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A review of the conservation status and survey methods for the live-bearing sea star *Parvulastra vivipara*

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ABSTRACT: The live-bearing sea star *Parvulastra vivipara*, 1 of only 6 Asteroidea species globally that gives birth to live young, had an uncertain conservation status due to data deficiencies and historical differences in research methods. Restricted to southeast Tasmania, its distinctive reproductive strategy, coupled with limited distribution, low genetic diversity, and geographically isolated populations makes *P. vivipara* populations highly susceptible to localised and global extinction. Since the species was described in 1969, ten different historical survey methods have been used to survey *P. vivipara* populations. Notably, the survey area at these locations has increased through time as *P. vivipara* abundances declined. In 2022, surveys revealed the persistence of *P. vivipara* populations at 10 of 15 historically documented locations. Five locations experienced local extinction of *P. vivipara* populations, 3 in the last 2 decades, and 4 locations had <150 individuals remaining. *P. vivipara* density has experienced a decline of 90% from the first surveys in 1974–2001 to recent surveys in 2022. Based on the current trajectory, it is predicted that the density of *P. vivipara* will decline to 1 ind. m^{-2} by 2033 and 1 ind. $site^{-1}$ by 2111, with some locations experiencing this decline even sooner. The rapid decline and restricted area of occupancy mean that *P. vivipara* qualifies for Critically Endangered status under IUCN Red List criteria A1 and B1. There is a pressing need for standardised and ongoing monitoring, management of key threats, and recovery strategies to bolster local and global *P. vivipara* populations against the threat of extinction.

KEY WORDS: Population status · Critically Endangered · Red List · Survey methods

1. INTRODUCTION

The state of knowledge regarding the conservation status of species worldwide remains inadequate, with efforts to quantify endangered or extinct species populations only gaining momentum recently, especially for invertebrates (Whittaker et al. 2005, Hoffmann et al. 2008, McCauley et al. 2015). Terrestrial and charismatic marine species that are easily observed and monitored over time have received considerable research focus to understand their extinction risks (Simberloff 1998, Jones et al. 2013). By contrast, other marine species often languish in obscurity, because their population changes go unnoticed underwater

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(Myers & Ottensmeyer 2005, Edgar et al. 2023). The disparity in attention is even more pronounced for small, rare, cryptic marine species, which are frequently underrepresented in surveys, resulting in a lack of comprehensive data about their distribution and ecology (MacKenzie et al. 2005, Bozec et al. 2011). This underrepresentation extends to the IUCN Red List of Threatened Species, which, despite assessing >150 000 species, includes only 15% that are marine species (https://www.iucnredlist.org/). The limited number of marine species listed as threatened is likely driven by deficits in data rather than accurate population trends (Alroy 2008, Mace et al. 2008).

Marine invertebrates, constituting 92% of oceanic life, receive disproportionately less attention when it comes to describing species and conservation status assessments (Chen 2021, Rogers et al. 2023). Thriving in diverse oceanic zones, from intertidal areas to the deep sea, marine invertebrates display remarkable adaptions for survival (Rogers et al. 2023). The great diversity of marine invertebrates underpins many ecologically important functions, including improvement of water quality, nutrient cycling, trophic food webs, and habitat engineering, as well as various human applications, such as aquaculture, fisheries, and medicine (Chen 2021). Among these, Asteroidea, or sea stars, play critical ecological roles as herbivores and predators, redistributing organic matter across trophic levels and influencing the distribution and abundance of other organisms (Iken et al. 2010, O'Hara & Byrne 2017, Rahman et al. 2018). Despite their significance, the abundance of many sea star species is in decline (Roediger & Bolton 2008, Rahman et al. 2018, O'Hara et al. 2019), warranting comprehensive spatial and temporal monitoring, particularly in zones where they form a major component of the benthic community.

The intertidal zone, often overlooked in marine conservation efforts, is home to many invertebrate species with remarkable resilience to abiotic and biotic factors (Fredston-Hermann et al. 2018). These species provide a multitude of ecological functions and services (Perkins et al. 2015, Dhanjal-Adams et al. 2016). However, burgeoning development and urbanisation accompanying the growth of the human population are causing notable and widespread impacts on intertidal habitats (Bugnot et al. 2021). Across the globe, many coastal cities have already lost more than half of their intertidal habitats through shoreline modification, dredging, agriculture/aquaculture, pollution, and climate change (Mieszkowska et al. 2006, Strain et al. 2019). Unfortunately, many intertidal habitats fall into a regulatory gap, not receiving the protection afforded by terrestrial or marine conservation laws. In Australia, for example, only a mere 2.6% of intertidal zones are afforded both marine and terrestrial protection (Dhanjal-Adams et al. 2016). The lack of protection places the many species supported by these habitats vulnerable to extinction (Mieszkowska et al. 2006).

Southeast Tasmanian intertidal shores are home to an endemic sea star, *Parvulastra vivipara*, commonly known as the Tasmanian live-bearing sea star (Dartnall 1969). *P. vivipara* is a small (maximum radius of 15 mm), orange-yellow sea star that is 1 of only 6 hermaphrodite Asteroidea species worldwide known to give birth to live young (Byrne 1996, Khan et al. 2019). Its distinctive reproductive strategy, coupled with its restricted distribution, low genetic diversity, and spatially separated populations, makes *P. vivipara* highly susceptible to localised and global extinction (Byrne 1996, Prestedge 1998, Keever et al. 2013). The species was listed as vulnerable in 2008 under the Threatened Species Protection Act 1995 and Environmental Protection and Biodiversity Conservation Act 1999 (https://www.threatenedspecieslink.tas.gov.au/Pages/Tasmanian-Live-bearing-Seastar.aspx). However, recent research by Parsons (2020) has revealed a dramatic population decline in the Pitt Water Estuary, the location containing the largest populations of *P. vivipara*, emphasising the urgent need for population-wide research to understand the extent of this decline and its underlying causes.

Historically, surveys of *P. vivipara* populations in southeast Tasmania have employed a wide array of methods (e.g. shoreline searches [Prestedge 1998], timed searches [Liversage & Byrne 2018], fixed and random quadrats [Rowland 2001], and transects [Parsons 2020]). The rationale for using different survey methods includes the need to address different research questions, account for site-specific variation in topography, consider the patchy distribution of some *P. vivipara* populations, and to navigate limitations in resources (Parsons 2020). However, the use of historical data collected with varying survey techniques can make it difficult to discern changes in species population abundances, due to methodological differences (Magurran & McGill 2010). In the case of *P. vivipara*, the diversity of survey methods and long intervals between surveys, coupled with the lack of information about the methods used to calculate density and population abundances, in some studies (e.g. Prestedge 1998, Rowland 2001), has potentially reduced our capacity to monitor changes in populations of the sea star effectively. It is essential to determine which of these commonly used historical methods can be used to undertake a quantitative survey of the global population, to ensure the availability of reliable data for assessing the conservation status of *P. vivipara*.

We conducted an extensive survey of all documented *P. vivipara* locations in southeast Tasmania. Our objectives were to determine the current population distribution and size, and evaluate the species' conservation status. To achieve this, we used a variety of methods, drawing upon historic surveys to establish a consistent time series. Additionally, we explored the relationship between area sampled and the density of *P. vivipara* to provide recommendations for future monitoring. Specifically, we (1) assessed conservation status of *P. vivipara* by providing density and population estimates, (2) trialed various historical survey methods to determine best practice for future surveys, and (3) investigated the relationship between survey area and sea star counts. This is the first comprehensive study of the global *P. vivipara* population.

2. MATERIALS AND METHODS

2.1. Study sites

Tasmania's rocky coastline spans ~2237 km (Short 2006), with only a small amount consisting of intertidal bedrock (Short 2006), which is suitable habitat for *Parvulastra vivipara*. The rocky intertidal shorelines in southeastern Tasmania are a mixture of dolerite, granite, and sandstone (Short 2006). These shorelines cover a spectrum of coastal environments, ranging from exposed areas subject to heavy wave action to sheltered bays and estuaries with virtually no wave action (Short 2006).

The live-bearing sea star *P. vivipara* has previously been recorded at 15 locations (kilometres apart) (Prestedge et al. 2001) in southeastern Tasmania (Fig. 1). Among these locations, the Pitt Water contains the largest population of sea stars distributed across 6 sites (metres apart), which are separated by the waterway or artificial structures. These include Midway Point Causeway, Sorell Causeway, Pitt Water Bluff, Northeast Midway Point, South Midway Point, and Barren and Woody Islands (Fig. 1). In these locations, *P. vivipara* populations are found on a variety of habitat types within the intertidal zone, including natural reef platforms, rocky shorelines, and estuarine beaches, as well as artificially constructed shorelines which contain a mixture of dolerite, sandstone, and granite rocky types. These rocky habitats are often on sheltered, gently sloping coastlines with low-medium locally generated wind-wave energy

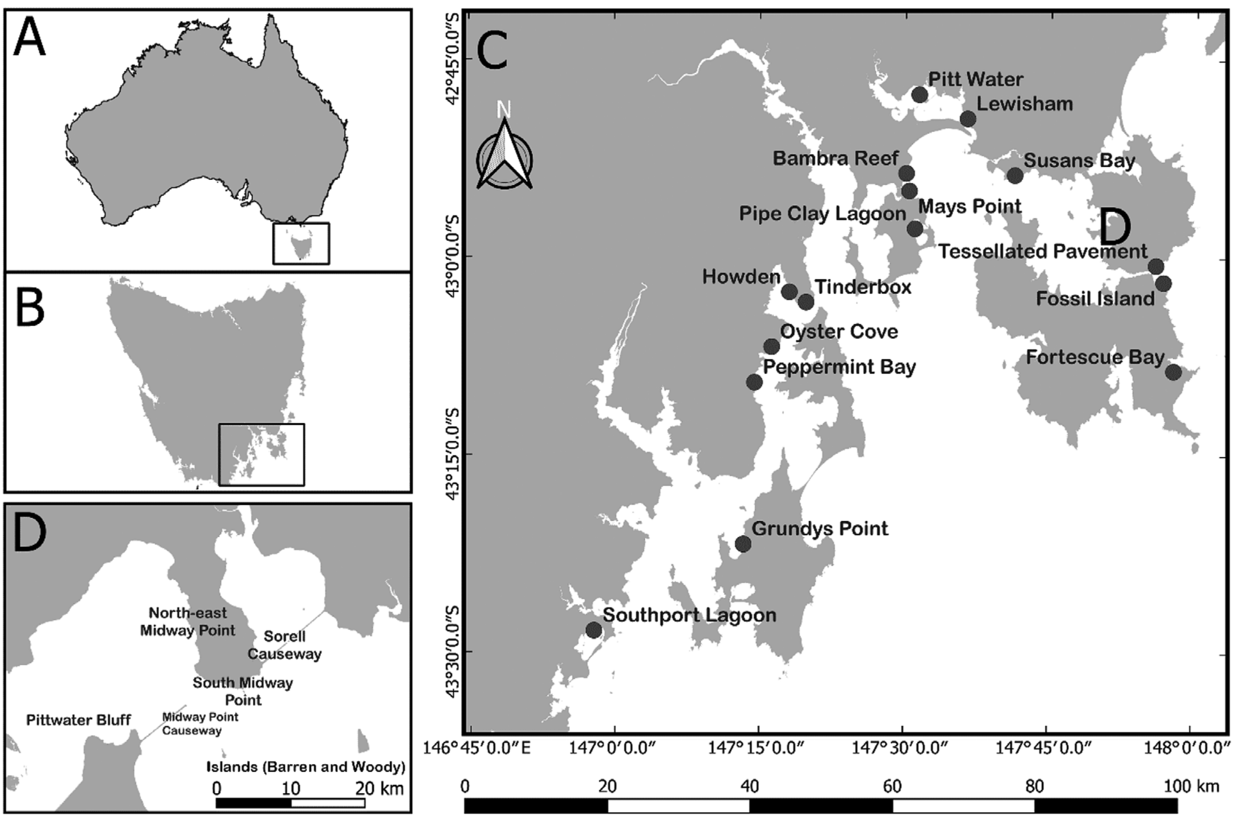

Fig. 1. (A) Australia, (B) Tasmania, and (C) the 15 historical locations and (D) 6 distinct sites in the Pitt Water where *Parvulastra vivipara* has been recorded

that typically give way to fine sand in the lower intertidal zone (Prestedge 1998). The tidal range is <1 m (Edgar 1984).

2.2. Distribution, density, and population abundances of *P. vivipara*

To determine the density of *P. vivipara*, we laid out a perpendicular (vertical) transect line from the high tide to low tide mark and recorded the number of sea stars on and under rocks in 0.5 m distance on each side of the transect (for full details, see Table S1 in the Supplement at www.int-res.com/articles/suppl/n054p341_supp.pdf). The transects were placed at historical points, but where this information (i.e. survey GPS points) was not available, they were placed randomly ~100 m apart.

To assess the extent of *P. vivipara*, we conducted surveys along the mid-tide mark running parallel (horizontal) to the shoreline (as determined from the perpendicular transects). We randomly selected rocks and counted sea stars found present on or under them for two 30 min intervals, covering the entire shoreline. The linear extent of the shoreline where *P. vivipara* was observed was recorded. The GPS coordinates for all perpendicular transects and parallel searches were recorded, and data was submitted to the Tasmanian Natural Values Atlas (https://www.naturalvaluesatlas.tas.gov.au/).

We calculated the density of *P. vivipara* per m^2 for each location and site across the entire length of the 1 m wide transects. To estimate population abundance, we determined the total area inhabited by *P. vivipara* by multiplying the linear length (obtained from timed parallel searches) and the width of the shoreline (derived from perpendicular transects) occupied by the sea star. Area was then multiplied by the density of *P. vivipara* per m^2 to obtain population abundance estimates.

2.3. Effect of survey area on *P. vivipara* density estimates

The most commonly used historical method for surveying *P. vivipara* populations was through perpendicular transects of varying width. To assess the effect of search area on *P. vivipara* counts, we also assessed the number of sea stars on or under rocks within varying widths (0.25, 0.5, 1, and 5 m) along the same perpendicular transects. We surveyed 2 or 3 transects at 4 sites within the Pitt Water (Midway Point Causeway, Sorell Causeway, Pitt Water Bluff, and South Midway Point) as well as an additional 6 locations (Lewisham, Susans Bay, Peppermint Bay, Pipe Clay Lagoon, Northeast Southport Lagoon, and Northwest Southport Lagoon). All surveys were conducted at low tide (≤0.3 m) between February and August 2022.

2.4. Historical methods used to survey *P. vivipara*

Since their initial discovery, *P. vivipara* populations have been assessed using various survey methods. To understand which locations were surveyed and the specific methods used, we undertook a literature review (Table S2). Subsequently, we extracted data on the density of *P. vivipara* (m^{-2}) at locations that had undergone population assessments at 2 or more distinct time points (Table 1). To ensure a more consistent dataset, we excluded data that primarily focused on targeted searches of *P. vivipara* in specific areas such as fixed quadrats (Prestedge 1998, Rowland 2001), fissures, or mussel beds (Rowland 2001), undefined search area (Prestedge 1998) or those that involved translocated populations (Aquenal 2005). These exclusions were made due to their limited scope, not encompassing population surveys across the entire location or natural populations.

Depending on the available metrics, *P. vivipara* density (m^{-2}) was either directly extracted from the literature, calculated by dividing the total abundance by total area searched, or derived from raw data.

2.5. Analysis

We used a generalised linear mixed-effects model with a quasi-Poisson distribution to examine the relationship between area searched (fixed, 0.25, 0.5, 1, or 5 m) and the density of *P. vivipara.* In this analysis, we included transect (26 levels) and site (random intercept, 10 levels) as random factors in the model. Furthermore, we used another generalised linear mixed-effects model with a quasi-Poisson distribution to examine changes in the density of *P. vivipara* between survey years (fixed, covariate) while accounting for the effect of site (random intercepts, 12 levels). Additionally, we considered orientation (perpendicular or parallel of the historical transects) and method (8 levels) as random factors in the model.

To determine whether transect and site in the first model or orientation and method in the second model were needed, we used the Bayesian information criterion (BIC), a criterion that balances model fit and

Table 1. Historical survey methods and sites used in the analyses of *Parvulastra vivipara* density estimates. See Table S2 for further information

Method	References	Description	Locations surveyed	Data source
Parallel 1 m^2 quadrats	Polanowski (2002)	Quadrat was placed at random positions	Fortescue Bay, Susans Bay	Extracted
Parallel 4 m^2 quadrats	Rowland (2001)	Quadrat containing a grid of elastic cord every 200 mm. Ten squares were randomly selected and sampled. Quadrats were placed randomly	Bambra Reef, Lumeah Point, Peppermint Bay	Extracted
Parallel shore-line search	Prestedge (1998), Rowland (2001)	Search of shoreline noting location of first and last found sea star	Bambra Reef, Fortescue Bay, Tessellated Pavement	Calculated
Perpendicular or parallel 0.25 m wide transects	Hoggins (1976), DPIW (2006)	Transect line laid out from high tide to low tide mark or in the mid tide; all sea stars within 0.25 m of 1 side of the transect were counted	Tessellated Pavement, Pitt Water Bluff, Northeast Southport Lagoon	Calculated, extracted
Perpendicular or parallel 0.5 m wide transects	Aquenal (2005, 2013), K. E. Parsons (unpubl. data)	Transect line laid out from high tide to low tide mark; all sea stars or in the mid tide within 0.25 m either side of the transect line were counted. At Bambra Reef, the search included 2 m long blocks, with each block 1 m^2 of reef	Pitt Water Bluff, Northeast Midway Point, South Midway Point, Midway Causeway, Bambra Reef	Raw data
Perpendicular 1 m wide transects	K. E. Parsons (unpubl. data)	Transect line laid out from high to low tide mark; all sea stars within 0.5 m of the transect line were counted	Islands	
Perpendicular 5 m wide transects	Parsons (2020)	Transect line laid out from high tide to low tide mark; all sea stars within 2.5 m either side of the transect line were counted	Pitt Water Bluff Northheast Midway Point, South Midway Point, Midway Point Causeway, Sorell Causeway, Lewisham	

complexity. The most parsimonious model, as indicated by the lowest BIC value, was selected for interpretation and did not include method or orientation in the second model.

Using the results from the chosen model, we determined the year in which *P. vivipara* could potentially become extinct (declines of 90%, decreased to 1 ind. m^{-2}, or decreased to 1 ind. $site^{-1}$) across all survey sites. The generalised linear mixed-effects models were implemented using the function glmmPQL in the package MASS. All models were checked for temporal autocorrelation with plots. Spatial autocorrelation was accounted for using site as a random effect in the model. All statistical analyses and plots were undertaken in R v.4.3.0 (R Core Team 2023).

3. RESULTS

Our results showed that *Parvulastra vivipara* is currently found at 16 sites, spanning 10 locations within southeast Tasmania (Fig. 2, Table 2). However, our survey also confirmed the local extinction of *P. vivipara* at 5 out of 15 historical locations, 3 of which occurred in the last 2 decades (Fig. 2).

The remaining sites where *P. vivipara* is still found include Bambra Reef at Roches Beach; Fortescue Bay and Tessellated Pavement on the Tasman Peninsula; Pitt Water Bluff, Northeast Midway Point, South Midway Point, Midway Point Causeway, Sorell Causeway, and Pitt Water Islands in Pitt Water and Lewisham; Susans Bay at Primrose Sands; Lumeah Point in Pipe Clay Lagoon; Peppermint Bay at Woodbridge; and Northeast and Northwest Southport Lagoon (Fig. 2). In Peppermint Bay, where *P. vivipara* was introduced, numerous hybrids were discovered; however, only the unmistakable live-bearing sea star individuals were counted. Additionally, we included data from 1 new site containing *P. vivipara* at Southwest Pipe Clay Lagoon (Parsons 2023a).

We estimate a population size of 41 629 individuals across the 9 extant locations (Table 2), and a total extent of occurrence of 16 940 m^2. The sites with the highest densities of *P. vivipara* were Bambra Reef,

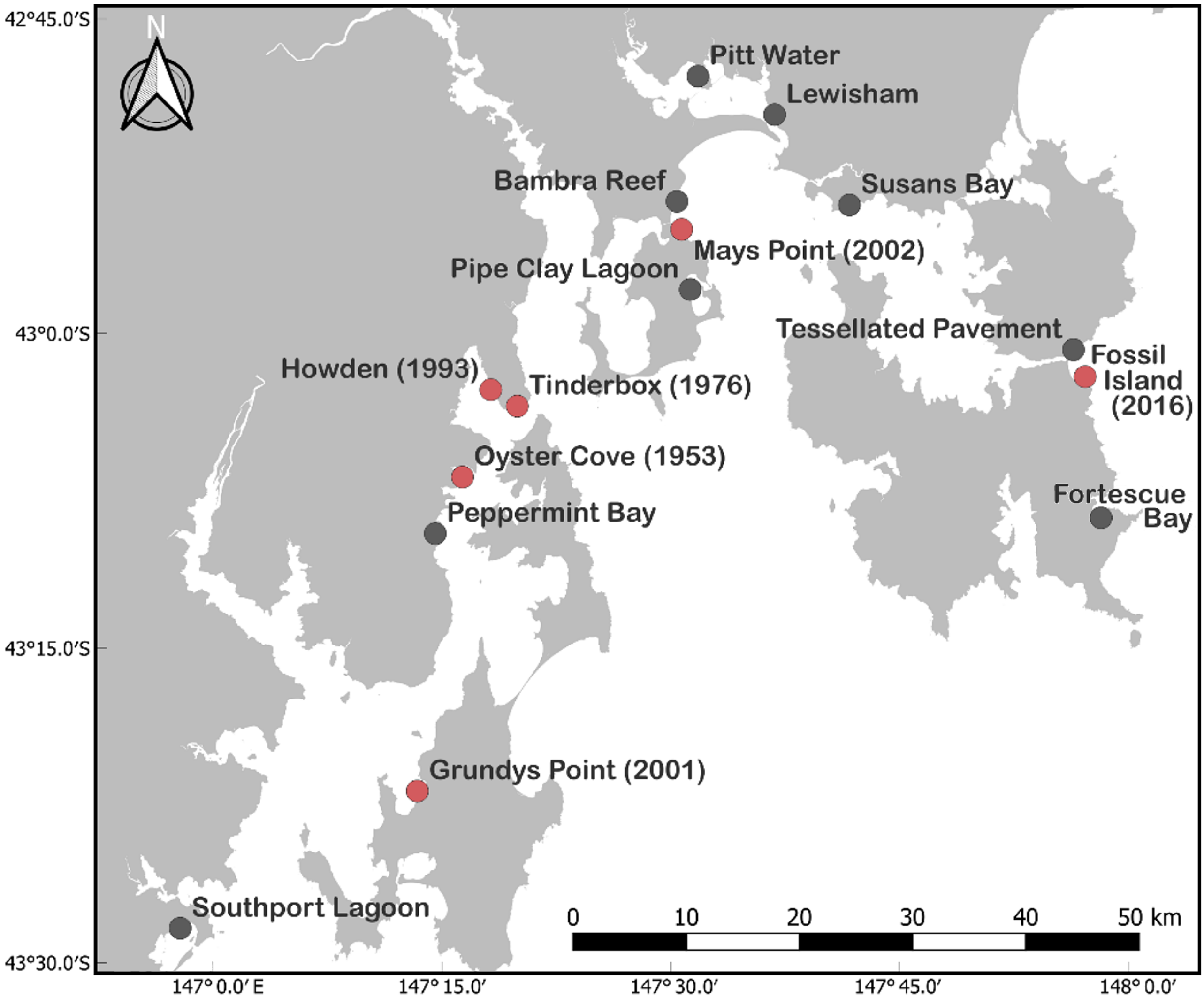

Fig. 2. Locations where *Parvulastra vivipara* was recorded in 2022. In locations where no *P. vivipara* was detected (red dots), the most recent year record of its presence is indicated

Northeast Southport Lagoon, Southwest Pipe Clay Lagoon, and the 2 causeways within Pitt Water (Table 2). Notably, Pitt Water had the highest area of occupancy and total abundance of *P. vivipara*, followed closely by Bambra Reef and then Pipe Clay Lagoon and Southport Lagoon. By contrast, at the remaining 4 locations, Fortescue Bay, Lewisham, Susans Bay, and Peppermint Bay, there were very small populations of *P. vivipara*, with estimates of <150 individuals (Table 2).

Our analysis showed there was a weak but significant negative relationship between the density of *P. vivipara* and the transect width across all sites (Table 3). The estimates of *P. vivipara* density showed a slight decline with increasing transect width (Fig. 3). This implies a negative relationship between *P. vivipara* detectability and transect width. However, this effect is very small compared to the variation between sites (Fig. 3).

Since the species was described in 1969, there have been 10 different methods used to survey *P. vivipara* populations (Table S1). These methods included perpendicular transects, parallel transects and quadrats and shoreline searches, each differing in the amount of area searched. Notably, perpendicular transects of varying widths (0.25, 0.5, 1, and 5 m) were the most consistently used survey method through time and across sites (Table 1, Table S1).

The densities of *P. vivipara* at all sites have shown a consistent decline through time (Fig. 4, Table 4). Notably, our data suggests there was a 90% reduction in *P. vivipara* between 1974 and 2001 (Fig. 4). Based

Table 2. Density (mean ± SE), area of occupancy and abundance of *Parvulastra vivipara* populations from the 2022 surveys

Location	Site	Shoreline type	Density per site (m^{-2})	Density per location (m^{-2})	Area of occupancy per location (m^2)	Total abundance per location
Pitt Water Estuary	Pitt Water Bluff	Estuarine beach	0.44 ± 0.20	1.47 ± 0.36	9125	13422
	Northeast Midway Point	Estuarine beach	1.18 ± 0.38			
	South Midway Point	Estuarine beach	0.12 ± 0.12			
	Pitt Water Islands	Estuarine beach	0.57 ± 0.24			
	Midway Point Causeway	Artificial	4.67 ± 1.64			
	Sorell Causeway	Artificial	4.07 ± 1.96			
Pitt Water Estuary	Lewisham	Rock platform		0.08 ± 0.08	31	2
Roches Beach	Bambra Reef	Rock platform		13.93 ± 3.29	945	13161
Pipe Clay Lagoon	Lumeah Point	Rock platform	1.30 ± 0.92	2.66 ± 1.78	3174	8418
	Southwest Pipe Clay Lagoon	Estuarine beach	4.59 ± 3.25			
Southport Lagoon	Northeast Southport Lagoon	Estuarine beach	5.66 ± 0.99	2.45 ± 1.36	2562	6272
	Northwest Southport Lagoon	Estuarine beach	0.31 ± 0.26			
Primrose Sands	Susans Bay	Rocky shoreline		1.14 ± 0.32	122	138
Tasman Peninsula	Tessellated Pavement	Rock platform		0.53 ± 0.13	205	108
Tasman Peninsula	Fortescue Bay	Rock platform		0.35 ± 0.23	22	8
Woodbridge	Peppermint Bay	Rock platform		0.14 ± 0.09	754	100

Table 3. Generalised linear model testing the relationship between search area (0.25, 0.5, 1, or 5 m) and the number of *Parvulastra vivipara*. **Bold** p-values: significant at $p < 0.05$

Random effects	Variance	SD		
Transect	0.67	0.82		
Site	2.61	1.62		
Fixed effects	**Estimate**	**SE**	***Z***	**p**
Intercept	0.07	0.32	0.21	>0.05
Area	−0.06	0.03	−2.02	**0.048**

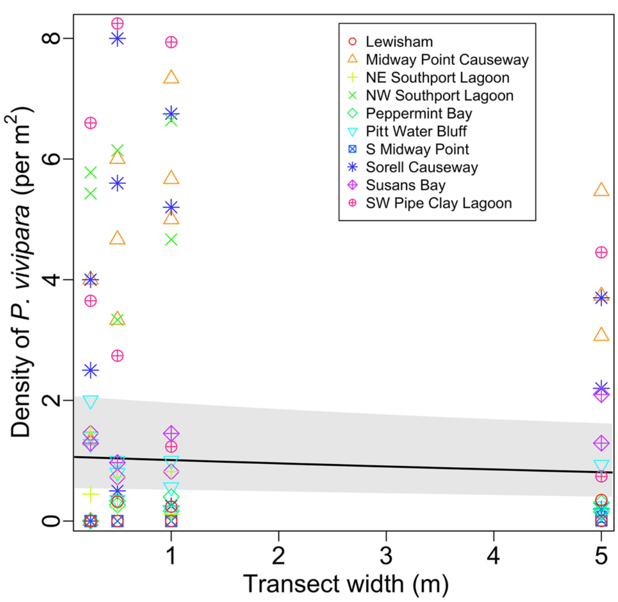

Fig. 3. Overall relationship between density (±95% CI) of *Parvulastra vivipara* and transect width (0.25, 0.5, 1, or 5 m) based on 2022 surveys

on the current trajectory, it is projected this species will decline to only 1 ind. m^{-2} by 2033 (95% CI: 2022–2050) and ultimately diminish to a single individual per site by the year 2111 (95% CI: 2086–2155) (Fig. 4).

4. DISCUSSION

Understanding the population status of threatened species is essential for their conservation and management. For many marine species, including the live-bearing sea star *Parvulastra vivipara*, this information is lacking. The present study revealed that

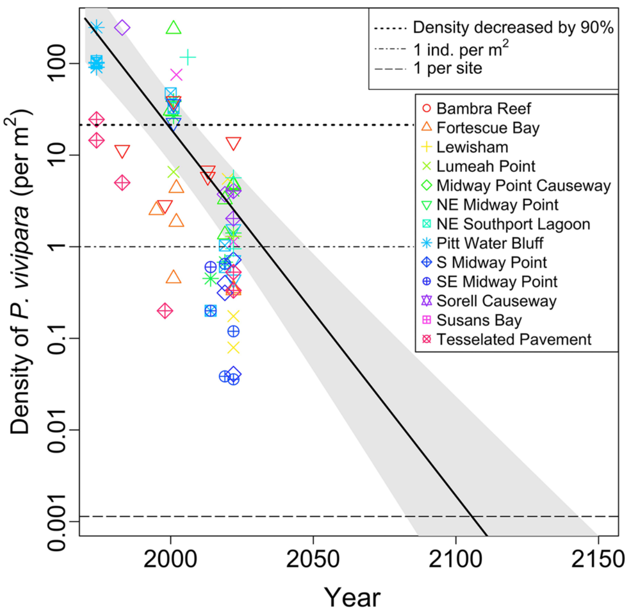

Fig. 4. Density (±95% CI) of *Parvulastra vivipara* through time based on historical and current surveys

Table 4. Generalised linear model testing the effects of survey year, site, and survey method on the density of *Parvulastra vivipara*. **Bold** p-values: significant at $p < 0.05$

Random effects	SD	Residual		
Site	1.09			
Method	0.87	3.11		
Fixed effects	Estimate	SE	*Z*	p
Intercept	187.53	21.26	−8.68	**<0.001**
Year	−0.09	0.02	−8.68	**<0.001**

there are approximately 41 629 remaining individuals of *P. vivipara*, distributed across 16 sites within 10 distinct locations and covering a total area of 16 940 m^2. The density of this species has declined by >90% from the first surveys between 1974 and 2001 to the recent surveys in 2022, with local extinctions recorded in 5 locations, 3 of which occurred in the last 2 decades. Extant sites hold small and fragmented populations, making them more susceptible to extirpation and extinction through increased vulnerability to environmental stochasticity, reduced gene flow, exposure to edge effects, and reduced adaptive capacity (Matthies et al. 2004, Mullu 2016). To prevent the global extinction of this species, there is a pressing need for greater consistency and continuity in survey methods, mitigation of key threats, and investigation of feasibility of population intervention and recovery strategies.

Among the remaining locations, the sites exhibiting the highest densities of *P. vivipara* aligned closely with historical records. In both the historic and current surveys, the causeways in the Pitt Water, and the natural rock reefs areas at Bambra Reef, Southwest Pipe Clay Lagoon, and Northeast Southport Lagoon had the highest densities of *P. vivipara* (Hoggins 1976, Aquenal 2005, 2013, DPIW 2006). Although the causeways in Pitt Water have demonstrated some of the most rapid declines in *P. vivipara* densities, the high initial abundance of sea stars in these locations likely contributed to the persistence of these populations. Notably, large densities of *P. vivipara* were also observed at the Pitt Water Bluff, Northeast Midway Point, South Midway Point, and Tessellated Pavement in the early 2000s (Rowland 2001, Aquenal 2005). However, by 2022, densities of *P. vivipara* at these sites had substantially decreased. The decline of *P. vivipara* populations at these key sites is likely linked to various localised anthropogenic impacts.

The known threats to *P. vivipara* populations include nutrient enrichment and sedimentation from agriculture and urban discharges and runoff and aquaculture activities (Prestedge 1998, Liversage & Byrne 2018). Key locations containing *P. vivipara* populations have been rated as severely or highly impacted by anthropogenic activities, as they are occupied by Pacific oyster (*Magallana gigas*) farms, surrounded by agricultural land, and affected by increasing urbanisation (Edgar et al. 2000). The influx of nutrients and sediment from these inputs alters benthic assemblages and availability of food and shelter for *P. vivipara* (Prestedge 1998). The proliferation of invasive species *M. gigas* and porcelain crabs *Petrolisthes elongatus* have been associated with declines in the abundances of *Parvulastra vivipara* and behavioural changes (Fitzpatrick 2023). Additionally, hybridisation between the native sea star *P. exigua* and *P. vivipara* poses a threat their genetic viability, reminiscent of the extinction of another native sea star, *Patiriella littoralis* (O'Hara et al. 2019). However, it is important to note that these threats have localised impacts primarily affecting specific locations, such as Pitt Water Nature Reserve, Pitt Water Estuary, Peppermint Bay, Pipe Clay Lagoon, Susans Bay, and Tessellated Pavement.

In other remote locations where *Parvulastra vivipara* populations are also declining, there is a growing likelihood that, similar to many other benthic invertebrates in southern Australia, the species is contending with the impacts of global climate change (Balogh & Byrne 2020, Edgar et al. 2023). Asterinid sea stars are known for their tolerance to various environmental factors such as temperature and salinity but face potential mortalities with prolonged exposure to higher temperature and lower pH conditions (Prestedge 1998, Byrne & Walker 2007, O'Hara et al. 2019). Drawing insights from a closely related species, *P. parvivipara*, researchers have demonstrated a negative correlation between population densities and increased water flow and wave energy (Roediger & Bolton 2008). Wave energy significantly contributes to the displacement of small boulders and the dislodgement of various taxa from hard substratum, exposing them to predation and diminishing habitat suitability (Roediger & Bolton 2008, Liversage 2015), and can lead to local extirpation of intertidal asterinid populations. However, waves of such intensity to entrain boulders would only be an ongoing issue on the open-ocean beaches or rocky shores or during extreme high-energy conditions in estuaries. These factors all have the potential to impact *P. vivipara* habitat and population abundances.

Our study revealed that historically, 10 different survey methods have been used to assess *P. vivipara* populations, which created challenges in accurately assessing the species' conservation status. We assumed that *P. vivipara* detectability was consistent across methods and through time; however, this may not be the case. Consequently, the exact year of its extinction remains uncertain. To improve future population assessments, we propose a standardise approach, and recommend quantifying the density of *P. vivipara* at each of the 16 remaining sites, annually.

We suggest sampling perpendicular transects of 1 m width from mid to low tide, where the species is found, with a focus on known spatial points recorded through transects and timed searches. These transects should be conducted at identified points and at intervals of at least every 10 m along the shoreline from the historical points. This approach will allow for comparison with most of the historical data. The timed searches, while useful for searching large areas of low complexity, do not allow comparisons of sea star densities between different locations and sites within locations. Integrating environmental DNA (eDNA) sampling of seawater (Beng & Corlett 2020) could further enhance survey accuracy by minimising habitat disturbance and facilitating the detection of juvenile *P. vivipara*, which are under-sampled by traditional survey techniques. Monitoring should be accompanied by proactive management of localised threats to increase the resilience of *P. vivipara* populations and prevent further unnoticed local extinctions.

The information provided in this study suggests that *P. vivipara* should be listed as Critically Endangered under the IUCN Red List categories and criteria (IUCN 2001). The rapid and ongoing population declines, coupled with unknown and unabated causes, as well as the limited area of occupancy, means this species meets the criteria to be classified as Critically Endangered under IUCN Red List criteria A2 and B1. Our findings also underscore the critical importance of managing the localised threats in all remaining locations containing *P. vivipara*. Notably, the increasing coastal development and intensified catchment uses in the Pitt Water are resulting in significant loss of habitat, and adverse impacts on the surrounding water quality, thereby placing the largest populations of *P. vivipara* at significant risk (Parsons 2020). To protect this species, key management measures could include the development of captive breeding facilities to bolster dwindling populations, the use of ecological engineering techniques to increase habitat availability (Parsons 2023b), the introduction of nutrient and sediment budgets to enhance the local water quality, diversion of storm water and sewage outfalls away from key intertidal habitats (Prestedge et al. 2001, Rowland 2001), assisted colonisation to new areas, and removal of key invasive species, in particular *M. gigas* and *Petrolisthes elongatus*, which compete with *Parvulastra vivipara* for space in the crevice (Fitzpatrick 2023). These strategies are essential for the conservation and recovery of *P. vivipara* in its intertidal rocky reef habitat.

We further highlight the notable scarcity of comprehensive ecological monitoring datasets for tracking the population status of species in intertidal temperate reefs within southeast Australia (Poloczanska et al. 2007, Edgar et al. 2023). This lack of data significantly heightens the risk of rapid species declines and potentially also extinctions occurring without detection, and prevents the capacity to implement appropriate management strategies for declining species. There is a pressing need for extensive monitoring using standardised and appropriate methods, especially for intertidal sea stars and other echinoderms in this region. This is because species within this phylum are particularly vulnerable to the effects of rising temperatures, sea level rise, and other impacts associated with global climate change, primarily due to disease outbreaks, boom and bust life cycles, and their calcified skeletons which make them susceptible to ocean acidification (Uthicke et al. 2009, Nicholls & Cazenave 2010, Gibson et al. 2011, Kaplanis et al. 2020). Additionally, it is essential to recognise that southeast Australia is a climate change hotspot, where many species are already at the edge of their range (Gervais et al. 2021), further heightening the importance of ecological monitoring in this region, which will allow us to track changes in species trajectories. Such monitoring efforts are critical for understanding and addressing the impacts of climate change on marine ecosystems and for allowing marine managers to implement timely conservation measures (i.e. assisted relocation, development of artificial habitats, and captive breeding programs) to protect existing and emerging threatened species.

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LITERATURE CITED

Alroy J (2008) Dynamics of origination and extinction in the marine fossil record. Proc Natl Acad Sci USA 105: 11536–11542

Aquenal (2005) Relocation program for the endangered livebearing seastar *Patiriella vivipara* at Pitt Water, Tasmania. Sorell Causeway bridge replacement project. Pitt and Sherry Engineering and Department of Infrastructure Energy and Resources, Hobart

Aquenal (2013) Population survey of the Tasmanian livebearing seastar *Parvulastra vivipara* at Bambra Reef. Clarence City Council, Hobart

Balogh R, Byrne M (2020) Developing in a warming intertidal, negative carry over effects of heatwave conditions in development to the pentameral starfish in *Parvulastra exigua.* Mar Environ Res 162:105083

Beng KC, Corlett RT (2020) Applications of environmental DNA (eDNA) in ecology and conservation: opportunities, challenges and prospects. Biodivers Conserv 29: 2089–2121

Bozec YM, Kulbicki M, Laloë F, Mou-Tham G, Gascuel D (2011) Factors affecting the detection distances of reef fish: implications for visual counts. Mar Biol 158:969–981

Bugnot A, Mayer-Pinto M, Airoldi L, Heery E and others (2021) Current and projected global extent of marine built structures. Nat Sustain 4:33–41

Byrne M (1996) Viviparity and intragonadal cannibalism in the diminutive sea stars *Patiriella vivipara* and *P. parvivipara* (family Asterinidae). Mar Biol 125:551–567

Byrne M, Walker SJ (2007) Distribution and reproduction of intertidal species of *Aquilonastra* and *Cryptasterina* (Asterinidae) from One Tree Reef, southern Great Barrier Reef. Bull Mar Sci 81:209–218

Chen EYS (2021) Often overlooked: understanding and meeting the current challenges of marine invertebrate conservation. Front Mar Sci 8:690704

Dartnall AJ (1969) A viviparous species of *Patiriella* (Asteroidea: Asterinidae) from Tasmania. Proc Linn Soc N S W 93:294–297

Dhanjal-Adams KL, Hanson JO, Murray NJ, Phinn SR and others (2016) The distribution and protection of intertidal habitats in Australia. Emu Austral Ornithol 116: 208–214

DPIW (Department of Primary Industry and Water) (2006) Threatened species survey of *Patiriella vivipara* and *Gazameda gunnii* in Southport Lagoon for the Southport Lagoon Conservation Area, George III Monument Historic Site & Ida Bay State Reserve Managment Plan 2006. Marine Environment Section, Marine Framing Branch (DPIW), Hobart

Edgar G (1984) General features of the ecology and biogeography of Tasmanian subtidal rocky shore communities. Pap Proc R Soc Tasman 118:173–186

Edgar GJ, Barrett NS, Graddon DJ, Last PR (2000) The conservation significance of estuaries: a classification of Tasmanian estuaries using ecological, physical and demographic attributes as a case study. Biol Conserv 92:383–397

Edgar GJ, Stuart-Smith RD, Heather FJ, Barrett NS and others (2023) Continent-wide declines in shallow reef life over a decade of ocean warming. Nature 615:858–865

Fitzpatrick J (2023) Effects of invasive species, porcelain crabs (*Petrolisthes elongatus*) and Pacific oysters (*Magallana gigas*) on the abundance and behaviour of the threatened species, *Parvulastra vivipara* (Tasmanian livebearing seastar). MSc dissertation, University of Tasmania, Hobart

Fredston-Hermann A, Gaines SD, Halpern BS (2018) Biogeographic constraints to marine conservation in a changing climate. Ann N Y Acad Sci 1429:5–17

Gervais CR, Champion C, Pecl GT (2021) Species on the move around the Australian coastline: a continental-scale review of climate-driven species redistribution in marine systems. Glob Change Biol 27:3200–3217

Gibson R, Atkinson R, Gordon J, Smith I, Hughes D (2011) Impact of ocean warming and ocean acidification on marine invertebrate life history stages: vulnerabilities and potential for persistence in a changing ocean. Oceanogr Mar Biol Annu Rev 49:1–42

Hoffmann M, Brooks T, Da Fonseca G, Gascon C and others (2008) Conservation planning and the IUCN Red List. Endang Species Res 6:113–125

Hoggins DD (1976) Comparative ecological studies of two intertidal sea stars *Patiriella vivipara* Dartnall, 1969 and *P. regularis* Verrill, 1913 (Asteroidea: Asterinidae). PhD dissertation, University of Tasmania, Hobart

Iken K, Konar B, Benedetti-Cecchi L, Cruz-Motta JJ and others (2010) Large-scale spatial distribution patterns of echinoderms in nearshore rocky habitats. PLOS ONE 5: e13845

IUCN (2001) IUCN Red List categories and criteria. IUCN, Cambridge

Jones JP, Asner GP, Butchart SH, Karanth KU (2013) The 'why', 'what' and 'how' of monitoring for conservation. In: Macdonald DW , Willis KJ (ed) Key topics in conservation biology 2. John Wiley & Sons, Chichester, p 329–343

Kaplanis NJ, Edwards CB, Eynaud Y, Smith JE (2020) Future sea-level rise drives rocky intertidal habitat loss and benthic community change. PeerJ 8:e9186

Keever CC, Puritz JB, Addison JA, Byrne M, Grosberg RK, Toonen RJ, Hart MW (2013) Shallow gene pools in the high intertidal: extreme loss of genetic diversity in viviparous sea stars (*Parvulastra*). Biol Lett 9:20130551

Khan M, Whittington C, Thompson M, Byrne M (2019) Arrangement and size variation of intra-gonadal offspring in a viviparous asterinid sea star. Zoosymposia 15: 71–82

Liversage K (2015) Habitat associations of a rare South Australian sea star (*Parvulastra parvivipara*) and a co-occurring chiton (*Ischnochiton variegatus*): implications for conservation. Pac Conserv Biol 21:234–242

Liversage K, Byrne M (2018) A note on life-history traits and conservation concerns for viviparous Australian seastars (*Parvulastra parvivipara* and *P. vivipara*). Res Ideas Outcomes 4:e29766

Mace GM, Collar NJ, Gaston KJ, Hilton-Taylor C and others (2008) Quantification of extinction risk: IUCN's system for classifying threatened species. Conserv Biol 22: 1424–1442

MacKenzie DI, Nichols JD, Sutton N, Kawanishi K, Bailey LL (2005) Improving inferences in population studies of rare species that are detected imperfectly. Ecology 86: 1101–1113

Magurran AE, McGill BJ (2010) Biological diversity: frontiers in measurement and assessment. Oxford University Press, Oxford

Matthies D, Bräuer I, Maibom W, Tscharntke T (2004) Population size and the risk of local extinction: empirical evidence from rare plants. Oikos 105:481–488

McCauley DJ, Pinsky ML, Palumbi SR, Estes JA, Joyce FH, Warner RR (2015) Marine defaunation: animal loss in the global ocean. Science 347:1255641

Mieszkowska N, Kendall M, Hawkins S, Leaper R, Williamson P, Hardman-Mountford N, Southward A (2006) Changes in the range of some common rocky shore species in Britain — a response to climate change? In: Queiroga H, Cunha MR, Cunha A, Moreira MH and others (eds) Marine biodiversity: patterns and processes, assessment, threats, management and conservation. Springer, Dordrecht, p241–251

Mullu D (2016) A review on the effect of habitat fragmentation on ecosystem. J Nat Sci Res 6:1–15

Myers RA, Ottensmeyer CA (2005) Extinction risk in marine species. In: Norse EA, Crowder EA (eds) Marine conservation biology: the science of maintaining the sea's biodiversity. Island Press, Washington, DC, p 58–79

Nicholls RJ, Cazenave A (2010) Sea-level rise and its impact on coastal zones. Science 328:1517–1520

O'Hara T, Byrne M (2017) Australian echinoderms: biology, ecology and evolution. CSIRO Publishing, Melbourne

O'Hara TD, Mah CL, Hipsley CA, Bribiesca-Contreras G, Barrett NS (2019) The Derwent River seastar: re-evaluation of a critically endangered marine invertebrate. Zool J Linn Soc 186:483–490

Parsons KE (2020) Assessment of the live-bearing seastar *Parvulastra vivipara* at the Sorell Causeways. South East Traffic Solution (SETS) — Hobart Airport to Sorell Highway duplication. Final report. Elgin Associates Pty Ltd and Pitt & Sherry, Hobart, Tasmania

Parsons KE (2023a) Live-bearing seastar *Parvulastra vivipara* investigations: receiver sites and habitat augmentation trials outside Pitt Water. Sorell Causeways Duplication Project, South East Traffic Solution (SETS). Pitt & Sherry and the Department of State Growth, Hobart

Parsons KE (2023b) Live-bearing seastar *Parvulastra vivipara* investigations: receiver sites and habitat augmentation trials in Pitt Water. Sorell Causeways Duplication Project, South East Traffic Solution (SETS). Pitt & Sherry and the Department of State Growth, Hobart

Perkins MJ, Ng TP, Dudgeon D, Bonebrake TC, Leung KM (2015) Conserving intertidal habitats: What is the potential of ecological engineering to mitigate impacts of coastal structures? Estuar Coast Shelf Sci 167: 504–515

Polanowski A (2002) The feeding behaviour, distribution and population genetics of the endangered sea star *Patiriella vivipara*. Hons dissertation, University of Tasmania, Hobart

Poloczanska ES, Babcock R, Butler A, Hobday A and others (2007) Climate change and Australian marine life. Oceanogr Mar Biol Annu Rev 45:407

Prestedge GK (1998) The distribution and biology of *Patiriella vivipara* (Echinodermata: Asteroidea: Asterinidae) a sea star endemic to southeast Tasmania. Rec Aust Mus 50:161–170

Prestedge G, Thrall P, Burdon J, Ash J (2001) Updated information and previously unpublished observations on *Patiriella vivipara*, a sea star endemic to southeast Tasmania. Tasman Nat 123:24–35

R Core Team (2023) R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna

Rahman M, Molla M, Megwalu F, Asare O, Tchoundi A, Shaikh M (2018) The sea stars (Echinodermata: Asteroidea): their biology, ecology, evolution and utilization. J Biotechnol Biomed Eng 1:1007

Roediger LM, Bolton TF (2008) Abundance and distribution of South Australia's endemic sea star, *Parvulastra parvivipara* (Asteroidea: Asterinidae). Mar Freshw Res 59:205–213

Rogers AD, Miloslavich P, Obura D, Aburto-Oropreza O (2023) Marine invertebrates. In: Maclean N (ed) The living planet: the state of the world's wildlife. Cambridge University Press, Cambridge, p 249–269

Rowland M (2001) Education and monitoring program for the endangered Tasmanian sea star *Patiriella vivipara*: project report & action plan for the Woodbridge Environmental Group. Marine and Coastal Research Tasmania, Hobart, Tasmania

Short AD (2006) Beaches of the Tasmanian coast and islands: a guide to their nature, characteristics, surf and safety. Sydney University Press, Sydney

Simberloff D (1998) Flagships, umbrellas, and keystones: Is single-species management passé in the landscape era? Biol Conserv 83:247–257

Strain E, Alexander K, Kienker S, Morris R and others (2019) Urban blue: a global analysis of the factors shaping people's perceptions of the marine environment and ecological engineering in harbours. Sci Total Environ 658: 1293–1305

Uthicke S, Schaffelke B, Byrne M (2009) A boom–bust phylum? Ecological and evolutionary consequences of density variations in echinoderms. Ecol Monogr 79:3–24

Whittaker RJ, Araújo MB, Jepson P, Ladle RJ, Watson JE, Willis KJ (2005) Conservation biogeography: assessment and prospect. Divers Distrib 11:3–23

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