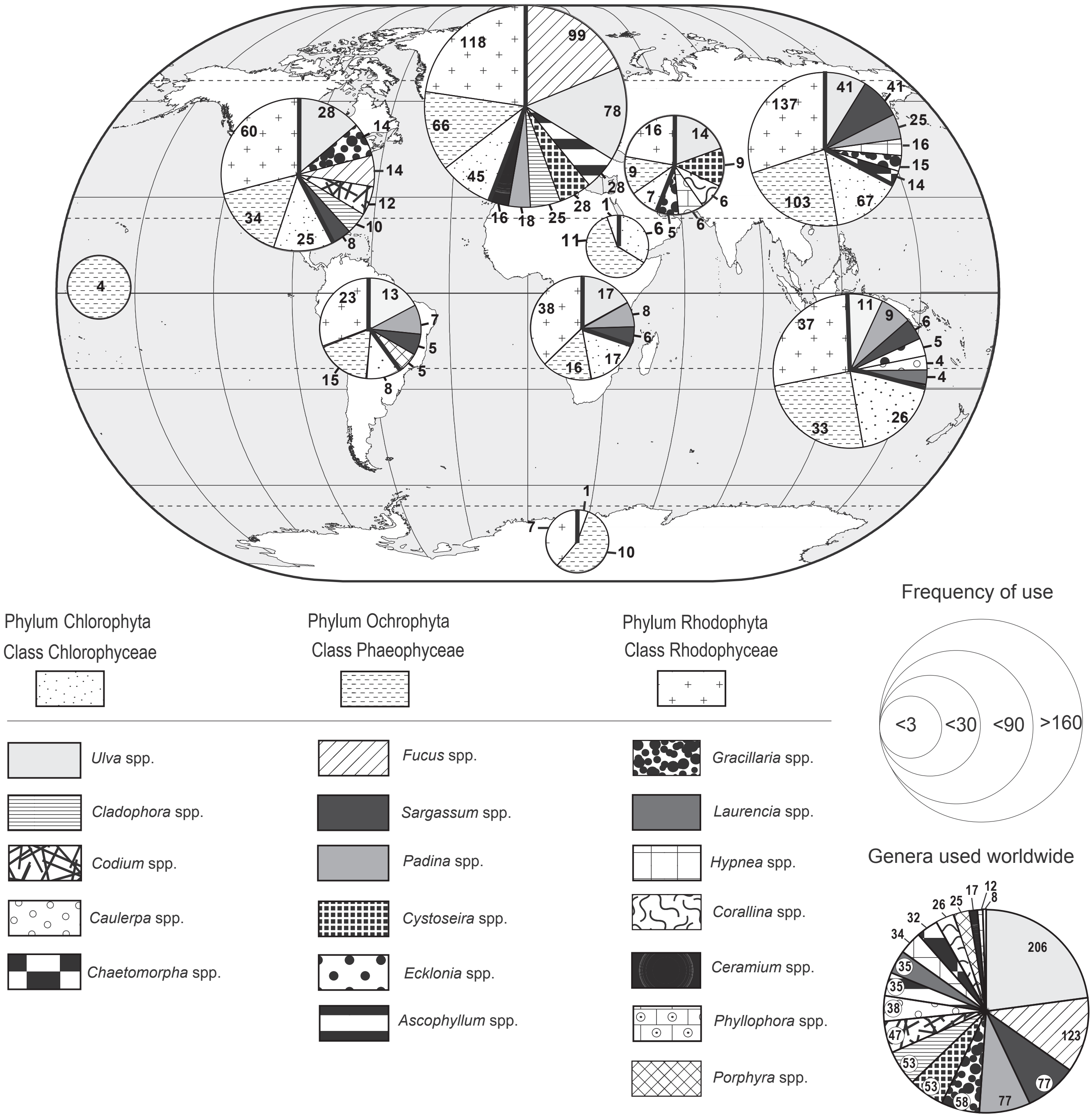

Fig. 1. Representation of the different genera and classes of macroalgae used in the passive biomonitoring technique in coastal waters in different continents and worldwide between 1952 and 2016 (n = 445). The frequency (number of publications) of use of the biomonitoring technique in each genera is indicated by the size of each circle. **Phyllophora* spp. is included in phylum Rhodophyta (class Florideophyceae).

access, within the last 64 years (1952–2016). We located the journals with SCOPUS, Elsevier's abstract and citation database of peer-reviewed literature. All articles reviewed concerned the use of native macroalgae to biomonitor pollutants (e.g. heavy metals, organic compounds or $\delta^{15}N$) and/or reported experiments involving methodological aspects of the technique. Those studies including both of these aspects were considered methodological studies.

The topic of most of the articles reviewed (94%) was pollution biomonitoring, while those articles concerning methodological aspects such as sampling methods and sample processing were much less abundant (6%), Fig. 2. Moreover, some articles provide little or no information about the techniques used (e.g. Tomlinson et al., 1980; El-Sayed and Dorgham, 1994). The number of articles on this topic increased greatly between the 1950s and 1995, since when they appear to have stabilized. Of those authors publishing in this field (Fig. S.1, Supplementary material), over 80% have only published one article. Indeed, very few authors (including members of research groups in Australia, China, Greece, Russia, Spain, Turkey, UK and the US) have published more than 5 articles on the topic (Fig. 1).

Most studies (97%) involved inorganic contaminants and very few involved organic contaminants (3%). The types of elements most frequently analysed were heavy metals (Cu, Zn, Cd and Pb in order of frequency), which were considered in more than 50% of the studies, followed by metalloids such as As and nutrients (e.g. N, Ca and Mg) (Fig. 3). The main organic pollutants studied were PCBs, PAHs and DDT or DDT metabolites (in order of frequency). Other elements and