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New ocean, new needs: Application of pteropod shell dissolution as a biological indicator for marine resource management

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ABSTRACT

Pteropods, planktonic marine snails with a cosmopolitan distribution, are highly sensitive to changing ocean chemistry. Graphical abstract shows pteropod responses to be related to aragonite saturation state, with progressing decrease in Ω_{ar} causing deteriorating biological conditions. Under high saturation state ($\Omega_{ar} > 1.1$; zone 0), pteropods are healthy with no presence of stress or shell dissolution. With decreasing Ω_{ar} (zone 1), pteropod stress is demonstrated through increased dissolution and reduced calcification. At $\Omega_{ar} < 0.8$ (zones 2 and 3), severe dissolution and absence of calcification prevail; the impairment is followed by significant damages. Pteropods responses to OA are closely correlated to shell dissolution that is characterized by clearly delineated thresholds. Yet the practical utility of these species as indicators of the status of marine ecosystem integrity has been overlooked. Here, we set out the scientific and policy rationales for the use of pteropods as a biological indicator appropriate for low-cost assessment of the effect of anthropogenic ocean acidification (OA) on marine ecosystems. While no single species or group of species can adequately capture all aspects of ecosystem change, pteropods are sensitive, specific, quantifiable indicators of OA's effects on marine biota. In an indicator screening methodology, shell dissolution scored highly compared to other indicators of marine ecological integrity. As the socio-economic challenges of changing ocean chemistry continue to grow in coming decades, the availability of such straightforward and sensitive metrics of impact will become indispensable. Pteropods can be a valuable addition to suites of indicators intended to support OA water quality assessment, ecosystem-based management, policy development, and regulatory applications.

1. Introduction

Fundamental changes in the ocean caused by human activities threaten the persistence of contemporary marine species and systems (Nagelkerken and Connell, 2015). Some of these changes are unprecedented in human history, challenging scientists and decision-makers to quickly develop new criteria by which to evaluate and mitigate the negative effects of ocean change. The global phenomenon of ocean acidification (OA) offers a case in point: our recognition of the problem is relatively recent and our scientific understanding is growing rapidly, yet we have no established means of evaluating the effects of OA in a regulatory or management context to address the integrity of ocean ecosystems or water quality assessment and monitoring (Chan et al., 2016).

Effective management under regulatory frameworks is often based on the use of environmental indicators—measurable variables that provide information about the environment in a simple, pragmatic, and scientifically sound manner. As no single indicator can reliably represent ecosystem status, ecosystem assessments generally use suites of indicators that are appropriate to specific management needs. These indicators serve as proxies for the range of attributes that societies associate with the status of ecosystem health and integrity (Harwell et al., 1999). Within science-policy frameworks such as the Driver-Pressure-State-Impact-Response

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framework (DPSIR; Bowen and Riley, 2003) and the National Oceanic and Atmospheric Administration (NOAA)'s integrated ecosystem assessment framework (IEA; Levin et al., 2009), suites of indicators provide information on the status and temporal trends of environmental conditions, species abundances, threats, and other attributes of interest, and ideally are linked to environmental assessment and management targets or thresholds. Indicator suites can play a critical role in proactive management of water quality (Boehm et al., 2015; Weisberg et al., 2016). To be effective, the responses of indicators to ecosystem changes should be predictable and distinguishable from natural variability, and should potentially provide "early warning" signals of impacts to ecosystem integrity. Given the seriousness of the threats OA poses to marine resources and ecosystem services, development of appropriate OA indicators and monitoring strategies is imperative for effective management (Boehm et al., 2015; Chan et al., 2016; Weisberg et al., 2016).

Euthecosome pteropods are shelled free-swimming marine planktonic snails. Their thin, aragonite shells are an adaptation to a completely pelagic lifestyle and render them sensitive to the corrosive conditions at aragonite saturation states (Ω_{ar}) ≤ 1 associated with OA. They are cosmopolitan in distribution and play important ecological roles in areas where they occur at high abundance, such as high-latitude seas and coastal and shelf waters (Bednaršek et al., 2016a). They have a narrow window for maintaining vital biological processes under corrosive conditions associated with OA (Bednaršek et al., 2014a,b). *Limacina helicina* is the most commonly studied species with respect to OA-induced responses over a wide range of diverse latitudinal gradients in tropical, temperate, and polar environments. The variety of responses include shell dissolution; declines in calcification rates, shell thickness, growth and survival; changes in vertical distribution; and lower abundances associated with long-term declines in Ω_{ar} (Bednaršek et al., 2016a).

Here we argue that shell dissolution in *L. helicina* is a reliable indicator of individual physiological response to Ω_{ar}, effectively representing overall condition of their exposure to OA conditions. Moreover, we attempt to demonstrate that shell dissolution is a good predictor of the likelihood of individual survival, in addition to providing good understanding of overall pteropod status in relation to OA .Shell dissolution can indicate pteropod biological response to OA in a manner that can be quantified and reported as a single metric, which is more cost-effective than measuring multiple, strongly correlated variables of pteropod condition. Furthermore, pteropod shell dissolution is indicative of OA conditions experienced by other surface ocean species that are critical to ecosystem functions and provide valuable services. While no single species or group of species can adequately capture all aspects of ecosystem change, pteropod shell dissolution may provide a biological indicator of the condition of marine waters with respect to OA, and thereby add a valuable indicator to the suite of indicators monitored in support of marine ecosystem-based management (EBM).

2. Methods

We first developed a series of plots based on functional relationships and critical response thresholds between aragonite saturation state and pteropod biology. Focal biological response variables included shell dissolution, calcification activity, and survival (Fig. 1a–c). Based on the fact that both, shell dissolution (Fig. 1a) and survival probability (Fig. 1c) are related to Ω_{ar}, a correlation between shell dissolution and survival was conducted (Fig. 1d). To develop duration-magnitude threshold, shell dissolution was plotted as a function of Ω_{ar} and exposure duration (Fig. 1e).

We used previously published data (Bednaršek et al., 2014a; Bednaršek et al. in review) for Fig. 1, and added 95% confidence intervals (CI). For calcification, CI was calculated using bootstrap analyses (1000 iterations). Percent shell dissolution (Fig. 1e) was calculated using forward-in-time trapezoidal integration of equation (14) in Bednaršek et al. (2014b). The thresholds were derived from Bednaršek et al. (in review) and Weisberg et al. (2016) (see Graphical abstract).

We then used an ecosystem indicator screening framework, developed by Kershner et al. (2011), Levin and Schwing (2011), and Williams et al. (2013), to evaluate pteropod shell dissolution as an indicator of OA effects on a marine ecosystem. Specifically, we rated pteropod shell dissolution as a candidate for inclusion in the suite of indicators of "ecological integrity," which the California Current IEA team defines as the ability of a system to support and maintain a community of organisms and ecosystem functions within a natural range of variability, and to withstand or recover from disturbances (Williams et al., 2013). Following the aforementioned framework, we established the degree to which the scientific literature on pteropod shell dissolution supports 17 criteria that describe the theoretical soundness, availability, and quality of data, and other attributes that contribute to the strength of a potential indicator (Table 1). The initial literature-based screening generated unweighted scores ranging from 0 (no evidence or conflicting evidence of support) to 1 (strong, consistent support) for each criterion (Kershner et al., 2011). However, the relative importance of each criterion is context-dependent; for example, matters of the cost-effectiveness and public understanding and acceptance of an indicator may be more important to some ecosystem assessment programs than others. It is thus essential that the screening criteria be weighted by scalars that rescale the raw indicator scores (Kershner et al., 2011; Levin and Schwing, 2011). Criteria weightings for the present analysis were based on a survey of 15 resource managers, policy analysts, and scientists from the US West Coast who were asked to rate how important they considered each criterion on a scale of 0 (strongly disagree that it is important) to 1 (strongly agree that it is important). Expert ratings were averaged and standardized (Levin and Schwing, 2011), then multiplied by the unweighted scores from the literature-based indicator criteria screenings, and then summed to produce a final weighted indicator score for pteropod shell dissolution, which could then be compared to other indicator scores for ecological integrity in the California Current Large Marine Ecosystem (CCLME; unweighted scores derived from Williams et al., 2013).

3. Results

3.1. Pteropod indicator index as a function of shell dissolution

Among the carbonate chemistry parameters, Ω_{ar} positively correlates with observed responses among pteropods, measured as shell dissolution, shell calcification, and survival (Figs. 1 and 2), and the similarity in thresholds indicates that all the processes are interrelated. At supersaturated Ω_{ar} states, there is no evidence of dissolution (shells are intact), and calcification processes are occurring (Figs. 1 and 2). The percent of individuals with severe shell dissolution positively corresponds closely to carbonate chemistry conditions (Bednaršek et al., 2014a). The threshold for shell dissolution occurs at $\Omega_{ar} \sim 1.1$–1.2 (pH of 7.80–7.85 and pCO_2 of around 650–700 ppm; Fig. 1a; Bednaršek et al. in review) where approximately 50% of examined pteropods are affected. The percent of individuals with severe shell dissolution positively corresponds closely to carbonate chemistry conditions (Bednaršek et al., 2014a). Decline in calcification begins at Ω_{ar} of 1.1–1.3 and declines significantly at the values <0.8 (Fig. 1b). Survival probability was highest under supersaturated conditions at Ω_{ar} > 1.2 ($pCO_2 \sim 683$ μatm; pH = 7.8) and declined linearly with saturation state (Fig. 1c). Establishing the correlation between the percent of individuals affected