Target journal:

Biological invasions

Reason for choosing the journal:

This journal is chosen for its relatively high impact factor reporting research concerning biological invasion and the relevance of the current findings to patterns of biological invasions and its potential implications for management and monitoring decision. The current study reported the biological invasion status within a long established Marine Protected Area, Lundy Island and the ecological impacts of the non-native marine algae, *S. muticum* and *C. okamurae* on the native algal community, which provides evidence for the needs to continuously monitor biological invasion.

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Assessing the impact of non-native marine algae on native intertidal algal community at Lundy Island – A Marine Protected Area case study

MSc in Conservation and Biodiversity

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I certify that this dissertation is entirely my own work and no part of it has been submitted for a degree or other qualification in this or another institution and give permission for a copy to held by my supervisor and distributed at their discretion.

Abstract

Invasion by non-native species incurs substantial economic and ecological impacts on the invaded territories, which has drawn international concerns and called upon concerted management actions. The marine ecosystem with borderless boundary is comparatively more susceptible to biological invasion than terrestrial ecosystem and majority of marine ecoregion has already seen settlement of different non-native marine species. Non-native marine algae are among other marine taxa to be posing the most substantial threats to the invaded native ecosystems. Studies on effects of marine algal invasion on native communities have been ongoing, however, few have been conducted in ecologically diverse areas such as Marine Protected Areas (MPAs). Current study assessed the general biological invasion status of intertidal shore on Lundy Island, an isle situated in the Bristol Channel and UK's first Marine Conservation Zone (MCZ), and the impact of invasion on native intertidal algal communities. Five non-native marine algae, *Asparagopsis armata*, *Bonnemaisonia hamifera*, *Caulacanthus okamurae*, *Colpomenia peregrina* and *Sargassum muticum* have been spotted at the south eastern intertidal shore of the island and their distributions were shown to be differential. Among the identified non-native marine algae, *C. okamurae* and *S. muticum* were the dominant non-native marine algae at Devil's Kitchen. Community analysis revealed that presences of the two non-native marine algae have no significant effect on the species richness, diversity and community composition of the invaded communities. The differential distribution of the non-native marine algae may shed light on better understanding of settlement and predicting the establishment of non-native marine algae. Long term monitoring of establishment of biological invasion on the island could lay the foundation for delineating the relationship between statutory marine protection and invasion success.

Introduction

Invasive non-native species (INNS), also known as invasive alien species, are non-native species, which spread out of their origin habitat through increased global trades, successfully propagate and take over habitats off their natural range (2022). The presence of INNS has risen as a global issue as they spanned 243 countries across the globe and have brought along substantial economic and ecological impacts (Turbelin et al., 2017). Annual economic cost associated with biological invasion has exponentially increased in Europe since 1960 and accumulatively amounted to US$140.2 billion between 1960 and 2020 (Cuthbert et al., 2021a). Globally, aquatic INNS costed US$345 billion and are foreseen to keep rising in the future (Cuthbert et al., 2021b). Nine hundred and ninety four INNS are recorded in the Global Invasive Species Database, of which 734 are categorised as terrestrial, 62 as marine, 71 as fresh water and remaining species as cross-system species (2022). Extinction of native species on isolated island have been reported following invasions of non-native species (Sax and Gaines, 2008). The global prevalence of biological invasion has prompted responsive actions to be taken. Tackling biological invasions have been advocated in international conservation targets, corresponding management and control measures of biological invasions have been in place across different regions.

The call for managing biological invasions has been initiated in global environmental conferences and adopted regionally and nationally. Listed as one of the international targets in the Convention on Biological Diversity, Aichi Target 9, further spreading and establishment of INNS have to be prevented, which has followed by formulation of different directives, strategies and measures in different regions and nations (Krämer, 2021, Secretariat of the Convention on Biological Diversity, 2005). In Europe, European Union (EU) adopted a Regulation to tackle INNS and required its EU members to introduce legislation regulating INNS under the Union’s concerns. Activities concerning the release and sale of non-native animals, planting and allowing to grow are prohibited by law in different EU countries (Wildlife and Countryside Act 1981, Government of Spain, 2007). Experts have intermittently advocated the action of researching the ecological impacts to manage biological invasion (Directorate of Democratic Governance, 2015). With the establishment of Protected Areas for conserving biodiversity, their effectiveness on biological invasion has also attracted researchers' interest (Holenstein et al., 2021, Paganelli et al., 2021). Biological invasions encompass multiple ecosystems and the extent of invasion and corresponding protection managements vary in different systems.

INNS management is implemented to different extents for different ecosystems. INNS found in terrestrial habitats are more prevalent and their ecological impacts, management cost and efficacy are more extensively studied than aquatic INNS (Peyton et al., 2019, Muñoz-Mas et al., 2021). More than 1,200 events of eradications of invasive vertebrates on islands have been recorded in more than 60 countries and territories, attributing to a success rate of approximate 88% (Island Conservation et al., 2018). Proposed to incur lower cost, marine INNS management is underrepresented (Muñoz-Mas et al., 2021). Invasion of marine INNS has already reached most continents with only 16% of ecoregion free from marine biological invasion (Molnar et al., 2008). Spread through multiple pathways as a result of increased trades, including shipping, aquaculture, canal construction and more, discharge of ballast water and fouling are believed to be the primary vehicles (Molnar et al., 2008, Pinteus et al., 2021). Among different marine INNS taxa such as fish, crustaceans, algae and mollusc, invasive marine algae pose the most substantial negative impacts to native communities, leading to the greatest decline in native taxa number in one meta-analysis study (Anton et al., 2019).

In the UK, eight non-native marine algae are included in the 2021 England biodiversity pressure from invasive species indicators, which are considered to be exerting a negative impact on native biodiversity (Department of Environment Food & Rural Affairs, 2021) and their impact studies around the region remain to be continuously assessed. Rapid assessments of INNS have been conducted and reported in Scotland (Harries et al., 2007, Collin et al., 2015, Nall et al., 2015) but ecological studies on non-native algae around the

English waters have been insufficient and restricted to limited number of invasive algal species such as *Sargassum muticum* (Nall et al., 2015)*,* an established non-native brown alga first discovered in British waters in 1971 (Joint Nature Conservation Committee, 1997). Over time, more and more non-native invasive algae have been discovered and considered pressing pressures to biodiversity (Department of Environment Food & Rural Affairs, 2021). Studies on various invasive algae including *Sargassum muticum* and *Asparagopsis armata*, conducted elsewhere have shown that their effects on the invaded native ecosystems could be highly variable, even across different locations on the shore (Staehr et al., 2000, Wernberg et al., 2001, Olabarria et al., 2009, Pacios et al., 2011, Guerra-García et al., 2012, Salvaterra et al., 2013, Silva et al., 2021). Locating preferred habitats for non-native marine algae settlements, either through empirical investigation or utilizing species distribution models (SDMs) that incorporate different environmental factors, as well as anthropogenic factors have also been advocated to help predict invasion success and hot spots for different invasive species (Katsanevakis et al., 2010, Lyons et al., 2020, Blanco et al., 2021). That calls for the needs for continuous and local assessment of biological invasions to support evidence-based decision making of management actions and provide relevant data for enhancing prediction models, especially in areas of ecological importance and under established management plan such as Marine Conservation Zones (MCZs), which are statutory Marine Protected Areas (MPAs) in the UK established under international commitments and national conservation directives to protect marine environment and achieve defined conservation objectives (Department of Environment Food & Rural Affairs, 2007).

Lundy Island, located 11 miles offshore of North Devon in the Bristol Channel, is the UK's first voluntary Marine Nature Reserve since 1973 and later converted into the first established statutory MCZ around British waters in 2013 under the Marine and Coastal Access Act (Marine and Coastal Access Act 2009). Coincidently, the first discovery of tetrasporophyte stage of a non-native alga *Asparagopsis armata*, *Falkenbergia* around the

UK waters was on Lundy Island in 1949 (Harvey and Drew, 1949). Discoveries of other widely studied invasive algae, such as *Sargassum muticum* and gametophyte stage of *Asparagopsis armata* on the island have been previously reported (Reach, 2000). Owning to its long established MCZ status, monitoring of marine intertidal and subtidal biodiversity on the island has been conducted regularly (Lundy Management Forum, 2017). However, previous records were mainly qualitative and lacked quantitative records of invasive algae, nor the impact studies of these biological invaders. This study aimed to assess the general status of biological invasion on Lundy Island as a MPA case study in the UK, which could provide insights into ecological understanding of biological invasion on a local scale, as well as its implications for biological invasion management. Focuses of current study includes (1) locating the distribution of non-native marine algae around the intertidal shore of Lundy and (2) once the occurrence of non-native marine algae identified, the impacts of the more dominant invasive algae on diversity and community composition of the native intertidal algal community will be investigated.

Material and Methods

Study Area

The study was conducted on Lundy Island (51º 10’22.73 ‘’N; 4º 39‘34.77‘’W) in the Bristol Channel, south west of United Kingdom. Situated at the Bristol Channel, the west side of the island faces the open north Atlantic Ocean whilst the east faces the Bristol Channel and mainland England. Owing to more roughed and less accessible terrain on the west side, current study was primarily conducted around the south east coast of the island, where the shores are accessible by walking from the top and less exposed. Survey sites include Quarry Beach, Devil’s Kitchen and Victoria Beach (Figure 1). Devil’s Kitchen is located at the south east coast of the island with slate shore housing rockpools, gullies and large boulders. Victoria Beach is a sheltered beach mainly filled with large boulders extended northward from Landing Beach, which is next to the island’s jetty with sand and slate pebbles. Quarry Beach is located midway of the east coast of rounded boulders and cobbles. Photos showing the topography of three survey sites are grouped in Figure 2.

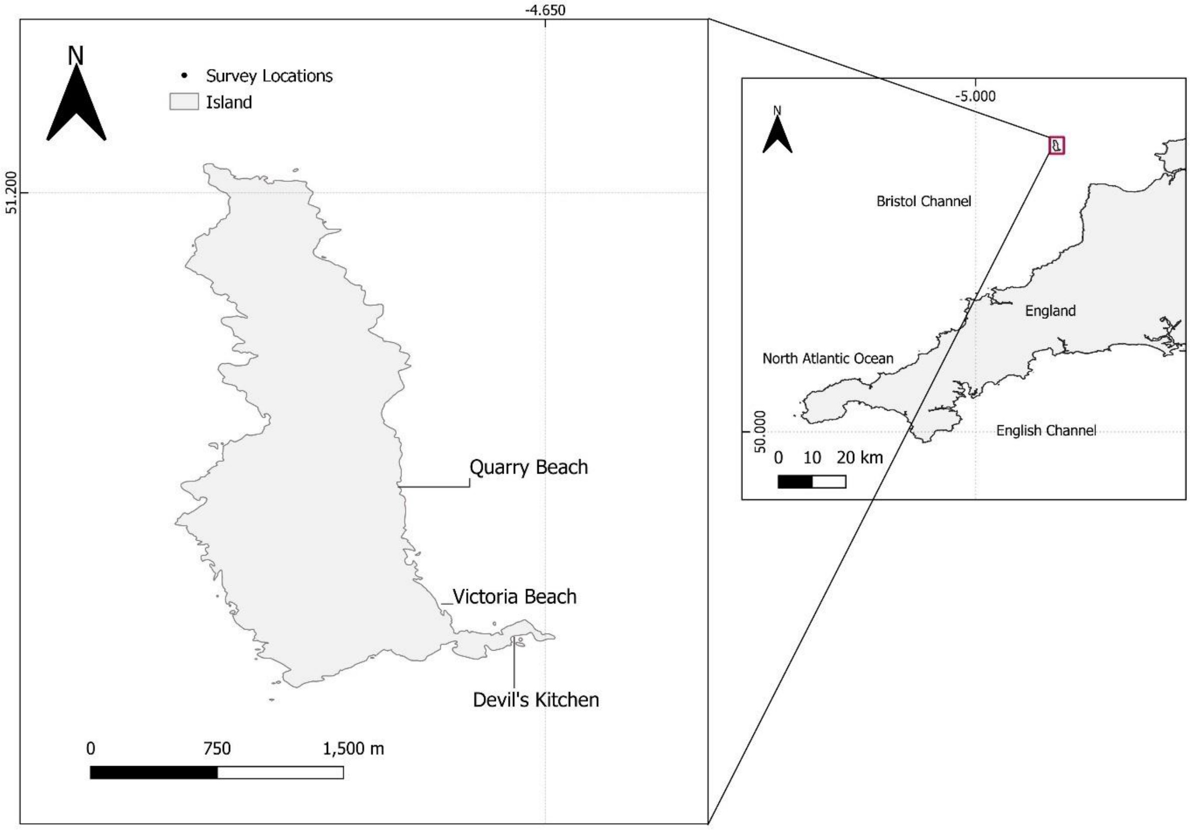

Figure 1. Map showing location of Lundy Island in the Bristol Channel and survey locations around the Lundy shores under the current study, which were Devil’s Kitchen, Victoria Beach and Quarry Beach.

Figure 2. Collage of photos showing the topography of the three survey sites: (A) Devil’s Kitchen, (B) Victoria Beach and (C) Quarry Beach. Victoria Beach and Quarry Beach have noticeably narrower tidal ranges.

Survey Design

The current assessment design involved two stages: in the first stage, a preliminary assessment of biological invasion status through identifying the presence and distribution, if any, of non-native algal species in the intertidal zone by transects was conducted at different survey sites; the second stage involved assessing the effects of selected dominant non-native algae on native algal community structure at survey sites where non-native algae were present. All surveys between higher and lower intertidal zones were conducted during low neap or spring tides of tide heights between 0.9 and 1.9m above Chart Datum. Survey period was between 18th May to 15th June 2022.

For assessing the general biological invasion status, list of nationally recognised non-native marine algal species was extracted from 'Identification guide for selected marine non-native species' as the target species (listed in Table 1) (Marine Biological Association of the UK, 2020). Preliminary assessments were conducted at Devil's Kitchen, Victoria Beach and Quarry Beach between 18th and 15th June 2022. Owing to both Victoria Beach and Quarry Beach having narrow tidal ranges, assessments were carried out along a belt transect (100m) at the lower intertidal shore of Victoria Beach and Quarry Beach, where most non-native algae settle, parallel to the shore line on 27th and 30th May 2022 respectively. Repeats at the two locations were conducted on 15th June and 13th June 2022 respectively. With a broader tidal range, two belt transects (100m) at Devil's Kitchen were conducted perpendicular to the shore line across the higher and lower intertidal zones on 18th and 20th May 2022, which were during low spring tides. The preliminary assessments have identified and located the presence of non-native algae with hand-held GPS recorded coordinates to determine the distribution of selected non-native algal species at the surveyed locations. Locations of invasive algae were mapped with the recorded coordinates using QGIS v3.16.11 (QGIS.org, 2022). As no non-native algal species was found in Quarry Beach, no further investigation on effect of non-native algae on native algal community was conducted there. It was observed that *S. muticum* was the dominant non-native alga in rockpools of

Devil’s Kitchen and *C. okamurae* on rocks and boulders around Devil’s Kitchen whilst *A. armata* was the dominant non-native marine alga at Victoria Beach. Taking into consideration of time restriction of field work period and occurrence of more non-native marine algae at Devil’s Kitchen, study on effects of non-native algal species on intertidal algal community composition was then decided to focus on *S. muticum* and *C. okamurae* at Devil’s Kitchen only. Surveys regarding the two focused species were conducted between 25th May and 12th June 2022.

Table 1. List of selected invasive non-native algae.

Non-native algal species	**Phylum**
Asparagopsis armata Harvey, 1955	Rhodophyta
Bonnemaisonia hamifera Hariot, 1891	Rhodophyta
Botryocladia wrightii (Harvey) W.E. Schmidt, D.L.Ballantine & Fredericq, 2017	Rhodophyta
Caulacanthus okamurae Yamada, 1933	Rhodophyta
Colpomenia peregrina Sauvageau, 1927	Ochrophyta
Codium fragile subsp. Fragile (Suringar) Hariot, 1889	Chlorophyta
Grateloupia turuturu Yamada, 1941	Rhodophyta
Undaria pinnatifida (Harvey) Suringar, 1873	Ochrophyta
Sargassum muticum (Yendo) Fensholt, 1955	Ochrophyta

S. muticum were predominantly found submerged in the water, either in rockpools across the intertidal zone or subtidal water. For investigation of impacts of presence of non-native alga, *S. muticum*, on native rockpool algal communities, pools of small size (0.1 – 1 m^2) along the higher to lower intertidal shore of Devil’s Kitchen were selected as they are the predominant pool sizes and it also allowed the quantification of algae abundance using quadrats. A total of seven pools were surveyed and categorised into two groups: four pools with *S. muticum* (Category S) and three pools without *S. muticum* (Category A). Each pools was photographed perpendicularly from above for later estimation of pool area using ImageJ software (Schneider et al., 2012). Pool dimensions and locations on the shore were noted to take into account of any environmental variations. To standardize the measurement of algae abundance in pools, quadrats were used to quantify the relative abundance of algae, in which presence of algae within a grid was recorded as 'present' and tallied as one grid count. There might be more than one algal species in that grid and all species present within would be tallied. Relative abundance of the algal species was then determined as number of grids the algal species was found present divided by the total number of grids of all agal species fell within.

C. okamurae grow primarily on rock and boulders in the lower intertidal shore. For studying the effect of *C. okamurae* presence on native algal communities, three line transects of 15m, each 5m apart, were conducted in mid to lower shore of Devil's Kitchen. Along the transects, random quadrats (50 cm x 50 cm with 5 cm x 5 cm grids) were placed to obtain the relative abundance of native and non-native algal species present within, in which presence of algae within a grid was recorded as 'present' and tallied as one grid count. A total of 12 quadrats were recorded and categorised into two groups: seven quadrats with *C. okamurae* (Category C) and five without *C.okamurae* (Category N). Relative abundance was then later analysed as number of grids the algal species was found present divided by the total number of grids of all agal species fell within.

Data and Statistical Analysis

All algae were identified to species level where possible using Seaweeds of Britain and Ireland guide (Bunker et al., 2017). When species could not be identified to species level on site, photographs were taken and later identified through seaweed keys, guide and published online resources. Algae not identified to species level were grouped to genus or taxonomic groups with distinct features.

For community impact analysis, replicates were categorised into 2 groups: (1) with and (2) without the non-native algae, *S. muticum* or *C. okamurae*. To assess the impact of presence of non-native algae on the native community composition, *S. muticum* and *C. okamourae* were excluded from the analysis. All relative abundance data were square root transformed before conducting statistical analysis to minimize dominance by specific abundant species. All recorded species were assigned a species code for easier community analysis in R and the complete list is summarised in Appendix I. To determine the community impact of presence of the non-native algal species, species richness, α- and β-diversity of each category were calculated and compared between groups. Species richness was defined as the number of species present in the sampled replicates. α-diversity was determined using Shannon-Weiner diversity index (H) and β-diversity using Whittaker's index and Bray-Curtis Distance Matrix. Test of significant differences in species richness and α-diversity between groups was carried out using ANOVA. For analysis with *S. muticum*, a generalized linear model (GLM, family = Poisson) of species richness against factors including pool dimensions, pool areas and pool locations on the shore was set up to test their effects on species richness. β-diversity of replicates was visualised using hierarchical clustering dendrogram. Differences in communities composition with relative abundance considered were determined with Bray-Curtis dissimilarity matrix and ordinated by non-metric multi-dimensional scaling (NMDS). Permutational multivariate analysis of variance (PERMENOVA) was applied to test the difference in community composition. All analyses were conducted using 'vegan' (2.6-2) package (Oksanen et al., 2022) in R Studio (v4.1.1) (R Core Team, 2022).

Results

3.1 Preliminary assessment of distribution of non-native algal species

Five non-native algal species were recorded from the transect surveys conducted at Devil's Kitchen and Victoria Beach. No non-native algal species were recorded at Quarry Beach. The recorded non-native algal species were *Asparagopsis armata*, *Bonnemaisonia hamifera*, *Caulacanthus okamurae*, *Colpomenia peregrina* and *Sargarssum muticum*. Records of *A. armata* were predominantly present at the low tide zone at Victoria Beach and almost absent from Devil's Kitchen. Two sightings of *B. hamifera* were present in Devil's Kitchen and one in Victoria Beach respectively at the low intertidal zone. Multiple isolated patches of *C. okamurae* were present on rocks at the lower intertidal zones of Devil's Kitchen. There was sighting of a clump of *C. peregrina* attached to *A. armata* at Victoria Beach. *S. muticum* were present in multiple pools at Devil's Kitchen, encompassing from the higher to lower intertidal zones. With more sightings, *A. armata* was the dominant non-native marine alga at Victoria Beach and *S. muticum* at Devil's Kitchen. Distributions and frequency of records of non-native algae are summarised in Table 2.

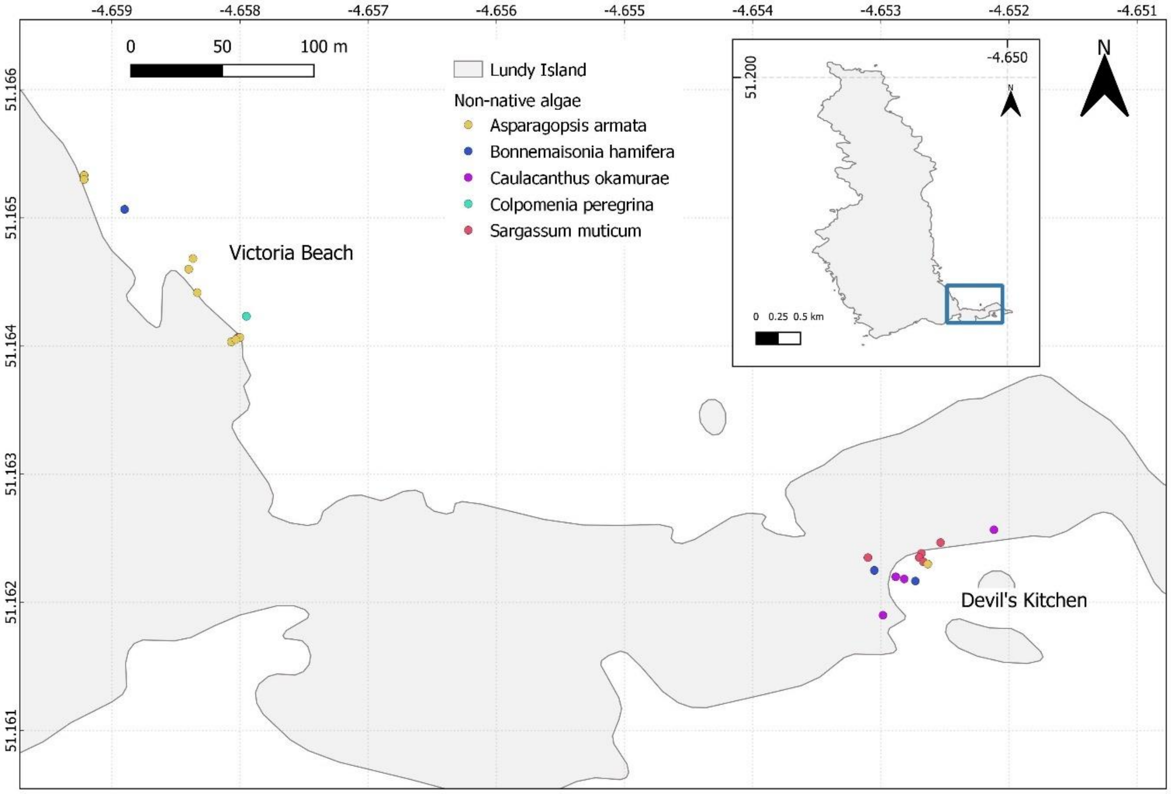

Figure 3. Map showing the distribution of five non-native algae around the south-eastern shore of Lundy Island, including Victoria Beach and Devil’s Kitchen.

Table 2. Records of non-native marine algae and their locations and distributions.

Identified non-native marine algal species	**Recorded sightings**	**Location(s)**	**Distribution**
Asparagopsis armata Harvey, 1955	10	Victoria Beach	Low tide zone
Bonnemaisonia hamifera Hariot, 1891	1 2	Victoria Beach Devil's Kitchen	Low tide zone
Caulacanthus okamurae Yamada, 1933	4	Devil's Kitchen	Lower intertidal rocks
Colpomenia peregrina Sauvageau, 1927	1	Victoria Beach	Low tide zone *attached to *Asparagopsis armata*
Sargassum muticum (Yendo) Fensholt, 1955	7 1	Devil's Kitchen Victoria Beach	Pools from higher to lower intertidal; low tide zone

3.2 Effects of S. muticum on α- and β- diversity of native algal assemblages in pools

There were a total of 16 algal species identified in the surveyed pools, of which three species were present only in pools with *S. muticum*, five in pools without *S. muticum* , six present in both categories. The list of species identified in respective categories are summarised in Table 3. The mean species richness in pools with *S. muticum* (S) was 5.75 ± 0.854 (SE) and the mean Shannon-Wiener Diversity Index was 1.673 ± 0.148 whilst that in pools without *S. muticum* (A) was 5 ± 1 and 1.562 ± 0.182 respectively (Figure 4). There was no difference in species richness (ANOVA: $F_{1, 5}$ = 0.327, P = 0.592) and Shannon-Wiener Diversity Index (ANOVA: $F_{1, 5}$ = 0.231, P = 0.651) between the two categories. Mean species richness did not vary significantly with pool dimensions and pool locations on the shore (GLM, Pool depth: x_1 = -2.44, P = 0.118; Pool area: x_1 = -2.55 , P = 0.110; shore location: x_2 = -1.31, P = 0.519). Hierarchical cluster dendrogram of beta diversity among pools based on Whittaker's Index and Bray-Curtis distance matrix revealed there were no distinct groupings of the two categories, only pools A2 and A3 showed the closet similarity in both dendrograms (Figure 5). The plot of NMDS showed the compositions of the two communities were different but the difference was insignificant (PERMANOVA: F = 1.807, df = 1, P = 0.113) (Figure 6).

Table 3. List of identified algal species in pools at Devil’s Kitchen. ‘+’ denotes present and ‘-‘ denotes absent. Pools with *S. muticum* are categorized as ‘S’ and those without ‘A’.

	Category	
Species	**A**	**S**
Ulva lactuca	+	+
Ceramium sp.	-	+
Cladophora rupestris	-	+
Corallinaceae crusts	+	+
Ulva intestinalis	+	+
Mesophyllum lichenoides	-	+
Chondrus crispus	+	+
Filamentous reds	-	+
Filamentous reds	-	+
Polysiphonia sp.	+	+
Corallina officinalis	+	+
Cladophora sp.	+	-
Filamentous browns	+	-
Polysiphonia sp.	+	-

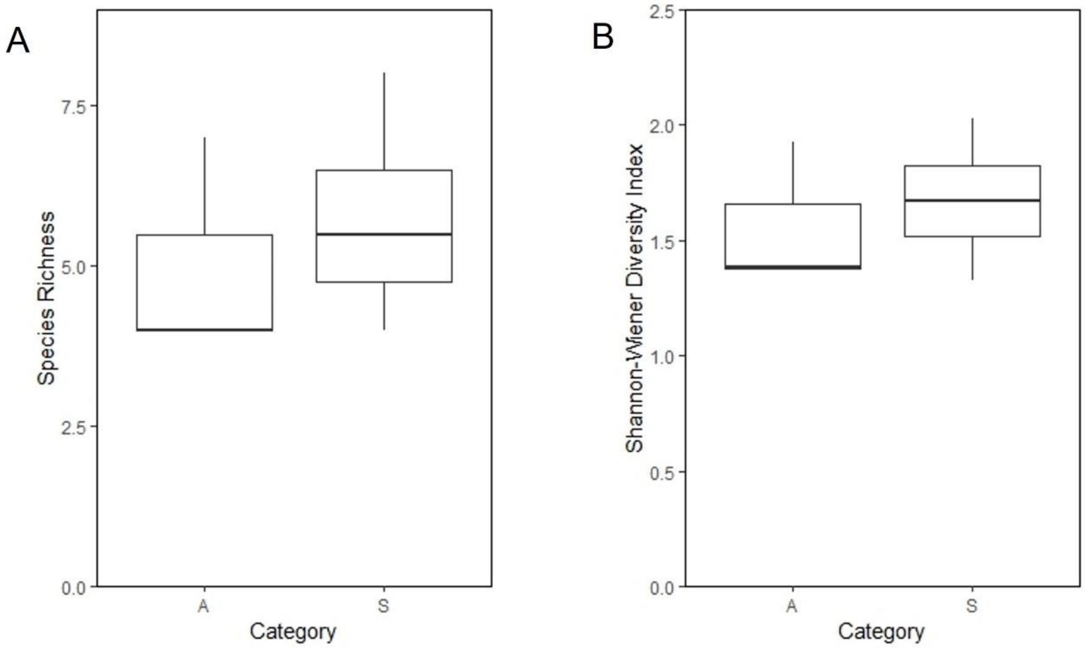

Figure 4. (A) Species richness and (B) Shannon-Wiener Diversity Index of pools with (Category S) and without *S. muticum* (Category A).

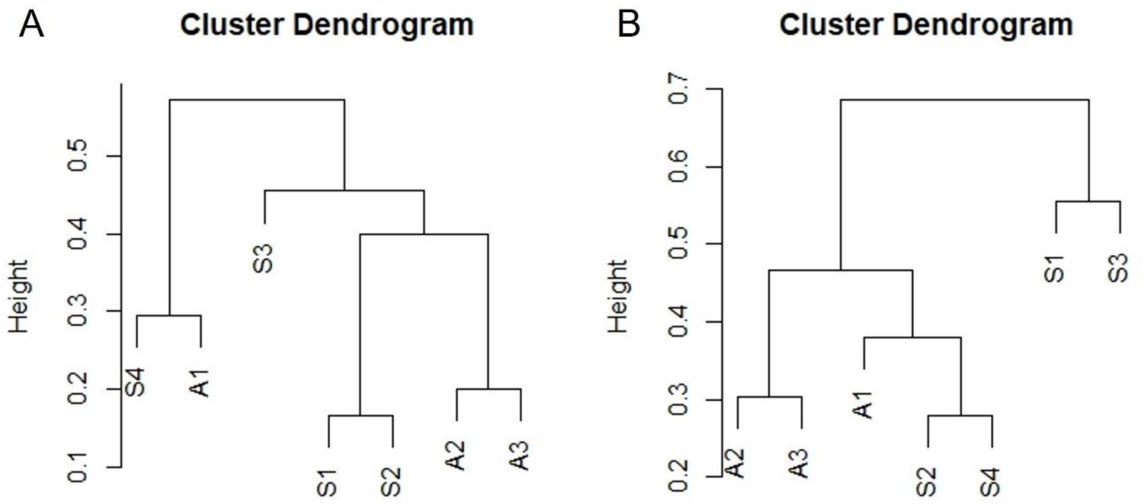

Figure 5. Hierarchical clustering dendrogram of pools with (S1-4) and without (A1-3) *S. muticum* using (A) Whittaker diversity index and (B) Bray-Curtis Distance Matrix.

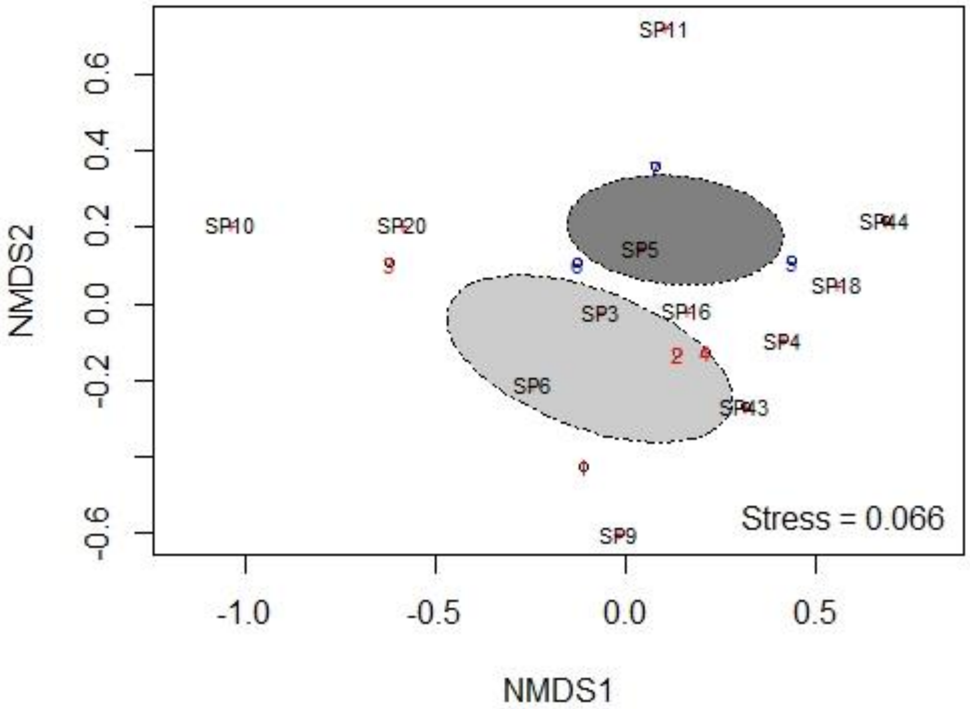

Figure 6. NMDS plot of algal assemblage of pools with (centroid in black) and without *S. muticum* (centroid in grey).

3.3 Effects of C. okamourae α- and β- diversity of native algal assemblages on rocks

Fifteen algal species were recorded in the surveys, of which eight were present in both categories, three present in quadrats without *C. okamurae* and four present only in quadrats with *C. okamurae*. The list of species identified in the quadrats are summarised in Table 4. Mean species richness and Shannon-Wiener Diversity Index in quadrats with *C. okamurae* (C) were 5.29 ± 0.680 and 1.56 ± 0.166 respectively and that in quadrats without *C. okamurae* (N) were 6.8 ± 1.80 and 1.85 ± 0.121 (Figure 7). ANOVA results suggested there was no difference in species richness ($F_{1,10}$ = 2.08, P = 0.18) and Shannon-Wiener Diversity Index ($F_{1,10}$ = 1.72, P = 0.219) between the two categories. Beta diversity analysis presented in hierarchical cluster dendrogram based on Whittaker's Index and Bray-Curtis distance matrix showed the two categories formed no distinguished groupings (Figure 8). Quadrats C5 and C6 had the closest resemblance in both dendrograms (Figure 8). NMDS plot revealed a slight overlap in community composition of the two categories and PERMANOVA suggested there was no difference in community composition of the two categories (F = 1.49, df = 1, P = 0.192) (Figure 9).

Table 4. List of identified algal species on rocks at Devil's Kitchen. '+' denotes present and '-' denotes absent. Quadrats with *C. okamurae* are categorized as 'C' and those without 'N'.

	Category	
Species	**C**	**N**
Chondrus crispus	+	+
Osmundea pinnatifida	+	+
Ulva intestinalis	+	+
Fucus vesiculosus	+	-
Ulva lactuca	+	+
Ceramium sp.	+	+
Corallina officinalis	+	+
Leathesia difformis	+	-
Lomentaria articulata	+	+
Himanthalia elongata	+	+
Ahnfeltia plicata	+	-
Cladophora sp.	-	+
Fucus serratus	-	+
Cladophora rupestris	-	+
Palmaria palmata	-	+

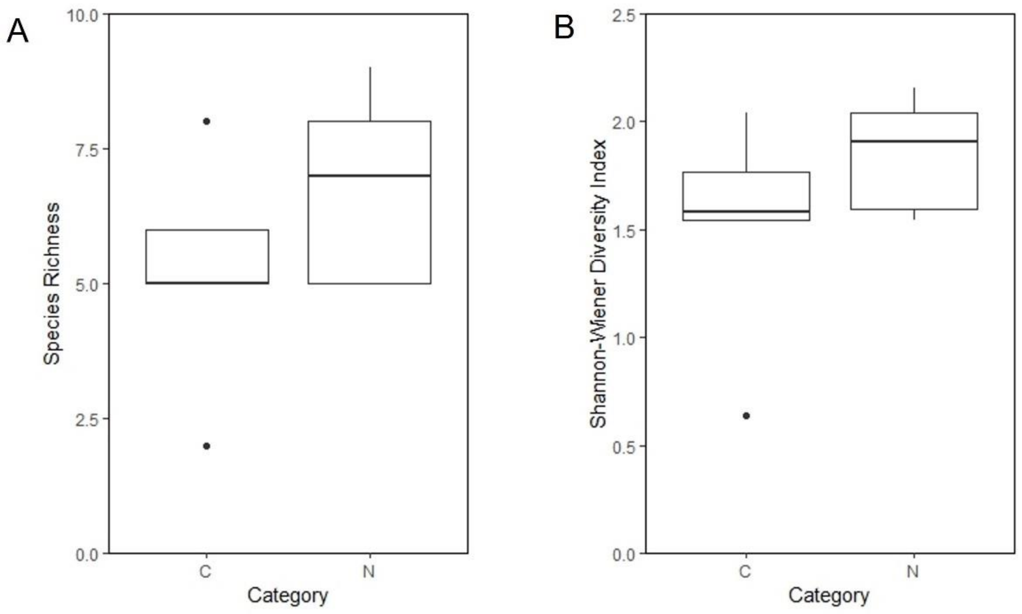

Figure 7. (A) Species richness and (B) Shannon-Wiener Diversity Index of pools with (Category C) and without *C. okamurae* (Category N).

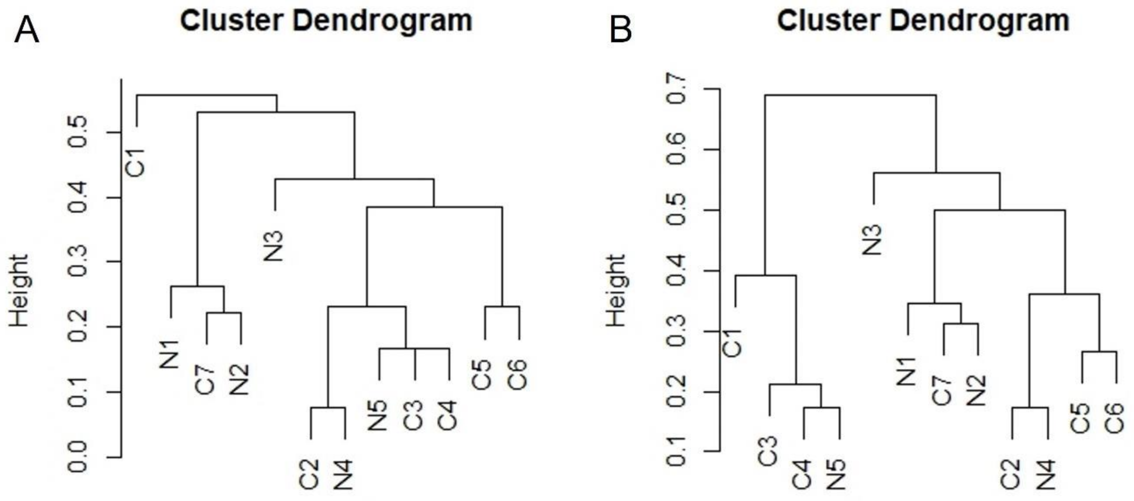

Figure 8. Hierarchical clustering dendrogram of quadrats with (C1-7) and without (N1-5) *C. okamurae* using (A) Whittaker diversity index and (B) Bray-Curtis Distance Matrix.

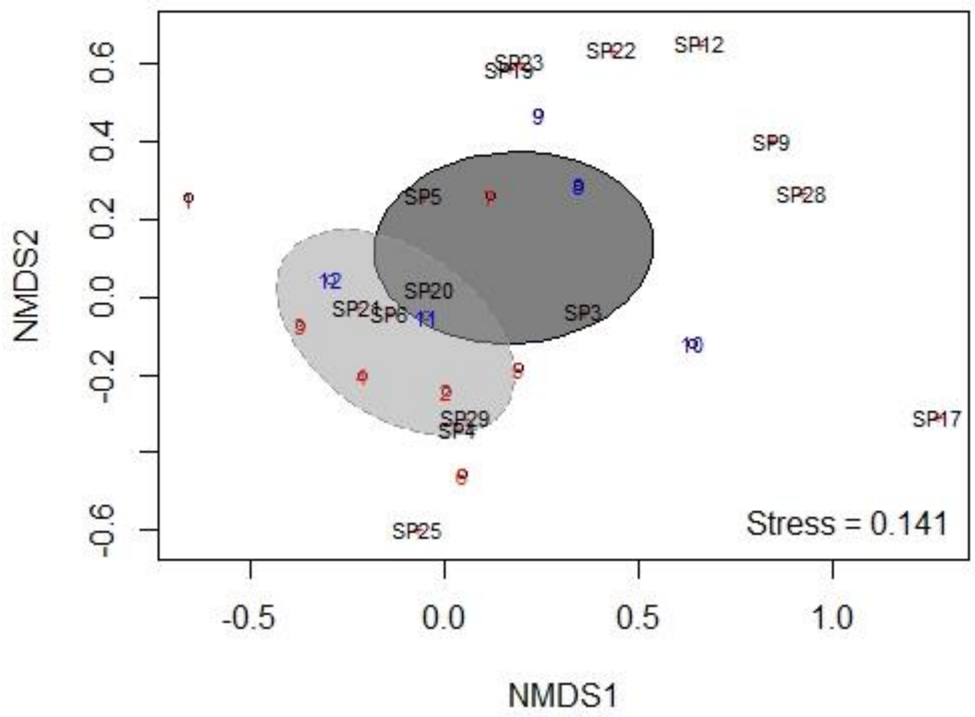

Figure 9. NMDS plot of algal assemblages of quadrats with (centroid in black) and without *C. okamurae* (centroid in grey).

Discussion

The occurrence of non-native marine algae on Lundy Island could be dated back to as early as first sighting of *Falkenbergia* in 1949 and sightings of other non-native algae from 1972 onwards (Harvey and Drew, 1949, Hainsworth, 1975, Reach, 2000), however, their distributions have not been intensively studied and impacts on native algal assemblage yet elucidated. Current investigation has revealed the algal biological invasion status and the presence of several non-native marine algae, including *S. muticum*, *A. armata*, *B. hamifera*, *C. okamurae* and *C. peregrina* on the south-eastern shore on Lundy and their occurrence were differential. *S. muticum* and *C. okamurae* were found to be the predominant non-native algae at Devil's Kitchen and their presences have shown to have no significant impact on the native intertidal algal community diversity and composition.

Presence of non-native marine algae on Lundy Island has been previously recorded in local reports of the island and comparing these records with the current findings may suggest a gradual spread or settlement of some of the non-native marine algae to the intertidal zone on the island. *B. hamifera* was first reported at the low water of Landing Bay in 1972, *A. armata*, the gametophyte stage at the subtidal of Landing Bay in 1975, *S. muticum* at the subtidal between north Rat island and the jetty in 1999, *C. peregrina* at Devil's Kitchen in 2012 and *C. okamurae* at Devil's Kitchen in 2021 (Hainsworth, 1975, Reach, 2000, Davis and Jones, 2012, Hiscock and Irving, 2022). Most of the previous records of these non-native algae were at low water or subtidal and few were reported from the intertidal zone in their first reports. Later reports in 1999 and 2012 have seen *A. armata* and *S. muticum* in rock pools at Devil's Kitchen and *C. peregrina* at Devil's Kitchen but habitat unidentified (Reach, 2000, Davis and Jones, 2012, Hiscock and Brodie, 2016). Current study focused on the intertidal shore and has spotted the occurrence of five non-native marine algae, suggesting the occurrence of identified non-native marine algae is not limited to subtidal shore of the island as in the earliest records. As there are lack of previous records of abundance of these non-native algae at the intertidal zone over the year, it is inconclusive to describe the changes in abundance over the past years. All non-native marine algae identified here have already been observed around south west England and all, except *C. okamurae*, are classified as established across the UK (NBN, 2022), which suggests that their occurrence could be a result of regional spread. Unpublished observation of *S. muticum* and *A. armata* has suggested year-to-year variation of abundance of these species (Hiscock, 2021). Future efforts should focus on longitudinal monitoring of establishment of these non-native marine algae on the island, with specific note on their variety and abundance.

Preliminary assessment of occurrence of non-native marine algae suggested a differential distribution of the marine invaders at the intertidal shores of the island. Previous studies have indicated that the occurrence of biological invasion takes place at proximity of artificial structures such as ports, marinas, jetties and etc where the invaders might be brought in by vessels (Glasby et al., 2006, Minchin, 2007). The findings on Lundy Island are in line with other reporting with most occurrence recorded around the island's jetty (Victoria Beach and Devil's Kitchen) but not in the intertidal zone of Quarry Beach located further north of the jetty, suggesting also that the spread of the biological invasion remained restricted at the time of surveys. The absence of marine invaders further north might also be attributed to the directions of tidal streams of the island, of which along the east coast of the island, tidal streams generally come from the north (Lundy Management Forum, 2017), making the marine invaders possibly arrived via vessels from the mainland unlikely to drift northward and settle. Further analysis of hydrology should be carried out to confirm such speculation. Of the more frequently recorded non-native marine algae, *S. muticum* and *A. armata*, their distributions varied and did not seemingly overlap with each other, in which *S. muticum* were predominantly found in rock pools at Devil's Kitchen whilst *A. armata* were recorded in the lower intertidal zone at Victoria Beach. The absence of *S. muticum* at Victoria Beach is probably mainly due to the different topographies and hence microhabitats between the two sites, in which Victoria Beach is absent of intertidal rock pools, where *S. muticum* are mostly situated within the intertidal zone. Reported previously, differences in microhabitat characteristics may be the factor undermining the reliability of the SDM for *S. muticum*, as compared with prediction models for other non-native marine algae, including *A. armata* (Blanco et al., 2021). Present findings highlight the importance of studying distributions, particularly in small spatial scales, of non-native algal species. At Devil's Kitchen, the differential distribution may imply different establishment status of the biological invasion of the two algal species and different determining factors on the establishment status. Both *S. muticum* and *A. armata* were known to occupy similar habitat range close to the lower intertidal to subtidal zone and they were reported to be present in rock pools (Smith, 2016, Silva et al., 2021). Previous reports of algal species on Lundy have recorded presence of both *S. muticum* and *A. armata* in pools at Devil's Kitchen (Hiscock and Brodie, 2016, Hiscock, 2021), which contradicted with current findings in this study. Despite a clearance programme of *S. muticum* has been carried out over the years (Hiscock and Brodie, 2016), there was still establishment of *S. muticum* observed in the current investigation but no records of *A. armata* in rock pools at Devil's Kitchen. Current findings may be suggestive of a more resistant establishment of *S. muticum* against removal programme. But the cause of disappearance of *A. armata* from rock pools at Devil's Kitchen remains elusive. The factors, whether they are environmental or ecological, contributing to the change in establishment status are far from conclusive because of lack of monitoring data and studies to give consolidated evidence supporting potential theories of change. Long term quantitative monitoring of algal communities and biological invasion on the island is essential to delineate the variation of abundance of non-native algae over time with possibility of including climate change effect (Beaury et al., 2019) and assist in bettering SDM of non-native algae invasion for informing evidence based management recommendations such as seasonal control and prioritizing invasion hot spots. At the same time, such data could be indicative of the mechanisms of spread of the non-native algae, which could provide crucial insights into controlling approaches, especially taking into consideration of habitat preferences for different non-native marine algae and other environmental factors that may determine establishment of the invaders.

Numerous research has focused on the vulnerability of or protection offered by biologically diverse MPA to biological invasion (Cacabelos et al., 2019, Blanco et al., 2020) and current findings on Lundy may add to collection of information for further understanding of their relationships. Intertidal pools and gullies at Devil's Kitchen housed the most numbers of non-native algae recorded, 4 out of 5 of the non-native algal species recorded in this study were present at Devil's Kitchen. Continuous monitoring of shores around Lundy Island has identified Devil's Kitchen having the most diverse algal composition of more than 200 algal specie recorded (Hiscock and Brodie, 2016). The higher frequency of non-native algae present there could be its location being slightly more exposed and unique topography of slate housing numerous rock pools, an acknowledged diverse habitat. Some studies have revealed that high biodiversity, in cases such as long established PAs, are more resistant to biological invasion but marine MPAs are more susceptible to invasion with higher invasion frequency (Gallardo et al., 2017). On the other hand, others have suggested that MPAs have limited effects on non-native algae distribution (Cacabelos et al., 2019, Blanco et al., 2020). Conservation effectiveness varies with MPAs and is reported to be location-specific, possibly related to different management approaches during conservation planning (Giakoumi et al., 2016, Caselle et al., 2018). Current findings on Lundy captured the glimpse of biological invasion status as it is limited by assigned field work period length. Long term assessment of biological invasion at Devil's Kitchen could provide more insight delineating the relationship between biodiversity and success of biological invasion.

Invasion of *S. muticum* in rock pools was shown to have no effects on native intertidal algal species richness, diversity and community composition from the current studies as suggested by the ANOVA and PERMANOVA analysis. *S. muticum*, native to South East Asia waters, have distribution spanning from Scotland to the Mediterranean in Europe and is listed as one of '100 Worst Invasives' in the Mediterranean (Streftaris and Zenetos, 2006, Harries et al., 2007). Similar impact studies on intertidal pools conducted in Southern California reported also lack of effects of invasion by *S. muticum* despite changes in abiotic factors such as reduced light penetration and temperature in pools (Smith, 2016). Current findings are resembling findings conducted at the intertidal zone of other locations. Impact studies of *S. muticum* at the intertidal zone conducted in Spain reported no effects on the community structure but negative impacts on total taxa number and certain algal functional groups (Olabarria et al., 2009). Despite statistically insignificant, current findings showed that species richness and Shannon-Wiener Diversity in pools with the presence of *S. muticum* were slightly increased, which may hint that the effects were not completely negative. A density dependent impact of *S. muticum* on native community diversity was also reported from a study in Canada, suggesting high density of *S. muticum* cover would exclude native algae whilst lower density would promote species richness as compared to complete removal (White and Shurin, 2011). Variable impacts of *S. muticum* invasion are not only reported at the intertidal. At the subtidal, findings were shown to have neutral or positive impacts on native algal assemblages (Staehr et al., 2000, Thomsen et al., 2005). It is also suggested that *S. muticum* invasion leads to seasonality of species richness and abundance pattern of algae (Thomsen et al., 2005). Whether their establishment on Lundy Island would resemble the same scenario remains to be investigated. Current study focused only on the algal community structure impact of the biological invasion, their effects on other native taxa have yet been studied. Also, only small rock pools have been investigated in the current study and may not be conclusive for pools of larger sizes, which have more complex community structure due to the added depth, surface area and varying abiotic factors such as light penetration.

Current community study on *C. okamurae* is the first around the UK waters and its impact findings could provide foundations for future impact studies. *C. okamurae* is native to Asia and Indo-Pacific water (Guiry and Guiry, 2022). The first record of presence of *C. okamurae* in the UK could be dated back to 2004 and now the non-native alga is considered well established as often abundant and dominating turf in some localised areas of the UK, including Kent, Cornwall and Devon (Department of Environment Food & Rural Affairs, 2021). Limited studies have been carried out on this non-native alga with only 6 searches appeared on Web of Science using the keyword '*Caulacanthus okamurae*' (Science, 2022). Present observation and investigation suggested *C. okamurae* grow often on *Osmundea pinnatifida* and *Chondrus crispus* but they have no effects on species richness, diversity and community composition of native algal community growing on rocks, suggesting that other native algae were not excluded in *C. okamurae* occupied areas. It was observed that *C. okamurae* grow as isolated turf patches on rocks and their seasonality growth trend was only recently be studied and was not conclusive of any seasonal variation (Day, 2018). Unknowns such as the turf size, density and their relations to community composition structure remain to be investigated. *C. okamurae* growing on rocks may also compete with other invertebrates of gastropods such as limpets, periwinkles and sea slugs, which also live on rocks. Further studies may investigate the effects of *C. okamurae* on other sessile invertebrates other than algal communities to have a more extended view of impacts of biological invasion on native biodiversity.

Biological invasion of non-native species have been incurring enormous economic costs and posing substantial threats to the invaded native ecosystems. Despite the initiatives to combat biological invasion on international and regional settings have been set up for decades, efforts put in managing biological invasions are unbalanced, in which marine INNS management is underrepresented. Non-native marine algae have been intensively studied and considered one of the worst invaders in the marine ecosystem. There is a lack of studies assessing the impact of biological invasions by non-native algae on MPA in the UK. Assessing the biological invasion status of the first statutory MCZ in the UK, Lundy Island as a case study, has revealed presence of five non-native marine algae in the intertidal shores. The differential distribution of these non-native marine algae may inform that future monitoring and enhancement of SDM for predicting invasion success, as well as controlling programme should be designed with species-targeted approach. Analysis on community impacts of two non-native marine algae, *Sargassum muticum* and *Caulacanthus okamurae* have been conducted and suggested to have no effects on the species richness, diversity and community composition of the native algal community. Current findings will lay the foundations for long term monitoring and community impact studies of non-native algae on the island for informed decision making of management approaches and control measures on biological invasion of the MPA.

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Appendix I. Species codes assigned to marine algae sighted in the surveys.

Species	**Assigned codes**
Ulva lactuca	SP3
Ceramium sp.	SP6
Cladophora rupestris	SP9
Corallinaceae crusts	SP16
Ulva intestinalis	SP4
Mesophyllum lichenoides	SP10
Chondrus crispus	SP20
Filamentous reds	SP45
Filamentous reds	SP43
Polysiphonia sp.	SP18
Corallina officinalis	SP5
Cladophora sp.	SP12
Polysiphonia sp.	SP44
Filamentous browns	SP11
Fucus serratus	SP28
Palmaria palmata	SP17
Lomentaria articulata	SP22
Himanthalia elongata	SP23
Leathesia difformis	SP29
Fucus vesiculosus	SP25
Osmundea pinnatifida	SP21
Ahnfeltia plicata	SP19