Persistent natural acidification drives major distribution shifts in marine benthic ecosystems

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Ocean acidification is receiving increasing attention because of its potential to affect marine ecosystems. Rare CO₂ vents offer a unique opportunity to investigate the response of benthic ecosystems to acidification. However, the benthic habitats investigated so far are mainly found at very shallow water (less than or equal to 5 m depth) and therefore are not representative of the broad range of continental shelf habitats. Here, we show that a decrease from pH 8.1 to 7.9 observed in a CO₂ vent system at 40 m depth leads to a dramatic shift in highly diverse and structurally complex habitats. Forests of the kelp Laminaria rodriguezii usually found at larger depths (greater than 65 m) replace the otherwise dominant habitats (i.e. coralligenous outcrops and rhodolith beds), which are mainly characterized by calcifying organisms. Only the aragonite-calcifying algae are able to survive in acidified waters, while high-magnesium-calcite organisms are almost completely absent. Although a long-term survey of the venting area would be necessary to fully understand the effects of the variability of pH and other carbonate parameters over the structure and functioning of the investigated mesophotic habitats, our results suggest that in addition of significant changes at species level, moderate ocean acidification may entail major shifts in the distribution and dominance of key benthic ecosystems at regional scale, which could have broad ecological and socio-economic implications.

1. Introduction

Rising levels of CO₂ released by anthropogenic activities are driving unprecedented changes in the chemistry of the oceans [1,2]. The mean ocean surface acidity has increased by 25–30% (equivalent to a drop of 0.1 pH units) since as the advent of the Industrial Revolution in the 1780s and is predicted to decline by a further 150–200% by the end of the century, representing an additional drop of 0.3 pH [3]. Changes in pH since pre-industrial times are happening at least 10 times faster than over the last 55 Myr [4]. The increasing interest in understanding how changes in pH and in the overall carbonate system will affect marine life has placed ocean acidification (OA) as one of the fastest-growing research areas in marine sciences over the last few decades [5]. Most research so far has been conducted by means of laboratory experiments on a wide range of marine organisms, which have shown different responses and sensitivities...
While experiments are essential to identify species responses to OA, they fail to predict its long-term consequences on marine ecosystems and whether organisms will adapt to increasing seawater acidity [9].

In situ observations of naturally occurring CO2 seafloor vents provide empirical data on marine ecosystems acclimatized to acidified waters. However, a small number of CO2 vent systems have been investigated to date [9–13]. These systems show significant decreases in the diversity, biomass and trophic complexity of benthic marine assemblages, major declines in the number of many calcifying organisms, and increased abundance of erect macroalgae, seagrasses or soft-corals [9–14]. Most of the CO2 vent systems studied so far were placed in very shallow waters (3–5 m depth), and therefore are poorly representative of the broad range of habitats that occur on the continental shelf. Very few studies investigating the biological effects of these systems at larger water depths have been performed in hydrothermal vents in the Aegean Sea [12] and in the northern Gulf of California [13], at 10–35 m and at 70–200 m, respectively.

Dominant habitats at mesophotic depths (the deepest part of the photic zone where light penetration is low, typically from 30–40 m to over 150 m) are usually characterized by a large dominance of calcifying organisms, such as endangered coralligenous outcrops and rhodolith beds in the Mediterranean Sea, which display a notable carbonate production (170–660 g CaCO3 m⁻² yr⁻¹) [15,16]. Calcareous red algae are the main framework builders in those two habitats, providing structural complexity and favouring biodiversity [16,17]. Given their wide spatial distribution and ecological roles, both habitats are among the most significant in the Mediterranean Sea [18]. Their critical ecological functions, the long life spans and low dynamics of the dominant species, as well as the high sensitivity to OA of coralline algae and other calcifying organisms dwelling in mesophotic depths [7,19] render coralligenous outcrops and rhodolith beds especially vulnerable to a high-CO2 ocean. In this study, we show the in situ effects of exposure to anomalously high natural seawater pCO2 over benthic habitats dominated by calcifying algae at 40 m depth in the Columbretes Islands Marine Reserve (northwest Mediterranean Sea).

2. Material and methods

(a) Study area and remotely operated vehicle survey

The Columbretes Islands emerge 30 nautical miles off the coast of Castelló (Spain, northwest Mediterranean Sea; figure 1a) and are the emerged expression of a 90 x 40 km, mostly buried volcanic field associated with the Neogene opening of the Valencia Trough [20]. The Columbretes form a tiny volcanic archipelago that consists of one main island, several islets and rocks, and a number of shoals. The presence of CO2 vents was examined with a Seavey Linx 1500 remotely operated vehicle (ROV) in September 2011 inside and outside the Columbretes Marine Reserve. The spatial distribution of these vents along this elevated rocky-bottom area was explored through five video transects, each 596–964 m long (electronic supplementary material, figure S1).
(b) Carbonate system parameters
Vents and water samples were collected in June 2012. Vent gases were collected from three separate bubble streams in six replicate 12 ml glass bottles, and analysed with a gas chromatograph (TraceGC Ultra, Thermo-Finnigan). Seawater carbonate chemistry and dissolved inorganic nutrients were measured on water samples collected by scuba divers in three sites (three samples per site) inside (V1, V2 and V3) and outside (C1, C2 and C3) the vents at 40 m depth using Niskin bottles (figure 1b,c). While control stations C1 and C2 were approximately located 25 m and 60 m far from the vent area, the third control station C3 was placed much farther (approx. 6.5 km far from the vent area) to check for any influence that could be attributed to vent proximity. Carbonate system parameters (pCO₂, CO₃²⁻, HCO₃⁻, DIC concentrations, and saturation states of calcite and aragonite) were calculated from pH (in total scale), total alkalinity (TA), temperature and salinity. Additionally, in nine stations covering the waters around the vents, seawater samples were taken at three depths (5, 20 and 40 m; eight samples for each depth) in order to study the spatial variability in pH (in total scale), TA, salinity, temperature and dissolved inorganic nutrients.

Temperature and salinity were measured with a SD204 SAIV A/S CTD. Samples for pH and TA measurements were collected in 0.5 l BOD glass bottles, poisoned with saturated mercuric chloride and stored in the dark at room temperature; samples were analysed on the same day of collection. Samples for inorganic nutrient analysis were collected on polycarbonate bottles and dissolved inorganic nutrients. The mean composition of the bubbling gas was 90.0% CO₂, 4.8% N₂, 1.7% O₂ and 0.2% CH₄, subsequently resulting in water acidification (electronic supplementary material, table S1). No sulfur was detected in the gas. Field observations and sampling were performed at the vents and in off-vent nearby control stations with equal ambient seawater salinity and temperature (figure 1c; electronic supplementary material, table S1). The escaping gas had no influence on the composition of the upper water layers, as shown by samples from 5 and 20 m depth above the vents, which fell within the range of off-vent stations (electronic supplementary material, table S2).

Statistically significant differences on the parameters (pH, CO₂, CO₃²⁻ and DIC concentrations) estimated in locations inside and outside the vents were assessed using linear mixed-effects models (LMM) [25]. The presence/absence of vents was treated as a fixed factor and the sampling station as the random effect. The normality of residuals and the model performance were visually inspected using residual distributions and quantile–quantile plots. The analyses were computed using vegan [26] and nlme [27] packages implemented in R.

3. Results
(a) Seawater chemistry
CO₂ vents occur between 36 and 48 m depth on the southernmost section of the Columbretes Islands Marine Reserve (figure 1a,b). The mean composition of the bubbling gas was 90.0% CO₂, 4.8% N₂, 1.7% O₂ and 0.2% CH₄, subsequently resulting in water acidification (electronic supplementary material, table S1). No sulfur was detected in the gas. Field observations and sampling were performed at the vents and in off-vent nearby control stations with equal ambient seawater salinity and temperature (figure 1c; electronic supplementary material, table S1). The escaping gas had no influence on the composition of the upper water layers, as shown by samples from 5 and 20 m depth above the vents, which fell within the range of off-vent stations (electronic supplementary material, table S2).

Statistically significant differences on pH and carbonate system parameters (CO₂, CO₃²⁻ and DIC) were found between locations inside and outside the vents (p < 0.0001, figure 2; electronic supplementary material, table S3). Water collected near the bottom in control stations displayed pH (total scale) values ranging from 8.04 to 8.08 and pCO₂ from 402 to 445 µatm, whereas at the vents pH (total scale) ranged from 7.80 to 7.95 and pCO₂ from 572 to 993 µatm, therefore illustrating a notable pH decrease (figure 2; electronic supplementary material, tables S1 and S3). The lowest pH (7.48) was measured at station V2, whereas the average value for the venting zone was 7.88, which is equivalent to a reduction of 0.2 units the average value found in control stations C1–C3 (electronic supplementary material, table S1). The increase in CO₂ led to an increase in the concentration of dissolved inorganic carbon (DIC), which was 86 µmol kg⁻¹ higher at the vents than off-vents at relatively constant values of TA (2561 µmol kg⁻¹), salinity (38.3 PSU) and temperature (14°C), and a decrease in CO₃²⁻ concentrations (figure 2; electronic supplementary material, tables S1 and S3). The mean saturation state of seawater for the calcium carbonate minerals aragonite and calcite was 4.39 ± 0.05–2.82 ± 0.03 s.d. at the control stations and 3.18 ± 0.28–2.05 ± 0.18 s.d. at the vents, respectively (electronic supplementary material, table S1). No changes in inorganic nutrients were

which were weighed after 24 h at 60°C. L. rodriguezii biomass was not estimated outside the vents, as it was totally absent.

(e) Statistical analyses
Variation in assemblage composition inside and outside vents was analysed on a Bray–Curtis (BC) similarity matrix of log-transformed total percentage coverage of all the species identified. Significant differences between algal community inside and outside the vents were estimated through a permutational MANOVA using the function adonis in the vegan package in R [24]. Significant differences on the parameters (pH, CO₂, CO₃²⁻ and DIC concentrations) estimated in locations inside and outside the vents were assessed using linear mixed-effects models (LMM) [25]. The presence/absence of vents was treated as a fixed factor and the sampling station as the random effect. The normality of residuals and the model performance were visually inspected using residual distributions and quantile–quantile plots. The analyses were computed using vegan [26] and nlme [27] packages implemented in R.

(c) Biological surveys
Scuba diving surveys were also made in June 2012 to quantify the main species of macro-organisms present at and off the vents at 40 m depth. In the same sites where seawater samples were collected, 12 quadrats (50 × 50 cm) were placed haphazardly over the vents (four quadrats in each of the three sites; V1, V2 and V3), while six (three quadrats in two of the three sites; C1 and C2) were placed off the vents at the same depth (40 m) (figure 1b,c). Within each quadrat, we collected all the macro-organisms present in order to characterize the assemblage at each station. Specimens were identified in the laboratory, where fresh weight and cover were determined in each quadrat. When present, the number of fronds of L. rodriguezii was also counted inside each quadrat.

(d) Biomass of Laminaria rodriguezii
To characterize the assemblage at the vents, fresh weight of all specimens of L. rodriguezii (n = 486) present in each one of the 12 quadrats (50 × 50 cm) was measured in the laboratory after removing the water excess spinning the samples for 30 s in a salad spinner. Dry weight was estimated using a subsample of individuals (n = 112),
detected between control and vent stations (electronic supplementary material, table S2).

(b) CO₂ effects on species and habitat distribution
Field surveys showed substantial seascape changes at the venting zone in comparison with off-vent areas (figure 3), including significant differences in community composition ($p < 0.001$). While a kelp forest by the endemic *L. rodriguezi* covered the bottom directly affected by venting, coralligenous outcrops and rhodolith beds (dominated by coralline algae, gorgonians and calcareous bryozoans) were only found a few metres off the vents (figures 3 and 4). At the vents, the kelp *L. rodriguezi* displayed biomass values between 22.1 and 116.5 g DW 2500 cm$^{-2}$ with densities ranging from 55 to 210 fronds 2500 cm$^{-2}$.

Other non-calcareous algae were found both at and off the vents (figures 3 and 4); in particular, fucoids such as the ochrophytes *Cystoseira zosteroides* and *Cystoseira spinosa*, as well as the rhodophyte *Phyllophora crispa* (electronic supplementary material, table S4). However, these species showed higher biomass off the vents (electronic supplementary material, table S4). By contrast, organisms with high-magnesium calcite skeletons such as coralline algae (*Spongites fruticulosum*, *Mesophyllum* spp., *Lithothamnion* spp., *Lithophyllum stictaeforme*) and bryozoans (*Turbicellepora avicularis*, *Reteporella* spp.) were totally absent at the vents, whereas they were either common (bryozoans) or dominating (coralline algae) off the vents (figure 4; electronic supplementary material, table S4). Only the aragonite calcifying species *Peyssonnelia rosa-marina* was found at the vents, displaying the highest biomass and coverage (electronic supplementary material, table S4).

4. Discussion

(a) Distribution shifts in complex structurally habitats
This study revealed that moderate decreases of pH lead to dramatic shifts in highly diverse and structurally complex benthic habitats thriving at depths rarely explored in terms of OA effects. Dominant habitats at mesophotic depths, such as coralligenous outcrops and rhodolith beds, mainly characterized by a large dominating of calcifying organisms, are replaced by forests of the deep-water kelp *Laminaria rodriguezi*, which becomes dominant at depths much shallower than under normal seawater conditions. To our knowledge, this study highlights for the first time that beyond the changes at species levels reported in most of previous studies, where some species are winners and others lose out [9–11], OA can lead to significant changes at habitat level, benefiting specific habitats and compromising other habitats, also leading to vertical distribution shifts as observed in terrestrial ecosystems as a consequence of global warming [28].

The presence of kelps and other fleshy macroalgae (such as fucoids) inside the vents indicates that they are favoured by the observed changes in the carbonate system parameters. This agrees with the positive response displayed by several macroalgae and seagrasses to elevated CO₂ concentrations through the increase of photosynthesis and growth rates [19,29,30]. Nevertheless, the dominance of the deep-water kelp *L. rodriguezi* observed in this study is noteworthy as this species is known to thrive between 65 and 95 m depth [31,32] and had almost never been reported before shallower than 50 m depth. These observations demonstrate that high CO₂ concentrations enhance the competitive abilities of *L. rodriguezi* at depths shallower than its common bathymetric range, thereby offsetting other existing environmental limitations (e.g. light or temperature) and allowing this species to grow at 40 m depth. The lower biomass displayed by fucoids (mainly *C. zosteroides*) inside the vents in comparison with the biomass of *L. rodriguezi* could be indicative of competition among fleshy algae. We hypothesize that *L. rodriguezi* outcompetes fucoids and other fleshy algae by inhibiting their growth due to the reduction in ambience light under the kelp canopy. Although the increase in competitive strength of seaweeds over other organisms (such as corals) as a function of CO₂ enrichment has been described previously [33,34], the impacts of OA on the interactions among algae under acidified conditions remain largely unknown. The competition between habitat-forming fleshy algae (i.e. kelps versus fucoids), as observed in this study, can result in further ecosystem shifts involving species substitutions.
(b) Contrasting responses of calcifying organisms

Organisms with high-magnesium-calcite skeletons such as coralline algae and bryozoans were completely absent at vent sites. Only the aragonite-calcifying *Peyssonnelia rosa-marina* was able to survive in the acidified waters, as previously noted in very shallow waters too [35]. Our results lend support to the idea...
that high-magnesium-calcifying organisms are more sensitive to OA than aragonite-calcifying ones [35,36]. They also challenge the widespread concern over the global fate of calcified algae in the near future, as there are species such as *P. rosa-marina* showing a moderate resilience to OA [36]. The recent discovery of calcium-magnesium carbonate (dolomite) in crustose coraline algae [37] and its lower solubility in comparison to magnesium calcite [38] suggest that some calcifying algae will not be doomed under moderate decreases in pH. This highlights the need of further research on the carbonate composition of these organisms.

(c) Long-term consequences of acidification for benthic ecosystems

The high variability in CO₂, pH and other carbonate system parameters observed in this study, as well as in other CO₂ vent studies [39], decreases the value of these sites as predictors of future ecosystem functioning under oceanic pH levels expected to occur at the end of this century [3]. However, pH variability has been stressed to enhance acclimatization or adaptation to acidification through repeated exposure to lowered pH conditions [40]. Although a long-term survey of pH variability would be needed to fully understand its effects on the structure and functioning of the investigated system, our results indicate that, regardless of variability in pH and other carbonate parameters, moderate acidification can drive dramatic and persistent changes in benthic ecosystems. Moreover, expected synergies of OA with warming and other stressors are likely to occur [41,42], which can result in even more drastic changes than the ones observed in this study.

Fucoids and kelps, globally recognized as key structural and functional elements of marine benthic ecosystems [43], are in decline, with some local extinctions already documented [44]. Our results suggest an enhancement of the populations of these habitat-forming fleshy algae under acidified conditions, and especially of kelps at mesophotic depths. OA will negatively affect coraligenous outcrops and rhodolith beds, which are extremely threatened habitats [18]. Our results also indicate a substitution of habitats dominated by calcifying algae by those dominated by erect fleshy algae, and the replacement of high-magnesium-calcite corallines by aragonite-calcifying algae (e.g. *Peysosomnella*) as main carbonate producers. The changes observed in the highly diverse and structurally complex mesophotic habitats of the Mediterranean Sea investigated in our study may have critical ecological and social implications for coastal ecosystems at large spatial scales in an increasingly acidifying ocean.

Data accessibility. All data and supplementary material are deposited in Dryad (http://dx.doi.org/10.5061/dryad.07677).

Authors’ contributions. All authors were involved with fieldwork and sample analyses. D.K.K. discovered the vent site. E.A., L.N., M.V., E.B., D.A., M.C. and C.L. analysed the data. A.D.H. analysed the gases and E.B. identified the species. C.L. drafted the initial manuscript and wrote the paper along with M.V., M.C. and E.B. All authors discussed results and commented on the manuscript.

Competing interests. We have no competing interests.

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