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Records of non-indigenous marine species at Palmyra Atoll in the US Line Islands

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Globally, introductions of non-indigenous species have caused dramatic economic and ecological damage. Most research on marine invasions has occurred in locations easily accessible by researchers, but much less is known about introductions to remote islands. In the central Pacific, Palmyra Atoll represents one of the last remaining quasi-pristine reef systems left in the world. In the 1940s the Atoll underwent extensive military modifications, potentially making it susceptible to invasive species. Here we describe the presence of five non-indigenous invertebrate and algal introductions at Palmyra, including two sponges, Haliclona (Sigmadocia) caerulea *and* Gelliodes fibrosa*; one bryozoan;* Zoobotryon verticillatum*; one hydroid,* Pennaria disticha *and one macroalga,* Acanthophora spicifera. *The Hawaiian Archipelago is the most likely source of the introductions via shipping or yachting activity to the Atoll. Currently, the impacts of these introductions remain unknown although future monitoring will assess the influence of these non-indigenous species on this remote reef system.*

Keywords: non-indigenous, introduction, sponge, algae, hydroid, bryozoan, lagoon, coral reef, Palmyra Atoll

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INTRODUCTION

The historic isolation of many Pacific island marine communities generally provides these with greater protection from direct anthropogenic impacts compared to coastal communities. However, many of these island ecosystems such as Johnston and Wake Atolls, and Howland and Baker Islands were drastically altered during World War II due to military construction work (Maragos *et al.*, 2008a). Both the alteration of habitats and the inadvertent and intentional transport of terrestrial and marine non-indigenous propagules began the transition of these habitats away from their pristine state.

Palmyra Atoll (Figure 1) in the US Line Islands is part of the Pacific Remote Island Areas (PRIAs) Marine National Monument created in 2008 and is administered by the US Fish and Wildlife Service of the US Department of Interior. The reefs surrounding Palmyra are richly diverse with high coral biodiversity (Williams *et al.*, 2008) and large numbers of apex predators, providing one of the last remaining baselines for a 'near pristine' reef system (Sandin *et al.*, 2008b). This atoll is a suitable site for studying historical alteration as it was developed into a military installation in the early 1940s, with upwards of 6000 servicemen stationed there during World War II (Dawson, 1959). Prior to development by the military, Palmyra was an undisturbed atoll with numerous small islets forming a perimeter around three distinct lagoons (Dawson, 1959). The military drastically altered the atoll by using dredged material from the lagoon to build up the islets, and create airstrips and connecting causeways. The causeways formed a perimeter road around the lagoons bisecting the eastern and central sections, essentially creating a fourth lagoon at the west end of the atoll and drastically altering the circulation patterns within the interior of the atoll (Dawson, 1959; Maragos, 1993; Maragos *et al.*, 2008a, b; Collen *et al.*, 2009). In addition, a navigation channel was excavated in the south-western end of the atoll to allow ships to enter the lagoon (Dawson, 1959). Therefore, the recent history of Palmyra Atoll is one of severe habitat alteration and potential exposure to terrestrial and marine non-indigenous species through anthropogenic transport mechanisms.

Dredging characteristically reduces habitat complexity and availability (Auster, 1998; Auster & Langton, 1998) heavily impacting the macrobenthos (Rosenberg, 1977; Wassenberg *et al.*, 2002), changing species composition, diversity and richness (Jones, 1992; Wassenberg *et al.*, 2002; Hiddink *et al.*, 2006). The dredging across the lagoons may initially have left non-indigenous species unchallenged due to the removal of the native biota as well as inadvertently creating conditions more suitable for introduced species over the recipient biota (Vitousek *et al.*, 1997).

The terrestrial non-indigenous species at Palmyra have been documented extensively (Dawson, 1959; Flint, 1992), but no non-indigenous marine species, which may threaten the reefs, have yet been described. Here we present details of the recently reported non-indigenous species at Palmyra Atoll. To date, one macroalgae species and four marine invertebrates have been documented as non-indigenous to this

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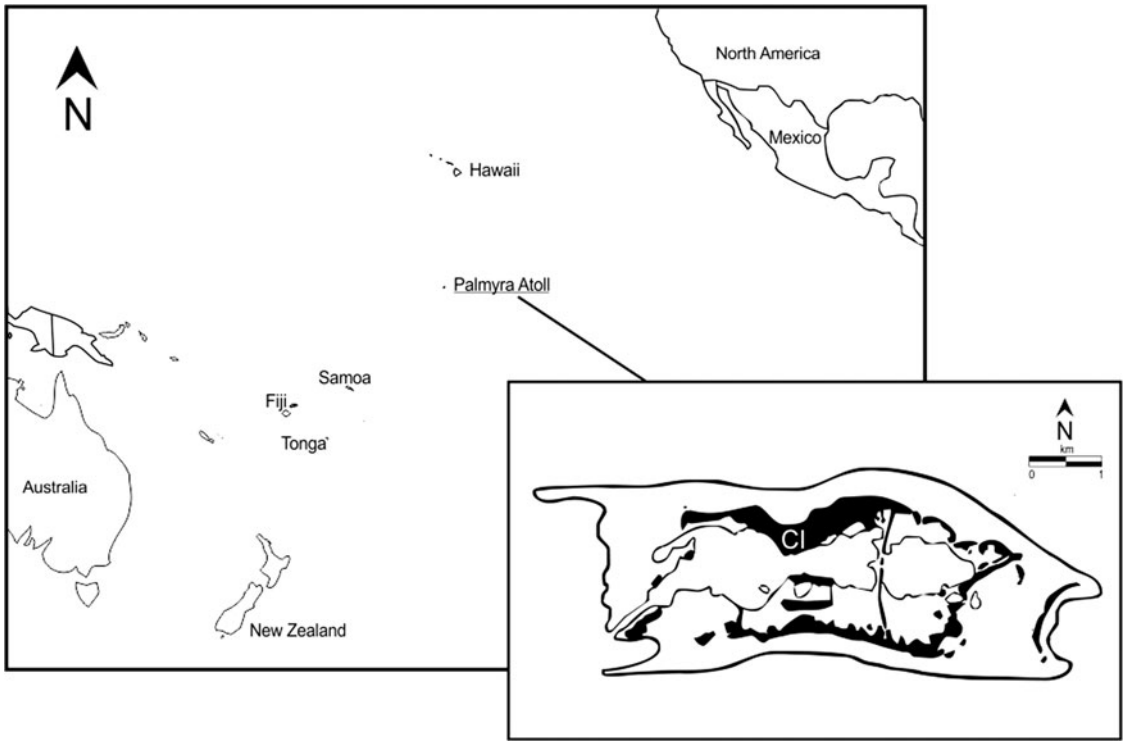

Fig. 1. Location of Palmyra Atoll within the Central Pacific Ocean. CI, Cooper Island.

remote atoll and include a red alga, two sponges, a hydroid and a bryozoan.

MATERIALS AND METHODS

Initial surveys for marine non-indigenous species began in 2002 through to 2009 under the auspices of inventory and monitoring activities conducted at Palmyra Atoll by the US Department of Commerce, National Oceanic and Atmospheric Administration (NOAA), Pacific Islands Fisheries Science Center and Coral Reef Ecosystem Division (CRED) (Godwin, 2002). These surveys examined both natural coral reef habitat and altered habitats in the lagoon including sea walls, docks and dredge spoil areas. Additional surveys began in 2008 by researchers from Victoria University of Wellington, New Zealand and the Scripps Institution of Oceanography associated with the Palmyra Atoll Research Consortium (PARC).

Surveys

The surveys for non-indigenous species at Palmyra Atoll were conducted by three institutes with independent objectives and therefore different, but appropriate, sampling methods were used for each.

ALGAE

An initial qualitative survey of *Acanthophora spicifera* (Børgesen, 1910) (see Figure 2) was conducted at a number of sites in 2002 and again in 2008 (as part of a lagoon restoration experiment). Regular annual quantitative monitoring takes place using $10 \times 1\ m^2$ quadrats along each of 2×25 m transect lines. Photographs of the benthos are taken and species abundance and composition are determined using image analysis software Photogrid© v1.0 (Bird, 2003). During 2008 a number of sites spanning from the western to eastern lagoons at 1–5 m depth were also surveyed.

NON-SPONGE INVERTEBRATES

The CRED surveys were conducted using two 25×2 m belt transects at each site. Suspected non-indigenous species were sampled and preserved for later taxonomic analysis.

SPONGES

Surveys for the non-indigenous sponges were conducted in 2008 across all four lagoons at twelve sites using $10 \times 1\ m^2$ quadrats subdivided into $20\ cm^2$ squares at depths of 6–8 m. Within each square, per species, we counted numbers of individuals, estimated the percentage area cover of both sponges and hard substratum and adjusted all data to the percentage of available substrate.

RESULTS AND DISCUSSION

Acanthophora spicifera

The red alga *Acanthophora spicifera* is currently the only known non-indigenous seaweed species present in the waters surrounding Palmyra Atoll. During surveys conducted in 2002, *A. spicifera* was not found around the atoll despite sampling a large number of sites including both lagoon and reef habitats (Godwin, 2002). However, in 2008 specimens of the alga were found conspicuously attached to several of the mooring buoys anchored in the western lagoon near

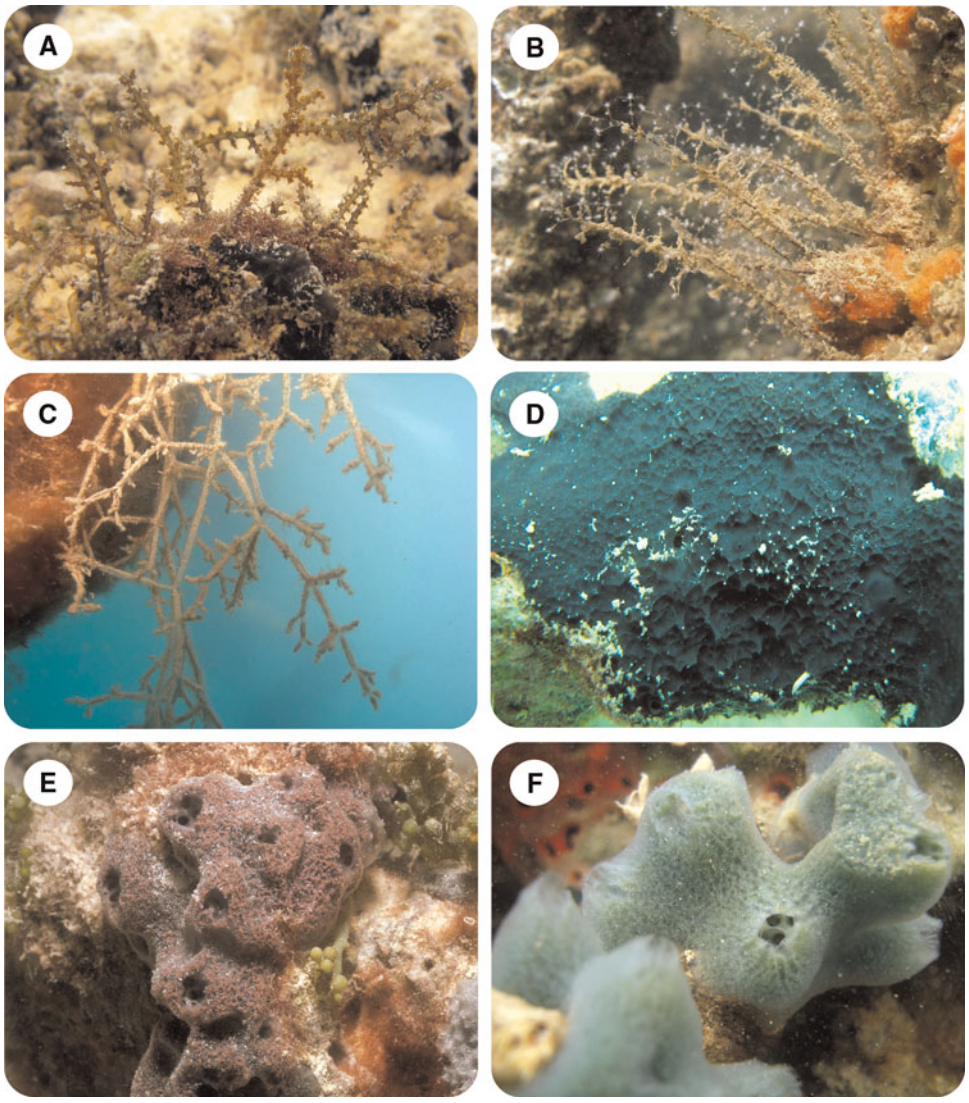

Fig. 2. Photographs of identified non-indigenous species at Palmyra Atoll. (A) *Acanthophora spicifera*; (B) *Pennaria disticha*; (C) *Zoobotryon verticillatum*; (D) *Gelliodes fibrosa*; (E) *Haliclona (Sigmadocia) caerulea* purple morph; (F) *Haliclona (Sigmadocia) caerulea* blue morph.

Cooper Island (see Figure 1), the current location of the field station. After this initial discovery, qualitative surveys were conducted around the lagoon and samples were found at the locations shown in Figure 3. *Acanthophora spicifera* is native to the western and south Pacific, the Indian Ocean and the Caribbean, but is a known invader in the Hawaiian Islands (Guiry & Guiry, 2010).

Acanthophora spicifera was originally introduced to the Hawaiian Islands in the 1950s via hull fouling on a barge that was brought from Guam to Oahu (Doty, 1961; Russell, 1992). This species has now spread throughout all of the main Hawaiian Islands and has most likely been transported via hull fouling of small vessels (Smith *et al.*, 2002). Privately owned yachts are allowed entrance to Palmyra's lagoons for short periods of time with special permission and permitting through the USFWS. Therefore, it is likely that *A. spicifera* was transported on the hull of a yacht or small vessel from Hawaii to Palmyra sometime between 2002 and 2008. It likely first established on a mooring near Cooper Island and either through sexual reproduction or asexual fragmentation spread throughout much of the shallow water habitats (>1 m, <10 m) in the lagoon. While *A. spicifera* is a red alga its coloration can be highly variable ranging from purple to brown and even yellow. The alga attaches to the substrate with a single holdfast and the upright portion of the thallus has an alternate branching pattern. All of the main branches are covered with short thick spines that radiate sporadically off of the algal thallus. On Palmyra this alga is primarily found on limestone flats or rubble zones spanning in depth from 1–5 m. There are currently no data indicating the ecological impacts (if any) of this algal invader on the already highly degraded lagoon ecosystem of Palmyra, but observational evidence suggests that numerous green sea turtles found on the atoll are consuming it (E. Sterling, personal communications). Specimens of fertile female plants were collected in July 2010 suggesting that A. *spicifera* is now reproducing sexually, which may help facilitate its spread around the atoll. To date this alga has not been found on the outer reef habitats, but future survey efforts should pay special attention to this and other algal invaders as they have the potential to alter the coral and coralline algal dominated fore reef and reef terrace habitats (Sandin *et al.*, 2008a). Documentation of the spread and ecology of *A. spicifera* around Palmyra Atoll could be very useful for

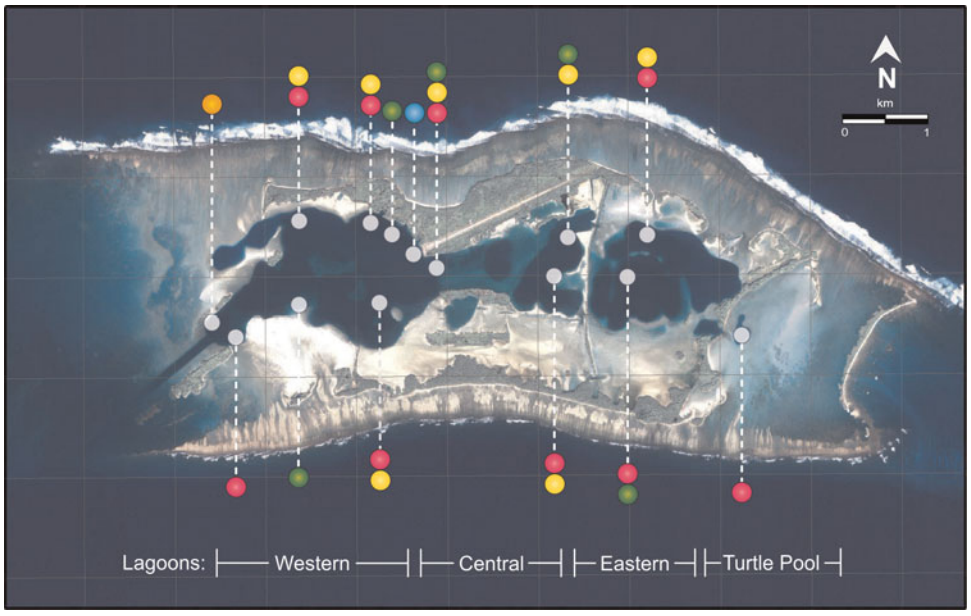

Fig. 3. Locations of non-indigenous species found across the lagoons at Palmyra Atoll. *Acanthophora spicifera*; *Pennaria disticha*; *Zoobotryon verticillatum*; *Haliclona (Sigmadocia) caerulea*; and *Gelliodes fibrosa*.

understanding the invasion ecology of this species in other locations. Finally, if any management or control strategy is going to be developed for *A. spicifera* on Palmyra a targeted monitoring programme should be established.

Pennaria disticha (hydroid) and *Zoobotryon verticillatum* (bryozoan)

The hydroid *Pennaria disticha* (Goldfuss, 1820) and the bryozoan *Zoobotryon verticillatum* (Della Chiaje, 1822) (see Figure 2) are the two recorded non-sponge invertebrate introductions to Palmyra Atoll.

Pennaria disticha, also known as the Christmas tree hydroid, is native to the western Atlantic and has now established within the western lagoon of Palmyra (see Figure 3). This species has become cosmopolitan in tropical and warm temperate seas and is a common sessile organism in harbours, natural lagoons and embayments. It has also been documented at remote coral reef habitats in the Hawaiian Archipelago (Godwin, 2006). *Pennaria disticha* has been observed to be an aggressive competitor for space in both man-made and natural habitats in the Hawaiian Archipelago (Godwin, personal observation). This behaviour has proved to be unpredictable with this species and could be associated with variations in environmental factors, which has been shown to be the case for hydroids in other locations (Boero, 1984).

Zoobotryon verticillatum is a stoloniferous bryozoan forming translucent colonies on hard substrates in bays and harbours. The colonies can form streaming masses and tangled mats that have been confused with macroalgae (Coleman, 1999). This species is found in many tropical and warm temperate waters around the world and has an uncertain home range (Carlton & Eldredge, 2009). *Zoobotryon verticillatum* is considered high risk by management agencies in the United States based on documented economic and ecological impacts (Nagy, 2006; Williams, 2007). Its presence was first recorded at Palmyra Atoll in 2008, at which time it was forming large bushy aggregations at a long-term monitoring site established by CRED in 2002 within the main navigation channel (see Figure 3). These concentrated aggregations have the potential to overgrow coral communities if they spread to fore reef locations and create habitat changes in the shallow subtidal areas of the lagoon. Pederson & Peterson (2002) showed that stoloniferous bryozoans create an ephemeral habitat in shallow subtidal zones that can cause shifts in species assemblages.

The distributions of *P. disticha* and *Z. verticillatum* can be attributed to their ability to foul boat hulls, which is well-documented in remote tropical ecosystems, such as the Hawaiian Archipelago (Godwin, 2003; Godwin *et al.*, 2004) and the Azores (Amat & Tempera, 2009). Palmyra Atoll receives maritime vessel traffic in the form of commercial re-supply vessels from Hawaii and sporadic visits from sailing yachts that have frequented ports in the tropical Pacific. Therefore, identifying the source populations for *P. disticha* and *Z. verticillatum* found at Palmyra Atoll would be difficult.

Haliclona (Sigmadocia) caerulea and *Gelliodes fibrosa*

The two non-indigenous sponge species in the lagoons at Palmyra Atoll (see Figure 3), are the Demosponges *Haliclona (Sigmadocia) caerulea* (Hechtel, 1965), and *Gelliodes fibrosa* (Wilson, 1925) (see Figure 2) from the order Haplosclerida. Both species are found around the main Hawaiian Islands (De Felice *et al.*, 2001; Coles *et al.*, 2006) usually in shallow water embayments, harbours and disturbed habitats, all with restricted water flow (De Felice *et al.*, 2001).

Haliclona caerulea (family Chalinidae), commonly known as the 'Blue Caribbean sponge' originates from the Caribbean Sea where it is found on rocks, dock pilings and mangrove

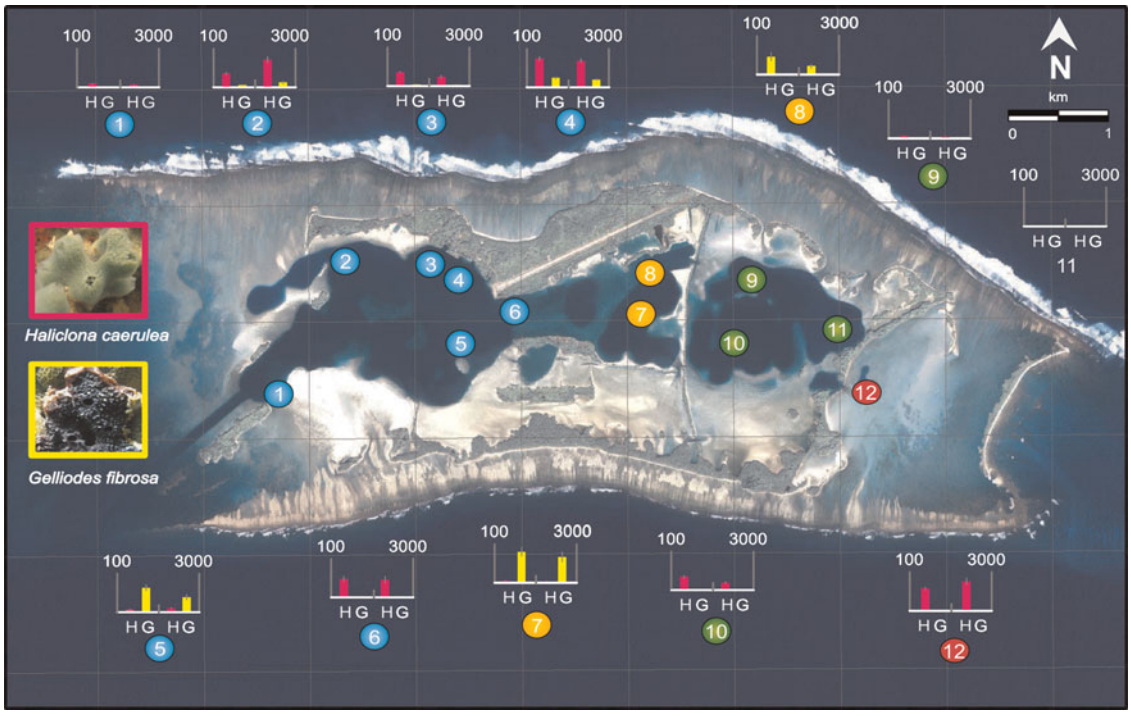

Fig. 4. Sponge densities (right hand side of graph), and area cover (cm^2) (left hand side of graph) of *Haliclona (Sigmadocia) caerulea* (H) and *Gelliodes fibrosa* (G) 10 × 1 m^2 quadrats at each of the 12 sites across the Western (1–6), Central (7–8), Eastern (9–11) and Turtle Pool (12) lagoons at Palmyra Atoll.

roots (Hechtel, 1965; Cubit & Williams, 1983; Wulff, 1997; De Weerdt, 2000). *Haliclona caerulea* is pale blue with a beige interior and is soft and easy to tear. Interestingly, the majority of individuals at Palmyra are found in association with the red branching coralline alga *Jania adherens*. The alga rarely protrudes from the sponge tissue and provides skeletal structuring and rigidity (Carballo & Avila, 2004). This mutualistic relationship also exists in individuals from the Pacific Coast of Panama (Wulff, 1997) and Mexico (Carballo & Avila, 2004), and changes the colour of the sponge from its characteristic pale blue to purple, making the sponge brittle, but still easy to tear. The purple forms retain some blue tissue, normally at the base of the sponge aiding in the identification of this species. *Haliclona caerulea* develops into thickly encrusting or massive forms approximately 40 cm in diameter and 2–15 cm in height. The oscules (0.5–1.5 cm diameter) are on top of thickly walled irregular volcano-like protrusions (1–5 cm in height). The megascleres are bent oxeas (170–230 μm), and the microscleres are C-shaped sigmas (25 μm) (De Felice *et al.*, 2001). The sigmas are common throughout the blue tissue, but less common in the purple forms (Hechtel, 1965).

Gelliodes fibrosa is characterized by its dark grey, blue/black appearance, and tissue, which is fibrous, hard to tear, and if repeatedly squeezed turns beige. It forms thick encrusting mats or branches with a smooth to conulose surface and regular extruding fibres. The oscules, usually found on the flatter encrusting individuals, indent before forming the opening. The megascleres are curved oxeas (160–180 μm) and the microscleres are sigmas (15 μm). *Gelliodes fibrosa* was originally described from the Philippines and was introduced to Hawaii in the 1990s and has now also been documented in Guam (De Felice *et al.*, 2001).

Spatial distribution patterns of *H. caerulea* indicate higher densities at sites across the northern edge of the western lagoon, the centre of the eastern lagoon and the eastern edge of Turtle Pool (see Figure 4). *Gelliodes fibrosa* was primarily located on the southern edge of the western lagoon, and the central lagoon. The abundance of both species was lower in the eastern lagoon, but interestingly *H. caerulea* also had high abundance in the far east of Turtle Pool. The reduction in sponge densities from the west to east lagoons may relate to the reproductive strategies of the sponges. Sponges can either fragment over short distances and/or produce larvae. The larvae are predominantly anchiplanic, remaining in the water column for only minutes to days, thus having limited dispersal capability (Maldonado, 2006). Increased densities of *H. caerulea* in the far eastern Turtle Pool suggests that sponge distribution patterns across Palmyra may not be limited by dispersal capabilities, but also influenced by environmental conditions across the lagoons.

It is most likely that *H. caerulea* and *G. fibrosa* were introduced to Palmyra from Hawaii, via fouling on ships and yachts (Godwin, 2003) or other structures (e.g. barges), as Hawaii has always been the predominant shipping connection to Palmyra (Dawson, 1959). Neither De Laubenfels (1950) or Bergquist (1967) recorded either species during their respective sponge surveys in Hawaii, therefore they are considered to be recent introductions.

The ecological impacts of *H. caerulea* and *G. fibrosa* at Palmyra are currently unknown; however, potential impacts include spatial competition with native fauna and a possible threat to corals (De Felice *et al.*, 2001). Sponges are also highly efficient suspension feeders, pumping up to 24,000 l of water a day (kg^{-1} of sponge) (Vogel, 1977) and removing carbon resources, such as plankton, as well as oxygen and

nitrogen from the water column (Reiswig, 1971, 1974). The vast quantity of water sponges pump each day means that in high densities they can significantly impact surrounding pelagic ecosystems (Bell, 2008), even potentially controlling phytoplankton levels (Peterson *et al.*, 2006).

CONCLUSIONS

The modifications to the lagoons at Palmyra during World War II have likely created an environment with reduced water quality and lower circulation now better suited to fouling communities. The presence of these non-indigenous species at such a remote atoll is most likely attributable to man-made transport mechanisms in the form of vessels arriving from harbours and coastal areas such as Hawaii where all five species are also listed as non-indigenous. Future monitoring to assess the invasive potential of all the non-indigenous species established at Palmyra is important to ensure their impacts on the lagoon and adjacent reefs are limited and not progressive.

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