FastTrack publication

Bull Mar Sci. 100(0):000–000. 2024
https://doi.org/10.5343/bms.2023.0104

research paper

Citizen science monitoring uncovers resilience of intertidal assemblages in a tropical urban environment

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2023 APCRS

Proceedings of the 5th Asia-Pacific Coral Reef Symposium

Guest Editors:
Zeehan Jaafar, Lionel Ng, Peter Todd, Karenne Tun, Danwei Huang

Handling Editor:
Danwei Huang

Date Submitted: 12 October, 2023.
Date Accepted: 29 March, 2024.
Available Online: 29 March, 2024.

ABSTRACT.—Coastal intertidal sand and mudflats are home to a rich and uniquely evolved ecological community. With increasing knowledge of the importance of these ecosystems and the threats they are facing, efforts to conserve them have become a priority to many coastal managers. However, these can be constrained by knowledge gaps and resource limitations, and citizen science is an emerging strategy to complement traditional methods of data collection. Intertidal Watch is a citizen science program that was set up in Singapore in 2016 to better understand and monitor the biodiversity of Singapore's urban tropical intertidal ecosystems. It also aims to increase public awareness of marine habitats by involving members of the community in citizen science. Through analyzing eight years of data collected by Intertidal Watch, this study documented rich ecological diversities in four intertidal sand and mudflats located in areas that had been reclaimed between the 1970s and 1980s, with evident community distinctions between a macroalgae-dominant site and the remaining seagrass-dominant sites. While there were fluctuations in biological populations over time, study sites were observed to largely remain resilient to changes in direct anthropogenic pressures. Our study highlights the power of citizen science in facilitating systematic conservation while bringing about positive community benefits.

Coastal regions contain two-thirds of the world's largest cities, supporting human populations three times as dense as the global average and experiencing accelerated rates of urbanization (Small and Nicholls 2003, McGranahan et al. 2007, Blackburn et al. 2013). It is therefore unsurprising that coastal ecosystems are particularly at risk from anthropogenic threats such as climate change, resource exploitation, pollution, and biodiversity loss (Pauly et al. 2005, Halpern et al. 2007, Halpern et al. 2008, United Nations 2021). A key question that has arisen in the face of these developments is the long-term impact of direct and indirect anthropogenic pressures on these habitats, one that citizen science can help address.

Citizen science programs are often used as a method to improve conservation outcomes by achieving comprehensive ecosystem monitoring and identifying habitats under threat (Roelfsema et al. 2016, McKinley et al. 2017, Gouraguine et al. 2019). These projects involve the collaboration of scientists and nonprofessionals in the collection and analysis of environmental data, increasing the capacity and scale of data collection possible within a given timeframe and resource budget (Dickinson et al. 2012, Bela et al. 2016). At the same time, citizen science gives members of the public an opportunity to gain awareness of local biodiversity, a crucial aspect in realizing conservation outcomes (Sodhi et al. 2011). It has been reported that those who participate in citizen science gain a greater appreciation of their natural environment and may even develop more proenvironmental behaviors as a result (Jordan et al. 2016, MacPhail and Colla 2020).

There are specific advantages to establishing citizen science programs in urban coastal environments. As previously mentioned, these environments experience acute impacts from development (Small and Nicholls 2003), making long-term biodiversity information critical to understanding ecological changes. Secondly, people living in urban areas often face extinction of experiences with nature (Leather and Quicke 2010), and greater exposure to the natural environment can bolster public sentiment towards stronger conservation targets (Soga and Gaston 2018). While citizen science programs have become increasingly popular in urban coastal and marine environments, such as coral reefs and seagrass habitats (Yaakub et al. 2014, Guest et al. 2016), it remains that these programs have not been extended to these ecosystems as widely as in terrestrial and freshwater habitats (Lim and Lim 2009, Cigliano et al. 2015, Ang et al. 2021). This could be due to perceived safety concerns, inaccessibility of sites, and costliness of equipment (Theobald et al. 2015). Therefore, the task facing conservation practitioners is to develop effective strategies to bring more citizen scientists into coastal ecosystems.

Singapore, a tropical island city-state in Southeast Asia, contains around 5.00 km^2 of intertidal sand and mudflats as of 2011 (Lai et al. 2015). Land reclamation has reduced much of this area since 1819, particularly from the 1960s onwards with the intensification of coastal development (Chia et al. 1988, Powell 2021). Hilton and Manning (1995) recorded a 75% reduction in intertidal sand and mudflats in Singapore between 1953 and 1993, and found a considerable portion of the remaining intertidal area significantly altered or fragmented by these developments. Few studies have documented biological communities on reclaimed intertidal sites in Singapore, and these remain largely qualitative (e.g., Tan et al. 2016, Lim et al. 2020). Studies have found that intertidal flats can support a diversity of uniquely adapted taxa and concurrently provide a multitude of ecosystem services, including serving as foraging grounds for a range of marine fauna, provisioning resources to coastal communities, and serving as substantial blue carbon stocks due to the high primary productivity of benthic macrophytes such as seagrass and macroalgae (Newell 1976, Smith 1981, Mouritsen and Poulin 2002, Hill et al. 2015, Phang et al. 2015, Tan et al. 2016, Espadero et al. 2020). Therefore, the strong research and conservation imperative for these habitats, along with their relative accessibility to the public, presented an ideal opportunity for the citizen science program Intertidal Watch (Koss et al. 2009, Kelly et al. 2020).

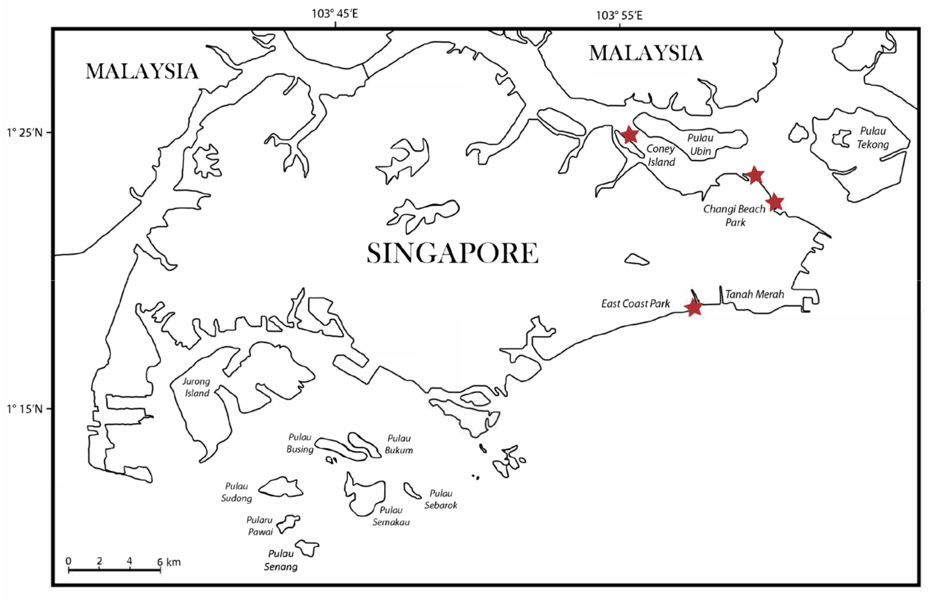

Figure 1. Map showing location of Intertidal Watch sites (red stars).

In line with Singapore's national targets under the National Biodiversity Strategy and Action Plan (NBSAP), the program Intertidal Watch was initiated to document the ecology of four urban intertidal flats to facilitate science-based decision making, while giving members of the public the opportunity to experience and learn more about Singapore's intertidal ecosystems (National Parks Board 2017, Convention on Biological Diversity 2020). This study summarizes the data collected by Intertidal Watch over eight years, comparing the assemblages of four intertidal study sites and analyzing the characteristics and trends of each site based on their floral and faunal communities. It also demonstrates how a program with minimal requirements in terms of running costs and entry level of participants can collect robust data to strengthen our understanding of these habitats.

Materials and Methods

Site Selection and Descriptions.—Intertidal Watch was conducted across four intertidal sand and mudflat sites adjacent to coastal parks in Singapore: Changi Beach Park Carpark 1 (CHG1), Changi Beach Park Carpark 7 (CHG7), Coney Island Area A (CONA), and East Coast Park Area G (ECPG; Fig. 1). These four sites have sandy substrate at the high shore zone which transitions into silty sediment at the mid-to-low zones, with seagrass and macroalgae macrophyte taxa. They were selected for their ease of accessibility to citizen scientists and sufficiently large intertidal flat areas and are all located in areas that were reclaimed between 1974 and 1987 as part of Singapore's coastal expansion (*The Straits Times* 1976, Ang 2018, Lim et al. 2020, Ministry of Defense Singapore 1974, 1975, 1978, 1983, 1987).

Survey Methodology and Volunteer Training.—Surveys were conducted between April 2016 and August 2023. The high (0–10 m from the high tide mark),

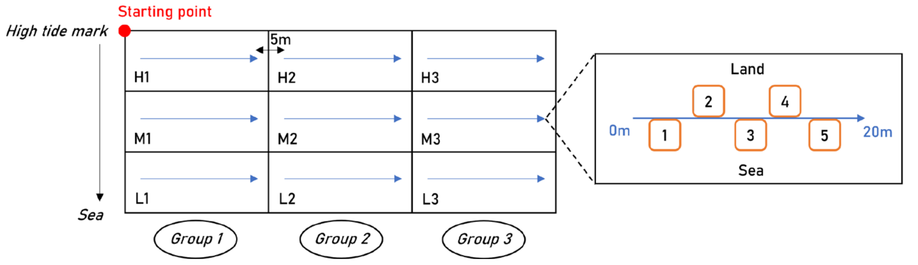

Figure 2. Zoning of shore into the High (H), Mid (M), and Low (L) zones, grouping of transects, and laying of quadrats (orange) along each transect line (blue).

mid (10–20 m from the high tide mark), and low (20–30 m from the high tide mark) zones of respective sites were marked from a fixed starting point, and three 20 m transects were placed within each zone, parallel to the shoreline. Five 0.5 × 0.5 m quadrats were then placed at random points along each of the transects, either on the landward or seaward side of the transect tape in an alternating fashion (Fig. 2). Each group surveyed one transect (five quadrats) in each of the high, mid, and low zones. At each quadrat, groups would first take a bird's-eye-view photo of the quadrat, estimate the percent cover of each floral species (with the remainder percentage representing bare ground), and count faunal individuals within each quadrat till exhaustion.

All groups first surveyed quadrats starting from the one closest to the starting point, proceeding rightwards and taking care to avoid disturbance of subsequent quadrats. Quadrats that could not be accurately verified or quantified due to being submerged were excluded from statistical analysis to reduce bias or errors. Notable species encountered at the survey sites outside quadrats were also recorded separately. Surveys were conducted over a two-hour period where the tide levels were below 0.3 m Chart Datum. As far as possible, each site was surveyed four times per year, within each of the following periods: the Northeast monsoon in December to early March, the Inter-monsoon from late March to May, the Southwest monsoon from June to September, and the second Inter-monsoon from October to November (hereby referred to as "seasons" throughout; Sin et al. 2016).

Intertidal Watch volunteers were recruited via NParks' various social media channels and email dissemination lists. Each survey group consisted of 3–4 volunteers and at least one NParks staff or volunteer who was experienced with the survey protocol and species identification. Before attending the surveys, volunteers were briefed on the survey protocol and identification of common intertidal species, either through an in-person training session or an online briefing video. Volunteers were provided with an identification guide for intertidal species at the survey site. Organisms were visually identified to the lowest taxonomic level possible (hereby referred to as "species" throughout). Species identifications and estimation of vegetation percent cover were agreed upon by group consensus. Where there were uncertainties in identification, experienced staff were consulted. In cases where the staff on-site were not able to identify the species, taxa experts were consulted via photographs. Photos of all species observed were also taken by volunteers and subsequently re-verified by staff post-survey.

Data Processing and Analysis.—All statistical analyses were conducted in R v4.2.2 (R Core Team 2022). When more than one survey was completed per season per site, the survey with the greatest number of surveyed quadrats was used in the data analysis. The diversity of flora and fauna in each site was calculated using the Shannon–Wiener diversity index. SIMPER analysis was conducted for the 10 most abundant floral and faunal species across the sites and was used to account for the contributions by different species to the dissimilarities between sites in pairwise comparisons (Clarke 1993). Community assemblages across sites and years were visualized using nonmetric multidimensional scaling (nMDS) under a log(1+x) transformation with the Bray–Curtis distance measure. A Bray–Curtis dissimilarity matrix was constructed for the assemblages, and a permutational multivariate analysis of variance (PERMANOVA) was used to measure the differences between the assemblages. The PERMANOVA was conducted using three factors: site (4 levels, fixed), year (8 levels, fixed), and season (4 levels, fixed). *P*-values for the SIMPER and PERMANOVA analyses were based on 999 permutations.

Additional PERMANOVAs and pairwise comparisons were conducted across years within sites (8 levels, fixed). nMDS, SIMPER, and PERMANOVA were carried out in the vegan package v2.6-4 (Oksanen et al. 2022). Each datapoint in the nMDS comprised data from one survey, while the SIMPER and PERMANOVA analyses comprised data from one group within a survey. One survey datapoint was removed from the faunal dataset for the nMDS, while three group datapoints were removed from the SIMPER and PERMANOVA analysis as they contained zero data. To understand the relationship between floral and faunal communities, a Pearson's rank correlation test was used to investigate the correlation between seagrass and macroalgae percent cover, respectively, with faunal species richness, density, and diversity within quadrats.

Results

Spatial and Temporal Trends in Intertidal Assemblages.—A total of 96 surveys were conducted and analyzed across the four sites over eight years. One hundred and sixty eight faunal species and 32 floral species were identified across 3149 quadrats (1211 in the high zone, 1127 in the mid zone, and 811 in the low zone) over the four sites. Faunal communities across sites largely comprised polychaetes, tunicates, molluscs, and arthropods while floral assemblages consisted of seagrass and macroalgae species. A total of 118 and 29 faunal and floral species respectively were recorded at CHG1, 121 and 28 faunal and floral species respectively at CHG7, 91 and 21 faunal and floral species respectively at CONA, and 101 and 29 faunal and floral species respectively at ECPG. Notable native species recorded across all sites included the locally vulnerable *Carcinoscorpius rotundicauda* (mangrove horseshoe crab) and *Tachypleus gigas* (coastal horseshoe crab) and the near threatened *Cymbiola nobilis* (noble volute; National Parks Board 2023a).

Average vegetation cover was higher in the sites at Changi Beach (CHG1 and CHG7) as compared to the other two sites (Fig. 3), while floral diversities across all four sites were comparable (Table 1). *Halophila ovalis* (spoon seagrass) was the dominant floral taxa in the Changi Beach sites, with an average percent cover of 40.16% and 34.76% across all quadrats surveyed in CHG1 and CHG7, respectively. In contrast, the macroalgae *Ulva* sp. (sea lettuce) contributed the most to vegetation cover in

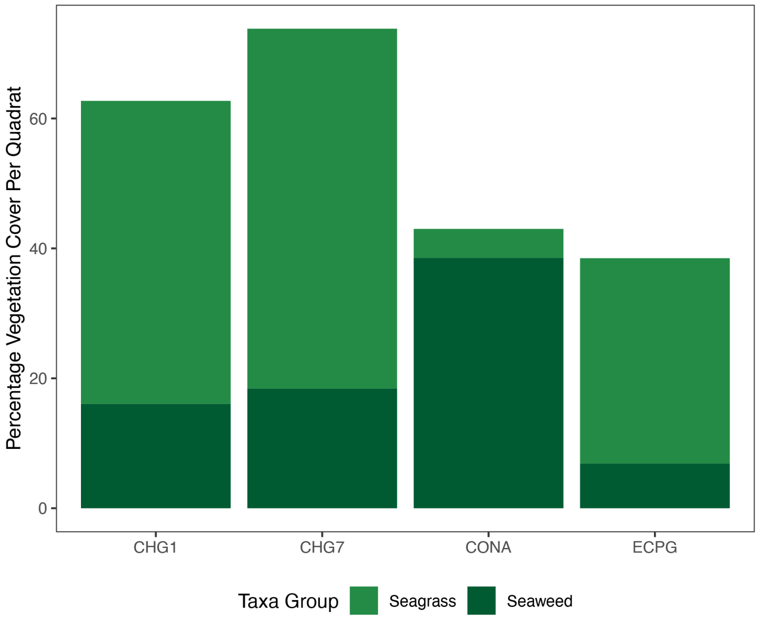

Figure 3. Average percent vegetation cover of quadrats across sites.

CONA (18.47%) while *Halodule* sp. (needle seagrass) was the highest contributor to vegetation cover in ECPG (17.45%).

The average faunal diversity of sites in CHG1, CHG7, and ECPG were markedly higher than that of CONA (Table 1), while the average density of faunal individuals per quadrat was considerably higher in CONA [68.75 (SD 67.27) individuals per quadrat] compared to other sites (Fig. 4). This is due to the quadrats in CONA being dominated by a large number of *Chaetopteridae* sp. (polychaete worms) across all zones, which made up 85.67% of the total number of faunal individuals recorded at this site.

Floral communities were significantly different across sites (PERMANOVA: $F_{3,265} = 30.9$, $R^2 = 0.24$, $P < 0.001$), years (PERMANOVA: $F_{1,265} = 19.2$, $R^2 = 0.050$, $P < 0.001$), and seasons (PERMANOVA: $F_{3,265} = 2.53$, $R^2 = 0.020$, $P < 0.001$). Faunal communities were significantly different across sites (PERMANOVA: $F_{3,262} = 32.1$, $R^2 = 0.26$, $P < 0.001$) and years (PERMANOVA: $F_{1,262} = 10.1$, $R^2 = 0.027$, $P < 0.001$), but not seasons. Further analyses to investigate these differences are reported below.

Associations Between Floral and Faunal Communities Across Sites.—The nMDS showed that floral communities within sites were more distinct from each other than faunal communities (Fig. 5). There were overlaps across all sites, particularly between the floral communities of CHG7 and ECPG and the faunal communities of CHG1, CHG7, and ECPG. Assemblages in CONA were more distinct from the other three sites, especially in terms of their flora.

For floral communities, SIMPER analysis elucidated that the differences across sites were largely driven by the most dominant species across all four sites, namely *Halophila ovalis*, *Halodule* sp., *Ulva* sp., and *Gracilaria* sp. (red algae; Online Table S1). These four species contributed to 45.5% or more of the dissimilarity in all pairwise

Table 1. Floral and faunal diversity indexes based on the Shannon–Wiener index (SD) and five most common flora and fauna species at each site based on average percentage cover per quadrat [% (SD)] and average faunal density per quadrat [individuals per quadrat (SD)], respectively.

CHG1		CHG7		CONA		ECPG	
Species	Mean (SD)	Species	Mean (SD)	Species	Mean (SD)	Species	Mean (SD)
Flora most common species							
Halophila ovalis	40.16 (35.18)	*Halophila ovalis*	34.76 (34.65)	*Ulva* sp.	18.47 (29.46)	*Halodule* sp.	17.45 (25.45)
Ulva sp.	4.42 (13.70)	*Halodule* sp.	21.53 (27.52)	*Gracilaria* sp.	7.28 (15.10)	*Halophila ovalis*	10.31 (19.45)
Halodule sp.	3.30 (13.30)	*Ulva* sp.	7.82 (20.2)	*Bryopsis* sp.	5.53 (18.87)	*Ulva* sp.	1.88 (7.36)
Gracilaria sp.	2.98 (8.82)	*Dictyota dichotoma*	2.06 (9.17)	*Caulerpa scalpelliformis*	4.48 (15.83)	*Gracilaria* sp.	1.30 (5.56)
Spyridia filamentosa	1.93 (6.90)	*Cymodocea rotundata*	1.98 (10.85)	*Halophila ovalis*	3.08 (12.34)	*Chaetomorpha* sp.	1.12 (5.00)
Flora Diversity Index	1.55 (0.44)	- - -	1.75 (0.42)	- - -	1.80 (0.39)	- - -	1.56 (0.41)
Fauna Most Common Species							
Didemnum psammatodes	3.63 (14.01)	*Diplosoma* sp.	5.29 (22.34)	*Chaetopteridae* sp.	58.90 (63.63)	*Cucumariidae* sp.	9.88 (36.25)
Chaetopteridae sp.	1.32 (6.27)	*Balanus* sp.	4.86 (25.97)	*Diogenes* sp.	1.91 (5.54)	*Chaetopteridae* sp.	3.72 (6.63)
Balanus sp.	1.14 (8.27)	*Diogenes* sp.	2.33 (7.47)	*Nassarius jacksonianus*	1.90 (4.02)	*Cercodemas anceps*	2.14 (12.14)
Cercodemas anceps	0.81 (1.41)	*Modiolus* sp.	1.92 (8.26)	*Cerithiidae* sp.	1.74 (6.05)	*Diogenes* sp.	2.13 (10.73)
Diogenes sp.	0.70 (1.89)	*Serpulidae* sp.	1.69 (10.48)	*Balanus* sp.	1.01 (10.78)	*Polychaete* sp.	0.95 (26.09)
Fauna Diversity Index	2.52 (0.57)	- - -	2.66 (0.60)	- - -	0.77 (0.420)	- - -	1.96 (0.49)

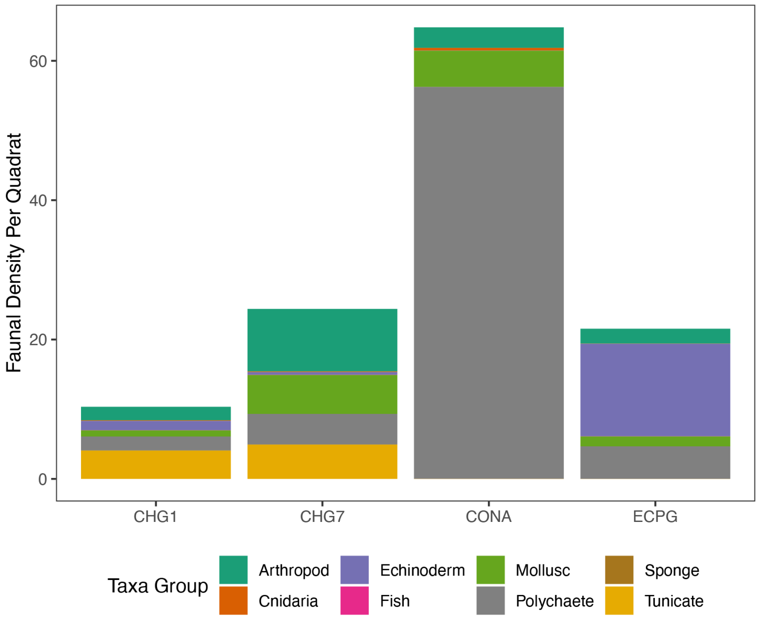

Figure 4. Average faunal density of quadrats (individuals per quadrat) across sites.

comparisons. The similarities between the floral communities of CHG1, CHG7, and ECPG were due to the dominance of *H. ovalis* and *Halodule* sp. in these sites. CONA, on the other hand, had *Ulva* sp., a type of macroalgae, as its most common floral species, which was a primary driver that made it more distinct from the other sites.

In terms of faunal communities, differences between sites were largely influenced by the abundance of *Chaetopteridae* sp. and *Didemnum psammatodes* (tunicate) as found in the SIMPER analysis (Online Table S2). *Diogenes* sp. (hermit crabs) was the only other species within the top 10 of all pairwise comparisons, responsible for between 2.9% and 8.3% of the differences. *Chaetopteridae* sp. drove the largest differences between CONA and the other three sites, accounting for 57.0%–65.6% of the differences between CONA and the other sites, respectively. Between ECPG and the other three sites, *Chaetopteridae* sp. and *Cucumariidae* sp. (sea cucumbers) were the two species that contributed most to differences in faunal communities, accounting for 13.1%–57.0% and 9.0%–18.8% of the differences between ECPG and other sites, respectively. Between CHG1 and CHG7, differences were most strongly driven by *Balanus* sp. (barnacles; 12.5%), *Didemnum psammatodes* (10.6%), *Diogenes* sp. (7.8%), and *Diplosoma* sp. (tunicates; 6.7%).

At the quadrat level, faunal species richness ($r = 0.19$, $P < 0.001$) and diversity ($r = 0.31$, $P < 0.001$) were both positively correlated to the percentage of seagrass cover, while faunal density was negatively correlated to the percentage of seagrass cover ($r = -0.17$, $P < 0.001$). There was no significant correlation between the percentage of macroalgae cover and faunal richness ($r = 0.03$, $P = 0.976$), while there was a positive correlation found between the percentage of macroalgae cover and faunal density ($r = 0.25$, $P < 0.001$) and a negative correlation between the percentage of macroalgae cover and faunal diversity ($r = -0.09$, $P < 0.001$).

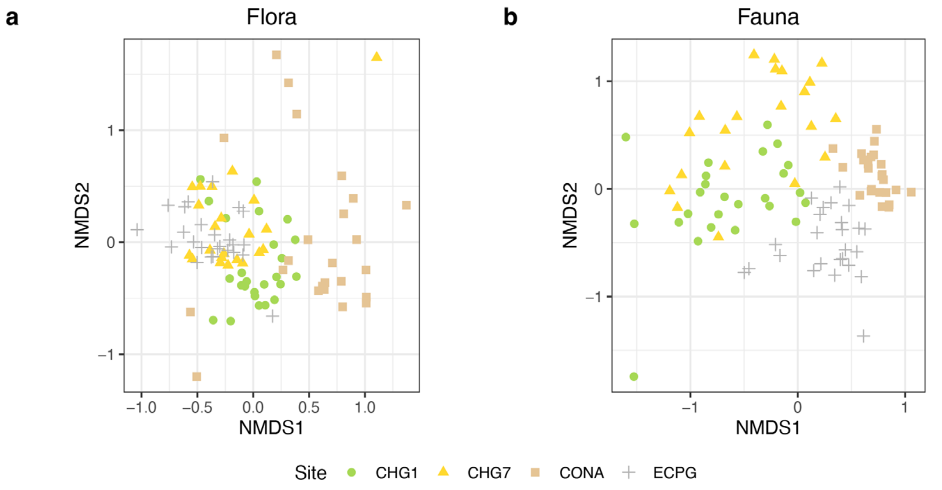

Figure 5. Nonmetric multidimensional scaling (nMDS) of (A) floral (stress = 0.1962069) and (B) faunal (stress = 0.1540288) communities.

Changes in Floral and Faunal Communities Over Time.—There were no discernable patterns in floral and faunal communities across years when aggregated across sites (Online Fig. S3). Hence, PERMANOVAs were further conducted to investigate differences within each site over time. From this, it was found that floral and faunal communities varied between years in all sites (Table 2). A shift towards algae dominance was observed in CHG1 in 2018, but this tapered in the subsequent years with a decrease in overall vegetation cover from 2021 onwards. In CHG7, the coverage of macroalgae in quadrats varied across years and was markedly higher in 2019 and 2021, while seagrass cover dropped from 2019 onwards (Fig. 6A). In ECPG, the site remained seagrass-dominated and vegetation cover stayed relatively consistent over the years except 2022, which recorded increases in both seagrass and macroalgae coverage. The differences across years were largely driven by variations in the proportions of seagrass species.

Faunal density in CHG1 remained relatively low throughout the study duration, though 2018 and 2019 saw higher numbers of tunicates and 2023 saw a higher number of arthropods per quadrat, in comparison to other years. The most noticeable changes in CHG7 were a similar increase in tunicate density in 2019, along with an increase in the number of arthropods (*Balanus* sp. and *Diogenes* sp.; Fig. 6B). The faunal taxa distribution in CONA remained relatively consistent, with fluctuating numbers of *Chaetopteridae* sp. We found that *Chaetopteridae* sp., *Cucumariidae* sp., and *Cercodemas anceps* (sea cucumber) fluctuated but generally increased over time

Table 2. Results of the permutational multivariate analysis of variance results for the analyses of differences across years (fixed, 8 levels) on floral and faunal assemblages within sites. *$P < 0.05$, ** $P < 0.01$, *** $P < 0.001$.

	Flora	Fauna
CHG1	<0.001 ***	<0.001 ***
CHG7	<0.001 ***	<0.001 ***
CONA	<0.001 ***	0.013*
ECPG	<0.001 ***	0.009 **

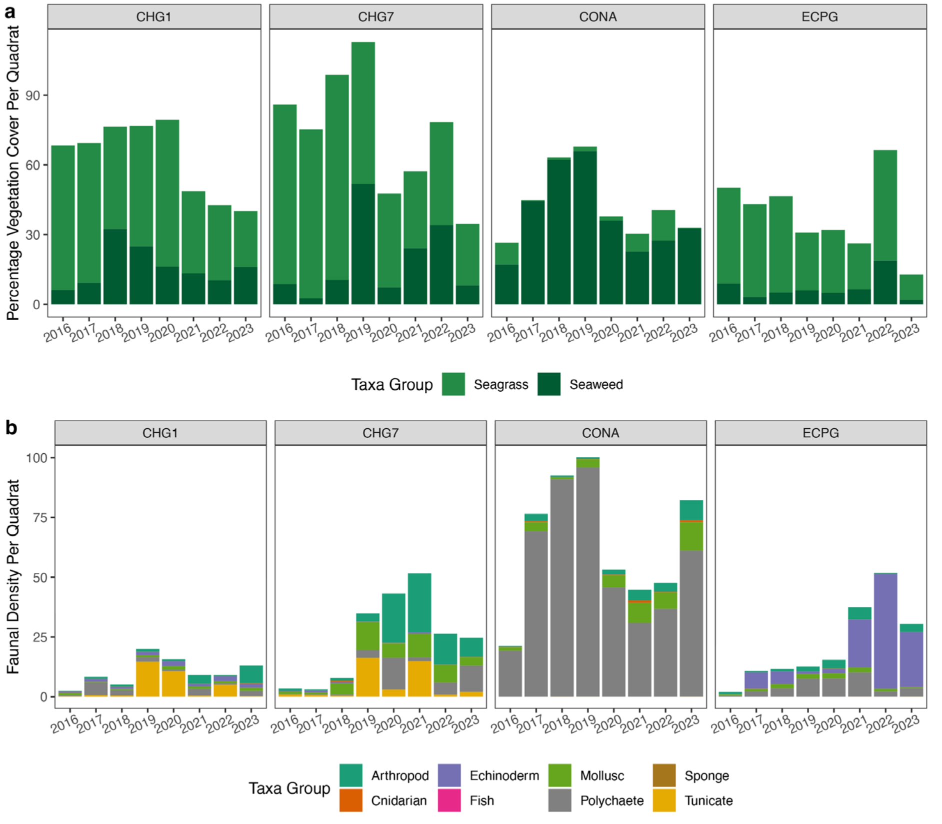

Figure 6. (A) Average percent vegetation cover of quadrats per year across sites and (B) average faunal density of quadrats (individuals per quadrat) per year across sites.

in ECPG. There was a particular surge in the number of *Cucumariidae* sp. in ECPG from 2021 onwards.

Volunteer Participation.—Intertidal Watch was consistently supported by over 50 unique volunteers per year over the eight years, over a wide range of ages and backgrounds. This represented 582 unique volunteers over the recorded duration, with 252 of these having volunteered for more than one survey (Table 3). There was a slight dip in 2020 where the number of volunteers per survey was reduced due to the social distancing measures introduced in light of the Covid-19 pandemic, and in 2022 where no surveys were conducted in the Southwest monsoon season due to insufficient low tides. Additionally, from 2022 onwards, volunteers were selected so that each group would have at least one experienced volunteer. As such, there was an increase in the number of repeated experienced volunteers and hence a drop in the number of unique volunteers per year.

Table 3. Number of unique volunteers in Intertidal Watch surveys per year.

Year	2016	2017	2018	2019	2020	2021	2022	2023
Total unique volunteers	154	89*	153	116	81	118	72	52

*43 participant names were not recorded in 2017 and were omitted from total unique volunteer number.

Discussion

Differences Between Community Assemblages Across Sites.—Surveys over the eight years revealed that floral and faunal community assemblages were distinct from each other across sites. Despite ECPG being the only south-facing site, CHG1, CHG7, and ECPG were observed to be clustered together closer to each other, with more overlaps between datapoints than each of them had with CONA, particularly in terms of their floral communities. Along with CONA being significantly dominated by macroalgae taxa, its faunal diversity was also lower than the other three sites, as quadrats were largely dominated by a single species, *Chaetopteridae* sp. Though the faunal diversities of CHG1, CHG7, and ECPG were higher than that of CONA, their faunal communities remained distinct from each other. Our findings are consistent with Lim et al. (2020) who did not find geographical clustering of intertidal species in Singapore based on a north-south divide. Instead, the dominant macrophyte taxa appeared to be the greatest driving factor in shaping the ecological communities at these sites. While both macrophyte types have been shown to enhance the structural and ecological diversity of soft sediment ecosystems (Boström and Bonsdorff 1997, Casares and Creed 2008, Fulton et al. 2019), our results suggest that seagrass may play a greater role in enhancing faunal richness and diversity in intertidal ecosystems compared to macroalgae, while macroalgal-dominant sites can support high faunal densities.

In nutrient-rich and light-limited environments, macroalgae tend to outcompete seagrasses (Duarte 1995, Valiela et al. 1997). CONA is situated within the narrow Johor Strait, which is known to be more turbid and nutrient-rich than the southern Singapore Strait and experience limited hydrological connectivity due to the presence of the Singapore-Johor Causeway (Gin 2000, Chou et al. 2019). CHG1 and CHG7, while similarly north-facing, are located in the wider, more open part of the strait towards the sea, which could have contributed to differences in macrophyte cover between these sites and CONA (Hasan et al. 2012, van Maren et al. 2014). Given the contributions that seagrass provide to intertidal biodiversity, our results give a clear imperative for the conservation of presently declining seagrass taxa in Singapore, which can be achieved in part by improving coastal water quality (Yaakub et al. 2014). On the other hand, we have shown that macroalgal habitats can support substantial faunal biomass and a differentiated faunal community compared to seagrass-dominant intertidal sites. Macroalgal contributions to blue carbon are also increasingly being recognized (Krause-Jensen et al. 2018). As such, further research should be undertaken to understand the varied ecological functions of these respective habitats.

Community Trends Within Sites Over Time.—Within sites, both floral and faunal communities showed significant changes across years, while only floral communities were differentiated across seasons. Macroalgae is understood to bloom seasonally in Singapore, peaking around the Northeast monsoon, which tends to bring higher rainfall and cooler sea surface temperatures (Low et al. 2018, Kwan et al. 2022). Despite these fluctuations, faunal communities were sustained across seasons, suggesting that these short-term changes had little impact on faunal assemblages.

The most pronounced temporal fluctuations in faunal communities are observed in CHG7 and ECPG, but there were no clear directional shifts across years over the study period (Online Fig. S3). These could have been driven by localized factors such as changes in substrate or water quality. For example, there was significant construction work adjacent to the site at ECPG throughout the study duration which appeared to have altered the substrate at ECPG to a siltier matrix (PR Cheo, Republic Polytechnic, pers comm). Benthic faunal communities can be influenced by substrate grain size (Abessa et al. 2019, Shi et al. 2019), and this could have played a role in the marked changes in faunal community over the period of monitoring. There were also reports of members of the public visiting all four sites and taking intertidal animals from June 2021 onwards, including crabs, clams, sand dollars, and sea cucumbers (Tan 2021, A Li, National Parks Board, pers comm). These new visitors typically collected these species as curios. In response, NParks initiated regular outreach efforts to educate members of the public against indiscriminately removing large numbers of organisms from these sites from June 2021 until December 2022, by which time the frequency of these activities had slowed (A Li, National Parks Board, pers comm). The removal of these organisms along with the increased trampling by visitors could potentially lead to deleterious community shifts (Keough and Quinn 1998, Murray et al. 1999, Hughes et al. 2009), but we found a lack of major observable changes in faunal densities and communities in the years following these incidents (Fig. 6, Online Fig. S3). In addition, overall vegetation cover did not fall drastically in these years. This suggests that these sites remained resilient to the increased pressures of gleaning and trampling in this instance. However, as our survey methodology did not specifically measure the occurrence of all species of interest across the entire site, our findings are limited in determining the full impact of these gleaning activities. For example, none of our quadrats documented the endangered *Holothuria scabra* (sandfish sea cucumber) or the near threatened *Arachnoides placenta* (cake sand dollar; National Parks Board 2023a), both commonly targeted species. Future surveys could prioritize recording the numbers of each species of interest across sites in response to such activities.

The Role of Citizen Science in Fostering Public Engagement and Recommendations for the Future.—The success of Intertidal Watch was owed to a steady recruitment and retention of volunteers, adequate training for volunteers and robust data verification processes. There was substantial public interest in Intertidal Watch, with survey registration often being oversubscribed and very rapidly reaching capacity. Volunteer numbers remained high throughout the study period, with new members joining the program and older members being retained year-on-year. Several long-term volunteers had given feedback that their awareness and knowledge of intertidal biodiversity had improved since volunteering. Through thorough volunteer training, visual ID guides on site, identification by group consensus, and an additional round of data verification post-survey, Intertidal Watch ensured the accuracy of data as best as possible, a challenge that many citizen science programs face (Conrad and Hilchey 2011). From 2022 onwards, Intertidal Watch also pivoted towards engaging a higher proportion of experienced volunteers towards the goal of increasing data accuracy and precision (Falk et al. 2019). The standardization of the sampling procedure further ensured that the data was translatable to scientific analysis (McKinley et al. 2017).

Despite these successes, Intertidal Watch does have its limitations in achieving the desired outcomes of citizen science. Generally, one survey is conducted at each site per season, which could lead to low statistical power of the data collected and fail to accurately capture the true community dynamics over time. Type II errors in determining community diversity could also occur if volunteers misidentify rare species as more common and frequently encountered ones. Furthermore, the number of volunteers that could be involved in each trip was limited within the survey methodology. As Intertidal Watch continues to expand, the program can explore increasing its sample size and volunteer engagement by conducting more regular surveys led by trained and experienced volunteers. In the years following its inception, it has also been complemented by citizen science efforts that directly identify and monitor species of conservation concern such as the Biodiversity Beach Patrol (National Parks Board 2023b). In addition, further inquiry into the specific feedback of volunteers to their involvement in the program would enhance this study by demonstrating the societal benefits of Intertidal Watch. Intertidal Watch has given both nature enthusiasts and members of the public with no prior experience alike the opportunity to visit intertidal habitats and contribute to ecological monitoring and is further supported by other efforts in NParks' toolbox of public outreach strategies to encourage environmental stewardship.

Conclusions

Ecological Establishment on Reclaimed Shorelines.—Over eight years of consistent data collection, Intertidal Watch has been able to elucidate the spatial and temporal trends of ecological assemblages across a range of sites, particularly highlighting the role of macrophyte taxa in shaping the faunal communities present within the habitat. Our results also present a case study of ecological communities establishing diverse populations in a reclaimed, urbanized habitat through natural recolonization and regeneration. Intertidal Watch study sites, despite all being on reclaimed coastlines, had species richness values comparable to that of naturally formed habitats, and have also been the focus of conservation efforts for locally threatened species (Cartwright-Taylor et al. 2011, Lim et al. 2020, Lim et al. 2022). While contending with habitat loss and fragmentation, NParks' wider conservation efforts aim to identify source and sink habitats within our waters and preserve connectivity pathways between key sites (URA 2022). This allows for the natural recruitment and succession of ecological assemblages under suitable conditions, such as in the coral and mangrove habitats in Tanah Merah and Pasir Ris, respectively (Lee et al. 1996, Wong et al. 2018). The richness of floral and faunal species in this study shed further light on the potential for modified habitats to recruit and sustain native biodiversity.

Citizen Science to Realize Conservation Management Outcomes.—The variation across these four study sites further points to the importance of conserving a range of habitats to maintain species diversity. Such programs establish a baseline of ecological data, which can be used to monitor the response of ecosystems to localized pressures, such as impacts from shore visitors, which is particularly crucial in urban coastal environments. However, more targeted analyses may need to be conducted to understand the drivers behind trends at respective sites. Ultimately, the goal of many citizen science projects is not only for scientific output, but for greater public engagement and ownership (Kullenberg and Kasperowski 2016, MacPhail and Colla

2020), which Intertidal Watch has achieved through its volunteer program. At the interface of science, policy, and community engagement, citizen science programs can and should be regarded as effective tools for both conservation research and education.

Data Availability

Data supporting the findings of this study are available in the article's Online Supplementary Material.

Acknowledgments

We would like to thank past NParks staff and interns, Aleron Lin, Audrey Lek, Bertrand Yan, Charmaine Ngon, Chiew Geok Yeng, Delaney Eng, Gwendolyn Chow, Jenny Fong, Kelly Yu, Margarette Chang, Mark Koh, Ng Ying Xuan, Rachel Guan, Ryan Chia, Shirley Lee, Sofie Kanematsu, Sze Yue, Tay Yuke Ling, Zhang Wei Qing, and Zoe Chin, along with all volunteers that have contributed to Intertidal Watch over the years. We thank the two anonymous reviewers and editors for their comments on the draft of the manuscript.

Literature Cited

Abessa DMS, Rachid BRF, Zaroni LP, Gasparro MR, Pinto YA, Bícego MC, Hortellan MA, Sarkis JES, Muniz P, Moreira LB, et al. 2019. Natural factors and chemical contamination control the structure of macrobenthic communities in the Santos Estuarine System. Community Ecol. 20(2):121–137. https://doi.org/10.1556/168.2019.20.2.3

Ang A, Jabbar S, D'Rozario V, Lakshminarayan J. 2021. Citizen science program for critically endangered primates: a case study from Singapore. Primate Conservation (35):179–188. Accessed 25 March, 2024. Available from: http://www.primate-sg.org/storage/pdf/PC35_Ang_et_al_Citizen_science.pdf

Ang M. Bedok & Tampines dug up & flattened to reclaim East Coast stretch over 20 years. Mothership; 25 September, 2018. Accessed 12 September, 2023. Available from: https://mothership.sg/2018/09/east-coast-land-reclamation-bedok-tampines/

Bela G, Peltola T, Young JC, Balázs B, Arpin I, Pataki G, Hauck J, Kelemen E, Kopperoinen L, Van Herzele A, et al. 2016. Learning and the transformative potential of citizen science. Conserv Biol. 30(5):990–999. https://doi.org/10.1111/cobi.12762

Blackburn S, Marques CA, de Sherbinin A, Modesto F, Ojima R, Oliveau S, Bolde C. 2013. Mega-urbanisation on the coast: global context and key trends in the twenty-first century. *In*: Pelling M, Blackburn S, editors. Megacities and the coast. London and New York: Routledge.

Boström C, Bonsdorff E. 1997. Community structure and spatial variation of benthic invertebrates associated with *Zostera marina* (L.) beds in the northern Baltic Sea. J Sea Res. 37:153–166. https://doi.org/10.1016/S1385-1101(96)00007-X

Cartwright-Taylor L, Yap V, Hsu C, Lou S. 2011. Distribution and abundance of horseshoe crabs *Tachypleus gigas* and *Carcinoscorpius rotundicauda* around the main island of Singapore. Aquat Biol. 13(2):127–136. https://doi.org/10.3354/ab00346

Casares FA, Creed JC. 2008. Do small seagrasses enhance density, richness, and diversity of macrofauna? J Coast Res. 2008(243):790–797. https://doi.org/10.2112/05-0565.1

Chia LS, Khan H, Chou LM. 1988. The coastal environmental profile of Singapore. Manila: The International Center for Living Aquatic Resources Management on behalf of the Association of Southeast Asian Nations/United States Coastal Resources Management Project.

Chou LM, Huang D, Tan KS, Toh TC, Goh BP, Tun K. 2019. Singapore. *In*: Sheppard CRC, editor. World seas: an environmental evaluation. Singapore: Academic Press.

Cigliano JA, Meyer R, Ballard HL, Freitag A, Phillips TB, Wasser A. 2015. Making marine and coastal citizen science matter. Ocean Coast Manage. 115:77–87. https://doi.org/10.1016/j.ocecoaman.2015.06.012

Clarke RK. 1993. Non-parametric multivariate analyses of changes in community structure. Aust J Ecol. 18:117–143. https://doi.org/10.1111/j.1442-9993.1993.tb00438.x

Conrad CC, Hilchey KG. 2011. A review of citizen science and community-based environmental monitoring: issues and opportunities. Environ Monit Assess. 176:273–291. https://doi.org/10.1007/s10661-010-1582-5

Convention on Biological Diversity. 2020. Singapore – country profile. Convention on Biological Diversity. Accessed 16 February, 2024. Available from: https://www.cbd.int/countries/targets?country=sg

Dickinson JL, Shirk J, Bonter D, Bonney R, Crain RL, Martin J, Phillips T, Purcell K. 2012. The current state of citizen science as a tool for ecological research and public engagement. Front Ecol Environ. 10:291–297. https://doi.org/10.1890/110236

Duarte CM. 1995. Submerged aquatic vegetation in relation to different nutrient regimes. Ophelia. 41(1):87–112. https://doi.org/10.1080/00785236.1995.10422039

Espadero ADA, Nakamura Y, Uy WH, Tongnunui P, Horinouchi M. 2020. Tropical intertidal seagrass beds: an overlooked foraging habitat for fishes revealed by underwater videos. J Exp Mar Biol Ecol. 526:151353. https://doi.org/10.1016/j.jembe.2020.151353

Falk S, Foster G, Comont R, Conroy J, Bostock H, Salisbury A, Kilbey D, Bennett J, Smith B. 2019. Evaluating the ability of citizen scientists to identify bumblebee (Bombus) species. PLOS ONE. 14(6):e0218614. https://doi.org/10.1371/journal.pone.0218614

Fulton CJ, Abesamis RA, Berkström C, Depczynski M, Graham NAJ, Holmes TH, Kulbicki M, Noble MM, Radford BT, Tano S, et al. 2019. Form and function of tropical macroalgal reefs in the Anthropocene. Funct Ecol. 33(6):989–999. https://doi.org/10.1111/1365-2435.13282

Gin KY-H. 2000. Dynamics and size structure of phytoplankton in the coastal waters of Singapore. J Plankton Res. 22(8):1465–1484. https://doi.org/10.1093/plankt/22.8.1465

Gouraguine A, Moranta J, Ruiz-Frau A, Hinz H, Reñones O, Ferse S, Jompa J, Smith DJ. 2019. Citizen science in data and resource-limited areas: a tool to detect long-term ecosystem changes. PLOS ONE. 14(1):e0210007. https://doi.org/10.1371/journal.pone.0210007

Guest J, Tun K, Low J, Vergés A, Marzinelli E, Campbell A, Bauman A, Feary D, Chou LM, Steinberg P. 2016. 27 years of benthic and coral community dynamics on turbid, highly urbanised reefs off Singapore. Sci Rep. 6:36260. https://doi.org/10.1038/srep36260

Halpern BS, Selkoe KA, Micheli F, Kappel CV. 2007. Evaluating and ranking the vulnerability of global marine ecosystems to anthropogenic threats. Conserv Biol. 21(5):1301–1315. https://doi.org/10.1111/j.1523-1739.2007.00752.x

Halpern BS, Walbridge S, Selkoe KA, Kappel CV, Micheli F, D'Agrosa C, Bruno JF, Casey KS, Ebert C, Fox HE, et al. 2008. A global map of human impact on marine ecosystems. Science. 319(5865):948–952. https://doi.org/10.1126/science.1149345

Hasan GMJ, van Maren DS, Cheong HF. 2012. Improving hydrodynamic modeling of an estuary in a mixed tidal regime by grid refining and aligning. Ocean Dyn. 62(3):395–409. https://doi.org/10.1007/s10236-011-0506-4

Hill R, Bellgrove A, Macreadie PI, Petrou K, Beardall J, Steven A, Ralph PJ. 2015. Can macroalgae contribute to blue carbon? An Australian perspective. Limnol Oceanogr. 60(5):1689–1706. https://doi.org/10.1002/lno.10128

Hilton MJ, Manning SS. 1995. Conversion of coastal habitats in Singapore: indications of unsustainable development. Environ Conserv. 22(4):307–322. https://doi.org/10.1017/S0376892900034883

Hughes AR, Williams SL, Duarte CM, Heck KL, Waycott M. 2009. Associations of concern: declining seagrasses and threatened dependent species. Front Ecol Environ. 7(5):242–246. https://doi.org/10.1890/080041

Jordan R, Gray S, Sorensen A, Newman G, Mellor D, Newman G, Hmelo-Silver C, LaDeau S, Biehler D, Crall A. 2016. Studying citizen science through adaptive management and learning feedbacks as mechanisms for improving conservation. Conserv Biol. 30(3):487–495. https://doi.org/10.1111/cobi.12659

Kelly R, Fleming A, Pecl GT, von Gönner J, Bonn A. 2020. Citizen science and marine conservation: a global review. Philos Trans R Soc Lond B Biol Sci. 375:20190461. https://doi.org/10.1098/rstb.2019.0461

Keough MJ, Quinn GP. 1998. Effects of periodic disturbances from trampling on rocky intertidal algal beds. Ecol Appl. 8(1):141. https://doi.org/10.2307/2641317

Koss RS, Miller K, Wescott G, Bellgrove A, Boxshall A, McBurnie J, Bunce A, Gilmour P, Ierodiaconou D. 2009. An evaluation of Sea Search as a citizen science programme in Marine Protected Areas. Pac Conserv Biol. 15(2):116. https://doi.org/10.1071/PC090116

Krause-Jensen D, Lavery P, Serrano O, Marbà N, Masque P, Duarte CM. 2018. Sequestration of macroalgal carbon: the elephant in the Blue Carbon room. Biol Lett. 14(6):20180236. https://doi.org/10.1098/rsbl.2018.0236

Kullenberg C, Kasperowski D. 2016. What is citizen science? – A scientometric meta-analysis. PLOS ONE. 11(1):e0147152. https://doi.org/10.1371/journal.pone.0147152

Kwan V, Fong J, Ng CSL, Huang D. 2022. Temporal and spatial dynamics of tropical macroalgal contributions to blue carbon. Sci Total Environ. 828:154369. https://doi.org/10.1016/j.scitotenv.2022.154369

Lai S, Loke LHL, Hilton MJ, Bouma TJ, Todd PA. 2015. The effects of urbanisation on coastal habitats and the potential for ecological engineering: a Singapore case study. Ocean Coast Manage. 103:78–85. https://doi.org/10.1016/j.ocecoaman.2014.11.006

Leather S, Quicke D. 2010. Do shifting baselines in natural history knowledge threaten the environment? Environmentalist. 30:1–2. https://doi.org/10.1007/s10669-009-9246-0

Lee SK, Tan WH, Havanond S. 1996. Regeneration and colonisation of mangrove on clay-filled reclaimed land in Singapore. Hydrobiologia. 319(1):23–35. https://doi.org/10.1007/BF00020968

Lim J, Ng YL, Yap L-M. 2022. Preliminary efforts to conserve native horseshoe crab species in Singapore. Nat Singap. Supplement 1:e2022126. https://doi.org/10.26107/NIS-2022-0126

Lim KC, Lim KS. 2009. State of Singapore's wild birds and bird habitats: a review of the annual bird census 1996–2005. Singapore: Nature Society (Singapore).

Lim LJW, Loh JBY, Lim AJS, Tan BYX, Ip YCA, Neo ML, Tan R, Huang D. 2020. Diversity and distribution of intertidal marine species in Singapore. Raffles Bull Zool. 68:396–403. https://doi.org/10.26107/RBZ-2020-0056

Low J, Fong J, Todd P, Chou L, Bauman A. 2018. Seasonal variation of *Sargassum ilicifolium* (Phaeophyceae) growth on equatorial coral reefs. J Phycol. 55(2):289–296. https://doi.org/10.1111/jpy.12818

MacPhail VJ, Colla SR. 2020. Power of the people: a review of citizen science programs for conservation. Biol Conserv. 249:108739. https://doi.org/10.1016/j.biocon.2020.108739

McGranahan G, Balk D, Anderson B. 2007. The rising tide: assessing the risks of climate change and human settlements in low elevation coastal zones. Environ Urban. 19:17–37. https://doi.org/10.1177/0956247807076960

McKinley DC, Miller-Rushing AJ, Ballard HL, Bonney R, Brown H, Cook-Patton SC, Evans DM, French RA, Parrish JK, Phillips TB, et al. 2017. Citizen science can improve conservation science, natural resource management, and environmental protection. Biol Conserv. 208:15–28. https://doi.org/10.1016/j.biocon.2016.05.015

Ministry of Defense. 1974. Singapore, 1:75,000. Series SMU 075, Sheet Singapore, Edition 1 SMU. Singapore: Mapping Unit, Ministry of Defense. *In*: Historical Maps of Singapore, digitized by Department of Geography, National University of Singapore, made available by NUS Libraries.

Ministry of Defense. 1975. Singapore, 1:25,000. Series SMU 025, Sheet 1 to 8, Edition 1 SMU. Singapore: Mapping Unit, Ministry of Defense. *In*: Historical Maps of Singapore, digitized

by Department of Geography, National University of Singapore, made available by NUS Libraries.
Ministry of Defense. 1978. Singapore, 1:50,000. Series SMU 075, Edition 2. Singapore: Mapping Unit, Ministry of Defense. *In*: Historical Maps of Singapore, digitized by Department of Geography, National University of Singapore, made available by NUS Libraries.
Ministry of Defense. 1983. Singapore, 1:50,000. Series SMU 075, Edition 3. Singapore: Mapping Unit, Ministry of Defense. *In*: Historical Maps of Singapore, digitized by Department of Geography, National University of Singapore, made available by NUS Libraries.
Ministry of Defense. 1987. Singapore, 1:50,000. Series SMU 075, Edition 4. Singapore: Mapping Unit, Ministry of Defense. *In*: Historical Maps of Singapore, digitized by Department of Geography, National University of Singapore, made available by NUS Libraries.
Mouritsen KN, Poulin R. 2002. Parasitism, community structure and biodiversity in intertidal ecosystems. Parasitology. 124 Suppl:101–117. https://doi.org/10.1017/S0031182002001476
Murray SN, Denis TG, Kido JS, Smith JR. 1999. Human visitation and the frequency and potential effects of collecting on rocky intertidal populations in Southern California marine reserves. CCOFI Rep. 40:100–106.
National Parks Board. 2017. Intertidal Watch. National Parks Board. Accessed 12 September, 2023. Available from: https://www.nparks.gov.sg/biodiversity/community-in-nature-initiative/intertidal-watch
National Parks Board. 2023a. Species list (red data book list). National Parks Board. Accessed 1 October, 2023. Available from: https://www.nparks.gov.sg/biodiversity/wildlife-in-singapore/species-list
National Parks Board. 2023b. Biodiversity beach patrol. National Parks Board. Accessed 16 January, 2024. Available from: https://www.nparks.gov.sg/gardens-parks-and-nature/parks-and-nature-reserves/sisters-islands-marine-park/biodiversity-beach-patrol
Newell RC. 1976. Adaptations to intertidal life. *In*: Adaptations to environment: essays on the physiology of marine animals. Oxford: Butterworth-Heineman. p. 1–82.
Oksanen J, Simpson GL, Blanchet FG, Kindt R, Legendre P, Minchin PR, O'Hara RB, Solymos P, Stevens MHM, Szoecs E, et al. 2022. vegan: community ecology package. R package v2.6-4. Available from: https://CRAN.R-project.org/package=vegan
Pauly D, Watson R, Alder J. 2005. Global trends in world fisheries: impacts on marine ecosystems and food security. Philos Trans R Soc Lond B Biol Sci. 360(1453):5–12. https://doi.org/10.1098/rstb.2004.1574
Phang VXH, Chou LM, Friess DA. 2015. Ecosystem carbon stocks across a tropical intertidal habitat mosaic of mangrove forest, seagrass meadow, mudflat and sandbar. Earth Surf Process Landf. 40(10):1387–1400. https://doi.org/10.1002/esp.3745
Powell MA. 2021. Singapore's lost coast: land reclamation, national development and the erasure of human and ecological communities, 1822–Present. Environ Hist. 27(4):635–663. https://doi.org/10.3197/096734019X15631846928710
R Core Team. 2022. R: a language and environment for statistical computing. v4.2.2. Vienna, Austria: R Foundation for Statistical Computing. Available from: https://www.R-project.org
Roelfsema C, Thurstan R, Beger M, Dudgeon C, Loder J, Kovacs E, Gallo M, Flower J, Cabrera KG, Ortiz J, et al. 2016. A citizen science approach: a detailed ecological assessment of subtropical reefs at Point Lookout, Australia. PLOS ONE. 11(10):e0163407. https://doi.org/10.1371/journal.pone.0163407
Shi X, Liu J, You X, Bao K, Meng B. 2019. Shared effects of hydromorphological and physico-chemical factors on benthic macroinvertebrate integrity for substrate types. Ecol Indic. 105:406–414. https://doi.org/10.1016/j.ecolind.2018.02.028
Sin TM, Ang HP, Buurman J, Lee AC, Leong YL, Ooi SK, Steinberg P, Teo SL-M. 2016. The urban marine environment of Singapore. Reg Stud Mar Sci. 8:331–339. https://doi.org/10.1016/j.rsma.2016.01.011

Small C, Nicholls RJ. 2003. A global analysis of human settlement in coastal zones. J Coast Res. 19(3):584–599. http://dx.doi.org/10.2307/4299200

Smith SV. 1981. Marine macrophytes as a global carbon sink. Science. 211(4484):838–840. https://doi.org/10.1126/science.211.4484.838

Sodhi NS, Butler R, Laurance WF, Gibson L. 2011. Conservation successes at micro-, meso- and macroscales. Trends Ecol Evol. 26(11):585–594. https://doi.org/10.1016/j.tree.2011.07.002

Soga M, Gaston KJ. 2018. Shifting baseline syndrome: causes, consequences, and implications. Front Ecol Environ. 16(4):222–230. https://doi.org/10.1002/fee.1794

Tan A. 2021. NParks to step up patrols, put up more signs to prevent manhandling of intertidal creatures. The Straits Times. Accessed 12 September, 2023. Available from: https://www.straitstimes.com/singapore/environment/nparks-to-step-up-patrols-put-up-more-signs-to-prevent-manhandling-of

Tan KS, Acerbi E, Lauro FM. 2016. Marine habitats and biodiversity of Singapore's coastal waters: a review. Reg Stud Mar Sci. 8:340–352. https://doi.org/10.1016/j.rsma.2016.01.008

The Straits Times. 1976. Biggest land reclamation contract in S-E Asia. The Straits Times. Accessed 6 September, 2023. Available from: https://eresources.nlb.gov.sg/newspapers/Digitised/Article/straitstimes19760304-1.2.84

Theobald EJ, Ettinger AK, Burgess HK, DeBey LB, Schmidt NR, Froehlich HE, Wagner C, HilleRisLambers J, Tewksbury J, Harsch MA, et al. 2015. Global change and local solutions: tapping the unrealized potential of citizen science for biodiversity research. Biol Conserv. 181:236–244. https://doi.org/10.1016/j.biocon.2014.10.021

United Nations. 2021. The second world ocean assessment: world ocean assessment II - volume I & II. United Nations Office of Legal Affairs. https://doi.org/10.18356/9789216040062

URA (Urban Redevelopment Authority). 2022. Stewardship of natural capital. Urban Redevelopment Authority. Accessed 15 January, 2024. Available from: https://www.ura.gov.sg/Corporate/Planning/Long-Term-Plan-Review/Space-for-Our-Dreams-Exhibition/Steward/Stewardship-Natural-Capital

Valiela I, McClelland J, Hauxwell J, Behr PJ, Hersh D, Foreman K. 1997. Macroalgal blooms in shallow estuaries: controls and ecophysiological and ecosystem consequences. Limnol Oceanogr. 42(5part2):1105–1118. https://doi.org/10.4319/lo.1997.42.5_part_2.1105

van Maren DS, Liew SC, Hasan GMJ. 2014. The role of terrestrial sediment on turbidity near Singapore's coral reefs. Cont Shelf Res. 76:75–88. https://doi.org/10.1016/j.csr.2013.12.001

Wong J, Chan Y, Ng CSL, Tun K, Darling E, Huang D. 2018. Comparing patterns of taxonomic, functional and phylogenetic diversity in reef coral communities. Coral Reefs. 37:737–750. https://doi.org/10.1007/s00338-018-1698-6

Yaakub SM, McKenzie LJ, Erftemeijer PLA, Bouma T, Todd PA. 2014. Courage under fire: seagrass persistence adjacent to a highly urbanised city–state. Mar Pollut Bull. 83(2):417–424. https://doi.org/10.1016/j.marpolbul.2014.01.012