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The Future of Benthic Indicators: Moving up to the Intertidal

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ABSTRACT

The use of benthic indicators has increased dramatically during the last decades. The number of articles published on the subject, as well as the number of citations, has been particularly increasing since the early 90's, notably in relation with the implementation of directives for the management of aquatic/marine ecosystems such as the Water Framework Directive and the Marine Strategy Framework Directive. Current benthic indicators suffer from severe drawbacks and their practical use is still discussed and might have reached a dead end. Indicators based on species composition are not totally satisfactory, mainly because they exhibit a high spatio-temporal variability (e.g. variable at both seasonal and pluri-annual scales) and are user-dependent (e.g. divergent results from US or Europe experts.) In turn, modifications of behaviour, metabolism, phenotype or stable isotopes composition in invertebrates usually occur at short time scales, compared to detectable changes in community composition, and makes their use particularly relevant as indicators of perturbation. It is argued in this paper that these functional indicators might be relatively quickly implemented in the intertidal, and represent an effective alternative to current benthic indicators.

Keywords: Benthic Indicators; Intertidal; Ecosystem Functioning; Anthropogenic Disturbance; Global Change

1. Introduction

Global climate change is now unequivocal [1,2], and publications on the topic are legion; see e.g. [3,4] for reviews. Coastal ecosystems are increasingly threatened by the combined effects of global warming and its direct and indirect consequences (e.g. erosion and sea level rise) and other major anthropogenic pressures (including habitat change, invasive species, eutrophication, chemical pollution, overexploitation [5]), which justify the development of ecological indicators to evaluate their health (see [6] for a review). The concept of indicators in aquatic ecology and ecosystem management is not recent and indicators are now considered as "mainstream tools" in assessing the quality of aquatic ecosystems [7]. Their use has increased dramatically during the last few decades [8,9], notably in relation with the implementation of international directions for the management of aquatic/marine ecosystems such as the Water Framework Directive (WFD, 2000/60/EC) and the Marine Strategy Framework Directive (MSFD, 2008/56/EC) in Europe (see e.g. [10]). In this context, due to their sedentarily and long life span, benthic organisms are considered as good integrators of environmental changes in marine ecosystems and have been extensively used as indicators for ecosystem changes (e.g. [9,11,12]). The practical use of current benthic indicators in marine ecosystems is, however, still fiercely discussed (e.g. [6]). In this paper, after a short review and bibliometric survey, I will stress how the study of intertidal ecosystems could help to implement new indicators that would, in tidal seas, complete, if not replace, current benthic indicators.

2. Benthic Indicators: Where Are We?

Benthic indicators (see e.g. [13,14] for definitions) are a particularly popular topic in marine sciences; the ISI Web Of Science (accessed April 10, 2013 for the combination "benthic indices or benthic indicator* and marine") returned 3306 papers published and 54,282 citations between 1967 and 2012. Papers dealing with benthic indicators are amongst the ten most cited papers in specialized journals such as *Marine Pollution Bulletin* ([15] and [16] with 363 and 272 citations, respectively) and *Ecological Indicators* ([17-20] with 69, 70, 89 and 93 citations, respectively.) The number of articles published on the subject, as well as the number of citations, has been drastically increasing since the early 90's (**Figure 1**).

The related mean annual growth rate [21,22] for the period 1991-2012 has subsequently been estimated from the slope α of the semi logarithmic plot of the number of articles published *vs*. time as 12.4% (**Figure 2**).

It is, however, well known that the growth rate of scientific publication is almost constantly raising [21,22]. Therefore, data from the ISI Web Of Science were also collected for all published papers and for papers published in marine sciences only (*i.e.* records containing "marine") for the period 1991-2012 (**Figure 2**). Using the approach described above, the mean annual growth rate for all fields combined was 4.1% and 7.0% for marine sciences specifically, both being significantly lower than the 12.4% for benthic indicators (t-test for slope comparison, $p < 0.05$.) Note that the sharp increase observed in the early 90's is also seen for marine sciences, but not for the overall outputs from the Web of Science. This feature was previously detected for several fields in ecology [23], for example for studies related to coastal biogeochemistry [24], pollution in estuaries [25] and

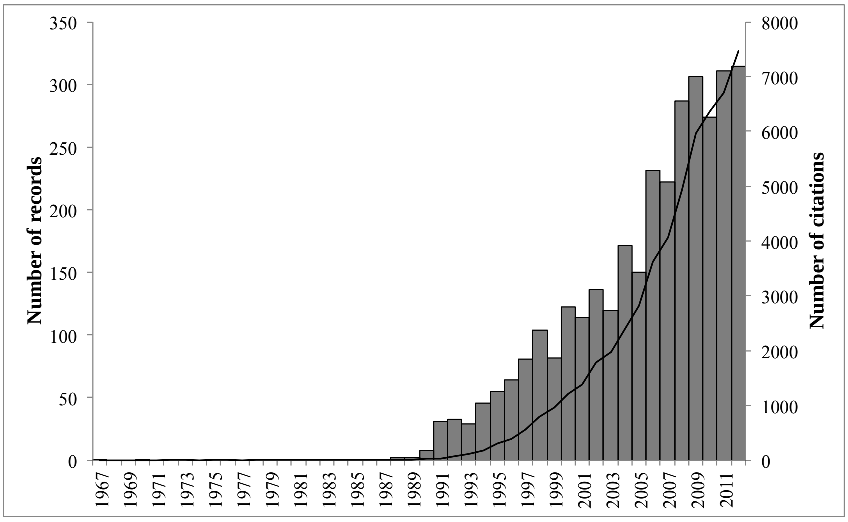

Figure 1. Number of publications (bars) and number of citations (solid line) in the field of marine benthic indicators (*i.e.* for the keywords combination "benthic indices or benthic indicator* and marine") recovered from the ISI Web of Knowledge database (accessed early March 2013) for the period 1967 (first reference in the field)-2012.

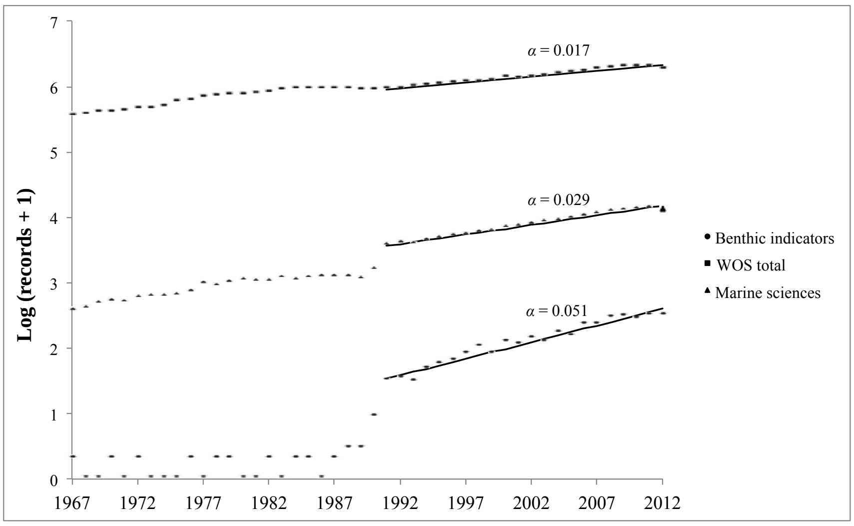

Figure 2. Number of records in the ISI Web of Science database (accessed early March 2013, semi logarithmic scale) for marine benthic indicators (*i.e.* for the keywords combination "benthic indices or benthic indicator* and marine", circles), marine sciences (*i.e.* for the keyword "marine", triangles) and total number of records in the database (squares). The slopes α from the linear regressions are given for the period 1991-2012.

eutrophication [26]. Interestingly enough, there is no significant change in the slope (summed cumulated function method [27]), hence in the growth rate, of publications on marine benthic indicators in the 2000's. This suggests that the vote and implementation of both the WFD (2000) and MSFD (2008) did not have any significant impact on the publication efforts, though more than 300 new methods were described for the WFD [9].

Due to the variety of existing benthic indicators, most of the recent papers aimed to compare their efficiency using different sampling methods (sampler and mesh size [28]), taxonomic levels [29,30], or testing experts from USA and Europe [31]. Numerous studies also compared the consistency of different indicators for evaluating the ecological status of a selected area [11,12,20,32-41]. Overall, these comparisons revealed inconsistencies between indicator responses, some sampling stations being classified either in a "*poor*" or "*high*" ecological status depending on the index used [32], or samples considered as either "*unaffected*" or "*severely affected*" depending on the expert [12,31]. This short review demonstrates, as recently stressed [6], that current benthic indicators suffer from severe drawbacks (**Table 1**) and do not fulfil the requirements for being "good indicators" *sensu* [42]. Most of them are usually specific to a habitat or geographical area (for a review see e.g. [20]) and highly variable at both seasonal [43,44] and pluri-annual scales [45]. Most authors usually agree on, for example, the general efficiency of the AMBI and the derived M-AMBI [34,37,40,41,46,47] or the relative ineffectiveness of the BOPA index [32,48,49]. However, the practical use of benthic indicators might have reach a dead end, since no real consensus has been reached yet and inter-calibration and standardisation are still needed, as shown by the ongoing inundation of papers related to comparesons or intercalibrations (see references here above).

Recently, indices have been developed (or revised) based on other benthic groups than macrofauna, such as macroalgae either alone [52,53] or combined with macrofauna [54], and meiofauna, including nematods [55] and foraminifera [56,57]. These indices however share disadvantages with macofauna-based indices, such as the requirement of a high degree of specialisation (particularly for some meiofaunal groups such as nematods [58]), and contribute to the current indicator inundation that sometimes leads to awkward situations when the indice values are much more difficult to determine than the environmental factor it is supposed to be representative of (e.g. living foraminifera assemblages diversity as an in

Table 1. Selected examples of the main drawbacks of current benthic indicators.

Drawback	Example	Reference
Expert dependence	Major differences in the ecological classification for 7% of the samples examined by expert from France and Algeria	[12]
	Major differences in the ecological classification for 58% of the samples examined by expert from Europe and USA	[31]
Methodological dependence	Major differences in the ecological classification for 28% to 48% of the stations analysed, depending on the sieving method (0.5 mm vs. 1 mm mesh size, tested on 3 different indicators)	[20]
	Major differences in the ecological classification for 17% to 83% of the stations analysed, depending on the sampling method (Van Veen grab vs. corere, tested on 7 different indicators)	[28]
Inconsistency between indicators	Five different biotic indices disagreed on the status of 65% to 90 % of the stations sampled in semi-ecnlosed systems and transitional waters	[33]
	Dissimilarity of the ecological status obtained by 6 indices varied from 3% to 64 % (stations sampled in coastal and lagoon locations)	[32]
	Major differences in the ecological classification for 74 % of the stations examined depending on the indicator used (3 tested)	[37]
Temporal variability	Major differences in the ecological classification of a single sampling station along a pluri-annual survey (using the M-AMBI and BENTIX indices)	[37]
	Major differences in the ecological classification of 3 sampling stations at the seasonal scale (5 indices tested)	[43]
	Major differences in the ecological classification of a single sampling station along a long-term (30 year) survey (6 indicators tested)	[45]
Operational limits	Five digits for the BOPA index (e.g. 0.04576 < BOPA < 0.13966 and 0.13966 < BOPA < 0.19382 for a good and moderate ecological status, respectively)	[50]
	Five digits for the BO2A index (e.g. 0.01951 < BO2A < 0.13100 and 0.13101 < BO2A < 0.19804 for a good and moderate ecological status, respectively)	[51]

dicator of dissolved O_2 concentration [56].) Besides, the claim that indicators' outputs and interpretation should be understood by non-scientists [38,59] (see however [60] for criticisms), leads to a jargon where some terms do not have any ecological reality anymore (this is the case for the widely used "*reference state*" [6,61]) or have different meanings in a management and a purely ecological context, such as "*ecosystem*" [62,63], which also contributes to the general confusion.

3. Where to Go Next?

As stated above, benthic indicators based on species composition are not totally satisfactory as communities can be disrupted but exhibit only minor changes in their composition (e.g. [64]). In turn, phenotypic and metabolic changes can be observed in impacted areas, even if the community structure (e.g. abundance, diversity) remains unchanged. Behavioural, metabolic, phenotypic and stable isotopes composition modifications in invertebrates usually occur at short time scales [4], compared to detectable changes in community composition (except in the extreme case of catastrophic events such as oil spills) and thus makes their use particularly relevant as indicators of perturbation. Regarding for example behavioural analysis, they have previously been underlined as "early warning" signals to assess the status of marine environments [65].

Most of the highest predicted cumulated impacts of humans on marine ecosystems are in areas of continental shelf and slopes, including hard and soft continental shelves and rocky reefs [5]. Ecosystem modifications in response to these changes include extinctions, changes in food web structures and shifts in geographical distribution of species [1]. In the latter case, intertidal organisms are considered as being potential harbingers of climate-driven changes in distribution patterns [66] because most of them live very close to their thermal tolerance limits [67,68]. Furthermore, intertidal areas are home to some of the highest rates of primary production in the world [69] and their status (sink/source) regarding the CO_2 global cycle is still uncertain [70]. Understanding their role in the global carbon cycle is, however, of primary importance since the efficiency of the global ocean carbon pump is expected to decrease [1,71] and about 40% of the carbon sequestration in the oceans occur along continental margins [72]. Thus, intertidal areas do not only occupy a keystone ecological position as a land/sea and air/water interface but also represent a compartment of primary importance to assess the impact of human activities and global warming on marine ecosystems [67]. Intertidal ecology is a productive field in marine sciences, as seen from the constant increase in published works on the intertidal environment since the early 90's (**Figure 3**).

Note that the related growth rate (5.7%), though significantly lower than the ones for benthic indicators and marine sciences, corresponds to a significantly more pronounced increase than the one observed in general sciences. One of the main advantages of the intertidal environment is its accessibility and the subsequent relative ease to observe the distribution and behaviour of organisms, and to perform manipulative experiments. This is particularly true for rocky shores that have been extensively used to study species interactions relatively early (60's and 70's), notably with the work of Connell [73], Paine [74] and Underwood [75]. Note that the re-

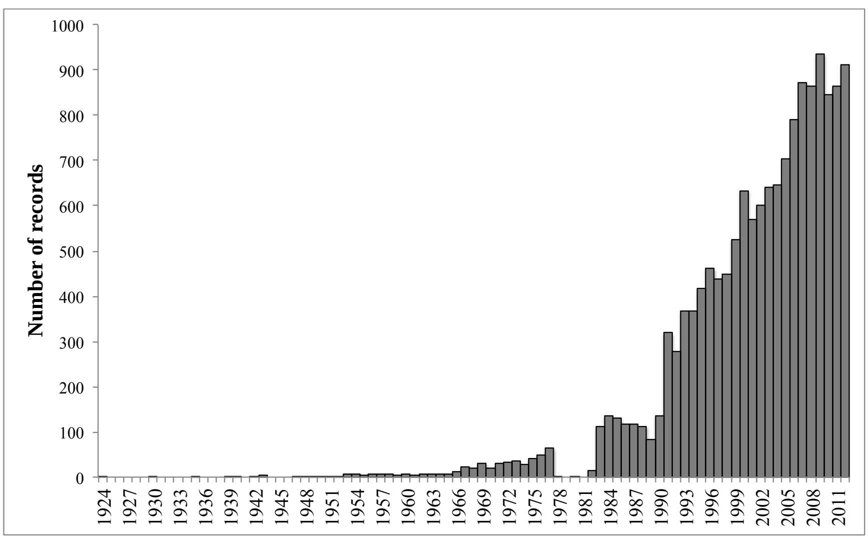

Figure 3. Number of publications in the field of intertidal ecology (*i.e.* for the keywords combination "intercotidal or intertidal") recovered from the ISI Web of Knowledge database (accessed early March 2013) for the period 1924 (first reference in the field)-2012.

vival of interest in intertidal ecology in the early 80's (**Figure 3**) matches with the first papers published on the primary production of microphytobenthos [76]. Ever since, soft sediment functioning has been continuously and increasingly studied, especially in areas where both human uses and impacts are manifest, *i.e.* estuaries (mudflats) and sandy shores (beaches.)

In this framework, the intertidal represents an ideal candidate for the development of new indicators and studies concerning the impact of anthropogenic (direct and indirect) disturbances on the functioning of intertidal systems have been multiplying during the last decade. Modifications in the behaviour, phenotype, metabolism or isotopic composition of intertidal invertebrates might be useful to detect non-natural changes in relation with e.g. alien species introduction [77,78], topographic modifications [79], the presence of plastic litter [80], metal contamination in sediment [81], exposition to pesticides [82,83], acidification [84,85] and temperature increase [86-88]. Furthermore, tools usually used to trace organic matter in the trophic network (*i.e.* stable isotopes and fatty acids) have also been used as indicators for environmental changes [89-91]. The monitoring of CO_2 fluxes at the air/sediment interface also appears to be particularly interesting since they are mainly dependent on variations in light and temperature at several scales [92,93], and have been shown to respond to direct and indirect consequences of global change. This includes climatic events (exceptional warm year [70]), micro- and macro-algal deposits in soft sediments [94-97], canopy loss on rocky shores [98], and most probably acidification [99].

Potential benthic indicators are thus numerous in the intertidal. However, the functioning of intertidal areas is known to be particularly complex, hence the difficulties in the estimation of the impact of climate change [66, 100]. Indeed, the interface position leads to sharp variations in the physical and chemical properties of the environment between immersion and emersion conditions, and the understanding of the impact of environmental stress is made particularly difficult due to theirspatio-temporal coincidence [101,102]. In addition, the sources of organic matter are numerous [103], leading to often challenging studies on trophic interactions and energy flows [104]. Therefore, a proper knowledge of the functioning of the main intertidal habitats (rocky shores, sandflats, mudflats, seagrass meadows) is required as a prerequisite to develop a baseline, or "relative reference state" [61]. This would require, beside usual laboratory experiments, long-term surveys and extensive field investigations. Long-term monitoring of CO_2 exchanges through automated measurements could be performed using the non-invasive eddy correlation technique which provides direct and continuous measurements of net CO_2 exchange at time scales ranging from hours to years [105], integrates large spatial scales, and has been proven efficient in intertidal areas [106]. This method represents a promising tool for large-scale estimations of CO_2 fluxes, but techniques such as benthic chambers are more amenable for the detection of fine processes. The situation is much more complicated for long-term, spatially extended, surveys of species distribution in relation with e.g. microhabitats or the collection of individuals for morphometric analysis. This kind of surveys requires important associated manpower and financial resources. It is nowadays recognise that projects that seek to collect field data on large geographical areas and/or over long time periods can only succeed with the help of 'citizen scientists' [107,108]. The intertidal being easily accessible and usually frequented by tourists or recurrent users, the help of volunteers can be relatively easily implemented. For example, citizen science has previously been successfully used to assess the presence of invasive crabs in the intertidal zone along more than 1000 km of coast in the USA [109]. Though usually based on structural factors (presence/richness of some species), citizen science could also be powerful for functional factors with the development of specific protocols and a minimum of training.

4. Conclusion: Are Science and Policy Compatible?

It is suggested here that new benthic indicators are needed and should be developed based on the functioning of the ecosystem rather than on community composition. In tidal seas, due to their key interface position, easy access, and coast effectiveness compared to the subtidal [101], intertidal areas offer a great opportunity to quickly develop such indicators. The first step will be to fill potential current knowledge gaps to clearly identify targets (species behaviour, composition, fluxes) and implement protocols that will be unambiguously understandable, hence usable by research consultancies and citizen scientists. There are, however, contradictory interests between science and management policies [59]. Some of the statements advocated here are usually fiercely argued against when discussed with colleagues involved in management e.g. "*why have benthic indicators reached a dead end*? *There are many publications, some introducing new ways for indicator development*", "*there are plenty of publications showing the ability of current indicators to detect pressure gradients*", "*there are plenty of papers showing that benthic indicators are indicating effects to marine communities, as required by legislation*", or "*legislation requires assessing the effects at the community or ecosystem level and legislation deal with managed pressure*". These quotations testify that legislation leads to 1) a profusion of publications related to benthic indicators that, though probably helpful for the bibliometric profile of some scientists, do not bring any definitive solution (outputs *vs.* outcomes [59]), 2) ignores the evolution of scientific knowledge that should be included in new management directives and 3) ignores exogenic unmanaged pressures. Elliott [59] recently adressed these problems and stressed that both exogenic unmanaged pressures and endogenic managed pressures should both be tackled in a multidisciplinary approach, and that the 'health' of the system should be considered at six different biological levels (cell, tissue, individual, population, community and ecosystem)···I further suggest "in the intertidal"!

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