Stressor intensity determines antagonistic interactions between species invasion and multiple stressor effects on ecosystem functioning


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Stressor intensity determines antagonistic interactions between species invasion and multiple stressor effects on ecosystem functioning

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There are persistent increases in the range and intensity of anthropogenic stressors exerted on the natural environment (Vitousek et al. 1997), despite efforts to mitigate these impacts through legislation such as the EU Habitats Directives (EU 1992) and the Australian Environment Protection and Biodiversity Conservation Act 1999. Loss of biodiversity is thought to be driven by ecological stressors such as habitat loss and fragmentation (Pimm and Raven 2000), species invasions (Simberloff et al. 2013), eutrophication (Smith et al. 1999), global warming (Schiel et al. 2004) or even ocean acidification (Kroeker et al. 2010). The individual impacts of such stressors on certain species or whole communities have been documented (reviewed by Kroeker et al. 2010 and Thomsen et al. 2011), however, multiple stressors often occur simultaneously (Crain et al. 2008). Multiple stressors may have simple additive effects on ecosystems, which could be predicted from previous studies of independent stressor effects (Kroeker et al. 2010, Dossena et al. 2012). Alternatively, stressors may interact with each other non-additively, leading to a cumulative impact that is either greater than (synergistic) or less than (antagonistic) the sum of the independent effects (Crain et al. 2008). Results from recent meta-analyses suggest that non-additive interactions are common and the nature of such interactions can vary with environmental context, such as habitat type or climatic conditions (Crain et al. 2008, Darling and Côté 2008). Currently, synergistic cumulative impacts are predicted to be most common, driven by the de-stabilizing effect of a primary stressor that reduces resistance of ecosystems to other stressors, thus, leading to ‘ecological surprises’ and potentially rapid declines in biodiversity and ecosystem functioning (Paine et al. 1998, Doak et al. 2008). Uncertainty surrounding the cumulative impacts of stressors and the context-dependency of potential interactions among two or more stressors demands more robust experimental work to disentangle such cumulative effects (Crain et al. 2008).

Coastal ecosystems are among the most economically valuable (Barbier et al. 2011) and heavily exploited (Lotze et al. 2006). Among the most ubiquitous stressors in coastal ecosystems are nutrient enrichment, the spread of invasive species and global warming (Lotze et al. 2006). Individually, these stressors can degrade habitats (Smith et al. 1999), change species distributions and assemblage structures (Dossena et al. 2012), and alter ecosystem processes (Thomsen et al. 2011). Non-additive interactions may occur where these stressors influence ecosystems simultaneously and lead to complex cumulative impacts (McKee et al. 2002, 2004).
Experimental design and set-up

The three factors manipulated in the experiment were: 1) presence of an invasive species (Sargassum muticum; fixed, two levels: invaded, non-invaded); 2) nutrient concentration (fixed, three levels: ambient, $N_+$, $N_++$; and 3) water temperature (fixed, three levels: ambient, $T_+$, $T_++$), yielding eighteen experimental treatments and ninety experimental units ($n = 5$, of all possible combinations). This factorial design allowed the independent and interactive effects of each of the stressors (all three factors at each level) to be tested. Treatments were allocated randomly to mesocosms, which were rearranged approximately weekly to minimise location artefacts (Bruno and O’Connor 2005).

The presence of an invasive species was manipulated by the addition of $S$. muticum (11 g). This fucoid algae, originating in northeast Asia, is invasive in northwest Europe and became established in Strangford Lough in 1995 (Boaden 1995). $S$. muticum is a strong competitor with native species and a driver of community structural changes (White and Shurin 2011). In non-invaded treatments, $S$. muticum was substituted with the morphologically similar (Wernberg et al. 2000) native fucoid Halidrys siliquosa (11 g) to control for biomass addition, thus, all synthetic assemblages contained similar total algal biomass (60 g) at the beginning of the experiment.

In nutrient enriched treatments, the inorganic nitrogen and phosphorus content of the mesocosms was elevated using slow release fertilizer pellets (11 N: 11 P: 18 K) contained in 50 ml nutrient diffusers (70 g in $N_+$ and 140 g in $N_++$ treatments) similar to Worm et al. (2000). Non-enriched treatments contained empty diffusers to limit experimental artefacts. To ensure that nutrient enrichment treatments were effective, water samples were taken after four weeks and analysed using an autoanalyzer. Water samples from enriched treatments had significantly greater concentrations of dissolved inorganic nitrogen (DIN), phosphorus and ammonium (Kruskal–Wallis test with multiple comparisons, ambient $< N_+ < N_++$, DF = 2, p $< 0.001$). Ambient nutrient enrichment treatments contained 1.63 $\pm$ 0.07 $\mu$m $^{-1}$ DIN, 0.38 $\pm$ 0.01 $\mu$m $^{-1}$ phosphate and 0.68 $\pm$ 0.03 $\mu$m $^{-1}$ ammonium (mean $\pm$ SE), typical of low summer nutrient concentrations in this region (Hydes et al. 1999). Medium nutrient enrichment ($N_+$) raised DIN content by 0.89 $\pm$ 0.224 $\mu$m $^{-1}$, phosphate content by 0.191 $\pm$ 0.018 $\mu$m $^{-1}$ and ammonium content by 0.533 $\pm$ 0.044 $\mu$m $^{-1}$ above ambient, while high nutrient enrichment treatments ($N_++$) elevated DIN by 1.112 $\pm$ 0.112 $\mu$m $^{-1}$, phosphate content by 0.376 $\pm$ 0.024 $\mu$m $^{-1}$ and ammonium content by 1.007 $\pm$ 0.091 $\mu$m $^{-1}$ above ambient. This increase of around 70% is in line with previous nutrient enrichment studies (Worm et al. 2000, Sugden et al. 2008, Canning-Clode et al. 2008).

There were also three levels of seawater temperature in the experiment: ambient, medium ($T_+$) and high ($T_++$). Mesocosms were warmed as required using submersible aquarium heaters (300 watt). Water temperature was increased by 1.86 $\pm$ 0.04°C ($T_+$; mean $\pm$ SE) and 2.44 $\pm$ 0.05°C ($T_++$) above ambient temperature (13.04 $\pm$ 0.03°C) during the experiment, which mimics current climate change predictions for this region (IPCC 2007) and tracked

**Methods**

This experiment ran for six weeks during June–July 2012 in outdoor flow-through mesocosms at Queen’s Univ. Marine Laboratory, Portaferry, Co. Down, Northern Ireland. The mesocosm array consisted of ten sea water tables, each containing eleven 45-l mesocosms supplied with sand filtered seawater direct from the adjacent Strangford Lough. Shallow coastal benthic assemblages were created to mimic rock pool communities on local shores, which are typical of the region and based on local field surveys. Synthetic assemblages comprised of six algal species ($Fucus serratus$, 21 g wet biomass; Laminaria digitata, 17 g; Corallina officinalis, 16 g; Mastocarpus stellatus, 3 g; Cladophora sp., 2 g; Ulva lactuca, 1 g), which were present in proportional abundance and biomass of each species in rock pools of similar size to the mesocosms. Algae were cleared of epiphytes manually and insecticide was used to remove unwanted epibiota. Algae were attached to plastic mesh (20 mm mesh size) in each mesocosm and seawater was aerated and renewed by dump buckets (approx. mean flow-through rate: 4 l min$^{-1}$) simulating wave action on rocky shores. Grazing gastropods were added to each mesocosm to incorporate a realistic grazing pressure on the algae based on surveys of the most abundant grazers in local rock pools. These were the limpet Patella vulgata (2.27 individuals m$^{-2}$), winkle, Littorina littorea (3.23 individuals m$^{-2}$) and topshell, Gibbula umbilicalis (4.63 individuals m$^{-2}$). Thus, typical grazing pressure was incorporated into the experimental design and each mesocosm had two limpets (dry biomass: 10.51 $\pm$ 0.44 g, mean $\pm$ S.E.), three winkles (7.53 $\pm$ 0.15 g) and four topshells (3.72 $\pm$ 0.08 g).

**EV-2**
natural variation. Water temperature within each mesocosm was monitored during the experiment and warming treatments were effective (mixed effects model, fixed factor: temperature treatment, random factor: mesocosm, with Tukey post hoc comparisons, ambient $< T + < T + t$, $DF = 2$, $p < 0.001$, Supplementary material Appendix 1).

Response variables

Gross assemblage productivity was estimated from dissolved oxygen concentrations using an optical probe after periods of artificially induced darkness and subsequent similar periods of sunlight (Nielsen 2001, Noël et al. 2010). Initial oxygen concentration was measured and then mesocosms were immediately covered with a lid and subject to a dark incubation period of 90–120 min to estimate respiration. After incubations, a second set of measurements for oxygen concentration were taken. A third set of measurements were then taken after a further 20–70 min light period that allowed photosynthesis to resume. Dark incubation periods were varied to ensure that a quantifiable change in dissolved oxygen concentration was achieved and light incubation periods were varied to avoid oxygen super-saturation (Noël et al. 2010). Gross assemblage productivity was calculated from the sum of estimates of net assemblage productivity and assemblage respiration. Productivity measurements were standardised for algal dry biomass (Griffin et al. 2010). Photosynthetically active radiation (PAR) was recorded during oxygen concentration measurement and mean PAR was $1345.41 \pm 18.46 \mu E \cdot m^{-2} \cdot s^{-1}$ (mean $\pm$ SE, $n = 270$).

Irradiance levels were above those recorded as saturating light in similar rock pool assemblages (600 $\mu mol$ photons $s^{-1} m^{-2}$, Arenas et al. 2009).

Dry biomass (dried at 60°C until a constant biomass) of each algal species was quantified at the end of the experiment to test for differences in algal assemblage structure and biomass accumulation among treatments. Total algal biomass accumulation was calculated as the sum of the difference between dry biomass at the beginning and the end of the experiment. Algal dry biomass at the start of the experiment was derived from wet-dry biomass relationships established for all species through the collection and drying (60°C until a constant biomass) of additional wet biomass samples.

Data analysis

Three-way analysis of variance (ANOVA) was used to test for non-additive cumulative effects among treatments on gross assemblage productivity and total algal biomass accumulation. This approach was utilised as interaction terms within an ANOVA test for deviations from the additive model and allow antagonistic and synergistic interactions among stressors to be identified (Billlick and Case 1994, Dunne 2010). To preserve the integrity of the experimental procedure, eighteen (out of ninety) experimental units were excluded from the analysis because precise grazer densities could not be assured for the duration of the experiment. This led to some uneven replication of treatments, however, all treatments were replicated a minimum of three times. To account for unequal replication of some treatments, type III sum of squares were used to calculate F-statistics. ANOVAs included the fixed factors invasion, nutrient enrichment and water temperature and included all possible interactions among these terms. Models were checked for homogeneity of variances using plots of standardised residuals versus fitted values as well as standardised residuals versus the explanatory variables used in each model and QQ-plots and histograms were used to test for normality in conjunction with Shapiro–Wilk and Levene’s tests. Gross assemblage productivity was transformed (cube root) to meet assumptions of normality and heteroscedacity. Post hoc pairwise t-tests (Tukey HSD) were used to make comparisons among levels of significant terms. Data were visualised using means and error (95% confidence intervals) plots to reflect the construct of the ANOVA and add clarification to the results, which is an accepted and informative approach to visualise results of multiple stressor studies (Blake and Duffy 2012, O’Gorman et al. 2012, Burnell et al. 2013). Permutational multivariate analyses of variance (PERMANOVA; Anderson 2001) was used to test hypotheses involving algal assemblage structure, based on Bray–Curtis resemblance matrices calculated from algal dry biomass data with 9999 permutations of residuals under a reduced model. This permutation method was chosen because it reduces type I error for multifactorial analysis (Anderson et al. 2008). Algal dry biomass data were fourth root transformed for multivariate analysis to meet assumptions of homogeneity of dispersions and to reduce the influence of the most abundant species on assemblage structure (Clarke and Warwick 2001). The dry biomass of $S$. muticum and $H$. siliquosa were not included in this analysis to distinguish the responses of other species to the presence of $S$. muticum from the response of $S$. muticum itself. Where significant differences were detected, post hoc pairwise t-tests were used to make comparisons among levels of significant terms. Similarity of percentages (SIMPER) analyses were conducted to test for individual algal species contributions to overall differences in assemblage structure (Clarke and Warwick 2001). The magnitude of all treatment effects were obtained through the calculation of generalised omega-squared ($\omega^2$) effect sizes (Olejnik and Algina 2003). Multi-variate analyses were undertaken in PRIMER ver. 6 (Clarke and Gorley 2006) and univariate analyses were undertaken in R ver. 2.14.2 (R Development Core Team 2011).

Results

The presence of Sargassum muticum increased gross assemblage productivity, however, the effect size was small (Table 1a, Fig. 1a). There were no effects of nutrient enrichment or warming and no interactive effects among any of the stressors on gross assemblage productivity (Table 1a, Fig. 1). The presence of the invasive alga $S$. muticum altered total algal biomass accumulation, however, this effect changed with nutrient concentration and temperature (Table 1b, Fig. 2). Post hoc tests showed that in the absence of $S$. muticum, total algal biomass accumulation was significantly lower in the medium nutrient treatment compared to ambient and high nutrient treatments (Fig. 2a). Whereas, when $S$. muticum was present there was no effect of nutrients on algal biomass accumulation (Fig. 2a). In addition, the response of algal biomass accumulation to increasing water temperature varied...
Table 1. Tests for the effects of the presence of an invasive species, nutrient enrichment and warming on assemblage responses: (a) ANOVA with type III sums of squares for effects of the treatments on gross assemblage productivity after six weeks; (b) ANOVA with type III sums of squares for effects of the treatments on total algal biomass accumulation after six weeks, and (c) PERMANOVA based on Bray–Curtis dissimilarity matrix calculated from algal dry biomasses (fourth root transformed to standardise individual species contributions) with 9999 permutations of residuals under a reduced model. Significant terms are highlighted in bold. \( \omega^2 \)-values are generalised omega-squared effect sizes. Negative \( \omega^2 \) are shown as zeros.

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>MS</th>
<th>F</th>
<th>p</th>
<th>( \omega^2 )</th>
</tr>
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<td>Invasion (Inv)</td>
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<td>0.014</td>
<td><strong>0.071</strong></td>
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<tr>
<td>Nutrient enrichment (Nut)</td>
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<td>0.636</td>
<td>0.000</td>
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<td>Temperature (Temp)</td>
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<td>0.391</td>
<td>0.678</td>
<td>0.000</td>
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<tr>
<td>Inv ( \times ) Nut</td>
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<td>0.002</td>
<td>0.307</td>
<td>0.737</td>
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<tr>
<td>Inv ( \times ) Temp</td>
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<tr>
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<tr>
<td>Inv ( \times ) Temp ( \times ) Nut</td>
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<td>0.006</td>
<td>8.049</td>
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</table>

Figure 1. Means (± 95\% confidence interval) of gross assemblage productivity in experimental treatments following the construct of comparisons within the three factor ANOVA. (a) Gross assemblage productivity in all treatments with the presence and absence of *Sargassum muticum* (analysis is based on 33 invaded and 39 non-invaded replicates as temperature and nutrient enrichment treatments were pooled); (b) Gross assemblage productivity in each of the nutrient enrichment treatments (each bar represents between \( n = 11 \) and \( n = 14 \) replicates as temperature treatments were pooled); (c) Gross assemblage productivity in each of the temperature treatments (each bar represents between \( n = 10 \) and \( n = 14 \) as nutrient enrichment treatments were pooled). Non-invaded treatments are denoted by open bars and invaded treatments are denoted by grey bars. * denotes groups of treatments that differ significantly (\( p < 0.05 \)).
The presence of \textit{S. muticum} led to a small, but statistically significant, increase in gross assemblage productivity, thus, providing support for the theory that invasive species can have wider ranging impacts beyond effects on single species (Simberloff et al. 2013). The mechanism behind this increased productivity in invaded assemblages may be associated with differences in the functional traits, such as phenology and growth rates, of \textit{S. muticum} compared to the morphologically similar native species, \textit{Halidrys siliquosa}.

Although both species are considered perennial, the phenology of \textit{S. muticum} and \textit{H. siliquosa} differ (Wernberg et al. 2013).
of the study, or owing to differences in limiting resources between natural and mesocosm systems (Stachowicz et al. 2008). We did not detect any effects of warming or nutrient enrichment on assemblage productivity rates, however, warming altered assemblage structure through increases in biomass of the ephemeral green alga, Ulva lactuca and declines in the biomass of the brown alga, Laminaria digitata in treatments with a warming of 2.4°C. Although statistically the effect size was small, this change in assemblage structure is of notable ecological interest owing to the importance of L. digitata for the functioning of coastal ecosystems. Laminaria digitata is a kelp species that thrives in colder waters and is thought to be near the southern limit of its geographical range on these shores (Smale et al. 2013). Kelp is a highly productive component of coastal ecosystems, supporting diverse communities and facilitating the provision of many coastal goods and services (Smale et al. 2013). Our findings support concerns that global warming may threaten kelp species, which are at the edge of their range, potentially causing range contraction and declines in associated ecosystem services (Smale et al. 2013). There was no reduction in assemblage productivity associated with the decline in biomass of L. digitata under warmed conditions, indicating that the corresponding increase in U. lactuca may have compensated in terms of maintaining assemblage productivity. Ephemeral algae, such as U. lactuca, have previously been shown to proliferate in increased warming scenarios (Schiel et al. 2004). Although L. digitata and U. lactuca are not functionally equivalent (Littler 1980), increases in U. lactuca biomass and productivity may have compensated for the decline of L. digitata and therefore account for the lack of an effect of warming on overall assemblage productivity. A similar compensation effect has been identified from recent field experiments where the proliferation of ephemeral species maintained community productivity after the loss of canopy species (Crowe et al. 2013). It has been shown that shifts in algal assemblage structure can maintain processes such as total biomass and production at similar rates, however, different algal species are rarely functionally equivalent in terms of multiple ecosystem properties, thus, true compensation cannot be inferred (Bruno et al. 2005, O’Connor and Bruno 2007).

In terms of the cumulative effects of stressors, we identified non-additive interactive effects on total algal biomass accumulation, however, contrary to previous work (Staehr and Sand-Jensen 2006), we found no evidence of an interaction between nutrient enrichment and warming on assemblage productivity. Nutrient enrichment could be expected to enhance the effects of warming on assemblage productivity through reduction of potential nutrient limitation (Staehr and Sand-Jensen 2006). However, our results suggest that nutrient supply may not be a limiting factor in this system, because there were no effects of nutrient enrichment on productivity rates or assemblage structure.

We have demonstrated how the effect of a stressor (e.g. nutrient enrichment) on total algal biomass accumulation was determined by the presence of a second stressor (e.g. an invasive species). For example, the decrease in algal biomass accumulation in medium nutrient enriched treatments seen in non-invaded assemblages, did not occur when the second stressor, the invasive species S. muticum, was present. This suggests that an antagonistic interaction occurred between these stressors. Antagonistic interactions have been identified between other pairs of anthropogenic stressors, such as between nutrient enrichment and ocean acidification (Burnell et al. 2013). In our study, total algal biomass accumulation was similar across treatments when S. muticum was present, whereas in non-invaded assemblages under medium nutrient enrichment and under high warming treatments there was a decline in algal biomass accumulation. The antagonistic interaction between the presence of S. muticum and warming effects on algal biomass accumulation may have been driven by differences in the reponses of H. siliquosa and S. muticum to warming. In non-invaded assemblages, H. siliquosa may have a reduced fitness in high warming treatments as water temperatures in these treatments were at the upper limits experienced typically by this species during the summer and, thus, could have led to a decrease in algal biomass accumulation in the non-invaded assemblages (Morris and Taylor 1983). In contrast, the positive effect of S. muticum on total algal biomass accumulation suggests that S. muticum is better adapted to take advantage of warmer water temperatures (Walther et al. 2009). Invasive species may have different tolerances to environmental variables, such as temperature, as a consequence of their different evolutionary environments (Byers et al. 2002). This rationale could explain why invasive species are sometimes better adapted to survive and respond successfully to opportunities driven by anthropogenic environmental change, such as increased resource availability from declines in native species (MacDougall and Turkingham 2005).

We have shown that in non-invaded assemblages, total algal biomass accumulation declined in medium nutrient enrichment treatments. The mechanism behind this non-additive effect is unclear, however, it is typical of the type of unpredictable results found when multiple stressors occur (Paine et al. 1998). One speculative explanation is that nutrient enrichment may have stimulated algal growth and increased levels of nitrogen in algal tissues through the storage of excess nutrients (Pedersen and Borum 1996). This could have provided a higher quality food source for grazing
gastropods and enhanced grazing activity, which may have constrained algal biomass accumulation (Boyer et al. 2004). At the high levels of enrichment, algal growth may have been enhanced to a point where the bottom-up effects of nutrient enrichment were greater than the top-down grazing effects leading to greater biomass accumulation than in medium nutrient enrichment treatments. Although this explanation is speculative because specific grazing rates (top-down control) was not quantified as part of this study, direct and indirect effects of different levels of nutrient enrichment may be a contributing factor to the differences in the importance of bottom-up and top-down control on algal growth and biomass as found in previous studies (Valdivia et al. 2008, Atalah and Crowe 2010). The current study is one of the few that has manipulated nutrient enrichment over more than two levels (but see Sugden et al. 2008, Canning-Clode et al. 2008). Many previous studies crossing a wide range of systems have tested for a presence or absence effect of nutrient enrichment (Blake and Duffy 2010, O’Connor and Donohue 2013). These studies have allowed generalisations to be formed (Smith et al. 1999, Sala and Knowlton 2006), however, there is no consideration of stressor effects occurring along an intensity gradient. Our study tested a range of nutrient enrichment and warming scenarios and highlights that there are more than simple presence or absence effect of stressors, which further complicates the prediction of interactive cumulative effects (Steudel et al. 2012).

The presence of antagonistic cumulative effects of multiple stressors on total algal biomass accumulation, but not on other assemblage responses (i.e. productivity), further highlights the unpredictable effects of multiple stressors on ecosystem functioning. Our findings provide strong empirical evidence of non-additive interactions among stressors, which is consistent with conclusions of recent meta analyses, indicating that antagonistic (Crain et al. 2008, Darling and Côté 2008), rather than synergistic cumulative effects are most prevalent (Sala and Knowlton 2006, Halpern et al. 2007). These non-additive interactions between the presence of the invasive species and other stressors exemplify how invasive species have a high potential for complex interactions owing to their context-dependent effects on biodiversity and ecosystem functioning (Thomsen et al. 2011, Simberloff et al. 2013).

To conclude, the presence of an invasive species affected functioning through both independent effects and non-additive interactive effects with other stressors. In this study, non-additive interactive effects were determined by stressor intensity and varied depending on the ecosystem process. The unpredictable nature of these interactions highlights the importance of considering a range of ecosystem processes and more importantly, gradients of environmental contexts or stressor intensities when aiming to identify, predict and mitigate the wider impact of multiple stressors on ecosystem functioning and services.

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