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Population biology and recruitment of the vulnerable sea cucumber, *Stichopus herrmanni*, on a protected reef

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Abstract

Populations of tropical sea cucumbers, harvested for bêche-de-mer, are in a perilous state of conservation, yet there remains a paucity of information on the biology of many harvested species. We examined the population biology of the commercially important curryfish, *Stichopus herrmanni*, across 2 years on Heron Reef, a protected zone in the Great Barrier Reef (GBR) Marine Park. *Stichopus herrmanni*, a species recently listed as vulnerable to extinction, is a major target species for the fishery operating in the GBR. The size class distribution and density of *S. herrmanni* were documented for six sites across Heron Reef. There was distinct spatial variation in the size and density of *S. herrmanni* across sites, with no significant difference between the 2 years. The smallest individuals found were 10 cm long, some of the only juvenile *S. herrmanni* documented in nature. Juvenile and sub-adult populations were found along the leeward reef edge of Heron Reef, a habitat characterized by shallow channels of sand between inter-tidal coral reef and crustose coralline algae (CCA). Juvenile nurseries of sea cucumbers are rarely observed in nature, making this an important observation for understanding the recruitment and population biology of *S. herrmanni*. The presence of juveniles in the consolidated CCA habitat each year in autumn following the summer spawning period, and the absence of small individuals several months later in spring, suggests an ontogenetic migration or displacement of these individuals to adult habitat. The distribution of larger *S. herrmanni* suggests intra-reef connectivity and migration into deeper lagoon areas. This study contributes to understanding the population dynamics of this vulnerable species, a consideration for fisheries management in light of increasing global harvest.

KEYWORDS

bêche-de-mer, curryfish, fisheries, Great Barrier Reef, holothuroid, juvenile

1 | INTRODUCTION

Tropical sea cucumbers are harvested globally to produce the high-valued trepang or bêche-de-mer product (dried body wall), which is primarily traded in the Asian market (Anderson, Flemming, Watson, & Lotze, 2011; Eriksson & Clarke, 2015). Owing to high market demand, sea cucumber populations are rapidly declining with over 70% of tropical sea cucumber fisheries deemed exploited, over-exploited or depleted (Anderson et al., 2011; Purcell et al., 2013; Purcell, Polidoro, Hamel, Gamboa, & Mercier, 2014; Eriksson & Byrne, 2015; Eriksson et al., 2015; Lane & Limbong, 2015). Following their overharvest, population recovery is often slow and negligible (Uthicke, Welch, & Benzie, 2004; Hasan, 2005; Price, Evan, Rowlands, & Hawkins, 2013; Lane & Limbong, 2015). As a result, 16 bêche-de-mer species were recently listed by the IUCN (The International Union for Conservation of Nature and Natural Resources) as threatened with extinction (Conand et al., 2014). As numbers of high-valued species decline, less valuable species take over as the major harvest targets, resulting in a serial pattern of depletion being documented for over 75% of sea cucumber fisheries worldwide (Anderson et al., 2011; Eriksson et al., 2015; Lane & Limbong, 2015), including in the management-intensive World Heritage Marine Park of the Great Barrier Reef (GBR), Australia (Eriksson & Byrne, 2015).

Deposit-feeding sea cucumbers play critical roles in sediment breakdown and nutrient cycling (Uthicke & Klumpp, 1998; Uthicke, 1999, 2001), encouraging seagrass and algal productivity (Wolkenhauer, Uthicke, Burridge, Skewes, & Pitcher, 2010), $CaCO_3$ cycling (Schneider et al., 2011, 2013), and serving as hosts to other epibenthic taxa (Purcell & Eriksson, 2014). The breakdown of $CaCO_3$ in the sea cucumber gut as a result of digestive processes is suggested to produce faecal casts that increase local alkalinity, potentially buffering the negative effects of ocean acidification and thereby assisting calcification on coral reefs (Schneider et al., 2011, 2013). Considering the important roles that sea cucumbers play in coral reef ecosystem function, it is imperative that we achieve a better understanding of their population biology.

Stichopus herrmanni is an abundant sea cucumber in the Indo-Pacific that inhabits sandy lagoon, seagrass and coral habitats around 0–30 m depth (Conand, 1993; Desurmont, 2003). This commercially important species is often found at high densities in association with coral reef structures (Conand, 1993; Eriksson, Fabricius-Dyg, Lichtenberg, Perez-Landa, & Byrne, 2010; Eriksson, Thorne, & Byrne, 2013), and is one of the major target species for fisheries operating on the GBR (DEEDI 2010, 2011; Eriksson & Byrne, 2015). Between 2007–11, catches of *S. herrmanni* expanded by around 200% per year on the GBR, without any baseline studies or abundance estimates to inform fisheries management (Eriksson & Byrne, 2015). Owing to such activities, *S. herrmanni* has suffered a 60–90% population decline over 50% of its global range, leading to its recent listing by the IUCN as vulnerable to extinction (Conand et al., 2014).

Studies on *S. herrmanni* and other sea cucumbers from unfished reefs indicate that undisturbed populations remain relatively stable in regard to total numbers and size class distribution across different habitat types (Conand, 2004; Uthicke et al., 2004; Thorne, Eriksson, & Byrne, 2012; Eriksson et al., 2013). Our current understandings of the biology and population ecology of *S. herrmanni* suggest that shallower reef sites support smaller individuals, with adults moving to deeper lagoon or reef slope habitats, increasing in size with depth (Conand, 1993; Eriksson et al., 2013; Palazzo, Wolfe, & Byrne, 2016). Post-recruitment growth and ontogenetic migration between juvenile and adult habitats are important components of a species' population structure and have considerable implications for effective fisheries management and conservation strategies (Gillanders, Able, Brown, Eggleston, & Sheridan, 2003). Juvenile sea cucumbers are rarely observed in nature (Conand, 1988; Shiell, 2004; Eriksson et al., 2010; Palazzo et al., 2016), and so information on the supply-side ecology of tropical sea cucumbers is poor. For commercial species, this hinders our ability to develop appropriate fisheries management strategies for adult populations (Grosberg & Levitan, 1992; Eriksson et al., 2013).

As a key target species for the GBR fishery, it is imperative that we develop a better understanding of the biology and ecology of *S. herrmanni* to facilitate improved measures of conservation. It is likely that patterns of overharvest will continue if appropriate management strategies are not applied (Anderson et al., 2011; Eriksson & Byrne, 2015; Eriksson et al., 2015). We investigated the population biology of *S. herrmanni* at Heron Reef, a protected reef in the Capricorn Bunker Region, Southern GBR. *Stichopus herrmanni* is particularly abundant in this region (Eriksson et al., 2010, 2013; Palazzo et al., 2016), and is heavily targeted by the local fishery (Eriksson & Byrne, 2015). Research on nearby One Tree Reef (~15 km from Heron Island), also a protected zone, revealed a pattern of ontogenetic migration of small *S. herrmanni* from shallow recruitment habitats to deeper lagoon regions as adults (Eriksson et al., 2013). We examined the population patterns on Heron Reef, documenting the density and size class distribution of *S. herrmanni* across 2 years focusing on a recently identified shallow water recruitment site (Palazzo et al., 2016), and deeper areas where large adults are typically found (Eriksson et al., 2013).

2 | MATERIAL AND METHODS

Five sites were surveyed across Heron Reef (23°26′31′′ S, 151°54′50′′ E; Fig. 1). These sites reflected different habitat types across Heron Reef and varied in depth (Fig. 1; Table 1; Jell & Flood, 1978; Jell & Webb, 2012). They included potential recruitment sites for *S. herrmanni* in shallow water crustose coralline algal (CCA) habitat (Palazzo et al., 2016). A sixth site, a manmade harbour, was also included (Table 1). Population surveys were completed in April 2015 and 2016, 3–4 months after the peak summer spawning period of the local population. The recruitment habitat was revisited in September (spring) 2015, 5 months later, to search for juveniles.

At each site, 20 transects (40 × 2 m) were haphazardly placed on sandy substrate per year, sometimes intercepting reef habitat. Each transect was considered a replicate within its respective site ($n = 20$/site). Surveys were conducted by walking and snorkelling along the transect lines during the day. No surveys were conducted at night as *S. herrmanni* does not exhibit differential nocturnal behaviour (Eriksson et al., 2013). All *S. herrmanni* within transects were counted, and the length and width of each individual were taken. Length was taken along the centreline and width along the widest part of the animal. Measurements were taken using a flexible tape measure without touching or disturbing the individual (Eriksson et al., 2013). Reef structures and crevices within the transects were carefully searched for cryptic individuals. Those positioned inside reef features were counted for density calculations but could not be measured. Total density was recorded for each transect and an average density calculated for each site ($n = 20$/site), each year. The length and width data for each *S. herrmanni* were used to plot the size class distributions.

2.1 | Statistical analysis

Data on *Stichopus herrmanni* length, width and density were analysed separately using two-way analysis of variance (ANOVA), with site and year as fixed factors. As required for ANOVA, homogeneity of

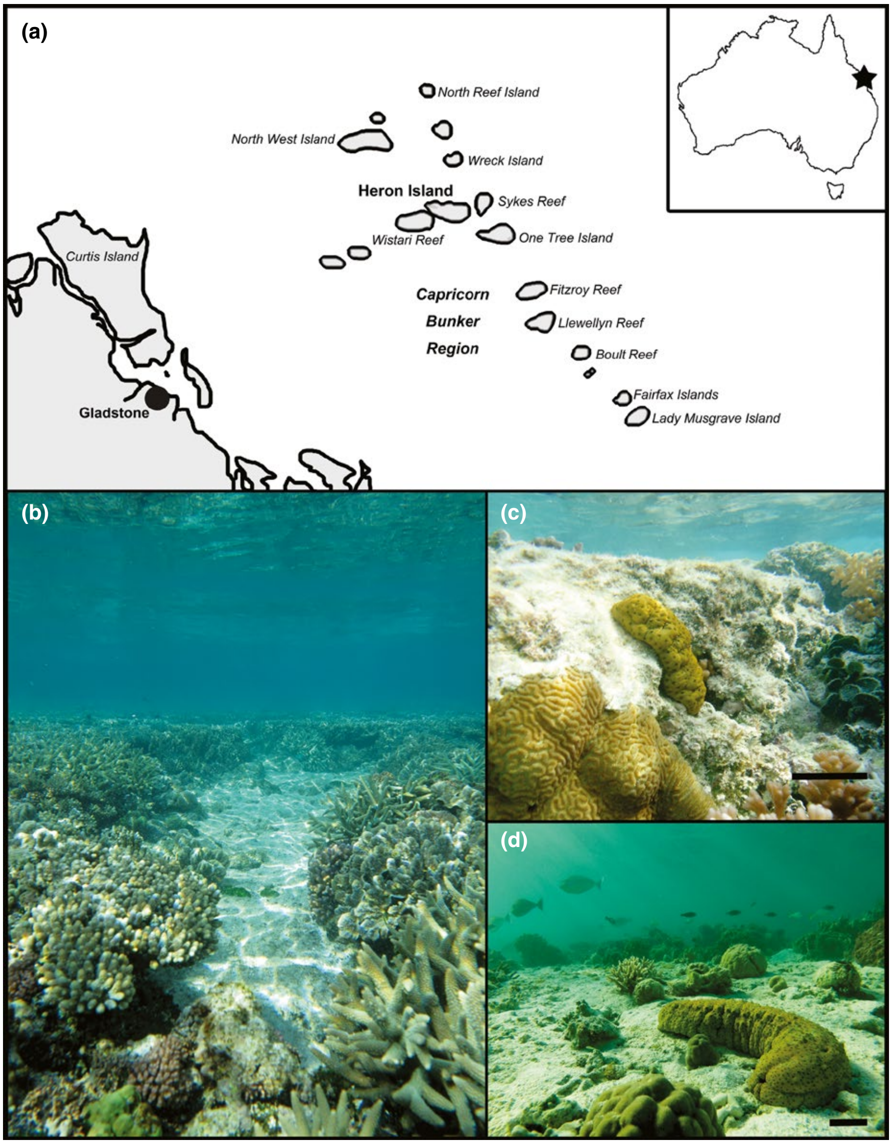

FIGURE 1 (a) Location of Heron Island and surrounding reefs, and images of (b) the shallow habitat typical of Site 1 (taken at high tide), (c) juvenile *Stichopus herrmanni* on shallow reef structure (Site 1), and (d) large adult in deeper lagoon habitat (e.g. Sites 3 and 6) (scale bars = 4 cm)

TABLE 1 Description of sites sampled across Heron Reef (Jell & Flood, 1978; Jell & Webb, 2012); depths are at low tide

site	description
leeward	
Site 1	reef-edge habitat characterized by dense inter-tidal reef and a thick crustose coralline algae (CCA) matrix. There are shallow (0–1.2 m) gutters of $CaCO_3$ sediment between inter-tidal reef structures (Fig. 1b, c), which are often exposed at low tide.
Site 2	shallow (0–1.5 m) sediment habitat with occasional patch reefs and conspicuous macroalgae. Reef surfaces are sometimes exposed at high tide.
lagoon	
Site 3	deeper (0.5–2.2 m) sediment habitat with numerous patch reefs with some macroalgal cover. Reef surfaces are rarely exposed at high tide (Fig. 1d).
windward	
Site 4	shallow (0–1.5 m) sediment habitat with occasional patch reefs and conspicuous macroalgae. Reef surfaces are sometimes exposed at low tide.
Site 5	reef-edge habitat characterized by dense inter-tidal reef and a thick CCA matrix. Shallow (0–0.6 m), with no or few sediment patches.
harbour	
Site 6	a deep (~1–4 m) man-made channel used as the harbour to access Heron Island. Artificial concrete bund walls influence the timing, height and strength of tides and currents (Gourlay & Hacker, 2008).

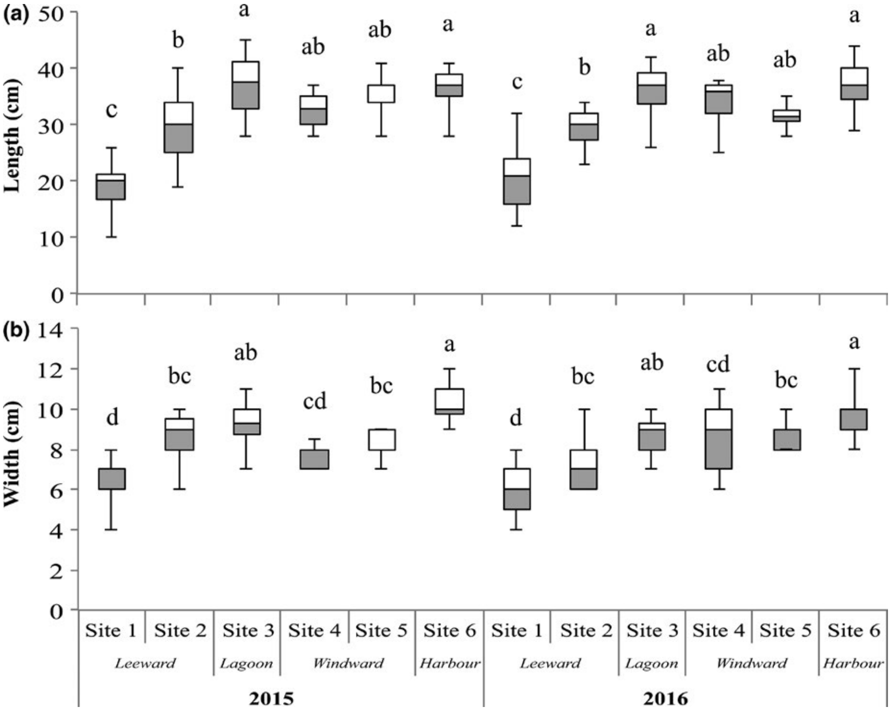

FIGURE 2 The (a) length and (b) width of *Stichopus herrmanni* measured at six sites across Heron Reef in 2015 and 2016. Boxes represent the interquartile range (25th and 75th percentile), the horizontal line is the median, and the whiskers represent the data range. Letters that are the same do not differ (Tukey's honest significant difference [HSD] test)

variance and normality was checked and confirmed for all data series (Quinn & Keough, 2003). Density data were arcsine transformed to normalize values. *Post-hoc* Tukey's honest significant difference (HSD) test was used to determine significant differences amongst sites. All data were analysed using JMP 501 (Cary, NC, USA).

3 | RESULTS

A total of 114 and 91 *Stichopus herrmanni* were measured across Heron Reef in 2015 and 2016, respectively. The size of sea cucumbers encountered ranged from 10–45 cm in 2015 and 12–44 cm in 2016 (Fig. 2). There were significant differences in the length [ANOVA, F(5,204) = 57.93, $p < .01$) and width [ANOVA, F(5,204) = 38.07, $p < .01$] of *S. herrmanni* across Heron Reef, but there were no significant differences in either length ($p = .63$) or width ($p = .45$) between the 2 years. Tukey's HSD tests revealed that the smallest individuals were found in the shallow leeward reef habitat (Site 1), ranging from 10–32 cm length and 4–8 cm width (Fig. 2a, b). There was an increase in the size of *S. herrmanni* encountered from this site towards the lagoon (Site 3) (Fig. 2a, b), with increasing depth (Table 1). The largest individuals were found in the deeper lagoon site (Site 3) and in the manmade harbour (Site 6), ranging from 26–45 cm in length and 7–12 cm width (Fig. 2a, b). A survey of the recruitment site in September 2015 failed to locate any juvenile *S. herrmanni* (K. Wolfe, personal observations).

The density of *S. herrmanni* was significantly different across the study sites [ANOVA F(5,239) = 14.79, $p < .01$], but not between years ($p = .066$). *Post-hoc* Tukey's HSD tests revealed that the highest density of *S. herrmanni* was found in the harbour (Site 6), at 218.75 and 168.75 individuals ind. ha^{-1} in 2015 and 2016, respectively (Fig. 3). Sites along the windward margin (Sites 4 and 5) had the lowest densities, between 31.25 and 56.25 ind. ha^{-1} (Fig. 3). There was a decrease in the density of *S. herrmanni* lagoonward from Sites 1 (131.25–175 ind. ha^{-1}) and 2 (87.5-156.25 ind. ha^{-1}), to Site 3 (75–100 ind. ha^{-1}) across both years (Fig. 3).

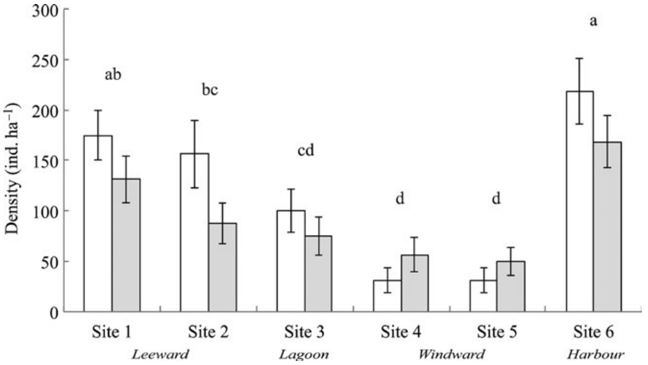

FIGURE 3 Average density (ind. ha^{-1}) of *Stichopus herrmanni* at six study sites across Heron Reef in 2015 (white bars) and 2016 (grey bars). Letters that are the same do not differ (Tukey's HSD test)

4 | DISCUSSION

4.1 | Population metrics at Heron Reef and patterns of early life history

There was no significant difference in the size distribution of *Stichopus herrmanni* between 2015 and 2016. In both years, the smallest *S. herrmanni* found were 10–12 cm long, which are some of the smallest individuals found for this species in nature (Shiell, 2004; Eriksson et al., 2010, 2013; Palazzo et al., 2016). At this size, *S. herrmanni* is considered to be an early juvenile (Conand, 1993; Shiell, 2004). We found just two other reports of juvenile *S. herrmanni*; one individual recorded to be 9 cm long in New Caledonia (Conand, 1993), and one at 11 cm on One Tree Reef (Eriksson et al., 2013). We also observed 37 sub-adults under the estimated size of sexual maturity for this species (<22 cm; Conand, 1993) across the 2 years, primarily along the shallow leeward reef margin (Sites 1 and 2). Previous long-term studies of *S. herrmanni* populations on One Tree Reef struggled to find individuals below 20 cm length, despite extensive searches (Eriksson et al., 2010, 2013).

The presence of small *S. herrmanni* in the leeward habitat in April in both years, and the absence of small individuals several months later in September, indicates that this is an important site for recruitment. Stichopodids are known to exhibit rapid growth from juveniles to adults, with body length plateauing at larger adult sizes (Conand, 1988; Hu et al., 2010; Eriksson et al., 2013). Under aquaculture conditions, a tropical *Stichopus* sp. (closely related to *S. herrmanni*) grew to ~20 cm length in 7 months (Hu et al., 2010). As *S. herrmanni* spawns in the summer (December–February) around Heron Reef (Eriksson et al., 2010; K. Wolfe, personal observations), the juveniles found in April (10–12 cm length) are estimated to have been 3–4 months old, assuming that they were the annual cohort. However, growth rates of *S. herrmanni in situ* are unknown. The lack of juveniles in the same site 5 months later suggests that these small individuals had grown and/or moved on to adult habitat, similar to the ontogenetic migration or displacement of this species observed at One Tree Reef (Eriksson et al., 2013).

Considering that the planktonic larval duration of several tropical Aspidochirotida sea cucumbers is generally short (14–21 days; Ramofafia, Byrne, & Batteglene, 2003; Hu et al., 2010), and that conspicuous populations of mature *S. herrmanni* occur in the region, we suggest that the leeward margin of Heron Reef may be an important self-seeding site. This leeward habitat is characteristic of shallow intertidal consolidated reef of corals and CCA. It is well known that CCA and associated biofilms trigger settlement in sea cucumber and other echinoderm larvae (Ramofafia et al., 2003; Dworjanyn & Pirozzi, 2008; Swanson et al., 2012), corals (Heyward & Negri, 1999; Harrington, Fabricius, De'ath, & Negri, 2004; Price, 2010) and molluscs (Roberts, Kaspar, & Barker, 2004; Williams, Craigie, Yeates, & Degnan, 2008). However, studies on the settlement preferences of sea cucumber larvae are scarce (Mercier, Battaglene, & Hamel, 2000). The presence of juvenile *S. herrmanni* in the mixed coral/CCA habitat along the leeward margin of Heron Reef suggests that CCA may be a key factor influencing recruitment to this site.

4.2 | Reef-scale patterns of ontogenetic migration

For marine species where juvenile nurseries have been found, it is common for these to be spatially and physically distinct from that of the adult, requiring ontogenetic migration between habitats (Gillanders et al., 2003; Shiell, 2004; Falkner & Byrne, 2006). Previous studies indicate that the migration of small individuals from shallow recruitment habitats to deeper lagoon habitats plays a major role in the population dynamics of *Stichopus herrmanni* (Conand, 1993; Eriksson et al., 2013) and other sea cucumber species (Hamel & Mercier, 1996; Hamel, Conand, Pawson, & Mercier, 2001; Slater, Carton, & Jeffs, 2010). This migration of juveniles and sub-adults from hard settlement substrates to areas of soft sediments may be driven by an ontogenetic change in diet (Slater et al., 2010).

The smallest individuals here (10–12 cm length) were recorded in shallow leeward coral/CCA habitat (0.2–1.5 m depth), whereas the largest were recorded in the deeper sandy lagoon (0.8–4 m depth), similar to the population dynamics of *S. herrmanni* documented previously for One Tree Reef (Eriksson et al., 2013). Larger individuals close to the maximum size for this species (50 cm length) occur in deeper areas of Heron Lagoon (3–6 m depth) (K. Wolfe, personal observations), typical of this species (Conand, 1993; Eriksson et al., 2013). We suggest that the large individuals residing in Heron Lagoon may have originated from juveniles migrating from their shallow water recruitment and nursery habitats, as suggested for *S. herrmanni* on One Tree Reef (Eriksson et al., 2013). We also note that large *S. herrmanni* are less able to retain a hold on the substrate and are readily displaced into deeper areas by wave action (K. Wolfe, personal observations).

There could be several ecological benefits for *S. herrmanni* moving lagoonward as they grow, including: (i) increased availability of productive lagoon sediments, suggesting increasing feeding potential (Larkum, Kennedy, & Muller, 1988; Eriksson et al., 2010; Slater et al., 2010); (ii) reduced exposure to wave energy, which causes displacement for large adults with a greater surface area : body size ratio (K. Wolfe, personal observations); and/or (iii) increased reproductive success with increased density of mature adults (*i.e.* the Allee effect).

4.3 | Implications for fishery management

Densities of *Stichopus herrmanni* in the marine protected areas of the Capricorn Bunker Region are some of the highest known for this species, reaching up to 736 ind. ha^{-1} (Eriksson et al., 2010, 2013). Although we present a lower density of *S. herrmanni* on Heron Reef (31.25–218.75 ind. ha^{-1}), our values are markedly higher than other records from the Northern GBR (10 ind. ha^{-1}; Hammond, Birtles, & Reichelt, 1985), Northwest Australia (0–14 ind. ha^{-1}; Skewes et al., 1999), New Caledonia (0–102 ind. ha^{-1}; Conand, 1993), the Torres Strait (0–21 ind. ha^{-1}; Skewes et al., 2004) and Papua New Guinea (0.1–31 ind. ha^{-1}; Kinch, Purcell, Uthicke, & Friedman, 2008).

Currently, the fishery operating on the GBR has a minimum size restriction for *S. herrmanni* of 35 cm (DEEDI 2011). In line with this size limit, no individuals observed in the leeward recruitment habitat (Site 1) could be removed. However, it would be legal to remove up to 24% of the population from Site 2, 67% from Site 3, 56% from Sites 4 and 5, and 80% from the harbour (Site 6), assuming that Heron Reef was not a protected zone. A similar trend was estimated for One Tree Reef (Eriksson et al., 2013). Although populations of small individuals may be protected from fishing pressure, areas with larger fecund adults could experience overharvest (Hasan, 2005; Eriksson et al., 2013). This is an important dynamic to understand as reproductive output increases with size for some sea cucumber species (Conand, 1993). However, the only published information on the reproductive biology of *S. herrmanni* is based on a single study conducted in New Caledonia (Conand, 1993). More research is needed on *S. herrmanni* on the GBR to better understand the reproductive output of this species and its reproductive cycle to identify suitable spawning fishery closure periods, and the ramifications of removing large fecund individuals from particular sites.

The ontogenetic migration of adults (potentially assisted by hydrodynamic displacement) within lagoon systems like Heron Reef and One Tree Reef appears to be an important feature of the population dynamics of *S. herrmanni* (Eriksson et al., 2013). Considering that these reefs are protected systems, it is important to determine the population structure of this species on nearby reefs in the Capricorn Bunker Region that are both open (*e.g.* Boult, Fitzroy, Lamont Reefs) and closed (*e.g.* Llewellyn, Sykes, Wistari Reefs) to the fishery. The patterns of ontogenetic migration from shallow nursery sites as documented for One Tree Reef and Heron Reef may not be a feature of submerged reefs that lack the shallow water consolidated coral/CCA habitat. Further, potential 'spill-over' effects from protected zones to fished zones are not known. The patterns of ontogenetic migration documented for the shallow reef systems here suggest that there would be limited or no adult spill-over to other reefs. However, stable reproductive populations of *S. herrmanni* on protected reefs would probably generate intra-reef connectivity through larval dispersal. It is necessary that we examine the population biology and ecology of *S. herrmanni* on fished and unfished reefs to better understand the impacts of fishery removal on long-term population sustainability.

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