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ABSTRACT

Alterations to colonization or early post-settlement stages may cause the reorganization of communities under future ocean acidification conditions. Yet, this hypothesis has been little tested by in situ pH manipulation. A Free Ocean Carbon Dioxide Enrichment (FOCE) system was used to lower pH by a ~ 0.3 unit offset within a partially enclosed portion (1.7 m$^3$) of a *Posidonia oceanica* seagrass meadow (11 m depth) between 21 June and 3 November 2014. Epibiont colonization and early post settlement stages were assessed within the FOCE setup, as part of the larger community-level study, to better understand the outcome for a multispecies assemblage and the ecological processes that result in reported community shifts under altered carbonate chemistry. Two types of artificial collectors (tiles and scourers) were placed within three treatments: a pH-manipulated enclosure, an un-manipulated control enclosure, and an open plot in the ambient meadow. Tiles and scourers were collected after one to four months.
Additionally, to see whether the outcome differed for communities in a later successional stage, previously settled scourer-collectors were also placed in the same three treatments. Enclosures acted to reduce settlement and migrant colonization. Scourers deployed for one to four months within the open-plot contained a community assemblage that could be distinguished from the assemblages within the enclosures. However, a comparison of enclosure assemblages on tiles showed evidence of a pH effect. There was lowered coverage of crustose coralline algae and fewer calcareous tube-forming polychaetes (Spirorbis sp. and Spirobranchus sp.) on tiles placed in the pH-manipulated enclosure compared to the un-manipulated enclosure. For assemblages in scourer collectors, shared and common taxa, in all treatments, were invertebrate polychaetes Psamathe fusca, Sphaerosyllis sp., Chrysopetalum sp., arthropods Harpacticoida, and Amphipoda, and the juvenile bivalve Lyonsia sp. Similar organism composition and abundance, as well as taxonomic richness and evenness, were found in scourers from both enclosures. Pre-settled scourers contained greater numbers of individuals and more calcified members, but the assemblage, as well as the growth rate of a juvenile bivalve Lyonsia sp., appeared unaffected by a two-month exposure to lowered pH and calcium carbonate saturation state. Results from this case study support the hypothesis that early stages of specific calcifiers (crustose coralline algae and calcareous tube-forming polychaetes) are sensitive to near future ocean acidification conditions yet suggest that negative effects on sessile micro-invertebrate assemblages will be minimal.

Keywords: Calcifiers; colonization; epiphytic community; early life history stages; ocean acidification, pH

1. Introduction
Because of the anthropogenic driven increase in atmospheric carbon dioxide (CO$_2$) and its dissolution in the ocean (25.2% of emissions in the decade 2006-2015; Le Quéré et al., 2016), the ocean is undergoing increased rate of change in carbonate chemistry. In the process of ocean acidification, the pH in the ocean declines, resulting in the decline in the concentrations of carbonate ions (CO$_3^{2-}$) and the increase in the concentrations of bicarbonate ions (HCO$_3^-$) and dissolved carbon dioxide (CO$_2$). Surface ocean average pH has decreased by 0.1 units since the pre-industrial era and an additional 0.07 to 0.33 units decrease is expected by 2100 (Gattuso et al., 2015). These changes in ocean carbonate chemistry are predicted to affect marine organisms (Kroeker et al., 2013) as well as populations and ecosystems (Gaylord et al., 2015).

Alterations in carbonate chemistry can have taxon-specific consequences on organism growth, reproduction, and survival (see reviews, Gattuso and Hansson, 2011; Kroeker et al., 2013). A decline in [CO$_3^{2-}$] has been shown to differentially affect the ability of calcifying organisms to precipitate calcium carbonate (CaCO$_3$) and has lead to subsequent increases in skeletal dissolution rates (Feely, 2004). Marine autotrophs that lack calcification, in contrast, may benefit from the increased CO$_2$ availability for photosynthesis (Koch et al., 2013). The concern is that by affecting energy allocation and mortality rates, ocean acidification impacts on the individual or population will also scale to shifts in the community (Kroeker et al., 2011).

Ocean acidification impacts on early life history stages may also lead to the reorganization of communities (Dupont et al., 2010; Kurihara, 2008). Many benthic species have a planktonic larval stage with a different morphology and ecology than the adult stage. The early life history stage of invertebrates and calcified algae is often found to be vulnerable to ocean acidification conditions (Jokiel et al., 2008; Kurihara, 2008). Ocean acidification impact can also vary with life-history stage within a species and affect the life-cycles of organisms in different
ways (Kurihara, 2008). For example, mollusc larvae and juveniles are often found to have a pronounced sensitivity to lowered pH (Gazeau et al., 2013). Lowered pH and CaCO$_3$ saturation state have been shown to impact rates of hatching, metamorphosis, larval and juvenile growth, and early survival from predation (Gazeau et al., 2010; Gazeau et al., 2013; Kurihara, 2008; Talmage et al., 2009). Furthermore, the sensitivity of echinoderms and molluscs in their earlier stages may be greater than other taxa (Kroeker et al., 2013). However, effects on early life-history stages in mixed populations are poorly understood because of the difficulty of culturing and rearing larvae.

Seagrass meadows are a model benthic system to examine effects on multispecies assemblages and ecological processes. They are composed of diverse taxa and are highly valued for the ecosystem services they provide (Hemminga and Duarte, 2000). For example, seagrass meadows play a fundamental role in maintaining populations of exploited fisheries (Jackson et al., 2015) and are global contributors to carbon sinks, with a net primary production (NPP) of 490 Tg C yr$^{-1}$ (Mateo et al., 2006).

In the Mediterranean Sea, *Posidonia oceanica* (L.) Delile forms dense monospecific meadows that cover 23% of shallow water substrate (< 50 m; Pasqualini et al., 1998). *Posidonia* leaves are settlement substrate for a variety of sessile and sedentary colonizers with pelagic larvae such as algae, bryozoans, and serpulid polychaetes. Vagile invertebrates with both brooding and pelagic life-history stages such as polychaetes, gastropods, amphipods, tanaids, and copepods tend to colonize the leaf stratum (Gambi et al., 1992; Gobert et al., 2006). Among these floral and faunal groups are several calcifiers (crustose coralline algae or CCA, several species of polychaetes that form calcified tubes, molluscs, and bryozoans) that contribute to carbonate cycling (Frankovich and Zieman, 1994; Perry and Beavington-Penney, 2005). Epiphytes are
major contributors to meadow production and nutrient cycling (Borowitzka et al., 2006; Romero et al., 2006) and invertebrate fauna transfer energy to higher trophic levels (Lepoint et al., 2000). In turn, algal and invertebrate abundances can be dependent upon seagrass density and its seasonal growth (Alcoverro et al., 1997; Mazzella et al., 1989). The tight coupling between organism abundances, the seasonal environment, and the diverse species and life-history stages make it difficult to predict future meadow ecology from studies on single to few species conducted in the laboratory.

Observations and conclusions drawn from naturally acidified ecosystems (volcanic CO\textsubscript{2} vents, spring inputs, and upwelling areas) predict changes in benthic community composition and abundances under ocean acidification (e.g. Hall-Spencer et al., 2008) although such shifts have been attributed to a variety of ecological processes. Most observations examining community assembly or abundances on artificial substrata support a reorganization of communities as a direct result of taxa sensitivity, tolerance, or benefit (Allen et al., 2016; Cigliano et. al., 2010; Crook et al., 2016; Donnarumma et al., 2014). A few studies indicate shifts in benthic abundances related to indirect effects of lowered pH, such as loss of habitat complexity or changes in competitors and prey (Garrard et al., 2014; Kroeker et al., 2012). In one study, species interactions in later successional stages amplified direct effects (Kroeker et al., 2012) to result in an altered community assembly at lowered pH from ambient. While these observations at naturally acidified ecosystems capture diverse species interactions and acclimation, they are not perfect predictors of future ocean ecology. Conclusions are often hindered by large temporal pH variability (Kerrison et al., 2011) and outcomes can also be confounded by other environmental conditions that vary across the pH gradient. Therefore, similar investigations on intact assemblages where only pH is manipulated could help to clarify
community change and the role of early life stages on community development under ocean
acidification.

In the present study, the impact of ocean acidification on epibiont colonization and
recruitment was assessed on artificial substrata in the framework of an *in situ* pH-manipulation
experiment (European Free Ocean Carbon Dioxide Enrichment; eFOCE). This community-level
experiment was designed to assess the impacts of ocean acidification on a *P. oceanica*
community in the Northwestern Mediterranean Sea (Cox et al., 2016). The specific study
presented here aimed at testing for the effects of ocean acidification on the micro-invertebrate
assemblage colonizing artificial surfaces within a *P. oceanica* meadow and it tested the
prediction that the sensitivity of early life history stages alters community formation. Artificial
substrata were used to standardize for differences in substratum, collect small invertebrates that
surround the leaves, and to follow community development to identify ecological mechanisms
that result in shifts. Because organisms have different preferences for settlement surfaces, two
types of artificial collectors (tiles and scourers) were placed within the experimental design of
the FOCE system (see Gattuso et al., 2014). This system is unique because it allows pH to be
manipulated continuously *in situ*, in an enclosure, at a fixed offset from ambient levels. This
FOCE design also consisted of an un-manipulated control enclosure and a plot, fully open to the
ambient environment. All tile collectors were placed in the three treatments of the FOCE setup at
the start of the pH manipulation. A set was collected each month to gauge effects on early
recruits and to follow assemblage development through time. Scourer collectors which often
target the collection of micro-invertebrates that surround the seagrass leaves were placed in the
FOCE setup and collected after one to four months to gauge impacts to recruitment and to test
for longer effects on the assemblage development. A second set of scourers were pre-settled
within the ambient meadow, collected, and then placed within the FOCE setup for two and four months to test whether the response of an assemblage, exposed in a later successional stage when ecological interactions such as competition and the physiology of adult forms, differs from the response of early recruits. At each collection interval, the community composition and organism abundances were compared. Additionally, the growth of a juvenile bivalve was compared to test whether the development of early calcifiers was impacted by lowered pH. Finally, because species diversity can indicate ecosystem function and it is predicted to be affected by ocean acidification, for scourer assemblages that were more complex, taxonomic richness and evenness were compared. Study results are discussed in the broader context of ocean acidification effects and published FOCE outcomes for epibionts found on natural leaves, which were collected simultaneously with tiles and for which negative impacts of lowered pH could not be detected. This planned comparison between settled artificial substrata and natural leaves was intended to test our working hypothesis that, in contrast to epibionts found on leaves, organism abundances and community formation on artificial substrata are not protected by the modification of carbonate chemistry at the proximity of leaves due to seagrass photosynthesis and are therefore more sensitive to any change in pH of the surrounding water.

2. Materials and methods

2.1. Experimental setup and system function

This study used the European FOCE (eFOCE) system which allows for the in situ manipulation of pH in benthic enclosures as an offset from ambient pH (Cox et al., 2016). It was deployed in the Bay of Villefranche, approximately 300 m from the Laboratoire d’Océanographie de Villefranche (NW Mediterranean Sea, France; 43°40.73’N, 07°19.39’E).
The study design consisted of two clear, 1.7 m$^3$ (2 m long x 1 m width x 0.85 m tall) perspex enclosures at 11 m depth that were open on the bottom to partially enclose a portion of the *P. oceanica* meadow. The enclosures were placed end-to-end approximately 1.5 m apart. The pH in one enclosure, referred to as the pH-manipulated enclosure, was lowered by ~0.3 units as an offset from ambient pH as measured on the total scale (pH$_T$). This offset was based upon the business-as-usual representative concentration pathway RCP8.5 following Ciais et al. (2013) and led to a decrease of pH$_T$ in the pH-manipulated enclosure to an average (± SD) pH$_T$ of 7.75 ± 0.13 and an increase in $p$CO$_2$ to 971 ± 323 μatm. pH was not manipulated in the second enclosure and it served as a control enclosure. A third treatment consisted of an open fiberglass frame of the same dimensions as the enclosure footprint (2 m$^2$) placed nearby (3 m from the pH-manipulated enclosure). It is referred to as an open plot and was used to account for any effects that could be generated by the enclosure structure. True replication (at the enclosure level) was not logistically feasible. It was sacrificed to control pH precisely within enclosures of a large enough size to contain *P. oceanica*. For further discussion on the study design of FOCE systems, the reader is encouraged to consult Gattuso et al. (2014).

The eFOCE system is fully described in Cox et al. (2016). Briefly, the pH in the pH-manipulated enclosure was altered using subsurface (3 m depth) supplied seawater pumped into a mixing tank, which was located on a surface platform. Pure CO$_2$ was bubbled into the mixing tank and the resulting low pH seawater was pumped, via tubing, underwater to the proximity of the benthic enclosures. Prior to entering the enclosures, low pH (pH$_T$ ~ 5.5) and ambient seawater were mixed in an underwater tube and a set (x3) of centrifugal pumps (6.7 L min$^{-1}$ each) injected ambient seawater in the control enclosure and lowered-pH seawater in the manipulated enclosure. Seawater inside enclosures was circulated by another set of centrifugal
pumps (four per chamber; 6.7 L min\(^{-1}\) each) and exited through two openings (12 cm diameter). Renewal time of seawater in each enclosure was ca. 1.5 h. The system contained a number of sensors: four potentiometric Seabird 18-S pH sensors located inside each enclosure and in each mixing tube and three Seabird 37 SMP-ODO CTD with SBE 63 O\(_2\) optodes and three LI-COR PAR (photosynthetic active radiation) sensors located in each enclosure and one nearby the enclosures (in ambient, close proximity to the open plot). Carbonate chemistry was determined from an average of total alkalinity and sensed temperature, salinity and pH\(_T\), in the R package, seacarb (Gattuso et al., 2015). Average alkalinity used in each calculation was determined from discrete water samples collected from within the enclosures and plot throughout the study (\(A_T\) mean ± SD, pH-manipulated enclosure, n =12, 2545.5 ± 8.0 \(\mu\)mol kg\(^{-1}\); control enclosure, n = 11, 2541.7 ± 12.2 \(\mu\)mol kg\(^{-1}\); open plot (or ambient), 2556 \(\mu\)mol kg\(^{-1}\), see Cox et al., 2016 for more details)

2.2. Experimental and environmental conditions

The study area, where enclosures and plots were located, can be described as a monospecific meadow of \(P.\) oceanica in a soft sediment bottom (see Cox et al., 2016). The pH\(_T\) in the meadow (ambient) ranged from a mean of 7.98 (± 0.06 SD) in September to 8.11 (± 0.04 SD) in June (Fig. 1). The mean saturation states of aragonite (\(\Omega_a\)) and calcite (\(\Omega_c\)) ranged from 3.1 to 3.6 and 4.9 to 5.4 from June to September, respectively. The diel pH\(_T\) change differed among months from 0.04 to 0.12. It corresponded to the daily change in CO\(_2\) concentration driven by community primary production, respiration and calcification.

The greatest difference between ambient open plot and control enclosure in monthly mean pH\(_T\) values was 0.06 units; the control enclosure being more acidic. The diel change in pH\(_T\) within the control enclosure was slightly greater than in ambient and was consistent in the pre-
and during acidification period (median ± median absolute deviation 0.14 ± 0.06 and 0.14 ± 0.06).

During the acidification period, the pH in the pH-manipulated enclosure was maintained at a mean -0.26 unit offset (monthly mean values ranged from -0.22 to -0.29 pH units) from the control enclosure (Table S1). In the pH-manipulated enclosure, the monthly mean values of saturation state with respect to aragonite ($\Omega_a$) ranged from as low as 2.0 (± 0.05 SD) in October to a high of 2.5 (± 0.06 SD) in August and saturation state with respect to calcite ($\Omega_c$) ranged from 3.0 (± 0.07 to 0.008 SD) in September and October to 3.8 (± 0.09 SD) in August. The median diel pH range in the pH-manipulated enclosure was two to three times larger than the control (monthly median ranged from 0.09 to 0.29 pH units).

Monthly differences were evident, particularly for temperature (mean monthly range: 17.7 to 24.2 °C) and PAR (mean monthly range: 1.3 to 7.3 mol photons m$^{-2}$ d$^{-1}$, Table S2) but these variables were similar in the ambient, control and pH-manipulated enclosures.

2.3. eFOCE timeline

The experiment comprised three periods in 2014: (1) the pre-acidification period, before pH was manipulated, from 15 May to 11 June, (2) the transition period from 12 to 21 June, when pH in the manipulated enclosure was slowly lowered by no more than 0.05 units per day until an offset of approximately -0.3 units was reached and (3) the pH-manipulated period from 22 June to 3 November during which pH in the pH-manipulated enclosure was maintained at a constant offset of ~ -0.3 units and settlement was monitored.

2.4. Artificial collectors

Tiles and scourers (or scouring pads) were used as artificial collectors to assess settlement and benthic assemblage development. Both collectors are commonly used to collect
adult or early life history stages of benthic organisms (e.g. Cigliano et al., 2010; Kroeker et al., 2012).

Tiles were 5 x 5 cm squares cut from 0.5 cm thick sheets of polyvinyl plastic. Surfaces were sanded with steel wool and tiles fixed, via Velcro, to 15 polyvinyl plastic black boards connected to a fiberglass stake. Seven tiles were arranged on each board (only 3 per board were used) in a longitudinal row with 0.5 cm between them. Scourers were rounded, 8 cm in diameter, and composed of enrolled coarse nylon mesh attached by a plastic tie to a fiberglass rod. Tiles and sets of scourers were handled differently and collected at different sampling intervals for specific examinations. The methods for each collector type are described (in order of occurrence) and an experimental outline can be seen in Fig. 2.

2.5. Scourer pre-settlement and calcein staining for growth measurements

Prior to the eFOCE experimentation, on 19 September 2013, many scourers were placed within the ambient meadow at 11 to 12 m depth to allow for settlement and community development. The fiberglass rod was staked into the substrate and the scourer sat at the surface of the seagrass canopy at the time of deployment. Three scourers were relocated on 24 June 2014 and used in the experiment.

Thirteen other scourers were placed in a similar manner within a 5 m² area on 6 February 2014 and collected after ~4 months (19 June 2014). These settled scourers were transported to the Laboratoire d’Océanographie de Villefranche, held in circulated seawater from the bay for 72 h under ca. 150 µmol photons m⁻² s⁻¹ (13:11 h light:dark cycle) and maintained at seawater temperature conditions (22-23 °C). After 24 h, the free-flowing addition of Bay water to the holding container was stopped, calcein (50 mg L⁻¹) was added, and organisms were fed ad libitum with the microalga Isochrysis galbana Parke. The staining lasted for 48 h then scourers
were removed, placed in separate seawater filled plastic bags, and taken by divers to the eFOCE setup.

2.6. Collector placement, collection intervals, and study design

On 23 June 2014, at the start of the acidification period (Time 0, T0) scourers and tiles on boards were placed into the plot and both enclosures (Fig. 2). Five boards (total of 15 boards) with tiles were staked by pushing the fiberglass rod into the soft substrate on the northern side of each plot and enclosure to face South. Seventeen scourers for each enclosure and 15 for the open plot (for a total of 49) were also placed on the northern side of the plot and each enclosure. Scourers were either attached to individual fiberglass rods and staked into soft sediment or were attached to a single fiberglass rod that was held in place on each side of the enclosure. All scourers sat at or above the seagrass canopy (0.5 to 0.7 m above the substrate) with at least 2 cm distance between them.

Collection of tiles and scourers occurred at one to four specified time-points, spaced apart by approximately four weeks, referred to as time (T) 1 to 4: T1 occurred on 30 July, T2 occurred on 3 September, T3 on 6 October, and T4 occurred on 10 November after 135 d of acidified conditions. It should be noted that the acidification of the pH-manipulated enclosure ended on 4 November 2014 while collections were made six days later.

Five tiles (one from each board) from each treatment location were collected at T1, T2, T3, and T4. In this manner, assemblage development was examined through time.

Out of the 17 scourers placed in each enclosure at T0 (15 for the open plot): (1) six were fresh (i.e. not pre-settled) scourers that were collected and replaced with six other fresh scourers at T1, T2, and T3 to assess monthly differences in settlement under ocean acidification, (2) five were fresh scourers that were left in place from T0 until T4 to assess lowered pH impacts on
assemblage development, (3) five (three for the open plot) were pre-settled for four months, stained scourers that were collected after two months (T2) and lastly (4) one scourer was pre-settled for nine months, and was collected at the end of the study (T4) in order to investigate lowered pH impacts on developed assemblages (and for #3, juvenile calcifier growth).

At each collection interval, divers removed each artificial collector, placed them into separate labeled plastic bags and brought them immediately to the Laboratoire d’Océanographie de Villefranche.

2.7. Organism identification and quantification

The 15 settlement tiles were kept in a temperature controlled (20 – 22 ºC) dark room for less than 24 h until scanning could be completed. A ZooScan (Hydroptic, France; Gorsky et al., 2010) was used to produce high resolution colour images (2400 dpi) of settled tiles. There were no canopy-forming macroalgae or large sessile macrofauna on tiles, thus “layering” did not occur and images could be directly analyzed.

Scans of settlement tiles were analyzed using ImageJ (imagej.net). There were few settlers at the first collection time point and these tiles were discarded from the analysis. The remaining scanned images were visually searched for fauna and, when encountered, individuals were identified and enumerated. Algae were also identified and the area occupied per tile was directly measured by adjusting the colour-threshold, followed by adjustments of the threshold on a converted 8-bit image. Adjustments were done to outline the algae and fill the space they occupied and surface area covered was estimated.

Each scourer was carefully un-rolled and washed onto a 0.35 mm mesh size. Retained organisms were transferred to 70% ethanol. Organisms were placed in Petri dishes and examined, sorted, identified, and enumerated under a microscope (Leica Wild M10).
Identification was conducted at the lowest possible taxonomic unit or, operational taxonomic unit (OTU). Organisms settled on tiles and analysed using the zooscan were mostly identified to broad functional categories. At the end of this process, each tile had a count of invertebrates, and an area determined for algae. For scourers, it was not possible to identify some young organisms to genus or species because identifiable structures were not yet visible. Polychaetes, gastropods, and bivalves were often identified to family and genus. Arthropods tended to be identified to Order. Echinoderms were mostly identified to Class. At the end of the process, for each scourer, there was a total count of individuals by OTU.

2.8. Growth rates

The bivalve *Lyonsia* sp. (Family Lionsiidae) within pre-settled, stained scourers was the only organism where a calcein mark was visible. Individuals were carefully placed in a horizontal position (hinge horizontal), in visible proximity to a scale bar, and photographed directly from above, through the binocular microscope. This resulted in 15, 5, and 8 imaged individual *Lysonia* sp. from 5, 2, and 3 scourers collected from the pH-manipulated enclosure, the control enclosure and the open plot, respectively. Images were analyzed using ImageJ. The complete bivalve shell and new growth were outlined by tracing the perimeter and their surface areas were estimated with the measure tool. Growth (area in mm$^2$) was provided as a proportion of new growth to total size (as area) and expressed as a rate (per day).

2.9. Statistical analyses

Tile and scourer data collected from T1 to T4 from the same plot or enclosure were considered replicates and values reported are mean ± standard deviation, SD. In addition, all photographed individuals were considered replicates and used to compare bivalve growth.
Two-way ANOVAs were used to test for differences in the abundances of functional groups (CCA, Serpulid polychaetes, and Other taxa) on tiles. Intervals (T2, T3, T4) and treatments (open plot, pH-manipulated and control enclosures) and their interaction (interval x treatment) were terms in the models. Prior to testing, CCA coverage (cm$^2$) failed to meet parametric requirements and a rank transformation was applied. Tukey’s or a Dunn’s post-hoc multiple comparison tests were used to identify pairwise differences ($P < 0.05$).

To test for differences in impacts from month to month, early assemblage development, and on previously settled assemblages, data from scourers were distributed into three groups as noted on Fig. 2 (1) scourers settled for a one-month duration collected at T1, T2, T3, and T4 (dataset #1), (2) scourers settled for four months; placed at T0 and collected at T4 (dataset #2), (3) scourers pre-settled for four months then placed at T0 and collected at T2 (dataset #3). Data from the scourers pre-settled for nine months, deployed at T0 and collected at T4 ($n = 1$ per treatment) were graphically presented but not statistically tested. Due to scourer loss in field, the number of replicate scourers may vary slightly from initial numbers placed.

All analyses presented for scourer data were done with OTUs. However, outcomes were similar when analyses were performed at the family, order, class, or phyla. Furthermore, for all statistical testing with scourer data, terms included were treatment (3 levels: pH-manipulated and control enclosures and open plot) and for dataset #1, the collection interval (4 levels: T1-T4) and their interaction.

A multivariate approach following the recommendations outlined in Anderson and Willis (2003) was taken to analyze scourer assemblages. A log$_{10}$ (X+1) transformation was applied and the Bray-Curtis Index was used to create a resemblance matrix. A two-way permutational-MANOVA (PERMANOVA) was run on each matrix with 999 permutations and type III sum of
squares, followed by a Monte-Carlo simulation. Post-hoc pairwise differences were tested when
a main effect was observed followed by a canonical analysis of principal coordinates (CAP).
CAP uses ordination to find the appropriate subset of axes (m) in principal coordinate space that
is best at discriminating among defined groups. The maximum leave-one-out allocation success
was used to determine group distinctness. Spearman rank correlation of organism abundances
with the axes was used to indicate which taxa were most responsible for separation.

Taxonomic richness (as number of OTUs), Pielou’s evenness index, and total number of
individuals per scourer was determined, followed by statistical comparisons using either a two-
way ANOVA (for dataset #1), Kruskal-Wallis, or one-way ANOVA. A rank transformation was
applied to values of evenness to meet parametric requirements. One-way ANOVA was also used
to test for differences in Lyonsia sp. growth. Tukey’s or Dunn’s post-hoc multiple comparison
tests were used to identify pairwise differences.

3. Results

3.1. Settlement on tiles

Organisms found on tiles and grouped to a category referred to as “Other taxa” were
brown colored crusts of algae (non-calcaerous species), cyanobacteria, and red filamentous
algae. These taxa were grouped because of the low occurrence of filamentous algae and
difficulty distinguishing brown colored crusts of algae from cyanobacterial mats in scans. CCA
and two calcareous tube worms, Spirorbis sp. and Spirobranchus sp. (only two individuals of
genus Spirobranchus) from the family Serpulidae were identified. Overall 0.3 to 18.6% of tile
surfaces were colonized by organisms and there were between 0 and 16 calcareous tube worms
per tile (n = 45 tiles).
CCA coverage significantly differed between treatments and sampling intervals (Table 1; Fig. 3A). On open tiles, the coverage of CCA was greatest and it gradually increased from T2 to T4 (Fig. 3A). The coverage at intervals T2 and T4 statistically differed. On control tiles, there was relatively lower coverage of CCA and the coverage also increased from T2 to T4. In contrast, CCA coverage on pH-manipulated tiles was never above 0.1 cm$^2$ and the change in coverage tended to be minimal (from 0.01 ± 0.00 at T2 to 0.00 ± 0.00 cm$^2$ at T4).

There was a significantly greater coverage of “Other taxa” on tiles from the open plot and control enclosure than on tiles from the pH-manipulated enclosure (Table 1, Fig. 3B). Differences were largely driven by the lower coverage observed at T2 on pH-manipulated tiles (0.23 vs 0.54 to 1.10 cm$^2$). For all treatments, the coverage of “Other taxa” increased from September (T2) to October (T3) and declined again in November (T4).

Calcareous tube-forming polychaetes (serpulids) occurred in significantly greater numbers on tiles from the open plot (monthly means ranged from 4 to 7 individuals) and the control enclosure (monthly means were about 4 individuals) than in the pH-manipulated enclosure (monthly means ranged from 0 to 2 individuals, Table 1, Fig. 3C). There was no statistical indication of a change in abundance with time.

3.2. Overall description of scourer assemblages

Out of a combined 106 scourers, 7,220 individuals from eight phyla were found and identified to 106 different OTUs. At least 77 families were identified with 33 identifications (31%) performed at the level of genus or species. The most abundant group of organisms were annelids (2,891 individuals) closely followed by arthropods (2,646 individuals), then by molluscs (1,569 individuals), echinoderms (28 individuals), cnidarians (6 individuals), ascidians (6 individuals), nematodes (5 individuals), nemerteans (4 individuals), and platyhelminthes (1 individual).
individual). Specifically, the most abundant taxa were the polychaetes *Psamathe fusca* (Johnston, 1836), *Sphaerosyllis* sp., *Chrysopetalum* sp., the arthropod orders Harpacticoida, and Amphilopoda, and the bivalve *Lyonia* sp. Taxonomic richness appeared to be the greatest within the phylum Annelida (44 OTUs), followed by Mollusca (33 OTUs), and Arthropoda (13 OTUs). All other identified phyla were composed of three or less OTUs.

3.3. Settlement on fresh scourers deployed for one to four months

3.3.1. Monthly availability of benthic colonizers

The organisms found in monthly deployed scourers differed between collection intervals. The composition and abundance of organisms at T2 and T3 were similar and statistically different from the composition and abundance at T1 and T4 (Table 2; Fig. 4). The assemblages were weakly discriminated within three CAP axes (n = 69, choice of m = 7, $\delta^2_1 = 0.36$, $\delta^2_2 = 0.20$, $\delta^2_3 = 0.09$) with low overall classification success (44.9%). Assemblages at T1 were most distinctive. Mis-classification increased for scourer assemblages at T2 and T3 and they were often confused (Table 2). The change in the abundances of two polychaete species and Gastropoda appeared to be driving these allocations (abundances have > 60% correlation).

Specifically, *Chrysopetalum* sp. and *Polyophthalmus pictus* (Dujardin, 1839) were more numerous at T1 and T4 than T2 and T3 (mean individuals ± SD, respectively: T1-T4, 7.0 ± 10, 0.5 ± 2.4, 0.4 ± 1.1, 2.7 ± 4.1 and T1-T4: 7.0 ± 0.9, 0.6 ± 1.1, 1.0 ± 1.5, 2.2 ± 2.9). Also clearly noticeable was the decline of gastropod colonizers from T1 to T4 (Fig. 4). Taxonomic richness and total number of individuals also varied by interval but evenness did not (Fig. 5; Table 2).

3.3.2. Enclosure effect on settlement

Data were most congruent with an effect caused from enclosures which acted to reduce settlement and migrant colonization (Figs 4, 5; Tables 2, 3). Assemblages settled on fresh
scourers (one month and four month deployments) from the open plot statistically differed from the assemblages found in the pH-manipulated and control enclosures (Table 2). Furthermore, nMDS (not shown) and CAP analyses (Fig. 6) showed clear discrimination of enclosure assemblages from the open assemblages (Table 3). To determine whether enclosure or open plot differences could be driven by random chance sampling, an iterative permutation procedure (SIMPROF, 1000 mean permutations, 999 simulations) was used on the monthly collected scourer data. Assuming same species abundance distributions (common species list) and random community assembly (by reshuffling), the Bray-Curtis similarity values for enclosures and open plot assemblages were greater than the 99% confidence envelope (8-12% resemblance) around the similarity profile predicted by the model. Therefore, there is genuine multivariate structure not likely due to chance but rather driven by the enclosure conditions. Polychaete and crustacean abundances were more numerous in settled scourers from the open plot (Fig. 4). The specific OTUs which had correlation values greater than 70% with discriminating axes can be observed on Fig. 6. In addition, taxonomic richness and total number of individuals were greater in the scourers collected from the open plot (Fig. 5, Table 2).

Many taxa were common in all treatments (Tables S3, S4). The SIMPER routine was performed on the dataset from monthly collected scourers. It indicated dissimilarities between enclosures and the open plot assemblages (80-82% dissimilar) were based largely (85-86% of cumulative contribution) upon the density of the shared common species and less upon unique species to enclosures or open plots. Nevertherless, out of 83 taxa found in monthly collected scourers, 18 were exclusively found in enclosures (total individuals per OTU < 7, combined) and 11 were exclusively found in the open plot (total individuals per OTU < 2, except 19 individuals of Musculus costulatus (Risso, 1826) and 15 individuals of Family Carditidae). Out of a
combined 49 taxa found in the scourers placed at T0 and collected at T4, 16 were exclusively found in the open plot (at < 7 total individuals per OTU, except 14 molluscs of the Family Carditidae, and 18 polychaetes *Spirobranchus* sp.) and 11 of the 49 were exclusively found in the enclosures at < 4 total individuals per OTU combined.

In addition, for scourers that were not pre-settled, the most abundant taxa were common at all locations (Tables S3, S4). In the monthly collected scourers, the polychaetes *Psamathe fusca*, *Chrysopetalum* sp., and the peracarid crustaceans Amphipoda, Isopoda, and Ostracoda were more numerous in the open plot but, were also in the 15 most abundant taxa in the enclosure assemblages. In the scourers placed at T0 and collected at T4, the biggest differences in terms of most abundant taxa was for *Spirobranchus* sp., it was in the 15 most numerous OTUs in the open and absent in the enclosures. When combined *Nerilla* sp. was in the 15 most abundant taxa in the enclosures (14 individuals) and only two individuals were found in the open plot.

3.3.3. *Enclosure comparison - settlement within one month*

Despite changes in monthly availability of colonizers, acidified enclosure assemblages were similar to control exclosure assemblages (Table 2). Overall the collection intervals, the five most numerous taxa, in combined order of abundance, were: Harpacticoida, *Psamathe fusca*, *Lyonsia* sp., Copepoda, and Trochidae (Table S3). CAP analyses had low to moderate success at discriminating between enclosures (Table 3). On average 6 to 9 and 5 to 9 taxa were found per scourer collected monthly from the pH-manipulated and control enclosure, respectively. Acidified enclosure assemblages had similar total number of individuals per scourer than control enclosure assemblages (Fig. 5, monthly mean range: 13 to 24 vs 16 to 26 for the pH-manipulated and control enclosure, respectively) and the assemblages were similar to each other in evenness
(monthly mean range: 0.95 to 0.96 vs 0.94 to 0.97 for the pH-manipulated and control enclosure, respectively).

### 3.3.4. Enclosure comparison - settlement within four months

After four months of deployment, the assemblage in scourers collected from the acidified enclosure was similar to the assemblage found within the control enclosure (Table 2). The five most numerous taxa settled over the four-month period, in combined order of abundance, were: Harpacticoida, *Psamathe fusca*, Amphipoda, Tanaidae, *Nerilla* sp. and *Polyphthalmus pictus* (Table S4). The CAP analyses had moderate to low success discriminating between assemblages within the control and the acidified enclosures (Fig. 6; Table 3), however, there was some visual separation (Fig. 6). Scaphopoda abundance and the polychaetes *Fauvelia* sp. and *Nerilla* sp. abundances most correlated to the axes (65, 65, 80%, respectively) that discriminated between enclosures, yet the patterns were not indicative of typical cited ocean acidification impacts. Scaphopoda, a calcifying group, and *Fauvelia* sp., a syllid polychaete, occurred in the scourers collected from the pH-manipulated enclosure (mean 2.5 ± 0.5 individuals for both taxa) and were absent in the control and in the open scourers; whereas individuals of the polychaete *Nerilla* sp. tended to be more numerous in the control enclosure (mean 2.6 ± 1.6 vs. 0.25 ± 0.5 and 0.5 ± 1.0 individuals in the open plot). Other taxa abundances that correlated in the direction of enclosure separation had lower correlation values (35 to 50%), occurred in one scourer at < 3 individuals, and their location of occurrence also does not support ocean acidification predictions for calcifiers. The calcifying groups identified to Order Ophiurida (brittle stars) and juveniles from the Family Serpulidae (calcareous tube worms) occurred in the pH-manipulated enclosure and the polychaete *Sphaerodorum* sp. (does not form calcified tubes) occurred in the control enclosure.
A total of 17 to 22 and 17 to 23 taxa were found per scourer at T4 collected from the pH-manipulated and control enclosure, respectively. They also had a statistically similar total number of individuals per scourer (Fig. 5; range: 17 to 45 vs 31 to 59 for the pH-manipulated and control enclosure, respectively) and had similar evenness (range: 0.94 to 0.97 vs 0.94 to 0.98 for the pH-manipulated and control enclosure, respectively).

3.4. Pre-settled scourers

The pre-settled scourers had 26 to 44 different taxa and 73 to 461 total individuals per scourer. The total number of individuals tended to be greater within scourers settled and deployed for longer duration. For example, the pre-settled scourers collected at T4 had between 366 to 461 (mean ± SD, 400 ± 92) individuals per scourer while the pre-settled scourers collected at T2 had between 73 to 414 (mean ± SD, 190 ± 85) individuals per scourer. In addition to polychaetes and arthropods the calcifiers *Spirobanchus* sp. and molluscs (*Lyonsia* sp., *Gastropoda* juveniles, class Bivalvia, family Trochidae, and *Musculus costulatus*) tended to be abundant (Table S5, S6).

There was no indication of an enclosure or pH effect on pre-settled scourers collected after two months of exposure (Fig. 7). Pre-settled assemblages did not statistically differ among treatments for all considered parameters (Table 2). The most numerous OTUs in the pre-settled scourers at T2 were the bivalve *Lyonsia* sp., the polychaetes *Psamathoe fusca*, *Sphaerosyllis* sp., and Copepoda (an arthropod; Table S5). Calcareous members of the assemblage (calcareous tube-forming polychaetes, gastropods, and bivalves) that were predicted to decline with lowered pH, actually tended to be more numerous in the pH-manipulated enclosure than in the control enclosure at T2 (Fig. 7).
Trends in organism density and in richness in pre-settled scourers collected at T4, however, tended to support an effect of lowered pH on assemblages and also showed indications of an enclosure effect (Figs. 5, 7). There was a greater taxonomic richness within the open plot, followed by a lowered richness in the control enclosure, with the least richness in the pH-manipulated enclosure (Fig. 5). The two enclosures were similar in terms of mean total number of individuals, and it was greatest in the open plot. The density of serpulid polychaetes (Spirobranchus sp.) and gastropods were considerably lower in the pH-manipulated enclosure (Fig. 7). In addition, there were 29 individuals of Syllis sp. (a non-calcifying polychaete) in the pH-manipulated enclosure but only four in the open plot and control enclosure. Evenness did not support any trend.

3.4.1. Bivalve growth

Lyonsia sp. were between 1.4 to 7.0 mm in length (surface area of 67 to 156 mm$^2$). Rates of growth, as a proportion of their initial total area, were found to be statistically similar between the enclosures (0.26 ± 0.13 and 0.25 ± 0.12 in 72 days for control and pH-manipulated enclosures, respectively) and differed between bivalves growing in the open plot (0.36 ± 0.13 in 72 days) and in the pH-manipulated enclosure ($df = 2$, $MS = 0.04$, $F = 3.5$, $P = 0.047$, open plot vs. pH-manipulated enclosure $q = 3.7$, $P = 0.04$).

4. Discussion

4.1. CCA and serpulids on tiles

CCA and serpulids found on tiles are reported members of Posidonia meadows (Borowitzka et al., 2006) and both taxa were clearly reduced in abundance by lowered pH. Other studies have found reduced recruitment of serpulid tube worms (Cigliano et al., 2010; Kroeger et al., 2012; Rodolfo-Metalpa et al., 2010) and CCA (e.g. Doropoulos et al., 2012; Donnarumma et al., 2012; Donnarumma et
al., 2014; Jokiel et al., 2008; Kuffner et al., 2008) at a pH$_T$ < 7.8. Although the spores and larvae lack calcified structures, settled CCA and tubes of *Spirorbis* are susceptible to dissolution because they are composed of calcite and/or aragonite (Ippolitov & Rzhavsky, 2015) or magnesian calcite; 11.3 to 11.7 mol% magnesium in carbonate (MgCO$_3$) for CCA (Cox et al., in press) and calcite with ~15% MgCO$_3$ reported for spirorbid tubes (Bornhold and Milliman, 1973). Several studies have shown dissolution, reduced calcification, or a loss of coverage for CCA under lowered pH (reviewed by Hofmann and Bischof, 2014; Koch et al., 2013; McCoy and Kamenos, 2015; Nelson, 2009).

In studies on multispecies assemblages in natural settings, the process attributed to observed shifts in benthic communities under lowered pH seems to vary, particularly for algal dominated communities. Indeed, some studies have attributed loss of calcifiers to direct sensitivity (Hall-Spencer et al., 2008; Jokiel et al., 2008; Martin et al., 2008; Price et al., 2012) while others have indicated losses through competition (Kroeker et al., 2012) or both (Donnarumma et al., 2014; Porzio et al., 2011). In the present study, reduced abundances of calcifiers on acidified tiles were seen at early stages of recruitment. Differences in abundance appeared to be driven by taxa sensitivity and not post-settlement competition because other taxa were also reduced by the lowered pH condition and there was still bare space available for colonization.

The *in situ* control of pH (present study) could explain any contrasting conclusions drawn from CO$_2$ vent observations which are relied upon extensively to predict future ocean ecology. For example, meadow ecology has been studied along CO$_2$ vents in *Posidonia* meadows in Ischia, Italy where the pH$_T$ varies in a gradient from 8.1 to 6.6 nearest the CO$_2$ source (e.g. Hall-Spencer et al., 2008). Kroeker et al. (2012) noted that there were fewer recruits of CCA on tiles
placed at lowest pH locations (mean pH$_T$ ~ 6.7); whereas recruits at locations with a mean pH$_T$
of ~ 7.7 and ~ 8.0 were similar in terms of size and coverage. Then, after four months,
competition favored filamentous algae and resulted in loss of calcifiers (both serpulids and
algae). Yet, the conclusions drawn from observations along CO$_2$ vents are hampered by the large
temporal pH variability that results from venting activity (Kerrison et al., 2011). In the cited
example, sensitive calcifiers may have recruited during periods of more favorable carbonate
chemistry.

Grazing could also have reduced non-calcified algae and masked competition in the
present study. There are a number of mesograzer invertebrates in seagrass meadows (Lepoint et
al., 2000; Michel et al., 2015) and invertebrate density and diversity, unlike in other studies
(Allen et al., 2016; Cigliano et al., 2010; Garrard et al., 2014; Hall-Spencer et al., 2008; Kroeker
et al., 2011), were not obviously affected by lowered pH conditions.

Interactions with the seagrass host may limit a negative outcome. Epiphytic calcifier
coverage on P. oceanica leaves collected from the eFOCE system during the same period did not
appear to be altered (Cox et al., in press). The use of an in situ system, which accounts for diel
pH fluctuations, may have allowed for the host plant to alter carbonate chemistry at the
proximity of the leaves and buffered potential effects of ocean acidification. Alternatively,
because response can vary with species or morphological thickness (Doropoulos et al., 2012;
McCoy and Ragazzola, 2014), algae that colonized tiles could have been more sensitive to
lowered pH conditions than those found on leaves. Nevertheless, this does not explain the
different responses observed for Spirorbis sp. that appeared to be the same species on tiles (this
study) and leaf surfaces (Cox et al., 2017). Consistent with the conclusion that host plants can
buffer potential negative effects of ocean acidification, Spirorbis spirorbis, maintained under a
moderate ocean acidification scenario, recruited on the macroalga *Fucus serratus* and their calcification rates were greater in daylight when algal photosynthesis occurs (Saderne and Wahl, 2013). However, they did not compare recruitment on algae to recruitment on artificial surfaces which would have shed light on the extent of the ability of algae to buffer impacts on epibiont early life stages.

4.2. Invertebrates within scourers

Many of the taxonomic groups observed on scourers were juveniles or adult stages of invertebrates and are reported members of the *Posidonia* epifaunal community (Cigliano et al., 2010; Gambi et al., 1992; Michel et al., 2015). Some such as crustaceans, gastropods, and echinoderms are mobile and have the ability to migrate or move to more favorable areas. In the present study, their recruitment/colonization appeared relatively resilient to lowered pH conditions as projected for the end of the century. In contrast, Cigliano et al. (2010), using scourers placed for one month along the CO$_2$ vent near Ischia (Italy), found a decreasing gradient of calcifier (foraminiferans, serpulid polychaetes, gastropods and bivalves) density from high to low pH$_T$ (~8.0 to 7.0). Few taxa (which lack calcified tubes) appeared more prevalent either at the mid (*Amphiglena mediterranea, Leptochelia dubia, Caprella acanthifera*) or low pH locations (*Syllis prolifera*). The different outcome to the present study could be explained by the greater range of pH$_T$ (~8.0 to 7.0) and, at least partially, by differences in community composition. Calcifying Foraminifera and serpulid polychaetes were common recruits in meadow locations away from vents in Ischia, Italy (Cigliano et al., 2010; Kroeker et al., 2011) and tended to be absent or much reduced in numbers on fresh scourers within the enclosures in the present study. When serpulids were observed in the present study, they did appear to be sensitive to lowered pH in early life history stages (on tiles) and perhaps in later adult stages with
prolonged exposure. It is also important to keep in mind that vent studies can be hampered by the presence of trace elements and are observational; making it difficult to imply causation (Kerrison et al., 2011; Vizzini et al., 2013).

Other studies focused on invertebrate adult stages (Kroeker et al., 2011) or seasonal influence (over similar months as the present study, Garrard et al., 2014) at the Ischia CO\textsubscript{2} vents mirror the observations of Cigliano et al. (2010). However, these authors attribute increases in particular arthropods or polychaetes to indirect effects, such as release of invertebrate predators or interactions with macrophytes. Predation has long been thought to be a structuring factor of invertebrate assemblages in seagrass meadows (Edgar, 1990; Heck and Thoman, 1981; Heck and Orth, 2006). In \textit{P. oceanica} meadows, Gambi et al. (1998) attributed seasonal differences in polychaetes to differences in fish predation and Stuaro et al. (2016) found total density and biomass of amphipods to be greater in ambient than within fish inclusion plots. In the present study, indirect effects from fishes cannot be addressed because they were excluded from enclosures. Furthermore, ocean acidification effects on fish predatory behavior have largely been ignored. However, predator foraging ability, as well as invertebrate density, are often related to seagrass density (Heck and Thoman, 1981; Orth et al., 1984). Elevated seagrass density and canopy structure has been suggested to facilitate habitat heterogeneity and lower predation ability (Garrard et al., 2014; Orth et al., 1984). In the present study, seagrass density was similar between enclosures and \textit{Posidonia} leaf biometrics and photosynthesis unaffected by lowered pH (Cox et al., 2016).

Results from the present study indicate that gastropods and bivalves can settle under moderate ocean acidification scenarios. These groups also occurred at similar mean pH at the vents (Kroeker et al., 2011). Juvenile Mytilidae occurred at greater numbers at a vent location
with a mean pH$_T$ of 6.7 than at a control site (pH$_T$ of 8.1; Garrard et al., 2014; Kroeker et al., 2011). The similar growth rates of *Lyonsia* sp. found in the two enclosures would also suggest that at least one calcifier was able to maintain growth. Therefore, it appears that in seagrass meadows, mollusc density and diversity is somewhat resilient to near future pH conditions. However, predation and other shell characteristics (hardness and elasticity) which may facilitate predation were not measured. Arthropods, particularly peracarids, and polychaetes (except *Serpulids*) appeared tolerant in the present study to lowered pH and also dominated assemblages at the lowest pH levels in all CO$_2$ vent studies; although there were species specific differences in distribution patterns (Allen et al., 2016; Cigliano et al., 2010; Garrard et al., 2014; Kroeker et al., 2011). Reduced or lack of calcification and internal acid-base regulation may account for their increased tolerance (Melzner et al., 2009).

Biodiversity can be an indication of ecosystem function. A loss or change is used to indicate ecosystem health (Hooper et al., 2005). In general, species richness is often greater in habitats with greater structure (Sunday et al., 2016) and seagrass meadows in the Mediterranean Sea provide refuge for numerous species and tend to be highly diverse (Borowitz et al., 2006). Indeed, the epibiont assemblage in the present study was taxonomically diverse and varied. Taxa richness in monthly collected scourers was lower on average and within range (5-9 enclosures, 15-20 in reference) of the richness in invertebrate taxa settled in one month (range 10-35) in a *Posidonia* meadow at the Ischia (Italy) volcanic CO$_2$ vent yet, the evenness in the present study had a higher range (0.91 - 0.99 this study, 0.6 - 0.9 in Cigliano et al., 2010). The concern is that ocean acidification will alter diversity both directly via loss of calcified species and indirectly by changing habitat structural complexity or density (Sunday et al., 2016). There are several predicted scenarios for effects on local diversity in seagrass or fleshy algal meadows under
elevated $pCO_2$ which are dependent upon whether the producer density or complexity is increased, replaced, or reduced. However, at low pH near volcanic CO$_2$ vents in the Mediterranean Sea, elevated seagrass density was not correlated with increases in local diversity (Sunday et al., 2016). The results from the present study do not support changes in local diversity via indirect effects with changes in the habitat complexity. Seagrass physiology and abundance as well as algal abundance were not affected by the pH manipulation in eFOCE (Cox et al., 2016). The reduction of calcifiers on tiles, however, would be congruent with a loss of local diversity through direct effects. Yet, the only decline in taxonomic richness associated with the lowered pH treatment was in the epibont assemblage found within the unreplicated, pre-settled scourers left in lowered pH for the duration of study.

It is not clear from the results of the present study how invertebrate assemblages will be affected in later development stages or with more prolonged lowered pH exposure. The similar invertebrate density and diversity between enclosures within pre-settled scourers after two months of exposure suggests species were able to survive, recruit, or were able to do both at the lowered pH and that outcomes were not affected by competition, predation, nor sensitivity at later life-history stage. In comparison, the pre-settled scourers in later stages of development, and left in acidified conditions for four months revealed a pattern congruent with ocean acidification predictions. The interpretation of the latter pre-settled outcome is limited by scourer replication. In addition, the study did not address differences in biomass, metabolism, or reproductive demands that could influence species interactions or larval production over a longer time scale.

4.3. Caveats

Large-scale unreplicated experiments, such as eFOCE, because of their unique qualities (e.g. pH manipulated at an offset in an intact community), size, and temporal scope can provide
valuable ecological information that may bolster the conclusions of laboratory or natural studies. Alternatively, they can provide a different hypothesis to pursue more thoroughly. The eFOCE study addressed a need for *in situ* manipulation to increase ability to predict future ecology. Additionally, the study design accounted for natural pH variation that is often ignored when pH is manipulated *in situ*. While large scale unreplicated experiments can provide valuable ecological information, they do have drawbacks (Davies and Gray, 2015; Hurlbert, 1984; Oksanen, 2001). Replicated enclosures were not feasible at this stage (see discussion in Gattuso et al., 2014). Therefore, alternative hypotheses that we cannot robustly exclude include (1) there were other small pH effects difficult to quantify (2) that the conflicting outcome is due to some ‘lurking’ variable. Yet, several recommended steps (Davies and Gray, 2015; Oksanen, 2001) were taken to try to reduce erroneous conclusions that may occur including: (1) care was taken to select study locations that were similar in depth and seagrass density to reduce confounding variables, (2) the environment was continuously monitored to ensure they were similar to those in ambient, (3) repeated measurements were made at the same location through time, and (4) comparisons from the pH-manipulated enclosure were made to two different spatial locations. The enclosure structure did inhibit colonization possibly by reducing water flow or general movement, yet assemblages had many of the same taxonomic members and dominant taxa were common in all locations.

5. Conclusions

It appears from results that specific calcifiers, such as CCA and serpulid polychaetes, are highly sensitive to ocean acidification and that small peracarid crustaceans and polychaetes without calcified tubes appear robust. In contrast to vent observations that tend to support shifts resulting from competitive interactions or physiological limits across a wider pH range, there
was evidence that near future pH conditions (pH_T 7.75) can impact the early life-history stages of the dominant calcifiers. Contrasting results within eFOCE on tiles and leaves also stresses the need to identify the extent of host plant buffering and take action to alleviate threats to host plants to minimize ocean acidification impacts on the community. Lastly, conclusion should be tempered or put into the context of results from other studies until more in situ pH manipulation studies are done that address the limitations of eFOCE and occur in variety of conditions that persist throughout the Mediterranean Sea.

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References


Fig. 1. Carbonate chemistry within ambient (open plot) and enclosures: averaged (± standard deviation, SD): Panel A, pH (on the total scale; pH$_T$), Panel B, partial pressure of carbon dioxide ($p$CO$_2$) and Panel C and D, saturation states with respect to aragonite ($\Omega_a$) and calcite ($\Omega_c$) for each month and for the period before and during acidification. The difference in pH$_T$ between the pH-manipulated and the control enclosure is also shown in Panel A.
Fig. 2. Artificial collectors used and collection intervals. Tiles were placed in the three eFOCE treatments (control and pH-manipulated enclosures and open plot) at the start of the acidification period (T0) and a set of three to five tiles from each treatment were collected every four weeks at sampling intervals T1 to T4 to examine assemblage development. Fresh scourers were also placed in three treatments at T0 to target the collection of sessile micro-invertebrates. These scourers were collected and replaced at monthly sampling intervals T1, T2, T3, T4 and collected after four months (placed at T0 left until T4) to examine the effects of ocean acidification on the micro-invertebrate assemblage over short and longer durations. Pre-settled scourers were settled in ambient for four to nine months. One set was stained for 48 h in calcien and deployed in the enclosures and open plot for two months. The other set of pre-settled scourers (n = 1) were deployed in each treatment and left for the duration of the study (four months). Pre-settled scourers were used to test whether the response of an assemblage exposed in a later successional
stage differs from assemblages developed under ocean acidification. Invertebrates in pre-settled scourers stained with calcein were used to measure calcifier growth.

Fig. 3. Mean abundance (+ SD) of operational taxonomic units (OTU) found on tiles placed initially during the pH manipulation and collected (n = 5) every four weeks (sampling intervals T2 to T4) from the pH-manipulated and control enclosure and the open plot. Letter groups and horizontal bars above the vertical bars are the significant ($P < 0.05$) results of pairwise tests (see Table 1). Other taxa category includes cyanobacteria, brown colored algal crusts, and filamentous algae.
Fig. 4. Mean density (individuals per scourer, ± SD) of taxonomic groups on scourers collected and replaced at sampling intervals T1, T2, T3, T4 (symbols connected by line) and collected after four months (placed at T0 left until T4, symbols only) from the pH-manipulated, control enclosures, and open plot. Plots are arranged by phylum and overall decreasing densities.
Fig. 5. Mean species richness, taxonomic evenness, and total number of individuals (± SD) found within fresh scourers (left) and pre-settled scourers (right) deployed within the pH-manipulated, control enclosures and open plot for one to four months. Fresh scourers were collected and replaced monthly at intervals T1, T2, T3, and T4 and are represented by symbols with lines while fresh scourers placed at T0 and collected at T4 are represented by symbols (no line). Pre-settled scourers were collected after two and four months of exposure.
Fig. 6. Discrimination of assemblages in fresh scourers collected and replaced at sampling intervals T2, T3, T4 (left) and collected after four months (placed at T0 left until T4, right) from the pH-manipulated, control enclosures, and open plot. Canonical analysis of principal coordinates (CAP) ordination plots based upon Bray-Curtis dissimilarities presented when a PERMANOVA indicated statistical differences (pairwise open plot ≠ enclosures, P <0.05). The plot shows the canonical axes that best discriminate assemblages within the three locations (pH-manipulated and control enclosures and open plot). Overlaid on the plot are correlations of original taxa variables with canonical axes, the circle aides in the visualization of the center of the biplot and the arrow indicates direction and strength (as length) of the correlation. A cut-off of > 70% in the biplot direction that separates open plot assemblage is shown and a cut off of > 35% in the biplot direction that separates enclosure assemblages is shown.
Fig. 7. Mean density (individuals per scouer, + SD when n > 1) of common taxonomic groups found in pre-settled scouers placed within the pH-manipulated, control enclosures and open plot for two and four months. Plots are arranged by phylum and overall decreasing abundances.
Table 1. Statistical results on abundance of operational taxonomic units (OTU) found on tile surfaces. Terms included treatment (pH-manipulated and control enclosure, and open plot) and sampling interval (T2, T3, T4) and their interactions. Pairwise results are found as letter groups on Fig. 1. Other taxa category includes cyanobacteria, brown colored algal crusts, and filamentous algae.

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<td>4.00</td>
<td>0.027</td>
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<td>1.02</td>
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Table 2. Statistical results from comparisons of scouerer assemblages (datasets #1-3). Terms tested included: treatment = pH-manipulated and control enclosures and the open plot and sampling interval = time (T) 1 to 4.

<table>
<thead>
<tr>
<th>Source</th>
<th>Assemblage structure</th>
<th>Taxonomic richness</th>
<th>Taxonomic evenness</th>
<th>Total # of individuals</th>
</tr>
</thead>
<tbody>
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<td></td>
<td>Source</td>
<td>Df</td>
<td>MS</td>
<td>F</td>
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<td>Residuals</td>
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<tr>
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<tr>
<td>Pre-settled scourers collected at T2 (dataset #3)</td>
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<td>Residuals</td>
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<td>Post-hoc pairwise comparisons</td>
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<td>P</td>
<td>Q</td>
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<td>Open, Control</td>
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<td>Open, pH manipulated</td>
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<td>0.003</td>
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<tr>
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<td>T2,T3</td>
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<td>0.4</td>
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</tr>
<tr>
<td></td>
<td>T3,T4</td>
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<tr>
<td></td>
<td>T4,T1</td>
<td>1.5</td>
<td>0.01</td>
<td>0.4</td>
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<td></td>
<td>T1,T3</td>
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<td>0.003</td>
<td>4.5</td>
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<tr>
<td></td>
<td>T2,T4</td>
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<td>0.001</td>
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<td>Settlement within four months (dataset #2)</td>
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<td>0.9</td>
<td>0.6</td>
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</tr>
<tr>
<td></td>
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<tr>
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<td>--------</td>
<td>--------</td>
<td>--------</td>
</tr>
<tr>
<td>Control</td>
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<tr>
<td>Open, Control</td>
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Table 3. Results of leave-one-out allocation success from the canonical analysis of principal coordinates (CAP) done on fresh scourer assemblages. The analyses were done using m (see below) principal coordinate axes based on the Bray-Curtis dissimilarities on log10(X + 1) transformed data. The percent classified correctly to either pH-manipulated and control enclosures and open plot are presented for fresh scourer assemblages (dataset#1 and #2).

<table>
<thead>
<tr>
<th>Settlement within one month at T1-T4 (dataset #1)</th>
<th>Settlement within four months (dataset #2)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sampling interval classification, m = 7</strong></td>
<td><strong>Treatment classification, m = 6</strong></td>
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<td>Classified</td>
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<tr>
<td>Original</td>
<td>Original</td>
</tr>
<tr>
<td>pH-manipulated</td>
<td>pH-manipulated</td>
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<tr>
<td>Control</td>
<td>Control</td>
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<tr>
<td>Open</td>
<td>Open</td>
</tr>
<tr>
<td>Total correct %</td>
<td>Total correct %</td>
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</table>

<table>
<thead>
<tr>
<th>Classified</th>
<th>T1</th>
<th>T2</th>
<th>T3</th>
<th>T4</th>
<th>Total</th>
<th>% Correct</th>
<th>Classified</th>
<th>pH-manipulated</th>
<th>Control</th>
<th>Open</th>
<th>Total</th>
<th>% Correct</th>
</tr>
</thead>
<tbody>
<tr>
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<td>17</td>
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Total correct % 44.9

<table>
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<th>% Correct</th>
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Total correct % 76.9