Supplemental Information for

**Evaluation of MPA designs that protect highly mobile megafauna now and under climate change scenarios**

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Appendix A: Species ecologies

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## 1. Reef manta ray

### 1.1 Habitat

Reef manta rays use nearshore habitats for foraging and to interact with cleaner fishes. High marine and terrestrial productivity within lagoons and reefs support important foraging habitats including atoll coastlines where high terrestrial productivity contributes to greater local zooplankton biomass at Palmyra (McCauley et al., 2012). Similarly, manta rays forage and visit cleaning stations in areas with relatively greater chlorophyll-*a* concentrations in other regions (0.3 mg m-3, Anderson et al., 2011; Jaine et al., 2012). Within-atoll currents transport terrestrial nutrients, which also increase biomass, biodiversity, and foraging opportunities at Palmyra Atoll and Kingman Reef (hereafter “Palmyra-Kingman MPA”) and in other regions (Graham et al., 2012; McCauley et al., 2012).

Heterogenous habitat features are also important. Throughout their range, manta rays occur in areas with access to strong currents (Andrzejaczek et al., 2020; Aquino et al., 2015; but see Barr and Abelson, 2019; and Rohner et al., 2013), forage in convergent frontal zones (Weeks et al., 2015) and with eddies (Jaine et al., 2014). They also use areas downstream from atolls, opposite to monsoon-driven currents, where current speed is low and biomass is high (Anderson et al., 2011). Tides mix water and introduce organisms and nutrients like oxygen into lagoons and manta rays display tidally-linked foraging behaviors (Armstrong et al., 2016; Jaine et al., 2012) and presence (Couturier et al., 2018; Peel et al., 2019b; Rohner et al., 2013). Mantas use rising tide (Ichsan et al., 2013), high tide and the slack tide after high tide (Peel et al., 2019b). More foraging occurs at cooler sea surface temperatures (SST; Armstrong et al., 2016; 21–23°C, Jaine et al., 2012), but temperature associations are regional; manta presence is positively (Jaine et al., 2012; Rohner et al., 2013) and negatively (Couturier et al., 2018) related to water temperature, with maximal presence maximal at 28°C (Peel et al., 2019b). Although mantas are known to swim to 672 m (Braun et al., 2014; Lassauce et al., 2020), they primarily forage along the reef (Peel et al., 2019a) and, at Palmyra, use ledge habitat (10–30 m, McCauley et al., 2014). Habitats with bathymetric gradients are also important for this species. Manta rays track diurnal vertical migrations (surface to 30–40 m) of mesopelagic zooplankton and make significantly shallower dives at night (Andrzejaczek et al., 2020; Braun et al., 2014), including at Palmyra (McCauley et al., 2014). However, the opposite pattern (deep nighttime dives) also occurs (Lassauce et al., 2020), demonstrating that behavioral differences could reflect differences in prey species composition and availability at different times of the diel cycle. Associations with cleaner fishes occur in both foraging areas and in other habitats. Cleaning events occur most frequently during high tides (Jaine et al., 2012) and ebb tides (O’Shea et al., 2010) and in calm water (Beaufort scale 1–3 (Barr and Abelson, 2019).

### 1.2 Range and relation to MPAs

Manta rays’ movements occur at multiple temporal scales that encompass daily movements between foraging areas and cleaning stations (tens of kilometers; Germanov et al., 2019; Jaine et al., 2012; Setyawan et al., 2018) and seasonal movements 100–500 km outside of home regions (Andrzejaczek et al., 2020; Couturier et al., 2018, 2011; Germanov and Marshall, 2014). Additional movements occurred over day–week timespans, such that they travel 12–100 km within home regions (Axworthy et al., 2019; Carpentier et al., 2019; Dewar et al., 2008; Germanov et al., 2019; Setyawan et al., 2018; Venables et al., 2020).

Of the studies that examined how manta rays used habitat within MPAs, the species generally remain within MPAs (Chagos Archipelago British Indian Ocean Territory, BIOT, Andrzejaczek et al., 2020; and Carlisle et al., 2019; Nusa Penida MPA, Indonesia, Germanov et al., 2019; Dungonab Bay and Mukkawar Island National Park MPA, Sudan, Kessel et al., 2017), though in Inhambane Province, Mozambique, an MPA network only protects 24% of habitat (Venables et al., 2020).

### 1.3 Suitability of the Palmyra-Kingman MPA

Palmyra Atoll and Kingman Reef contained most habitat features important to manta rays (heterogenous reef habitat, high productivity, tidally-influenced lagoons). However, this single, stationary, atoll-centered MPA barely encompassed their mean movement range that was calculated from worldwide distributions (**Table B1; Figure 3A**), though they remained near Palmyra in one tracking study (**Figure 3C**; McCauley et al., 2014). Occasional long-distance travel (100–500 km) was not well understood, but likely was related to breeding and foraging via the seasonal timing of currents, fronts, and productivity in other regions (Andrzejaczek et al., 2020). Palmyra and Kingman’s proximity to other reef systems within the Line Islands could provide access for individuals to additional breeding populations for gene exchange and increased foraging habitats, and an MPA network could better encompass inter-reef movements (**Table 2**). Mantas likely benefit from regulatory protections because they are susceptible to fishing pressure, by-catch (Steinke et al., 2017), and tourism (Venables et al., 2016) in other regions. Decreased habitat suitability in the western central Pacific due to climate change could be tempered by unaffected habitat in the northern Pacific Remote Islands Marine National Monument (PRIMNM; **Figure 4A**) but mantas could be susceptible to decreased prey availability and other ecosystem-level effects that may require them to travel further for resources.

## 2. Grey reef shark

### 2.1 Habitat

Grey reef sharks use different parts of the reef for foraging, shelter, and as daily aggregation sites. The transition zone between reef and pelagic waters also provides key habitat via access to high productivity, heterogenous habitat, and varied current speeds. Grey reef sharks comprise a large amount of the biomass in the fore-reef zone (Bradley et al., 2017; Friedlander et al., 2010; NOAA, 2012) and are abundant on both exposed reefs and outer reefs at Palmyra and in other regions (Field et al., 2011; Filous et al., 2017; Holzwarth et al., 2006; McKibben and Nelson, 1986; Papastamatiou et al., 2009). Throughout their range, density and abundance are positively associated with chlorophyll-*a* concentrations (Nadon et al., 2012) and the biomass of planktivorous fish (Tickler et al., 2017), respectively. Reef habitat also provides access to seasonal prey including spawning reef fishes in Palau (Etpison and Colin, 2018; Mourier et al., 2016; Rhodes et al., 2019). Access to reef habitat with strong tides is also beneficial because tides mix lagoon waters, which increase biomass, chlorophyll-*a*, and foraging opportunities. For example, grey reef sharks track spawning aggregations of Moorish idols (*Zanclus cornutus*), which occur 30–60 min after high tide (Etpison and Colin, 2018). Grey reef sharks also use parts of the tidal cycle to access cleaning stations: they are significantly more abundant at cleaning stations during ebb tide in Australia (O’Shea et al., 2010; but see Speed, 2011) and low tide in Palau (Vianna et al., 2013).

Heterogenous habitat occurs via low and high tide, where grey reef sharks seek shallow low tide areas and deep high tide areas at Johnston Atoll (Economakis and Lobel, 1998). Sharks also seek shelter with regular diel migrations throughout the water column (Barnett et al., 2012; Field et al., 2011; Lea, 2016; Papastamatiou et al., 2018), though light sensitivity may also be a physiological driver of vertical movements (Lisney and Collin, 2008). Grey reef sharks largely avoid deep water (>72 m, Espinoza et al., 2014), but several individuals have traversed deep water (>500 m, White et al., 2017). They dive to >100 m at Palmyra (Papastamatiou et al., 2018) and the deepest recorded dive depth is 276 m in Niue (Friedlander et al., 2017).

Transitional habitat between reefs and pelagic water also provides grey reef sharks with access to currents for foraging and waters with varied temperatures important for behavioral thermoregulation. Sharks use leeward areas in Hawaiʻi (Wass, 1971) and reef channels that provide access to strong currents in Australia (Field et al., 2011). Access to moving water (current velocities of 51–67 cm s-1) also provides foraging opportunities for young (Orr, 2019). Shark abundance increases at daily (Economakis and Lobel, 1998) and seasonal (29°C at 60 m, Vianna et al., 2013) maximum and near-maximum temperatures (28°C, Richards et al., 2012), and density doubles with every 2.5°C increase in water temperature across the central Pacific Ocean (Nadon et al., 2012).

### 2.2 Range and relation to MPAs

Habitat continuity among reefs is important for grey reef sharks’ short-distance (<20 km; Dwyer et al., 2020; Field et al., 2011; Filous et al., 2017; Vianna et al., 2013) and long-distance movements (Barnett et al., 2012; Chin et al., 2012; Heupel et al., 2010) throughout their range. Regular travel occurs within and outside local reef networks, with occasional longer-distance excursions, resulting in small home ranges at Palmyra and throughout the Pacific Ocean (10–100 km2, Bradley et al., 2017; McKibben and Nelson, 1986; Rhodes et al., 2019). Grey reef sharks were tracked in only one satellite tracking study, and they remained within 66.2 ± 143.9 km (median ± SE) of the tagging site for 40–466 days at Palmyra (White et al., 2017).

Grey reef sharks spend time on both sides of MPA boundaries (BIOT MPA, Carlisle et al., 2019; Great Barrier Reef Marine Park MPA, Australia, Espinoza et al., 2015; Molokini Marine Life Conservation District, USA, Filous et al., 2017; Kephara Marine Sanctuary, Federated States of Micronesia, Rhodes et al., 2019; Ningaloo Marine Park, Australia, Speed et al., 2016; PRIMNM, USA, White et al., 2017), but can be susceptible to fishing inside and adjacent to MPAs (Bradley et al., 2019; White et al., 2017).

### 2.3 Suitability of the Palmyra-Kingman MPA

High productivity and heterogenous reef habitat provide grey reef sharks with suitable habitat at the Palmyra-Kingman MPA. Grey reef sharks from Palmyra rarely traveled to other Line Islands, but a network of MPAs would be beneficial among adjacent reef habitats for individuals that do travel because they are susceptible to targeted fishing and by-catch (e.g. Bradley et al., 2019) and were caught outside the Palmyra-Kingman MPA, indicating limited protections exist for some individuals (White et al., 2017). A single, stationary MPA may provide sufficient protection for individuals with high site fidelity (**Table 2**), but the extent to which the Palmyra-Kingman population travels to other areas and are at-risk to fishing deserves further study. Protected corridors between Palmyra-Kingman and other Line Islands could also benefit this species (e.g. Filous et al., 2017), especially with respect to predicted shifts in suitable habitat the western central Pacific and consistent habitats in the Line Islands (**Figure 4B**).

## 3. Green sea turtle

### 3.1 Habitat

Adult and juvenile green sea turtles mainly use shallow water environments like Palmyra Atoll and Kingman Reef as foraging grounds (Sterling et al., 2013). Within the shallow, nearshore environment, access to heterogenous habitats is important for food, thermoregulation, and shelter requirements that vary among age classes. At Palmyra and throughout their range, green sea turtles forage on coralline algae (Sterling et al., 2013) and at reef drop-offs (Heithaus et al., 2007; Naro-Maciel et al., 2018). Diet differences among age classes (Ballorain et al., 2010; Sterling et al., 2013) are partially driven by significant use of different seafloor substrates (Chambault et al., 2020). Thermal thresholds are important for ectothermic sea turtles. Juvenile green sea turtles stay within the 10-m isobath, indicating narrow temperature requirements for some size classes (Chambault et al., 2020). Similarly, green sea turtles make short seasonal migrations to different depths within non-breeding foraging grounds that reflect redistribution of a preferred isotherm and some prey species (Broderick et al., 2007; Godley et al., 2002). Throughout their range, adult green sea turtles use foraging habitats that combine frequent SST frontal zone activity, upwelling regions, and thermal thresholds (≥25°C, Seminoff et al., 2008). Tides provide access to nearshore foraging opportunities and shelter during both high (Chambault et al., 2020) and low tide (Taquet et al., 2006) in the Indian Ocean. Green sea turtles also avoid predators by making regular diel migrations throughout the water column (Hatase et al., 2006; Hays et al., 2020; Luschi et al., 1998; Papi et al., 2000).

In addition to heterogenous reef and reef-adjacent habitats, water temperature and chlorophyll-*a* are important for describing broader habitats. SST is the most important factor associated with sea turtle population density in the Pacific Ocean, and population density is greatest with high chlorophyll-*a* concentrations (>0.2 mg m-3) at reefs throughout the Pacific (Becker et al., 2019).

### 3.2 Range and relation to MPAs

At foraging grounds, green sea turtles move very little (mean ± SD: 34.7 ± 64.8 km, **Table B1**). However, habitat continuity may be regionally important; for example, green sea turtles in Japan forage extensively throughout 1,000 km of islands (Hamabata et al., 2015).

Green sea turtles use MPAs disproportionately; they nest in the BIOT MPA but only spend 5–8% of their time within MPA boundaries (Hays et al., 2014). Hawaiian green sea turtles transit through the Papahānaumokuākea Marine National Monument (USA) just 30% of the time (Balazs et al., 2017). Conversely, at the Palmyra-Kingman MPA, nearly all individuals remain within the MPA while foraging (Naro-Maciel et al., 2018), which is consistent with other global observations on foraging grounds (Scott et al., 2012).

### 3.3 Suitability of the Palmyra-Kingman MPA

Green sea turtles may be well-suited for MPA protection because they have small home ranges in their foraging areas, high site fidelity, and long inter-breeding intervals (**Table 2**; Scott et al., 2012). Additionally, all size classes occur at Palmyra (Sterling et al., 2013), indicating that sufficient heterogeneous resources exist for all age classes. However, migration routes could benefit from partial protection within a network of MPAs that would also decrease risk of by-catch (Fiedler et al., 2012) and injuries from boats (Work et al., 2015). Predicted decreases in suitable habitat under climate change throughout PRIMNM could adversely affect green sea turtles because increased temperatures are expected to reduce coralline algae food for green sea turtles and physiological stress associated with reduced food availability could reduce lifetime fecundity (Stubbs et al., 2020). However, equatorial upwelling in PRIMNM could help maintain SST within green sea turtle optimal temperature range; this could be especially important at Jarvis Island, which has the region’s greatest population density (3.7 turtles km-1; Becker et al., 2019).

## 4. Yellowfin tuna

### 4.1 Habitat

Yellowfin tuna occur almost exclusively in pelagic habitats. Preferred habitat features are driven by behavioral physiology (e.g., travel to thermoclines and oxyclines) and local oceanographic features that enhance productivity. Overall, yellowfin tuna occur in the SST range 15–30°C (Dunn and Curnick, 2019; Gonzáles-Andrés et al., 2016; Hazen et al., 2013; Hu et al., 2018; Lopez et al., 2017b; Song et al., 2008; Zagaglia et al., 2004). Local thermoclines and oxyclines constrain habitat among size classes (Gonzáles-Andrés et al., 2016; Nimit et al., 2020) such that maximum depths are limited by heat loss rates; yellowfin tuna adults (> 3 years old) occur and spend more time at deeper depths than younger individuals (Aldana-Flores et al., 2018; Schaefer et al., 2011). Physiological regulation is also evident in tunas’ seasonal movements: in the Pacific Ocean, they approach the surface more during summer and follow seasonal shifts of the 18°C isotherm (Schaefer et al., 2011), and dive depths are related to seasonal shifts in mixed layer depth (Schaefer et al., 2007). Yellowfin tuna presence is negatively correlated with water temperature at 50 m (Dunn and Curnick, 2019; but see Jorgensen et al., 2016) and with thermocline gradients (Lopez et al., 2017b).

Three habitat features that enhance productivity and prey abundance are especially prominent: water depth and bottom topography; chlorophyll-*a* concentrations; and surface currents. Important yellowfin tuna bathymetric habitat includes complex bottom topography (e.g., rocky ledges), shallow water (e.g. over seamounts, Gonzáles-Andrés et al., 2016), deep water (Lopez et al., 2017a), and fish aggregating devices (FADs) anchored in deep (800 m) water (Filous et al., 2020). Local productivity is important: yellowfin tuna use waters with intermediate (0.09–0.1 mg g-3; Song et al., 2008) to high chlorophyll-*a* concentrations (0.2–1.4 mg g-3; Gonzáles-Andrés et al., 2016; Hu et al., 2018) and chlorophyll-*a* concentrations are significantly positively correlated with tuna abundance (Zagaglia et al., 2004) and presence (Fraile et al., 2010; Lopez et al., 2017b) in the Atlantic and Indian Oceans. However, chlorophyll-*a* and net primary productivity are poor predictors of yellowfin tuna trophic position throughout the world (Pethybridge et al., 2018), indicating that complex factors affect the movements of both tunas and their prey. Mesoscale surface currents are also important. In the Indian Ocean, yellowfin tuna occur at the edges of divergence zones (Nimit et al., 2020) and in cyclonic eddies (Tew Kai and Marsac, 2010) but avoid anticyclonic eddies (Potier et al., 2014). Current speed is negatively correlated with tuna presence in the Atlantic Ocean (Lopez et al., 2017a) and the abundance of smaller individuals (<10 kg), but positively correlated with the abundance of large (>10 kg) tuna in the Indian Ocean (Dunn and Curnick, 2019).

### 4.2 Range and relation to MPAs

Yellowfin tuna are highly mobile and traveled farther than all other species (**Figure 3**). Yellowfin tuna have lifetime displacements of up to 700 km (Sibert and Hampton, 2003) and some populations regularly move 150–1,500 km (Fonteneau and Hallier, 2015; Richardson et al., 2018; Schaefer et al., 2011, 2007). Individuals also remain near drifting FADs that travel 100–200 km (Matsumoto et al., 2016; Tolotti et al., 2020) and some make short-duration (<24 hr) movements away from anchored FADs (Ohta and Kakuma, 2005; Rodriguez-Tress et al., 2017).

Yellowfin tunas stay within the BIOT MPA (Carlisle et al., 2019) and they are semi-resident inside the Ascension Island MPA (U.K. Overseas Territory), occasionally moving up to 100 km beyond for spawning, where they are at risk to fishing (Richardson et al., 2018). In the Phoenix Islands MPA, which contains a spawning area, yellowfin tuna may remain inside the MPA for their lifetimes, but also contribute to sustainable management of this fishery (Hernández et al., 2019; Rotjan et al., 2014).

### 4.3 Suitability of the Palmyra-Kingman MPA

Yellowfin tuna may travel hundreds of kilometers and use pelagic habitats with high productivity and large temperature gradients. However, retention near FADs and near spawning areas could indicate that stationary MPAs may protect yellowfin tuna (Filous et al., 2020; Hernández et al., 2019). Large MPAs could encompass this highly mobile species, although tunas will remain at-risk to fishing outside of MPA boundaries that may include spawning grounds (Richardson et al., 2018). Mobile MPAs that shift with dynamic oceanography including thermal and productivity fronts (Tew Kai and Marsac, 2010) could also benefit tunas. A combination of stationary and mobile MPAs may help protect critical habitat while also supporting sustainable fisheries management for this species.

## 5. Sooty tern

### 5.1 Habitat

Sooty terns are foragers that depend on tuna to feed successfully in pelagic habitats throughout the world (Au and Pitman, 1986; Jaquemet et al., 2005). During the breeding season, terns are central place foragers that are constrained to several hundred kilometers surrounding colonies like those that exist at Palmyra Atoll. Vast, pelagic habitats are hard to quantify and knowledge of sooty tern habitat at sea is limited; overall, wind, water depth, productivity, and SST are important. With a flapping flight style, sooty terns have low wing-loading that enables them to fly with high energy efficiency while traveling long distances relatively quickly (Hertel and Ballance, 1999), though abundance is not related to wind speed in Australia (Gorta et al., 2019). Sooty tern associations with pelagic bathymetric features were described from incidental observations at-sea where they were associated with shelf breaks (Mondreti et al., 2020) and observed at various water depths (de Boer et al., 2014) in the Atlantic and Indian Oceans. Sooty tern habitat associations were significantly related to depth and slope in some regions (Jaquemet et al., 2014; Monia, 2019), but not others (Daudt et al., 2019; Jaquemet et al., 2005; Mannocci et al., 2014). Similarly, conflicting results were reported when associating with chlorophyll-*a* concentrations (0.1 mg m-3 chlorophyll *a*, Ballance et al., 1997; Daudt et al., 2019; Dunlop, 2011; Gorta et al., 2019; Hyrenbach et al., 2006; 0.15 mg m-3 chlorophyll *a*, Mondreti et al., 2020); these conflicting results are likely a reflection of their dependence on subsurface predators for foraging. Distances traveled during the breeding season are greatly influenced by local prey availability in the Seychelles (Neumann et al., 2018)

Regional productivity (Devney et al., 2009; Jaquemet et al., 2007) and temperatures are associated with breeding participation, indicating that variable ocean conditions and food abundance (or tuna distribution) affect breeding in the Pacific and Indian Oceans. The long (2–4 wk) pre-lay exodus prior to egg-laying (Jaeger et al., 2017) could be used by terns to evaluate ocean conditions and resources that affect subsequent reproductive success. SST is positively associated with lay date in the Indian Ocean (Jaquemet et al., 2007) and negatively associated with chick-feeding metrics (e.g. meal mass and feeding frequency) and adult mortality (Colchero Aragonés, 2008; Erwin and Congdon, 2007) in Gulf of Mexico and Australia. Significantly larger flocks occur over deeper thermoclines in the Pacific Ocean (Ballance et al., 1997; Ribic et al., 1997), but regional thermocline depth is negatively correlated with breeding population size (Devney et al., 2009). Throughout their range, regions with different SST availability reveal that sooty terns occur in areas with significantly warm SST (Dunlop et al., 1988; Gorta et al., 2019; Hyrenbach et al., 2006; Mannocci et al., 2014; Monia, 2019) and in some regions, in areas with significantly cool SST (Daudt et al., 2019).

### 5.2 Range and relation to MPAs

Sooty terns regularly take long breeding season foraging trips and distances vary among colonies and within ocean basins (mean ± SD: 444.1 ± 431.5 km; **Table B1**). The pre-lay exodus may range thousands of kilometers from colony sites (Jaeger et al., 2017). Movement corridors are also important: sooty terns use consistent commuting corridors during the breeding season (Soanes et al., 2015) and exhibit inter-annual site fidelity to non-breeding areas (Jaeger et al., 2017).

Sooty terns nest in many colonies surrounded by MPAs (e.g. Papahānaumokuākea; PRIMNM; Seychelles), but just one study evaluated movements (sourced from Flint, 1991) within the context of the Johnston Atoll MPA (PRIMNM) boundaries, where terns regularly exceed the MPA boundary by >400 km (Maxwell and Morgan, 2013).

### 5.3 Suitability of the Palmyra-Kingman MPA

Relatively few data were available that characterized sooty tern pelagic habitats to inform whether the ocean surrounding the Palmyra-Kingman MPA had suitable habitat. However, sooty terns regularly travel long distances that exceed the Palmyra-Kingman MPA boundary (**Figure 3A**). Largescale MPAs (LSMPAs), a network of pelagic MPAs, and mobile MPAs that shift with the movement of thermal fronts and accommodate spatial variability driven by ocean climatic events (Game et al., 2009; Maxwell et al., 2020) could better protect this highly mobile species, if predictable links between oceanography and movements can be made. Reliance by sooty terns on subsurface predators, especially tunas, also highlights the mutual importance of MPAs for pelagic fishes, but also reveals how sooty terns might be adversely affected by climate change that affects tunas (Feare et al., 2007; Maxwell and Morgan, 2013).

## 6. Red-footed booby

### 6.1 Habitat

Red-footed boobies are plunge-divers that forage in pelagic habitats in association with sub-surface predators. During breeding, red-footed boobies do not visit the same locations during consecutive foraging trips (Gilmour et al., 2018; Weimerskirch et al., 2005a) in the Pacific and Indian Oceans, and instead may rely on dynamic, ephemeral features for foraging. Their habitats reflect a combination of central place foraging constraints, regional variations in subsurface predators and prey availability, and local wind conditions. Throughout their range, red-footed boobies forage up to 200 km from their nests (Kappes et al., 2011; Mendez et al., 2020, 2017; Young et al., 2015, 2010), thus constraining the pelagic habitat available to them. The availability of optimal habitat is important; nesting activity peaks when the 23°C isotherm is within 200–400 km of the colony in the Indian Ocean (Le Corre, 2001). Near-colony constraints also result in use of shallower water compared with other booby species, and water depth often covaries with additional oceanographic variables that are important for describing foraging habitats throughout their range (Gilmour et al., 2018; Kappes et al., 2011; Mendez et al., 2017; Young et al., 2015).

Red-footed boobies are pantropical and habitat characteristics vary regionally. For example, variations in chlorophyll-*a* concentrations result in contrasting behavioral patterns between and within ocean basins (Gilmour et al., 2018; Mendez et al., 2017) and contrasting at-sea observations of associations with high and low chlorophyll-*a* concentrations (Ballance et al., 1997; Mendez et al., 2016; Weimerskirch et al., 2005a). Variability in the availability of locally-available prey affect dive depths; dives are 4x deeper in the Indian Ocean than in the Pacific Ocean (Adams et al., 2020; Le Corre, 2001; Lewis et al., 2005; Schreiber, 2003).

With relatively high wing-loading (Van Oordt et al., 2018), red-footed boobies rely on local wind conditions to transit and forage efficiently (e.g. wind velocity of 3–6 m sec-1, Kappes et al., 2011; Weimerskirch et al., 2005b) and individuals will when wind speed is low (Schreiber and Chovan, 1986).

### 6.2 Range and relation to MPAS

Red-footed boobies traveled 86.3 ± 47.7 km (mean ± SD) from nests during foraging trips, though these distances varied greatly among colonies and ocean basins (**Table B1**). At Palmyra Atoll, 10% of core red-footed booby habitat areas occur outside MPA boundaries, and 21% of core habitat occur outside Papahānaumokuākea (Young et al., 2015; **Figure 3B**).

### 6.3 Suitability of the Palmyra-Kingman MPA

Red-footed boobies had a restricted foraging range closer to the colony compared with other pelagic species. However, a single, stationary, atoll-centered MPA barely encompassed their mean movement range (**Figure 3**). Red-footed boobies could benefit from a mobile MPA because they rely on subsurface predators, patchy prey, and ephemeral oceanographic processes within a small range (<100 km) of the nest. Their reliance on subsurface predators, however, also increases potential adverse effects of climate change if subsurface predator abundance decreases, or if predators forage deeper in the water column (Chambers et al., 2011; Maxwell and Morgan, 2013).

## 7. Great frigatebird

### 7.1 Habitat

Great frigatebirds, like sooty terns and red-footed boobies, also are pelagic foragers that rely on subsurface predators for foraging, yet they are unique among this group because they do not have waterproof plumage and cannot land on the water. This may help explain some of the contrasting habitat associations observed for this species. Contrasting observations of frigatebird occurrences with chlorophyll-*a*, SST, and eddy circulation could reflect underlying regional differences in productivity, temperature, and currents that drive habitat associations with subsurface predators. For example, great frigatebirds are positively (Jaquemet et al., 2005; Weimerskirch et al., 2010) and negatively (Thiers et al., 2014; but see Weimerskirch et al., 2004) associated with chlorophyll-*a* concentrations throughout their range. Great frigatebirds also occurred with both warm water (Dunlop et al., 1988; Smith and Hyrenbach, 2003; Thiers et al., 2014) and cool water (Jaquemet et al., 2005) in the Indian and Pacific Oceans. Similar to sooty terns and red-footed boobies, great frigatebirds also use the SST range 23.8–25.8°C, though SST gradients are not related to foraging behaviors in the Indian Ocean (Tew Kai and Marsac, 2010). Great frigatebirds use cyclonic eddies (Weimerskirch et al., 2010), the edges of cyclonic eddies and waters with greater relative eddy kinetic energy (Tew Kai and Marsac, 2010), the frontal zones between eddies where geostrophic currents are strongest (Jaquemet et al., 2014), and Lagrangian coherent structures (Tew Kai et al., 2009) in the Indian Ocean.

Great frigatebirds have more consistent relationships with bathymetry and wind. Stationary features including seamounts, deep water (>200 m), and off-shelf habitat provide some consistency when describing great frigatebird habitats, and could help identify regions commonly searched or that have increased chances for encountering subsurface predators throughout their range (Gilmour et al., 2012; Schreiber, 2003; Smith and Hyrenbach, 2003; Weimerskirch et al., 2004). Great frigatebirds are negatively associated with areas with greater bathymetric slope (Thiers et al., 2014) and they do not appear to associate with shelf habitat (Jaquemet et al., 2014) in the Indian Ocean. Great frigatebirds have one of the lowest wing-loadings among all seabirds (Brewer and Hertel, 2007), and they can fly great distances with very little energy expenditure and especially with optimal wind velocities (>15–18 km hr-1, Schreiber and Chovan, 1986). Overall, great frigatebirds exhibit a positive relationship between flight speed and wind velocity (Weimerskirch and Prudor, 2019), though they avoid tail winds when leaving their colony on foraging trips (Collet et al., 2020) in the Indian Ocean. Atmospheric thermal fronts also enable great frigatebirds to travel large distances and make faster ascents and descents (De Monte et al., 2012).

### 7.2 Range and relation to MPAs

Great frigatebirds travel 324 ± 317 km (mean ± SD) during breeding season foraging trips (**Table B1**). They exhibit one of the longest parental care periods among seabirds (14 months, Schreiber and Ashmole, 1970) requiring central place foraging females to rely on seasonally-shifting resources surrounding atolls. Male great frigatebirds abandon the nest after 4.5–6 months (Lagarde et al., 2004) and do not have this prolonged constraint and are free to travel much farther than females.

Chick-rearing great frigatebirds travel up to 160 km outside the Papahānaumokuākea boundary (Gilmour et al., 2012), and one study estimated mean travel distances at Johnston Atoll exceeded MPA boundaries by >500 km (Maxwell and Morgan, 2013; mean distances sourced from Weimerskirch et al., 2004).

### 7.3 Suitability of the Palmyra-Kingman MPA

Great frigatebirds typically travel several hundred kilometers while foraging in association with subsurface predators. The small, stationary Palmyra-Kingman MPA provides limited protection for this pelagic species (**Table 2**). Mobile MPAs that track thermal front and eddy habitats (Tew Kai and Marsac, 2010) might best benefit great frigatebirds, especially given their reliance on Palmyra’s pelagic waters year-round throughout their 14-month breeding cycle. Great frigatebirds would also benefit from MPA designs that considered spatiotemporal aspects of important, facultative sub-surface predators (e.g., fishing regulations; adequate MPA sizes).

## 8. Bottlenose dolphin

### 8.1 Habitat

Bottlenose dolphins use nearshore and pelagic habitats. Two ecological forms (coastal and oceanic ecotypes) can occur in the same region yet occupy different ecological niches. Many open, transient populations also exist (Santos-Carvallo et al., 2015). The specific ecotype(s) that occur at Palmyra Atoll and Kingman Reef are not documented, but habitat features there common to both ecotypes are available. Bottlenose dolphins have been observed to feed at significantly higher trophic levels than other atoll delphinids, although overall interspecific dietary niche overlap can be minimal (Young et al., 2017). Depth is the most common factor that distinguishes co-occurring coastal and oceanic ecotypes (oceanic uses >100 m, Díaz-Gamboa et al., 2018; coastal uses 0–18 m, Simões-Lopes et al., 2019). Depth, productivity, and slope thresholds also distinguish foraging habitats of coastal (0–2 mg m-3 chlorophyll-*a*, no significant slope or depth distinctions) and oceanic (400–800 m deep, >2 mg m-3 chlorophyll-*a*, 0–5° slope) ecotypes (Guevara-Aguirre and Gallo-Reynoso, 2016).

Depth, slope, and water temperature describe important foraging habitat features that are common to bottlenose dolphins of unspecified ecotype throughout their range. Water depth is the most important feature describing foraging habitats in the Gulf of Mexico and Atlantic Ocean (0–1,000 m, De Rock et al., 2019; 0–18 m, Moreno and Mathews, 2018). Bottlenose dolphins move in and out of atolls with the tide (McGovern et al., 2020; Shane et al., 1986), and forage during high tide in the intertidal zone (<10 m deep, Vermeulen, 2018) throughout their range. Bottlenose dolphins also use slope habitats (Bonizzoni et al., 2019), including shelf breaks (Llapapasca et al., 2018; Rodriguez-Ferrer et al., 2020) and relatively shallow slopes (De Rock et al., 2019; Vassallo et al., 2020) throughout their range. They use upwelling areas (Ballance et al., 2006) and transit during downwelling phases (Santos-Carvallo et al., 2018). SST is positively related to bottlenose dolphin presence (Davis et al., 1998; De Rock et al., 2019; Sánchez-Cabanes et al., 2017; but see Thilakarathne et al., 2015) and is a significant predictor in habitat suitability models (De Rock et al., 2019; Llapapasca et al., 2018; but see Bonizzoni et al., 2019) and models that predict certain behaviors (Guevara-Aguirre and Gallo-Reynoso, 2016). Water temperatures at 100 m and the depth of the 15°C isotherm, however, do not predict presence (Davis et al., 1998). The predictive capacity of some temperature-related factors may be related to seasonal thermoregulatory behaviors among certain dolphin prey (Moreno and Mathews, 2018).

### 8.2 Range and relation to MPAs

Bottlenose dolphins remain within 45.6 ± 43.1 km (mean ± SD) of their initial tagging locations (**Table B1**) though these ranges varied widely for both ecotypes. Among coastal ecotypes associated with continental shelves, most individuals stay within 15–200 km of their tagging locations (Balmer et al., 2019; Hartel et al., 2020; Paschoalini and Santos, 2020; Pleslić et al., 2019; Shane et al., 1986). The coastal ecotype associated with islands travels tens of kilometers, though these behaviors differ among archipelagoes (20 km, Hawaiʻi, USA, Baird et al., 2009; 30–130 km, Canary Islands, Spain, Tobeña et al., 2014). Central-place foraging distances are more difficult to assess for the oceanic ecotype, which ranges 1–4,500 km from their initial tagging locations (Klatsky et al., 2007; Milmann et al., 2017; Tanaka, 1987; Wells et al., 1999).

Bottlenose dolphins exhibit high behavioral plasticity, differing social networks and behaviors, and regular inter-island movements that cause them to use both sides of MPA boundaries (Bay of Islands MPA, New Zealand, Hartel et al., 2015; Canary Islands Special Area of Conservation, Spain, Tobeña et al., 2014). Dolphin home ranges are larger than the Cres-Lošinj Special Marine Reserve MPA, Croatia (Pleslić et al., 2015), but distinct sub-populations appear to be better contained by small, separate MPAs located throughout the United Kingdom (Nykänen et al., 2018).

### 8.3 Suitability of the Palmyra-Kingman MPA

Protecting diverse habitats at the Palmyra-Kingman MPA could benefit both coastal and oceanic ecotypes. The combination of atoll-based shallow, warm water and adjacent oceanic, deep, cooler water with variable primary productivity could suit both ecotypes. The stationary small Palmyra-Kingman MPA may provide sufficient coverage for the coastal ecotype (**Figure 3A**), but the wider-ranging oceanic ecotype may benefit more from a larger MPA or a network of MPAs. Mobile MPAs might also better accommodate the scale of pelagic movements expected for the oceanic ecotype’s especially if the timing for shifting zones matched certain life history stages (e.g. Hartel et al., 2015). Bottlenose dolphins would also benefit from regulations that restrict fisheries and interactions with boats (Pirotta et al., 2015), especially for food-limited populations (New et al., 2020).

## 9. Melon-headed whale

### 9.1 Habitat

Melon-headed whales use both nearshore and pelagic habitats. During the day, large pods of melon-headed whales rest outside coral reefs and at night they travel offshore to forage at depth (Brownell et al., 2009; Kiszka et al., 2010) throughout their range, including at Palmyra Atoll. Nighttime dives range from 200–400 m, where they likely feed on vertically migrating squid (Joyce et al., 2017; West et al., 2018).

Melon-headed whales are very under-studied, and overall habitats are unknown, with most information from incidental observations. Marine productivity could be important; melon-headed whales occur near *Sargassum* mats (de Boer, 2013) that host high productivity and biodiversity in pelagic regions (Gower et al., 2006; Moser and Lee, 2012). Depth also could be important; although melon-headed whales occur over steep (14–20%) slopes (Gannier, 2009; Palacios et al., 2012), no statistically significant slope habitats are known (Gross et al., 2009; Kiszka et al., 2011). Eddies and upwelling regions also appear to be important because melon-headed whales use the edges of eddies (Woodworth et al., 2012). In the Maldives (Indian Ocean), they are more likely to be sighted closest to the equator rather than throughout the rest of the archipelago (which ranges 0.5°S to 7°N), highlighting important habitat exists near zones of persistent equatorial upwelling (Anderson, 2005). Relationships with temperatures are mostly unknown; in French Polynesia they occur in association with 25°C SST (Gannier, 2000), but there is no well documented SST predictor in Sri Lanka (Thilakarathne et al., 2015). Many studies simply report SST ranges where this species was observed (de Boer, 2010; Maze-Foley and Mullin, 2006; Miyazaki and Wada, 1978; Mullin et al., 1994).

### 9.2 Range and relation to MPAs

In three studies, Melon-headed whales traveled 222.3 ± 350.5 km (mean ± SD) from their initial tagging locations (**Table B1**).

Melon-headed whales are sighted <10 km outside the Bar Reef Marine Sanctuary MPA, Sri Lanka (Bröker and Ilangakoon, 2008; Ilangakoon, 2008).

### 9.3 Suitability of the Palmyra-Kingman MPA

The current stationary Palmyra-Kingman MPA likely only protects melon-headed whales during the day when they rest near the reef (Baumann-Pickering et al., 2015). Longer-distance movements to facilitate foraging in pelagic waters at night would be better contained by a larger MPA that encompassed both diel habitat types. Though the edges of eddies could be important foraging habitat (Woodworth et al., 2012), there are not enough data on movements or habitat associations to determine potential efficacy of mobile MPAs in pelagic habitats that shift with dynamic ocean processes. Under climate change, melon-headed whales would have reduced suitable habitat throughout PRIMNM, but less change was predicted for the Line Islands. Accordingly, MPA networks might be expected to best buffer predicted effects of future climate change.

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