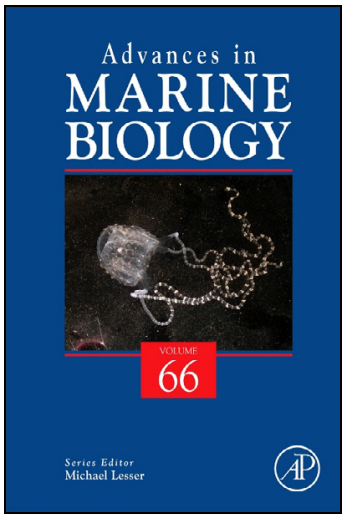

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CHAPTER FOUR

The Coral Sea: Physical Environment, Ecosystem Status and Biodiversity Assets

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Contents

Abstract

The Coral Sea, located at the southwestern rim of the Pacific Ocean, is the only tropical marginal sea where human impacts remain relatively minor. Patterns and processes identified within the region have global relevance as a baseline for understanding impacts in more disturbed tropical locations. Despite 70 years of documented research, the Coral Sea has been relatively neglected, with a slower rate of increase in publications over the past 20 years than total marine research globally. We review current knowledge of the Coral Sea to provide an overview of regional geology, oceanography, ecology and fisheries. Interactions between physical features and biological assemblages influence ecological processes and the direction and strength of connectivity among Coral Sea ecosystems. To inform management effectively, we will need to fill some major knowledge gaps, including geographic gaps in sampling and a lack of integration of research themes, which hinder the understanding of most ecosystem processes.

Keywords: Tropical sea, Ecosystem function, Connectivity, Food web, Pristine ecosystems, Collaborative research

1. INTRODUCTION

Anthropogenic pressures have altered marine ecosystems to the point where they no longer represent baseline conditions (Butchart et al., 2010). Even areas not directly affected by human activities are subject to climate change and ocean acidification, and truly 'pristine' seas are a thing of the past (Halpern et al., 2008). Approximately half of the global human population is concentrated within 200 km of the world's coastlines on 10% of the earth's land area, enhancing direct impacts on our oceans, such as exploitation of marine resources (Foley, 2013), extraction of oil and minerals (UNEP-WCMC, 2007) and the input of waste, pollutants and nutrients (Zirino et al., 2013). This is especially true of tropical seas and their coastlines, fringed by high-density and increasing human populations, which threaten

marine species, ecosystem functioning and food security (Burke et al., 2011). This is a major concern, considering that tropical seas support a range of environments characterised by high species diversity (coral reefs and seamounts) or biomass (e.g. pelagic aggregations), despite being generally oligotrophic (McKinnon et al., 2014).

The Coral Sea is among the 4% of the ocean relatively unaffected by human impacts (Halpern et al., 2008). It is bounded by the Australian continental shelf to the west; the northern limit extends from southeastern Papua New Guinea (PNG) to the southeastern Solomon Islands; the eastern limit follows the Vanuatu archipelago, joining Pine Island to the south of New Caledonia and Elizabeth and Middleton Reefs at its southeastern limit; and the southern boundary is the parallel of 30° south (Figure 4.1A). The Coral Sea covers ~4,791,000 km^2, making it the second-largest tropical marginal sea after the Philippine Sea (McKinnon et al., 2014). It borders the biodiversity hotspots of the Great Barrier Reef (GBR) and Coral Triangle (Robert et al., 2002), as well as the highly productive Tasman Front (Baird et al., 2008). The Coral Sea is generally oligotrophic, and has topographic and oceanographic features that support high biodiversity and iconic megafauna, as well as underpinning pelagic fisheries and their associated human livelihoods. Tuna fisheries in the Coral Sea and in adjacent seas are an important economic resource to the countries with Coral Sea Exclusive Economic Zones (EEZs) (Williams and Terawasi, 2012).

So far, pelagic fisheries are the only field where transboundary management has been implemented in the Coral Sea. Spatial management planning has not extended beyond Australia's EEZ; marine protected areas (MPAs) established by New Caledonia, Vanuatu, the Solomon Islands and PNG are relatively small and largely restricted to coastal waters (Figure 4.1B). Recently, Australia's bioregional planning process resulted in the establishment of a large no-take MPA in the eastern half of Australia's Coral Sea, covering 502,654 km^2 of pelagic and deep-sea benthic habitats (DSEWPaC, 2013), and New Caledonia pledged to declare its 1.4 million km^2 Coral Sea territory an MPA at the Pacific Islands Forum in September 2012 (Environment News Service, 2012). The importance of establishing MPAs in deep-sea and pelagic ecosystems, including in international waters, is increasingly discussed (Game et al., 2009), and there has been a rising number of large MPAs globally (90,000 to >1,000,000 km^2).

The lack of coordination in scientific research programmes of the nations with Coral Sea EEZs has led to incomplete and fragmented knowledge of key ecosystems in the region. Without identifying and monitoring areas

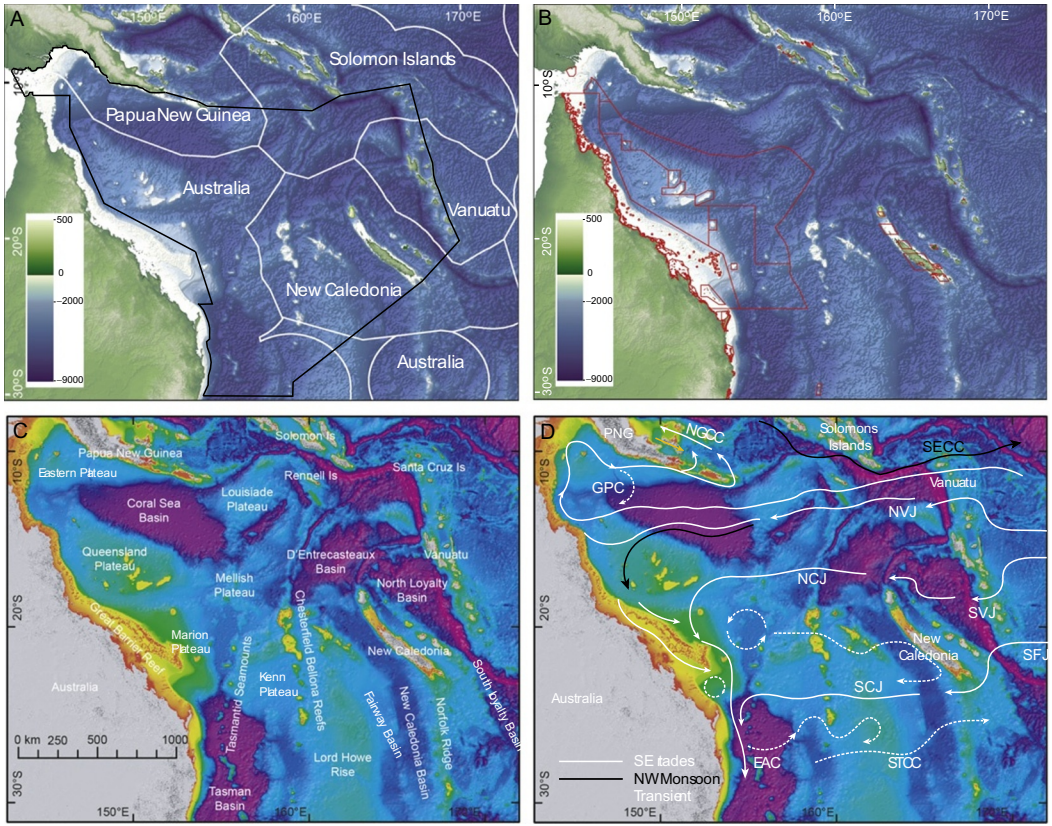

Figure 4.1 (A) Boundaries of the Coral Sea set by the International Hydrographic Organization (black line) and EEZ boundaries (white line). This chapter considered all marine areas >200 m depth or beyond the shelf break of continents and major islands. (B) Marine protected areas within the Coral Sea, including those within territorial waters of each jurisdiction. (C) Major topographic features of the Coral Sea. (D) Oceanography of the Coral Sea, including major surface currents and fronts. NGCC: New Guinea Coastal Current, mirroring the deeper New Guinea Coastal Undercurrent; GPC: Gulf of Papua Current, including the North Queensland Current and Hiri Gyre; SECC: South Equatorial Countercurrent; Jets of the South Equatorial Current (SEC): NVJ: North Vanuatu Jet; NCJ: North Caledonia Jet; SVJ: South Vanuatu Jet; SFJ: South Fiji Jet; SCJ: South Caledonia Jet; EAC: East Australian Current; STCC: Subtropical Countercurrent.

of high conservation values and key drivers of ecosystem function that underpin them, it will be difficult to maintain biodiversity assets into the future. The collation and synthesis of existing information for the whole Coral Sea are critical first steps toward the identification of globally important and vulnerable areas. Understanding connectivity between habitats within the Coral Sea and with the adjacent Coral Triangle, GBR, western Pacific and temperate boundaries will shed light on the Coral Sea's regional role and importance (e.g. Hobday et al., 2011; Treml et al., 2008).

In a sister publication, we have reviewed the biodiversity, ecosystem function and management issues facing tropical marginal seas globally (McKinnon et al., 2014). Here, we concentrate on the Coral Sea specifically, bringing together existing knowledge of Coral Sea ecosystems, identifying the significance of the Coral Sea within the western Pacific region and highlighting knowledge gaps (Table 4.1). The geographic scope of this chapter excludes continental shelf habitats and associated features (e.g. the GBR), and shallow waters of major islands (e.g. the New Caledonian barrier reefs and lagoons and the islands of Vanuatu). We begin with an analysis of research trends in the Coral Sea to distinguish research themes and regions that are well studied from those that have been neglected. We then describe various facets of the Coral Sea ecosystem, from physical drivers (tectonics, geology and physical oceanography), through ecosystems (plankton communities, benthic ecosystems and demersal and pelagic fish communities), to species of human interest (fisheries and iconic and protected species groups). Within each section, we present a summary of current knowledge and knowledge gaps, and discuss links between physical drivers and ecosystems. We then highlight key features and processes of the Coral Sea, focusing on connectivity between habitats within and beyond the Coral Sea. We conclude by discussing future research themes that would be most useful in supporting regional management.

2. RESEARCH TRENDS

Research in the Coral Sea spans more than a century, beginning with expeditions in the late 1800s, such as the *HMAS Challenger* oceanographic expedition of 1873–1876. Much of this early work is no longer readily accessible and has not been included in our analyses. We compiled a database of all documents on the Coral Sea, based on ISI Web of Science searches, identification of research reports by the authors, and soliciting input from government and nongovernment organisations and research institutions from all nations surrounding the Coral Sea. Documents were classified by year,

Table 4.1 Major knowledge areas and gaps for the Coral Sea by research theme

Themes	Key knowledge	Regional context/ importance	Connectivity	Major knowledge gaps
Tectonics and topography	Good maps, descriptions of developmental history of basin-scale topography. An understanding of complex bathymetry. Good descriptions of tectonic activity on eastern edge. History of Gondwanan fragmentation is known.	Geological and evolutionary history are closely linked. Considered one of the basal centres of speciation. Complex topography interacts with regional-scale currents as major driver of productivity patterns.	Combination of geological history and sea-level fluctuations alternately creating dispersal barriers and likely stepping stones through time. Present-day Coral Sea reefs may be stepping stones connecting western Pacific reefs and the Great Barrier Reef.	Fine-scale mapping (e.g. some seamounts are unnamed). A better understanding of the links between geological history and evolution of species is needed.
Physical oceanography	Broadscale mean circulation is well documented. Effects of topographic features on the formation of oceanic jets are partly known. Some understanding of the relationship between currents and ENSO.	Water masses that pass through the Coral Sea are redistributed poleward and equatorward, and eventually join the eastern equatorial region.	Major currents form links (depending on depth) between the subtropical gyre and the southwest Pacific, Coral Triangle and GBR and between tropical waters and temperate Tasman Sea. Tropical waters and equatorial band extend through to the Solomon Sea.	Vertical extent of currents is unresolved for most areas. Variability of the currents and of the water properties at seasonal, interannual and longer timescales is poorly known. Variability of connectivity pathways and of the equatorward and poleward redistribution of waters is poorly known. Connectivity between Pacific and Indian Oceans through northern Australia is unclear.

Continued

Table 4.1 Major knowledge areas and gaps for the Coral Sea by research theme—cont'd

Themes	Key knowledge	Regional context/ importance	Connectivity	Major knowledge gaps
Climate	Dominant summer and winter climate patterns understood. Patterns in SST and cyclogenesis related to differences between El Niño and La Niña.	Water masses that pass through the Coral Sea influence global climate patterns. Relationships exist between variations in currents and climate in eastern Australia and New Zealand, and in the equatorial thermocline water properties.	Climate drivers (especially ENSO) influence physical and biological oceanography and linked ecological communities.	Variability of regional response to climate drivers (ENSO, PDO, and at longer timescales) in terms of temperature, precipitation and cyclone activity is unknown. Lack of evidence of secular change in temperature and physical forcing.
Biological oceanography	Oligotrophic character dominated by picoplankton and microbial processes. Role of myctophids and squid in top predator aggregations. Importance of the 'jelly food web' in the northern Coral Sea.	Ephemeral and/or seasonal aggregations feed large pelagics that sustain important recreational and commercial fisheries. Hiri Gyre entrains larvae of important species (rock lobsters and eels).	Interactions between climate, physical oceanography and topographic complexity drive ecological processes and productivity in the pelagic realm. Remote sources of iron, nutrients (volcanic plumes), N_2 fixation with drifting *Trichodesmium* blooms.	We need a better understanding of topographic controls on productivity. The trophic fate of productivity needs to be explored. Zooplankton community structure is unknown. Trophodynamics and production are unknown. Micronekton taxonomy, distribution and abundance/ biomass are virtually unknown.

				Productivity regimes supporting large biomasses are unclear. Population connectivity is unknown. Spatiotemporal variability and relationships to predator distributions need to be resolved.
Benthic ecosystems	Steady progress toward regional-scale seabed mapping, with targeted fine-scale mapping of key features, e.g. coral reefs and seamounts. Shallow (<20 m) reef communities relatively well known (but see gaps). Emerging knowledge of deep systems, including mesophotic reefs. Coral reef communities are impacted by climate change and are regularly impacted by Coral Sea cyclones.	Several distinct biogeographic realms within the Coral Sea. Different population structure between isolated reefs of the Coral Sea and large islands, for fish, algae and invertebrates. Endemism on coral reefs is low but present according to current sampling efforts Isolated oceanic reefs far from human disturbance could provide long-term refugia from human and climate impacts, including at mesophotic and greater depths.	Complex gene flow, showing dispersal from east to west, from north to south and across the Torres Strait for different taxa and species at a range of timescales. Low-dispersal species evolve as isolated populations. Deep-sea cold-water corals with links to NZ and Tasmanian coral communities.	Biodiversity of benthic invertebrates poorly known for many reefs, seamounts, plateaux and deep sedimentary areas. Intra- and interregional connectivity is poorly understood, including between reefs, between seamounts and continental slope, between depth zones and between faunal groups with contrasting life histories. Virtually no knowledge of benthic ecological processes, including benthopelagic coupling.

Continued

Table 4.1 Major knowledge areas and gaps for the Coral Sea by research theme—cont'd

Themes	Key knowledge	Regional context/ importance	Connectivity	Major knowledge gaps
		Complex patterns of biodiversity distribution between seamounts and bathyal domains. A large reservoir of species new to science at bathyal depths.		Phylogeography and biogeography of major reef taxonomic groups remain to be studied in the Coral Sea and adjacent regions. Coupled biophysical processes of transport at mesoscale and small scale remain unknown.
Demersal fish	Described for many shallow (<20 m) reef communities. There is some knowledge of deeper demersal fish in the southern plateaux. North–south gradient in diversity and biomass for reef fish becoming clearer.	Some reefs still in good to excellent condition, with abundant and diverse fish communities.	May play a role in linking GBR and New Caledonia to adjacent regions. Historical importance as these reefs were emergent during glaciations and were then important stepping stones.	Assembly rules for reef fish at the reef level unresolved. Little knowledge of demersal fish, especially in the north. Intra- and interregional gene flow unknown. Gene flow and migration between the seamount fauna and the continental slope unknown. Phylogeography and biogeography at the regional scale (Coral Sea and adjacent regions) are unknown.

Pelagic fish	Ecology and niche segregation of commercial top predators described. Only known black marlin spawning ground identified. Increasing knowledge of neritic tunas.	World's only known black marlin spawning aggregation. Coral Sea spawning grounds for a number of large pelagics.	Stock structure of some pelagic fish indicates trans-Pacific stock structure and migration. Movements of some pelagics link basin-scale regions, e.g. movements of large fish and sharks between western Pacific islands and Australian shelf and between temperate Tasman and tropical Coral Seas.	Need to establish population connectivity and migration pathways between the Coral Sea and adjacent regions. Relationship between movement and oceanographic/climate drivers is unresolved. Little knowledge of unfished species. Some basic biological parameters for some species (distribution, growth, reproduction, etc.) are poorly known. Spatial extent of spawning areas and residency times is unknown.
Fisheries	Invertebrate and ornamental fishing on most reefs well documented. Low demersal fisheries productivity (e.g. *Eteline* spp.).	Coral Sea may represent major source of recruitment of large pelagics to fisheries off eastern Australia.	Stock structure of some pelagic fish indicates trans-Pacific connectivity. Movements of some pelagics link basin-scale regions, e.g. movements of	Population connectivity and migration pathways between the Coral Sea and other regions of the WCPO are unclear.

Continued

Table 4.1 Major knowledge areas and gaps for the Coral Sea by research theme—cont'd

Themes	Key knowledge	Regional context/ importance	Connectivity	Major knowledge gaps
	Good catch records for most commercial pelagic fleets.		large fish and sharks between western Pacific islands and Australian shelf and between temperate Tasman and tropical Coral Seas.	Better observer coverage on pelagic fisheries is needed to increase representativeness of the data in space and time and acquire more information on non-target species. Need for better knowledge of population genetic structure at the regional scale (Coral Sea and adjacent regions). Poor catch records for game fish industry. Extent of illegal, unreported and unregulated fishing is poorly known.
Iconic and protected species	Population dynamics and nesting success known for some seabirds and sea turtles from a few cays. Some knowledge of the genetic structure of sea turtle and humpback whale populations.	Important nesting, resting and feeding areas for turtles and seabirds. Whale sharks attracted by myctophid aggregations. Group V humpbacks and other cetaceans may breed in the Coral Sea.	Migrations and movements of megafauna link terrestrial and marine ecosystems, and continents (e.g. birds), and basin-scale regions (e.g. loggerheads).	Occurrence, distribution and migration pathways for most species are unknown. The mechanism behind the negative effect of ENSO on bird success is unknown. Relationship/predation between seabirds and marine

	Detection of a decline in sea snake populations.	Migration pathways for several species, including humpback whales	fauna (fish and cephalopods) are not understood. Data on the occurrence, distribution and abundance, population genetic structure, connectivity, population trends, growth, reproduction of sea snakes are needed. Connection between humpback whales observed on the Chesterfield Islands and the migratory path or reproductive area of substocks Ei or Eii is not understood. Connection of Indo-Pacific bottlenose dolphin to Australian or New Caledonian population is not understood. Phylogeography and biogeography at the regional scale (Coral Sea and adjacent regions) are unknown for most species.

discipline and EEZ; for ecological and biological studies, minimum and maximum geographic coordinates were also recorded. Between 1954 and 2012, 1434 scientific documents were published on the Coral Sea (Appendix 1; see supplementary material in the web version of this chapter). Even though the bulk of this published research was conducted in the past decade, surprisingly, the Coral Sea has been relatively neglected; the rate of increase in publications over the past 20 years has been slower than for total marine research globally (Figure 4.2A). Much of the literature (41%) on the Coral Sea is from 'grey' literature, although the bulk is from peer-reviewed literature (59%); both types of documents had a similar trajectory of increase (Figure 4.2A).

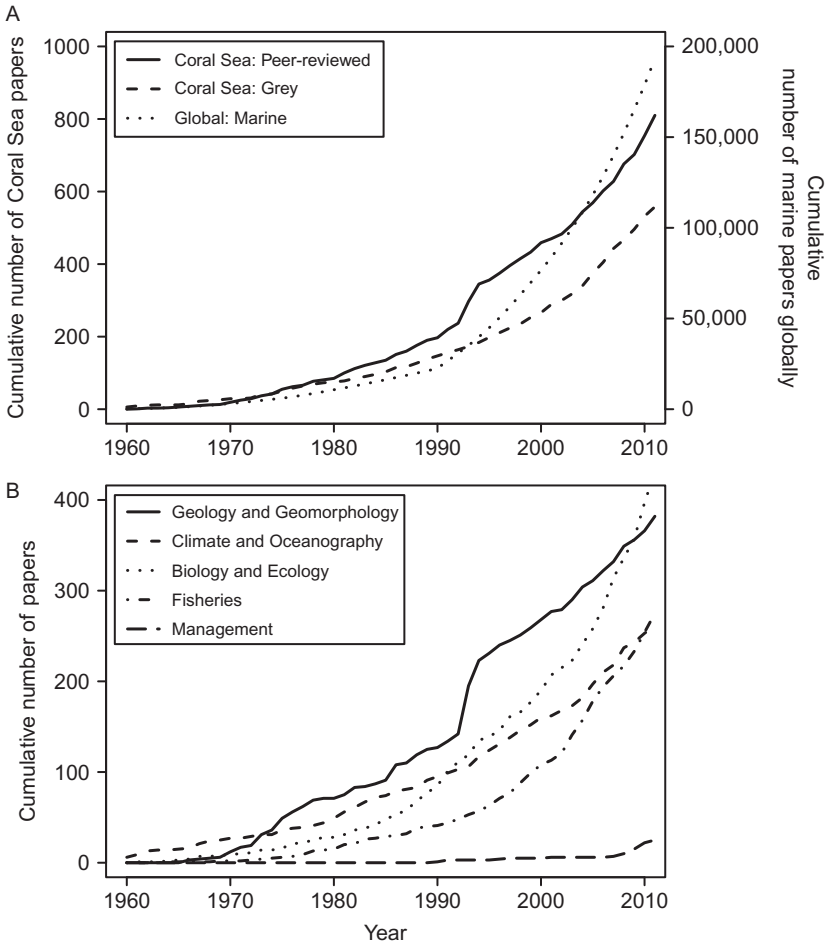

Figure 4.2 Research trends in the Coral Sea. Cumulative number of papers from 1960 to 2012. (A) For peer-reviewed and grey-literature Coral Sea research and peer-reviewed global marine research trends. (B) For major scientific disciplines studied in the Coral Sea (grey and peer-reviewed literature).

Ecological and biological studies were most common (31.5%), followed by geology and geomorphology (27%), fisheries (20.5%), climate and oceanography (19.1%), other disciplines (1.3%—including tourism, archaeology, sociology, history and economics) and management (0.6%). Earliest studies were reports of descriptive oceanographic cruises and taxonomic collections, with a rise in geological, geomorphological and sedimentological studies in the mid-1970s (Figure 4.2B). The past decade has seen a larger proportion of fisheries and ecological studies and a number of cross-disciplinary studies that combine ecological variables or fisheries catch rates with oceanographic or geological data. Management studies have only increased in the past few years.

To examine the spatial distribution of research effort in the Coral Sea, we included the central latitude and longitude and spatial extent of ecological studies in our compiled database. Most research has been conducted within Australian (31%) and New Caledonian (25.8%) waters. EEZs of PNG, the Solomon Islands and Vanuatu accounted for 13.6%, 12.6% and 16.9% of research, respectively. Ecological and biological studies have focused overwhelmingly on the oceanic coral reefs of the Coral Sea, with less work addressing seamounts, continental slopes, plateaux and the deep sea (Figure 4.3). The greatest proportion of documented ecological research comes from the Chesterfield Plateau, followed by the Loyalty Islands

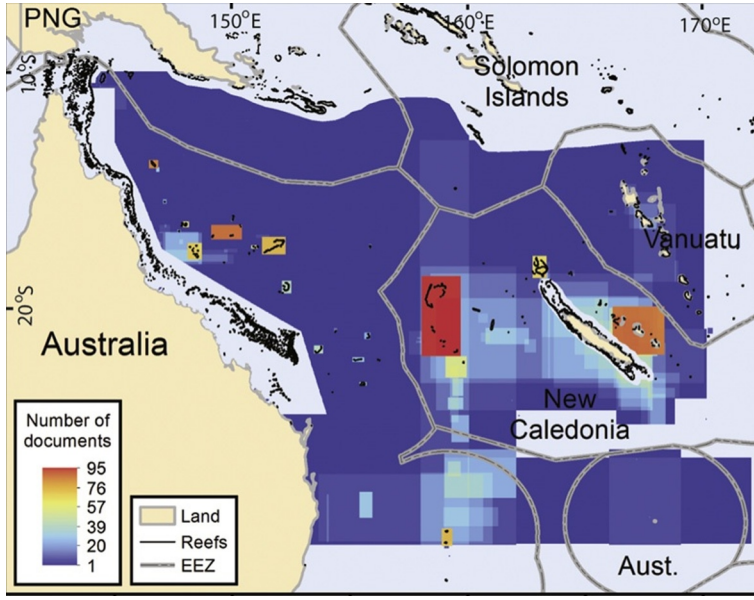

Figure 4.3 Spatial distribution of the number of ecological research documents from 1954 to 2012.

and reefs of Australia's Queensland Plateau (particularly Osprey Reef, the Coringa–Herald complex and Lihou Reef; Figure 4.3).

3. THE PHYSICAL SYSTEM

A complex geological history interacts with present-day topography, major currents and a tropical climate influenced by El Niño–Southern Oscillation (ENSO) to set the foundation for the Coral Sea's ecology. Aspects of the region's geology, oceanography and climate are well understood and documented, allowing some inference of drivers of ecological processes and likely pathways of connectivity.

3.1. Tectonics and topography

Between the Australian continental shelf to the west and the Solomon Islands and Vanuatu island arcs to the east, the Coral Sea consists of a series of basins interrupted by plateaux and rises (Collot et al., 2011; Pelletier, 2006; Figure 4.1C). Most of the major geological features of the Coral Sea seabed are derived from the fragmentation of Gondwana during the Cretaceous (Mortimer et al., 1998); the plateaux and rises to the east of Australia (Lord Howe Rise, Norfolk/New Caledonia Rise) are continental in origin. The deepest parts of the Coral Sea (the Coral Sea basin, the d'Entrecasteaux and South and North Loyalty Basins) are made of oceanic crust (Pelletier, 2006). The structure of other parts of the Coral Sea, such as the Fairway and New Caledonia Basins, is still under debate, as it is unclear whether they are also composed of oceanic crust (Auzende et al., 2000) or thinned continental crust (Lafoy et al., 2005).

The basins formed through seafloor spreading or continental stretching and crustal thinning, dominated by the oceanic accretion of the Tasman (84–52 Mya) and Coral Sea basins (65–52 Mya); the stretching and thinning of continental crust of the Fairway and New Caledonia Basins (~70 Mya); and the opening of the South Loyalty Basin (~100–56 Mya), the d'Entrecasteaux Basin (~56–33 Mya) and the North Loyalty Basin (45–35 Mya; Figure 4.1C). The region's major subduction zone is at the eastern dipping point of the North Loyalty Basin at the d'Entrecasteaux Zone, a convergent zone that began ~7 Mya. Currently, the Australian plate moves in a NNE direction at 7 cm $year^{-1}$ and is subducted under the Pacific Plate along the New Hebrides (or Vanuatu) and South Solomon Trenches at 9–17 cm $year^{-1}$ (Calmant et al., 2003; Pelletier et al., 1998).

The Tasmantid and Lord Howe seamount chains are ancient volcanic hot spots (McDougall and Duncan, 1988). Kenn Reef in the north is the oldest seamount of the Tasmantid chain, with a predicted age of 38 My (Exon et al., 2006). The Bellona and Chesterfield Reefs, on the northern part of the Lord Howe seamount chain, are tentatively dated at 25 Mya (Missegue and Collot, 1987).

The shallowest of the large plateaux are the Eastern, Queensland, Marion, Mellish, Kenn and Chesterfield–Bellona Plateaux; the Lansdowne Bank; the New Caledonia lagoons and d'Entrecasteaux reefs; and the Loyalty Rise, all of which host emergent reefs, cays and islands. Some of these are among the world's largest atolls, such as the Chesterfield and Lihou Reefs. Sea-level variation controlled platform facies; rising and higher sea levels promoted carbonate deposition, whereas falling and lower sea levels restricted carbonate deposition, increased terrigenous input and in many cases resulted in exposure of the platforms (Davies et al., 1989). Various studies of the palaeofauna suggest successive episodes of connection and isolation between the Gondwanan supercontinent and its fragments (Collot et al., 2011). Some reefs formed on natural high points of the plateaux, and the structure of present-day reefs suggests that reef growth kept pace with plateau subsidence and sea-level rise for the last 25 My (Davies et al., 1989).

3.2. Physical oceanography

The dominant feature of the circulation in the Coral Sea is the westward-flowing South Equatorial Current (SEC) and its bifurcation at the Australian continental margin (Ridgway and Dunn, 2003; Kessler and Cravatte, 2013a; Figure 4.1D). The SEC redistributes South Pacific thermocline waters from the subtropics to the equator and the Southern Ocean (Qu and Lindstrom, 2002). The southern arm of the bifurcation feeds the southward-flowing East Australian Current (EAC), the major western boundary current of the South Pacific Gyre, and the northern arm forms the Gulf of Papua Current, which flows northward along the Queensland coast and turns eastward along the southern rim of PNG (SPICE Community, 2012), and feeds into the New Guinea Coastal Undercurrent that subsequently enters the Solomon Sea. In 2005, the Southwest Pacific Circulation and Climate Experiment (SPICE) was initiated to provide improved understanding of Coral Sea circulation (Ganachaud et al., 2013).

Within the Coral Sea, the SEC comprises narrow filaments and jets created by the complex island, reef, seamount and ridge topography (Couvelard et al., 2008; Gourdeau et al., 2008). Major westward currents are the North

Vanuatu Jet, the North Caledonian Jet and the episodic South Caledonian Jet (Figure 4.1D). Eastward countercurrents are also present in the lee of the Vanuatu and Fiji islands (Kessler and Cravatte, 2013a). This interaction of hydrodynamics and topography is an important influence on local mixing processes. The Coral Sea transit of the waters advected by the SEC and bifurcating equatorward is important because changes in the temperature or the water transport toward the equator can modulate the ENSO cycle and trigger Pacific-scale climate feedbacks (Ganachaud et al., 2013). South of the bifurcation, EAC thermocline waters are important drivers of eastern Australian and New Zealand climate; seasonal and interannual changes in advection influence the air–sea heat flux and atmospheric conditions (Roemmich et al., 2005).

Current pathways depend on the depth of the relevant water masses (Kessler and Cravatte, 2013a; Figure 4.4), linked to the vertical tilt of the bifurcation latitude at the Australian coast: at the surface, the bifurcation is at ~15° S; at 500 m, it is at ~23° S. Warm, low-salinity waters dominate at the surface. A high-salinity and poorly oxygenated water mass, Subtropical Lower Water, is subducted in the eastern subtropical Pacific (Donguy, 1994) and spreads westward into the Coral Sea through the North Vanuatu Jet, appearing as a subsurface salinity maximum at 100–200 m (Kessler, 1999).

Subantarctic Mode Water and Antarctic Intermediate Water are formed in the Southern Ocean and entrained into the anticyclonic South Pacific Gyre, which projects them into the Coral Sea at a depth of between 400 m and 1000 m. These water masses are advected through the region by the SEC following pathways dictated by the island groups (Maes et al., 2007) and with components spreading poleward and equatorward following the bifurcation. Underlying the intermediate waters throughout the South Pacific, there is an oxygen minimum centred at ~2000 m (Sokolov and Rintoul, 2000). At even greater depths, the spreading of water masses is increasingly constrained by topography. The Lower Circumpolar Deep Water, identified by a weak salinity maximum, is found in the South Pacific over a depth range of 2500–3000 m. Deep layers of the Coral Sea are fed by components of Lower Circumpolar Deep Water from the east (via the SEC) and, from the south, from the Tasman Abyssal basin through a narrow passage at 24° S (Sokolov and Rintoul, 2000). Whilst there are strong tidal currents through the shallow Torres Strait to the northwest (mostly <20 m), the mean flow is small (0.1 m s^{-1}) and makes a negligible contribution to the Coral Sea water mass structure (Saint-Cast and Condie, 2006). Circulation features in the Coral Sea vary on seasonal to multidecadal timescales, but the magnitude and drivers of this variability are not well understood.

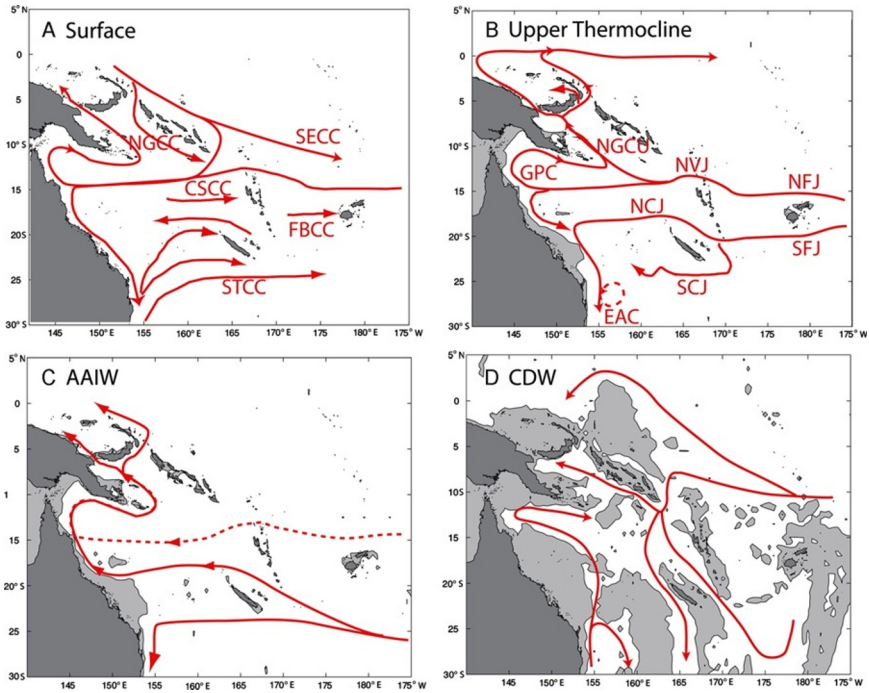

Figure 4.4 Main currents for different water masses within the Coral Sea. (A) Surface currents; (B) Upper thermocline currents; (C) Pathways of Antarctic Intermediate Water (AAIW) (800–1200 m); and (D) Path of Circumpolar Deep Water (CDW) through the deep channels in the region (<3500 m). NGCU: New Guinea Coastal Undercurrent; GPC: Gulf of Papua Current; NVJ: North Vanuatu Jet; NCJ: North Caledonia Jet; NFJ: North Fiji Jet; SFJ: South Fiji Jet; SCJ: South Caledonian Jet; EAC: East Australian Current. NGCC: New Guinea Coastal Current; STCC: Subtropical Counter Current; SECC: South Equatorial Counter Current; CSCC: Coral Sea Counter Current; FBCC: Fiji Basin Counter Current.

3.3. Climate

The most important driver of interannual climate and oceanographic conditions in the Coral Sea is the ENSO pattern, with major changes in sea surface temperature (SST) and sea level north of 15° S over 3–7 year cycles. During El Niño events, waters in the northwestern Coral Sea cool and sea level drops, and the SEC entering the Coral Sea north of Vanuatu swings westward (Kessler and Cravatte, 2013b); the reverse pattern is true of La Niña years. ENSO-related temperature anomalies can penetrate to the base of the mixed layer (100 m; Holbrook et al., 2005). There has been a

quasidecadal change in ocean properties of the southwest Pacific Ocean over the past 60 years, associated with a spin-up/spin-down cycle of the South Pacific Gyre (Hill et al., 2011), which may be related to decadal variations in ENSO (Holbrook et al., 2011). Over the past 50 years, the South Pacific Gyre has intensified, due to a poleward shift in the circumpolar westerly winds driven by the trend in the Southern Annular Mode (Cai and Cowan, 2007). The EAC may have strengthened in the south (Ridgway, 2007), and modelling studies suggest a corresponding decrease in SEC strength (Cai and Cowan, 2007) and an associated region of enhanced warming off southeastern Australia (Ridgway, 2007).

There is also seasonal variability of the atmospheric conditions in the Coral Sea. During winter, trade winds over the Coral Sea bring dry conditions, with SST between 23 and 24 °C around New Caledonia and 27–28 °C in the Gulf of Papua (Figure 4.5). In summer, the South Pacific Convergence Zone reaches its southernmost position, with heavy precipitation in the Gulf of Papua, SST generally >28 °C and trade winds converging from the south toward the South Pacific Convergence Zone (Figure 4.5). Depending on prevailing conditions, cyclones are most likely to develop in summer.

The Coral Sea experiences both an increased intensity of cyclones and enhanced rainfall during La Niña events, with the opposite trend during El Niño periods (Vincent et al., 2011). Potential drivers include a strengthening of the wind vertical shear between the upper troposphere and lower troposphere and a weakened convective potential during El Niño and the opposite pattern during La Niña (Menkes et al., 2012). Cyclones can be highly damaging for shallow environments and coral reefs in particular (Emanuel, 2005), but they can also supply the photic layer with enough nutrients to support up to 15% of the annual mean new production in this oligotrophic sea (Christophe Menkes, unpublished data).

Climate projections suggest a continuation of observed patterns, but there will be minor changes in the currents south of 12° S (Ganachaud et al., 2011). The strength of the SEC transport entering into the Coral Sea and the Gulf of Papua Current transport toward the equator are expected to increase (Sen Gupta et al., 2012). Warming is expected to continue, with faster rates in the upper 100 m (Table 4.2). In the past decades, the rate of warming in the Coral Sea has been closely aligned with global trends of SST increase of 0.6 °C within the upper 100–200 m, with a broadscale cooling at greater depths extending to 25° S (Durack and Wijffels, 2010). These changes have led to increased stratification, potentially limiting the vertical

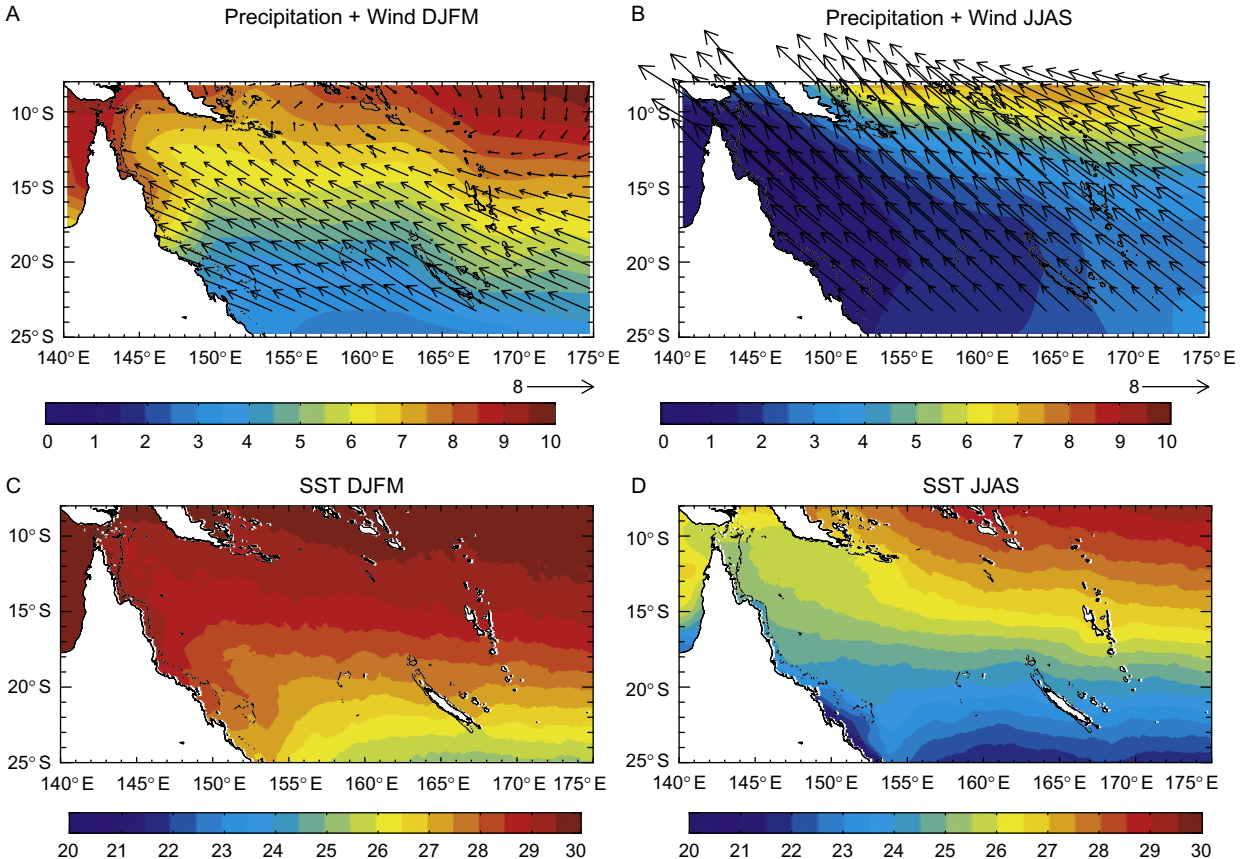

Figure 4.5 (A) Contours of precipitation (mm day^{-1}) from GPCP data during summer (DJFM) with arrows from Qscat wind stress for the same months. The GPCP climatology is computed for 1979–2010. The Qscat climatology is computed for 2000–2009. (B) Precipitation contours for winter (JJAS). (C) SST from AVHRR during summer (DFJM), and (D) during winter. The AVHRR V4.1 climatology is computed for 1985–2010.

Table 4.2 Projected threats (vulnerabilities) of pelagic systems to climate change

Variable	Prediction	Vulnerability of the pelagic system
Water temperature	To increase by 0.7–0.8 °C by 2035	Low
Mixed layer depth	To become shallower	Moderate to high
Changes in upwelling	Dependent on location, upwelling may increase or decrease	Low
Solar and ultraviolet radiation	Increased cloud cover, rainfall but potentially higher ultraviolet radiation	Low
Dissolved oxygen	To decrease by <5% by 2100	Low
Ocean acidification	Aragonite saturation state to decline, potentially affect calcification rates	Low

Summarised from Le Borgne et al. (2011).

exchange of nutrients, decreasing subsurface dissolved oxygen concentrations (Stramma et al., 2008) and reducing oceanic pH in the region due to increased absorption of CO_2 (Bindoff et al., 2007). Projections suggest that these patterns will intensify (Ganachaud et al., 2011).

To calculate average temperature change in the Coral Sea over the past 50 years, we used HadISST 1.1 data (http://badc.nerc.ac.uk/view/badc.nerc.ac.uk__ATOM__dataent_hadisst). For future temperature projections, we used CSIRO-Mk3.6.0 data from the PCMDI5 (Program for Climate Model Diagnosis and Intercomparison) data archive, interpolated onto a 1° grid. We extracted annual temperature anomalies for the four RCPs (Representative Concentration Pathways) considered by IPCC AR5 (i.e. RCP 2.6, RCP 4.5, RCP 6.0 and RCP 8.5) and used these to project the HadISST data series forward to 2100. It must be noted that these results are based on outputs from a single model, and further studies should assess these in a multi-model framework. SST in the Coral Sea warmed by 0.089 °C per decade between 1960 and 2009 (Figure 4.6). Projected warming in the future ranges from 0.85 °C by 2100 for RCP 2.6 to 3.17 °C for RCP 8.5 (anomalies of 5-year means at the start and end of the time series). RCP4.5 and RCP6.0 show intermediate increases of 1.17 and 1.51 °C, respectively, over the twenty-first century.

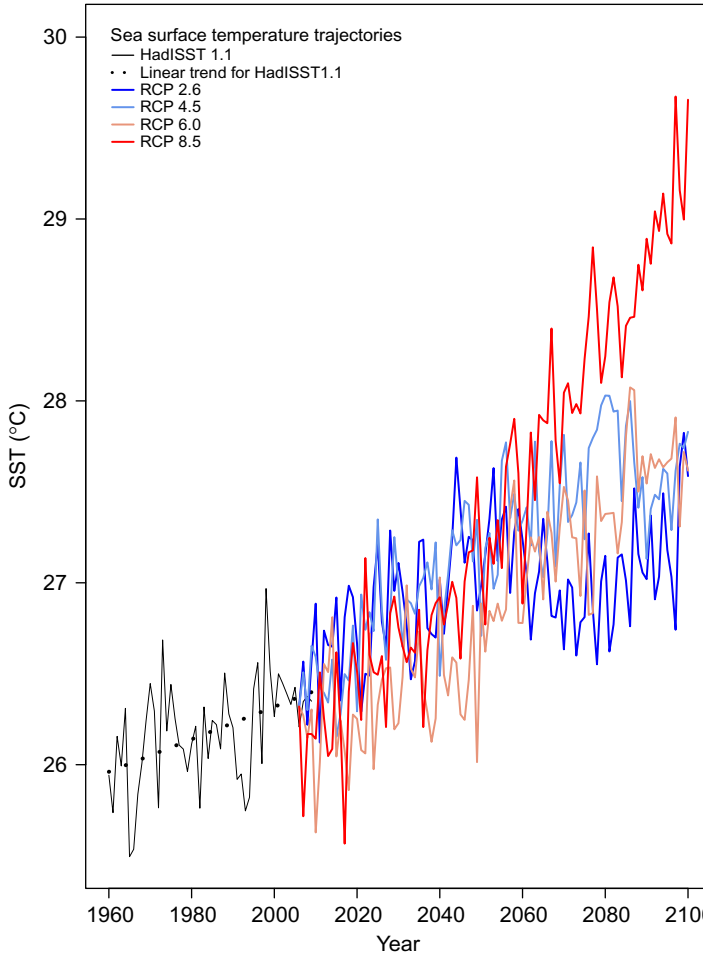

Figure 4.6 Sea surface temperatures for the Coral Sea over the period 1960–2100. Historical temperatures are taken from HadISST 1.1, whilst projections according to four IPCC Representative Concentration Pathways were derived using anomalies from the CSIRO-Mk3.6.0 data. A linear trend is fitted to the HadISST data to illustrate the historical warming trend in the region.

4. BIOLOGICAL OCEANOGRAPHY

The ecology of pelagic habitats is closely linked to oceanography and climate, especially in the upper oceanic layers where most research has focused. The availability of inorganic and organic nutrients, influenced by water movement, temperature, salinity and climatic conditions, sustains

phytoplankton assemblages that form the basis of pelagic food webs. Pelagic production and community structure are also influenced by topographic features. Here, we summarise current knowledge of nutrients, phytoplankton, zooplankton and micronekton in the Coral Sea.

4.1. Nutrients and their supply

The water column of the Coral Sea is characterised by low nutrient concentrations in the surface mixed layer, whilst nutrient concentrations increase and temperatures cool below the thermocline (Figure 4.7). Mixed layer depths offshore vary from ~25 to 125 m, depending on the location, season, wind-stress history and regional dynamics (Furnas and Mitchell, 1996). 'New' nutrients are episodically introduced into the surface layer by atmospheric forcing of the ocean surface in the form of momentum, heat, freshwater fluxes and cyclones; ENSO-driven climate variability can therefore influence nutrient availability. Strong rotational forces associated with eddies deflect ocean density, either lifting nutrients into surface waters (cyclonic rotation) or depressing surface waters (anticyclonic rotation). On top of this direct effect, impacts of eddies on the ecosystem are expected on the sides of the eddies due to localised geostrophic and ageostrophic processes (e.g. Dandonneau et al., 2003). In the Coral Sea, eddies associated with the EAC are most pronounced and therefore the most likely areas of localised elevated nutrient content. Other weaker eddy activity also originates from the instabilities of the SEC currents further to the east (Chelton et al., 2011). Spatial variations in wind forcing lead to divergent and convergent currents, resulting in regions of upwelling and downwelling, respectively. Interactions of large-scale current features with island, reef and seamount topography produce wakes or vortices on the lee side of the obstacle, which dissipate energy and trap suspended and floating material and particles (Couvelard et al., 2008). This was observed around Cato Island (Suthers et al., 2004), and probably applies to islands throughout the region. Internal waves or vertical perturbations of density surfaces generated by the interaction of the barotropic tide with the shelf break or other topographic features drive the nutricline toward the surface during the passage of wave crests. Leaching of guano from seabird rookeries can also cause local enrichment near cays and islands (McCauley et al., 2012).

Micronutrients, most commonly iron, often limit the productivity of ocean environments. Though there are relatively few studies, concentrations of iron appear to vary regionally, with the northern Coral Sea more

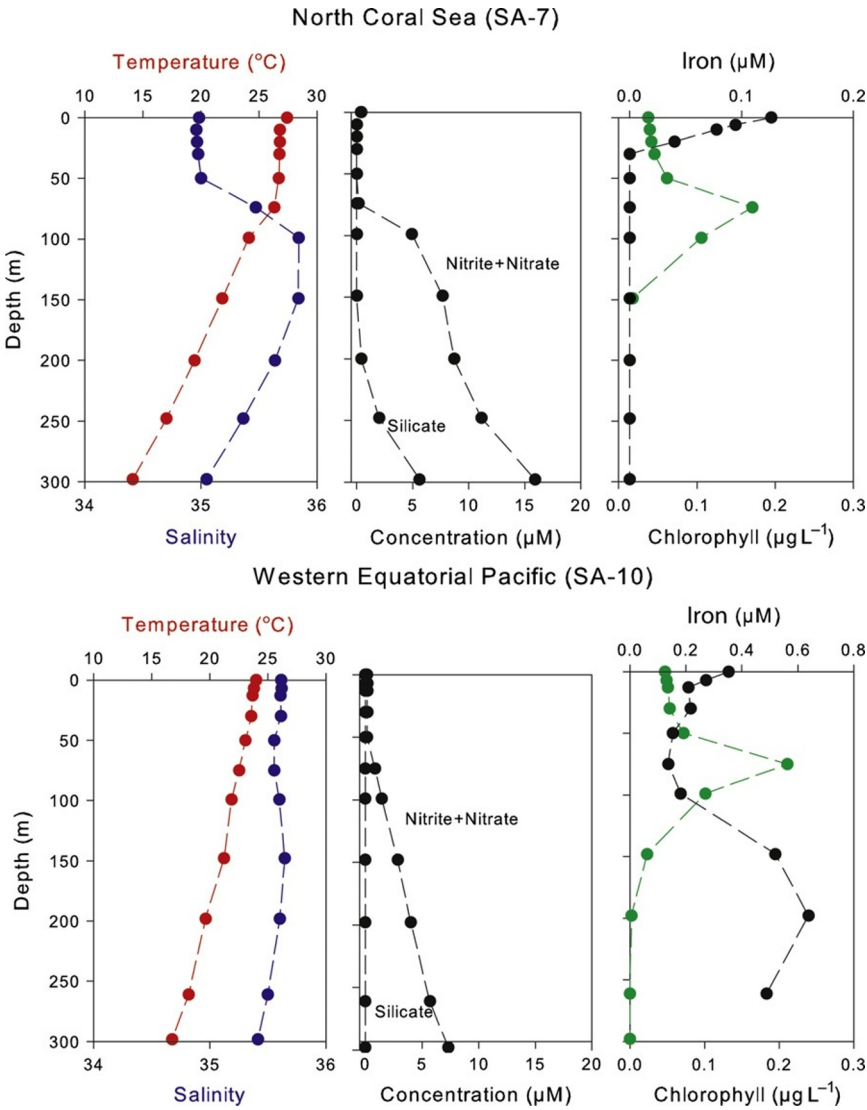

Figure 4.7 Vertical profiles of temperature, salinity, nitrite plus nitrate, silicate, chlorophyll a, total dissolvable iron in the northern Coral Sea and the adjacent western Pacific Ocean. *From Obata et al. (2008).*

iron-deficient than the western Pacific Ocean (Figure 4.7; Obata et al., 2008). Several groups of microorganisms living in surface layers of the Coral Sea have the ability to fix atmospheric N_2 (diazotrophy; Moisander et al., 2010). Recent work indicates that nitrogen fixation by heterotrophs may

exceed that of autotrophs in the open ocean (Halm et al., 2012). The importance of nitrogen fixation in the world's oceans is poorly understood but is likely to be significant (Karl et al., 2002); this is especially true of the Coral Sea, where surface rafts of *Trichodesmium* are common (Dupouy et al., 2011; McKinna et al., 2011).

4.2. Phytoplankton and primary production

Coral Sea circulation maintains a deep thermocline and nutricline reaching 110 m in the central Coral Sea, whilst other processes maintain higher production at its edges and near islands (Figure 4.8). Low nutrient concentrations in the surface waters of the Coral Sea lead to low surface phytoplankton biomass (<0.2 μg chl L^{-1}) and slow rates of production, although this can vary with ENSO (Condie and Dunn, 2006). There is a deep chlorophyll maximum (nutricline) near the top of the thermocline, where concentrations can double (Figure 4.7; Furnas and Mitchell, 1996).

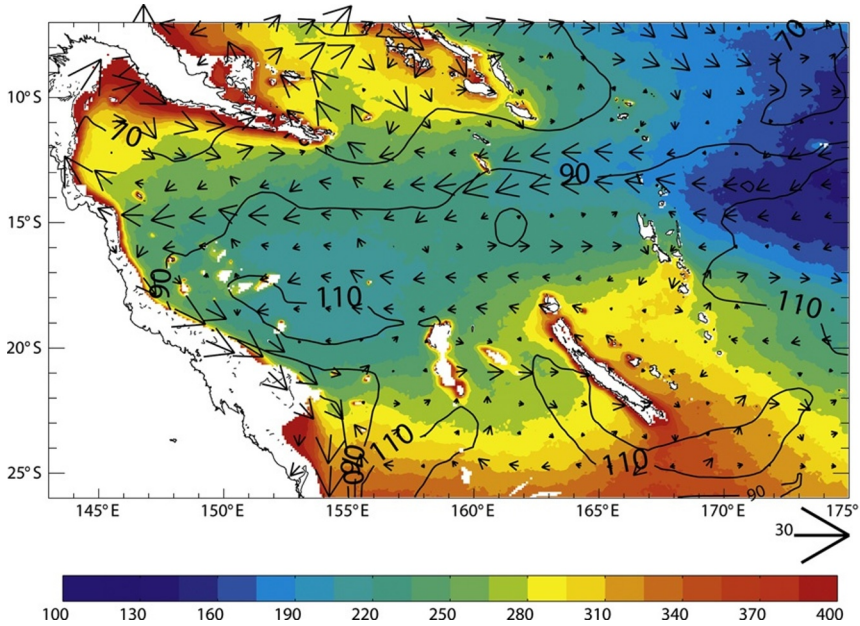

Figure 4.8 Average primary production estimates from satellite data for the period 1998–2007, VGPM: http://www.science.oregonstate.edu/ocean.productivity/ (Behrenfeld and Falkowski, 1997), in mg C m^{-2} h^{-1}. Areas deeper than 200 m have been masked. The mean depth (m) of the 1 μM L^{-1} nitrate isopleth is extracted from the CARS 2009 climatology—http://www.marine.csiro.au/dunn/cars2009/ (Ridgway et al., 2002). Vectors: mean 0–150 m total geostrophic currents.

At most oceanic sites within the Coral Sea, light penetrates deeply into the water column, producing a deep euphotic zone (I_z >0.1% I_0) up to 100 m deep. Fastest rates of primary production are in the well-lit (20–50% I_0) near-surface layer (20–30 m). Nutrients to support primary production within the near-surface zone are largely supplied by *in situ* mineralisation of organic N and P by bacteria and microbial grazers, but ratios of dissolved inorganic N ($NH_4 + NO_2 + NO_3$): P (PO_4) in the mixed layer indicate chronic nitrogen limitation of phytoplankton and bacterial biomass production (e.g. Furnas, 1991). Ellwood et al. (2013) found that phytoplankton north of the Tasman Front were primarily limited by N, but further north iron availability probably limits primary production.

Picoplankton (<2 μm) are the largest component of phytoplankton biomass and primary production, contributing 39–82% of total chlorophyll in the oceanic Coral Sea (Furnas and Mitchell, 1996). Greatest contributors to this size class are the cyanobacteria *Synechococcus* spp. and *Prochlorococcus* spp. and, to a lesser extent, small eukaryotic algae. Nanoplankton (2–20 μm in size and comprising mostly diatoms, dinoflagellates and flagellates) are an important component of phytoplankton biomass under certain conditions (Furnas and Mitchell, 1996; Tenório, 2006). Populations of the diazotrophs UCYN-A (<1 μm, photoheterotrophic) and cyanobacteria *Crocosphaera watsonii* (3–8 μm, photosynthetic) and *Trichodesmium* (Campbell et al., 2005; Moisander et al., 2010) have distinct vertical and horizontal distribution within the Coral Sea, owing to their temperature and light preferences and requirements for phosphate and iron (Dupouy et al., 2004; Campbell et al., 2005). Large phytoplankton (>10 μm, e.g. Trichodesmium) can fix the bulk of available nitrogen at very high rates (up to 1.8 nmol l^{-1} h^{-1}). Elevated 15 nitrogen accumulation (up to 0.83 nmol l^{-1} h^{-1}) was always observed in the <10 μm fraction, representing a mean of 31 ± 20% of total nitrogen fixation, up to 98% at the oceanic DIAPAZON sampling site in the Loyalty Channel (21°S, 165°E, Garcia et al., 2007; Masotti et al., 2007). A new *Trichodesmium* ecotype adapted to low light was discovered at depth in the Coral Sea (Neveux et al., 2006, 2008).

Jitts (1965) divided the Coral Sea into two regions based on their productivity, with a boundary at ~20° S; the central Coral Sea (15 mg C m^{-2} h^{-1}) and the more oligotrophic southern Coral Sea (11 mg C m^{-2} h^{-1}). These hourly rates are at the low end of those reported from margins of the Coral Sea by Furnas and Mitchell (1996), which ranged from 16 to 58 mg C m^{-2} h^{-1}. At the eastern entrance of the Coral Sea, *in situ* measurements made during the Pandora cruise in 2011 found primary production

Table 4.3 Means and ranges of primary production rates measured in the Coral Sea region

Region	Mean primary production mg C m^{-2} day^{-1}	Range	Reference
Gulf of Papua (estuarine)	159 ± 210	2–693	Robertson et al. (1993, 1998)
Gulf of Papua (shelf)	318 ± 225	134–942	Robertson et al. (1993, 1998)
Central Coral Sea (1985)	243 ± 74	117–330	Furnas and Mitchell (1988)
Central Coral Sea (1988)	431 ± 211	21–462	Furnas and Mitchell (1988)
Solomon Sea	491 ± 277	106–701	Furnas and Mitchell (1988)
Papuan Barrier Reef boundary	989 ± 956	247–3030	Furnas and Mitchell (1988)
Great Barrier Reef boundary (East Australian Current)	493 ± 297	189–944	Furnas and Mitchell (1988) and Furnas (unpublished)
Great Barrier Reef shelf	680		Furnas and Mitchell (1988) and Furnas (unpublished)
New Caledonia lagoon	460 ± 165		Clavier et al. (1995)

ranges from 8 to 33 mg C m^{-2} h^{-1}. Changes in methodology may account for the higher productivities observed in later studies, but a robust estimate of *in situ* primary production is hindered by the paucity of data. Nevertheless, some trends are apparent: more productive sites at the margins of the Coral Sea have shallower surface mixed layers and a greater proportion of larger (>10 μm) phytoplankton (Table 4.3). These primary production values can be complemented by indirect estimates from satellites in noncoastal regions (Figure 4.8), which suggest higher production at the edges of the Coral Sea south of 17° S and lower production north of 17° S.

4.3. Meso- and macrozooplankton

All published studies on Coral Sea zooplankton are from the epipelagic zone and used comparatively coarse plankton nets (i.e. >200 μm) that do not quantitatively sample the most numerous, but small, zooplankton in tropical seas. Sampling has therefore only glimpsed the top of the mesopelagic zone,

and the bathypelagic and abyssal zones remain unsampled. Additionally, sampling has been confined to margins of the Coral Sea, such as coastal areas of New Caledonia (Le Borgne et al., 2011) and of the GBR (McKinnon et al., 2005). The only plankton research in the Australian sector of the Coral Sea has concerned zooplankton biomass in the island wake around Cato Reef (e.g. Suthers et al., 2006). However, the Coral Sea shares attributes with other tropical marginal seas, where protistan (e.g. ciliates) and gelatinous grazers account for a high proportion of zooplankton primary consumers. Mesozooplankton such as copepods become more abundant in areas where 'new' nutrients are introduced, and these are important prey to visual predators such as fish larvae (McKinnon et al., 2014).

To our knowledge, there are no production rate measurements of zooplankton in the Coral Sea other than the study of Shushkina (1971), who measured production to biomass ratios; small copepods had P–B ratios of 22–28%, small chaetognaths 15–20%, herbivorous copepods 6–10% and carnivorous copepods 5–8%. The gelatinous zooplankton of the Coral Sea is characterised by a high relative abundance of pelagic tunicates such as larvaceans, salps, doliolids and pyrosomes, together with large concentrations of narcomedusan jellyfish such as *Pegantha* spp., *Aegina rosea* and *Solmundella bitentaculata*, which are known to be specialist predators of gelatinous prey (Dhugal Lindsay, unpublished data).

4.4. Micronekton

Trophically, micronekton (fauna 2–20 cm) links plankton to mid- and top-order predators in the Coral Sea. There are >350 species of fish, crustaceans and squid in the micronekton in the Coral Sea (Valerie Allain, unpublished data). This micronekton is distinct from the nearby Tasman Sea fauna (Griffiths and Wadley, 1986). Flynn (2012) identified a Coral Sea biogeographic region based on lanternfish (Myctophidae) distribution, coinciding with Condie and Dunn's (2006) biogeographic boundary at ~25° S, which also functions as a boundary for demersal fishes (Last et al., 2005). Biogeochemical indicators also show evidence of a transition zone at ~25–28° S (Hobday et al., 2011; Revill et al., 2009). This differs slightly from the productivity boundary identified by Jitts (1965) at ~20° S (see Section 4.2).

Micronekton species diversity differs between seamounts (Flynn and Paxton, 2012), open waters (Young et al., 2011) and the vicinity of reefs and islands (Allain et al., 2012). On a seamount in the western Coral Sea, the Dana lanternfish *Diaphus danae* aggregate in spring, attracting top

predators (Flynn and Paxton, 2012). At the southern end of the Coral Sea, oceanic waters have a broad mix of micronektonic fishes dominated by the myctophids, Warming's lanternfish *Ceratoscopelus warmingii* (Young et al., 2011).

In New Caledonia, daytime biomass was greatest at ~400–500 m depth, with the dominant fish species belonging to the families Gonostomatidae, Sternoptychidae, Myctophidae, Opisthoproctidae, Scopelarchidae and Phosichthyidae, similar to the dominant fish families previously recorded by Grandperrin (1975) off New Caledonia. At night, a large proportion of this biomass migrates toward the surface. The 200–400 m layer is depauperate, but a peak in biomass was recorded on the eastern slope of the Chesterfield atoll between 200 and 300 m depth, with large schools of hatchetfish *Polyipnus* (Sternoptychidae; Valerie Allain, unpublished data).

5. BENTHIC ECOSYSTEMS

High diversity and habitat complexity in Coral Sea benthic ecosystems is conferred by the region's large geographic extent and complex seafloor topography across a broad range of depth (surface to >5000 m) and latitude (~8–32° S; Figure 4.1). The region has a complex biogeographic history (Sections 3.1, 9) and is bathed by ocean currents from numerous sources, including the biodiverse Indo-West Pacific region (Section 3.2). The primary benthic ecosystems of the Coral Sea can be broadly characterised as coral reefs, seamounts, deep shelf and abyssal (bathyal) habitats. Most benthic ecological studies in the Coral Sea have been conducted on shallow (<20 m) communities. Sampling of deeper habitats has been scarce. An increased use of enabling technology such as swath-acoustic seabed mapping and camera platforms is rapidly expanding knowledge of mesophotic coral communities (e.g. Bongaerts et al., 2011), but research in bathyal habitats remains localised.

In general, photosynthetic organisms or organisms with photosynthetic symbionts (scleractinian corals, zooxanthellate octocorals and sponges) dominate to depths of ~60 m, with transition to, then dominance by, azooxanthellate filter feeders (notably octocorals) in 60–140 m (Dalzell et al., 1996). Mesophotic, or low-light, coral-based ecosystems have only recently been observed directly, but are thought to be potentially vast—extending along at least the 900 km of submerged shelf-edge reefs in the central GBR (Bridge et al., 2011). In New Caledonian waters, gorgonians,

brachiopods and sponges become the dominant benthic taxa below the shelf edge (Richer de Forges, 1998), and galatheid crustaceans dominate the motile deep-sea macrofauna (Rowden et al., 2010b). At depths >700 m, the absence of a latitudinal pattern in assemblage structure of ophiuroids was attributed to the continuity of Antarctic Intermediate Water in the Coral Sea (O'Hara et al., 2011).

5.1. Coral reefs

Shallow reefs represent <1% of the total Coral Sea area (Heap and Harris, 2008; Figure 4.9), but are biodiversity hot spots, since coral reefs worldwide host 25% of the world's known marine biodiversity (Plaisance et al., 2011).

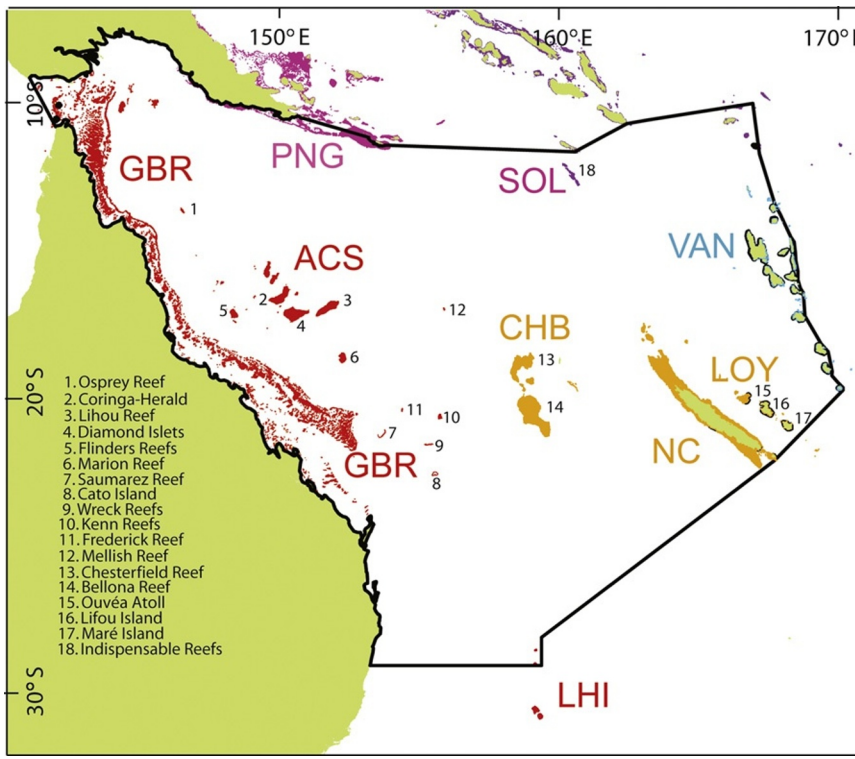

Figure 4.9 Distribution of the major coral reefs in the Coral Sea and surrounding areas. GBR: Great Barrier Reef; PNG: Papua New Guinea; SOL: Solomon Islands; ACS: Australian Coral Sea; CHB: Chesterfield and Bellona; LHI: Lord Howe Island; NC: New Caledonia; LOY: Loyalty Islands; VAN: Vanuatu. Data from the Millennium Coral Reef Mapping Project (Andréfouët et al., 2006).

The widespread occurrence of shallow coral reefs across the Coral Sea from the GBR to New Caledonia suggests an important role as 'stepping stones' between these areas.

There have been sporadic surveys of the flora and fauna of Coral Sea reefs in New Caledonian and Australian waters since the 1960s and, to a lesser extent, on Vanuatu, Solomon Islands and PNG reefs. For instance, there are at least 56 documents published about Australia's Herald Cays, whilst only one ecological study has investigated the Indispensable Reefs and Rennell/Bellona Islands, an analogous reef system in the Solomon Islands (Sulu et al., 2002). Extensive multitaxa sampling by the Santo 2006 expedition around Espiritu Santo Island identified Vanuatu as a biodiversity hotspot (Bouchet et al., 2011), but outlying reefs and islands of Vanuatu remain unexplored. Researchers still routinely find new species, new records and range extensions (e.g. Borsa et al., 2013; Randall and Kulbicki, 2005; Randall and Walsh, 2010). These discoveries include not just small or cryptic species, but also large, iconic species such as, for example, the giant clam *Tridacna tevoroa*, which was discovered in Tonga and Fiji in 1990 and recorded for the first time on Lifou Island (New Caledonia) in 2000 (Bouchet et al., 2001) and on Lihou Reef (Australia) in 2008 (Ceccarelli et al., 2009).

There is little knowledge of patterns or gradients of coral reef benthic biodiversity or community structure across the Coral Sea, apart from the general decline in species richness of many reef organisms with increasing distance from the Coral Triangle (Messmer et al., 2012). The most recent checklist of scleractinian corals in New Caledonia (which includes the New Caledonian barrier reef) lists 309 species in these waters alone (Pichon, 2006), compared to over 500 in the whole Coral Triangle (Veron et al., 2011). The Chesterfield Islands alone host 866 species of fish (Kulbicki et al., 1994), compared with over 3000 reef fish species recorded in the much larger Coral Triangle (Veron et al., 2011). Macroalgal research has resulted in an inventory of hundreds of species from PNG, the Solomon Islands, Espiritu Santo in Vanuatu and New Caledonia including the Chesterfields and Loyalty Islands (e.g. Silberfeld et al., 2013). Based on the published data (Bittner et al., 2011; Dijoux et al., 2012) the number of species in several macroalgal groups show that New Caledonia displays higher species richness than surrounding areas, making this a macroalgal diversity hotspot. Collating these individual inventories may be a useful first step for identifying gradients in abundance and species richness (see Section 6.1.1).

Reefs and cays in the Coral Sea are relatively undisturbed (Young et al., 2012). Coral cover, the most common measure of reef condition, is typically low in exposed habitats and on smaller reefs, and higher in sheltered habitats and on larger or interconnected reefs with lagoons. Estimates of reef-wide coral cover range from 7% (Coringa–Herald), through ~40% (d'Entrecasteaux Reefs), to 60% (Osprey Reef; Ceccarelli, 2011; Garrigue et al., 2000). In many shallow habitats (slopes, reef flats and lagoons), the dominant biotic benthos is low-profile turf algae and crustose coralline algae. Community structure and density of motile reef-dwelling organisms (invertebrates and fish) are heavily influenced by reef size, exposure, isolation, latitudinal position and fine-scale topographic complexity (Ceccarelli et al., 2009; Kulbicki, 2007).

Only three published studies have addressed ecological processes on Coral Sea reefs, linking higher internal bioerosion rates to low sedimentation on oceanic reefs (Hutchings et al., 2005), indicating that reef sponges contribute little (~10%) to benthic productivity (Wilkinson, 1987) and identifying a high regeneration rate of corals following a bleaching mortality event on Lihou Reef, Australia (Ceccarelli et al., 2009). Identifying reefs with a high capacity for recovery is important in a time of large-scale coral reef degradation (Polidoro and Carpenter, 2013), where more than half of the world's reefs are severely degraded and one-third of the world's 845 species of reef-building corals are considered to be at elevated risk of extinction (Carpenter et al., 2008). Coral cover in the GBR has declined by 50% in the past 27 years (De'ath et al., 2012). In future, relatively unimpacted reefs such as those of the Coral Sea are likely to become rarer. The potential for limited resilience on isolated reefs increases the risk of local extinctions (Graham et al., 2006).

5.2. Seamounts

Seamounts are widespread in the deep Coral Sea, and form part of prominent seabed features including the Tasmantid seamount chain, Lord Howe Rise, Norfolk Ridge and Louisiade cluster (Figure 4.10). It is predicted that there are 500 individual seamounts in the Coral Sea (Yesson et al., 2011), based on an ecological definition that includes seamounts, knolls and hills (Heap and Harris, 2008). Some seamounts support isolated and rich benthic communities, elevated faunal biomass (Rowden et al., 2010a) and possibly unique biodiversity (Castelin et al., 2010), but these properties do not characterise all seamounts and are not quantitatively defined for seamounts in the

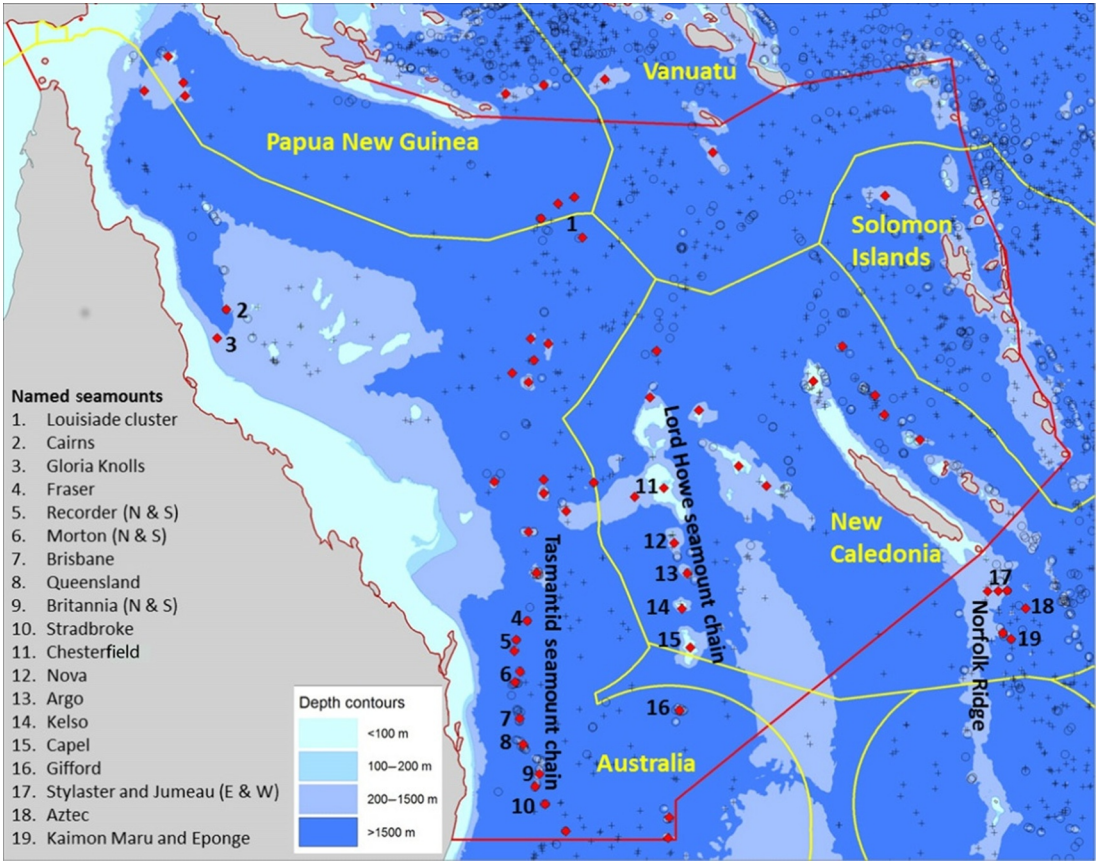

Figure 4.10 Locations of Coral Sea seamounts with the primary seamount chains labelled, and the named seamount clusters and seamounts identified; the prominent and sampled seamounts are highlighted (red diamonds) (CenSeam Project, http://censeam.niwa.co.nz/). The predicted distribution of large (>1000 m elevation) (○) and smaller (<1000 m elevation) (+) seamounts follows Yesson et al. (2011). Boundary lines identify the Coral Sea (red line) and EEZs (yellow lines) (VLIZ Maritime Boundaries Geodatabase, http://www.marineregions.org/).

Coral Sea. For instance, some Lord Howe Rise seamounts support diverse, high-density fauna (Williams et al., 2010), but abundance can be sparse on others (Anderson et al., 2011). Known between-seamount differences in the Coral Sea include limited overlap of macrofauna between the Chesterfield Ridge and the Norfolk Ridge (Richer de Forges, 1998) and considerable differences in macrofauna on New Caledonian seamounts with summits in a similar bathymetric zone (Rowden et al., 2010a). The Chesterfield Ridge seamounts have very low biomass compared to those on the Norfolk Ridge (Richer de Forges, 1998), whilst the Lord Howe Rise and Fairway and Lansdowne Ridges host *Halimeda* algal banks and a rich macrofauna (Richer de Forges et al., 2000). Endemism is scale-specific, and some reports of small-scale endemism could be artefacts of undersampling (O'Hara et al., 2011; Samadi et al., 2007).

Whilst the general environmental drivers of seamount benthic community structure include depth and proximity to the photic zone, geomorphology and substratum type, productivity, chemistry and hydrodynamics of the overlying water column (Clark et al., 2010), these factors have not been systematically studied on Coral Sea seamounts. Elsewhere, many seamounts support relatively high biomass of plankton and higher consumers compared to the surrounding ocean, particularly in oligotrophic regions (Clark et al., 2010), and may contribute to their use by migratory pelagic species as mating, feeding and nursery grounds (Shank, 2010). Coral Sea examples include the Cairns Seamount (Flynn and Paxton, 2012) and the Tasmantid seamount chain (Williams et al., 2012a). However, *in situ* production (via increased vertical nutrient fluxes and material retention) may be less important than interruption of deep scattering layers that permit advection and trapping of zooplankton and micronekton (Clark et al., 2010).

Connectivity between seamounts could be expected to be low, especially when separated by large expanses of open water. However, the similarity of the sponge community on the top of the Britannia Seamount (off Brisbane) with some Norfolk Ridge seamounts (south of New Caledonia) suggests connectivity between them. Recent population genetic studies, in the Coral Sea and elsewhere, have found higher than expected connectivity between seamounts and adjacent slopes (Baco and Cairns, 2012), but not for all taxa (e.g. molluscs, Castelin et al., 2010). This is, in part, because population structure is also significantly influenced by dispersal mechanisms and other life history strategies (Samadi et al., 2006). Genetic differentiation among depth strata of the same seamount suggests that depth may drive genetic structure in populations on individual seamounts (Miller et al., 2010).

5.3. Bathyal habitats

The most extensive research programmes targeting deep-sea species in the Coral Sea, the MUSORSTOM Tropical Deep-Sea Benthos Program and CIDARIS expeditions, described >2000 new species (Richer de Forges, 1998). At shallower depths (~1000 m), off-slope GBR debris flows (Gloria Knolls) were mapped and sampled in 2007/2008, revealing rich cold-water coral communities with similarities to those found at equivalent depths elsewhere in the western Pacific (Beaman and Webster, 2008). The New Caledonian bathyal environment, including the Loyalty Basin and its slopes, the Norfolk Ridge and the Lord Howe Rise, is one of the best known in the Pacific (Richer de Forges et al., 2005; Roux, 1994).

Deep-sea benthic communities in the Coral Sea, including microbial assemblages in deep-sea soft sediments (Alongi, 1992), are primarily structured along depth gradients (Richer de Forges, 1998) and with some classes of geomorphological structures (Anderson et al., 2011; Beaman and Harris, 2007). Generally, species richness declines with depth, especially below 800 m (Castelin et al., 2011). The density of organisms, however, does not necessarily follow the same pattern. In the deep Loyalty Basin, few species (primarily ophiuroids and asteroids) were found in high abundance, whilst abundance was lower but species richness higher on the Loyalty Rise lower slope (Richer de Forges, 1990). Slopes of the Loyalty Basin and the Norfolk Ridge revealed 'living fossils', including stalked crinoids, sponges and pterobranchs previously thought to have been extinct since the Jurassic (Roux, 1994).

Quantitative surveys of micro- and meiobenthos in sediment habitats in ~300–1600 m depths in the western Coral Sea identified conspicuous depth-related changes in community composition, together with relatively high levels of phytodetritus and low concentrations of organic carbon and nitrogen compared to sediments in other deep areas (Alongi, 1987). These patterns—including abundant protozoan populations at depth—suggest potentially rapid microbial activity and detrital utilisation in deep surface sediments on the floor of the western Coral Sea. Densities of protozoans, meiofauna, and macroinfauna, and bacterial densities and productivity, are related to (cool) temperatures and materials transported from shallow waters.

6. FISH COMMUNITIES AND FISHERIES

The Coral Sea hosts demersal and pelagic fish communities, both of which are targeted by fisheries. Demersal fish communities are stratified by depth, with a distinct fish fauna associated with coral reefs; demersal fisheries

tend to target deepwater fishes. The largest ecosystem in the Coral Sea is pelagic, and correspondingly pelagic fishes such as tunas and billfishes have been the focus of much attention in relation to fisheries research. We summarise information on fish communities, including a hierarchical cluster analysis on existing coral reef fish checklists, and present catch data from demersal and pelagic fisheries in the Coral Sea. Even though the greatest direct human impact on the Coral Sea comes from fisheries, the extraction level within the Coral Sea, compared with other areas of the western Pacific, is relatively small.

6.1. Demersal fish

The Coral Sea remains Australia's largest knowledge gap for demersal fishes due to the paucity of biological surveys, with the inference that this is also true for other biota (Last et al., 2005). The best information on the Coral Sea's demersal fishes comes from shallow reefs (Allen, 2008; Kulbicki, 2007). For depth-constrained demersal fishes (and other biota), large-scale biogeographic patterns often mirror those of terrestrial and freshwater species, having shared similar histories of rifting, rafting and dispersal. Deep ocean trenches and basins can act as barriers to dispersal, and a recent investigation of the biogeography of Australian fishes (Last et al., 2011) suggests the region is even more biogeographically complex than previously thought. Of the teleost specimens examined in detail from the western Coral Sea, many are new to science or endemic to the Coral Sea, and sister species indicate separation of the Queensland and Marion Plateaux (P. Last, pers. comm.).

6.1.1 Coral reef fishes

The Coral Sea is one of the world's richest regions for reef fishes. Checklists for the whole region (including the GBR and New Caledonian barrier reefs) include 2480 species, representing 62% of Pacific reef fishes and 38% of global reef fishes (Parravicini et al., 2013). However, reef fishes have been surveyed on few reefs, using disparate methods, complicating Coral Sea-wide assessments of patterns of biodiversity, endemism and taxonomic and trophic structure. To address these problems, we gathered available datasets and performed a hierarchical cluster analysis to compare checklists from individual reefs in the region (Appendix 2; see supplementary material in the web version of this chapter). Coral Sea reefs form a related group, characterised by high diversity and low endemism compared to reefs further south (northern New Zealand, New South Wales and the Kermadec reefs). A southern Coral Sea group, represented by Elizabeth and Middleton Reefs and related to the reef fish fauna of the Capricorn–Bunker reefs (GBR), Lord Howe Island and Norfolk Island, links the tropical Coral Sea fauna to cooler-water assemblages of southern reefs (Figure 4.11).

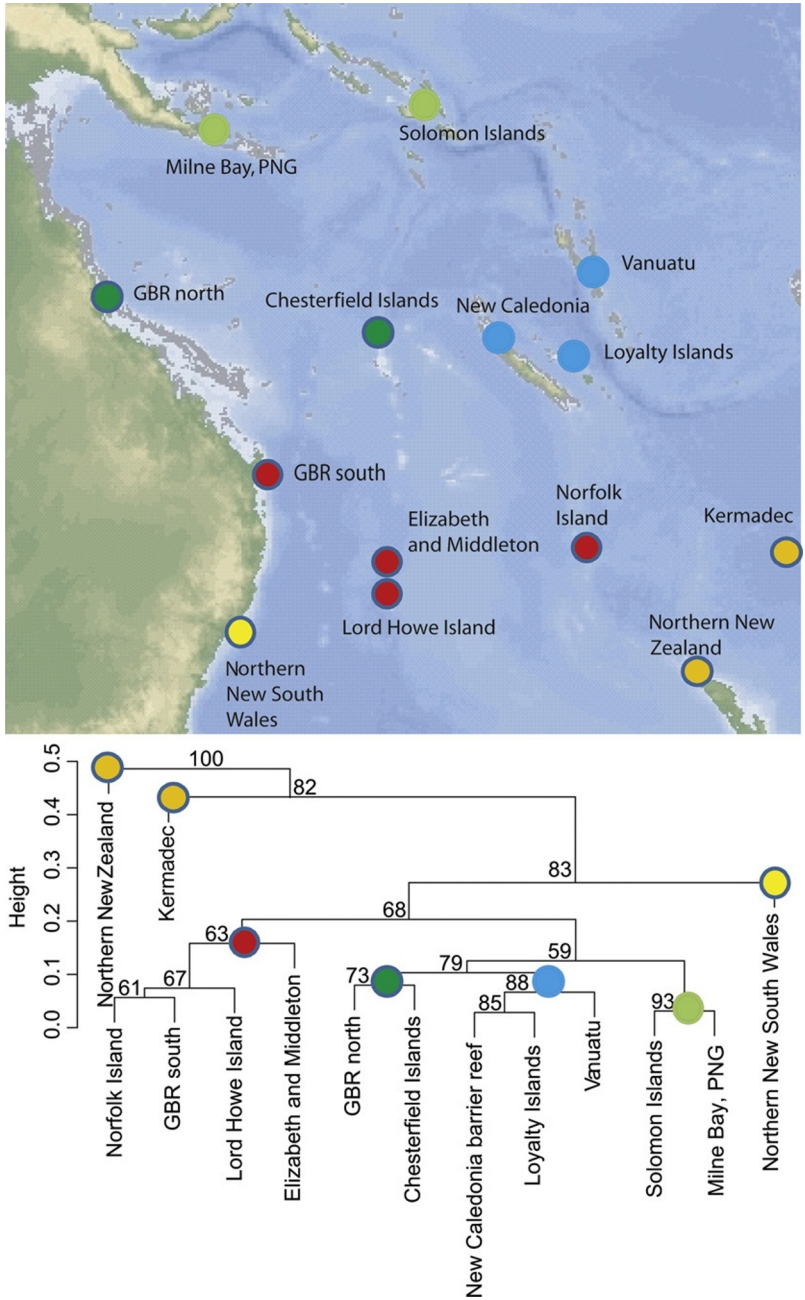

Figure 4.11 Taxonomic composition of shallow reef fishes across the Coral Sea. Numbers represent the cophenetic variation based on 1000 bootstraps. Methods and references used to compile the checklists for this analysis are provided in Appendix 2.

There are north (equatorial) to south (poleward) gradients in species richness, size and trophic role of reef fishes in the Coral Sea. Species richness declines with distance from the equator, with 200 species per 3000 m^2 on the Lihou and d'Entrecasteaux reefs and 43–60 species per 3000 m^2 on Elizabeth and Middleton Reefs (Appendix 2, Tables S4 and S5; see supplementary material in the web version of this chapter). Gradients in life history characteristics include an equatorward increase in the proportion of small (<15 cm) and planktivorous taxa and a poleward increase in larger species that are predominantly piscivores, macroalgal browsers and mobile invertebrate feeders (Appendix 2, Table S3; see supplementary material in the web version of this chapter). Recent data collected with Reef Life Survey methods (Edgar et al., 2010) on 13 reefs in the Australian Coral Sea, from the Herald Cays in the north to Elizabeth and Middleton Reefs in the south, also detected a species richness gradient—albeit not as dramatic—ranging from 529 species per 3000 m^2 in the Herald Cays to 287 species per 3000 m^2 on Middleton Reef.

Biomass estimates on New Caledonian reefs ranged from 80 g m^{-2} in the Chesterfield Islands to 463 g m^{-2} at Astrolabe Reef (excluding sharks). These values were higher than on the New Caledonian barrier reef (Appendix 2; Tables S4 and S5; see supplementary material in the web version of this chapter) and within the range reported for some of the most pristine coral reefs in the world (Graham and McClanahan, 2013). High biomass was linked to a high abundance of top predators (e.g. sharks, large groupers and carangids), large piscivores and invertebrate feeders (emperors, snappers, Napoleon wrasse *Cheilinus undulatus* and eagle rays) and herbivorous surgeonfishes, which could represent over half of the total biomass at Astrolabe and d'Entrecasteaux reefs. Diversity and abundance tended to decrease with increasing isolation and latitude and decreasing habitat size (Appendix 2, Figures S2 and S3; see supplementary material in the web version of this chapter). Species richness was dominated by invertebrate feeders (39%), followed by piscivores, herbivores and omnivores, whilst abundance was dominated by plankton feeders (46%), followed by herbivores and invertebrate feeders. The contribution of regional endemics to diversity and relative abundance increased from <1% on the northernmost reefs to >30% on the southern reefs (Lord Howe, Elizabeth and Middleton Reefs; see also Edgar et al., 2010).

6.1.2 Deepwater fishes

Deepwater fishes in the Coral Sea are known from individual expeditions targeting specific areas and often linked to fisheries; species identification is often problematic. The most extensive and best-documented exploratory fishing expeditions and scientific sampling have been conducted in New

Caledonian and Australian waters (e.g. Williams et al., 2006). HALIPRO 2 sampled deep ichthyofauna between 230 and 1860 m in the southeastern Coral Sea, and 40% of collected species were new to science (Grandperrin et al., 1997). Exploratory deepwater fishing in the Solomon Islands, Vanuatu and New Caledonia discovered >200 species of deepwater demersal fishes belonging to 93 genera (Dalzell and Preston, 1992), although many more were not identified. Last et al. (2005) found that of ~1500 fish species from Australian continental slopes, 21% did not have current names, and many were likely to be new to science. Given the paucity of sampling, we could expect similar levels of complexity and novelty among demersal fishes of the Coral Sea. Eteline snappers, which are targeted by small-scale fisheries in most South Pacific nations, are an important part of the deepwater fish fauna (Table 4.4).

6.2. Deepwater fisheries

6.2.1 Catch

Small-scale commercial fisheries became established in PNG, the Solomon Islands, Vanuatu and New Caledonia after the exploratory fishing expeditions in the 1970s and 1980s indicated potential for commercial development of deepwater resources (Dalzell and Preston, 1992). Reported landings from these fisheries have been inconsistent at best, precluding reliable estimates of total catch from any country. In Australia, a small number of commercial vessels have participated in deepwater fisheries in the Coral Sea since the late 1960s. Catches from these fisheries have varied considerably over time, but in 2010–2011, total catch was over 70 t in the Commonwealth Coral Sea Fishery (Woodhams et al., 2012) and around 7 t in the Queensland Deep Water Fin Fish Fishery (Holmes, 2012).

Artisanal deepwater fisheries in the Coral Sea predominantly use manually operated vertical drop lines with multiple hooks. Deepwater snappers (genera *Etelis* and *Pristipomoides*) are the primary species targeted by these fisheries, although a wide range of other species are harvested, including other snappers (in the genera *Paracaesio*, *Aphareus*, *Aprion* and *Lipocheilus*), groupers (*Hyporthodus*, *Epinephelus* and *Saloptia*), carangids (*Seriola* and *Caranx*), emperors (*Wattsia*), pomfrets (*Brama* and *Taractichthys*), snake mackerel *Gempylus serpens*, dogtooth tuna *Gymnosarda unicolor*, oilfish *Ruvettus pretiosus* and sharks (Dalzell and Preston, 1992). In Australia, deepwater fisheries in the Coral Sea use motorised vertical drop lines, trotlines (bottom set longlines) and traps to target the same suite of species, in addition to temperate deepwater species such as hapuku *Polyprion oxygeneios*, bar cod *Epinephelus ergastularius* and blue-eye trevalla *Hyperoglyphe antarctica* (Woodhams et al.,

Table 4.4 Species composition of demersal fish caught by drop-line and longline sampling over the outer barrier reef slope, off western New Caledonia, in water depths 65–350 m (Adrian Flynn, unpublished data)

Scientific name	English name	French name
Serranidae (groupers)		
Epinephelus amblycephalus	Blunt-headed rock cod	Loche rouge à 6 bandes claires
Epinephelus magniscuttis	Speckled grouper	Loche à grosses écailles
Hyporthodus septemfasciatus	Seven-lined rock cod	Loche bagnard
Epinephelus cyanopodus	Blue maori	Loche bleue
Epinephelus chlorostigma	Brown-spotted grouper	Loche pintade
Mycteroperca morrhua	Comet grouper	Loche morue
Lutjanidae (snappers)		
Etelis carbunculus	Ruby snapper	Vivaneau chien rouge
Etelis coruscans	Flame snapper	Vivaneau flamme
Pristipomoides filamentosus	Rosy jobfish	Vivaneau rose
Pristipomoides multidens	Goldband snapper	Vivaneau poulet
Pristipomoides flavipinnis	Goldeneye jobfish	Vivaneau jaune
Aphareus rutilans	Rusty jobfish	Lantanier rouge
Lutjanus malabaricus	Saddle-tailed perch	Perche écarlate
Lutjanus bohar	Red bass	Anglais
Lethrinidae (emperors)		
Lethrinus olivaceus	Long-nosed emperor	Bec de cane malabar
Lethrinus miniatus	Sweetlip emperor	Gueule rouge
Wattsia mossambica	Mozambique large-eye bream	Brême olive
Carangidae (trevallies)		
Seriola rivoliana	Almaco jack	Carangue amoureuse
Holocentridae (squirrelfishes)		
Sargocentron spiniferum	Sabre squirrelfish	Poisson-écureuil

Continued

Table 4.4 Species composition of demersal fish caught by drop-line and longline sampling over the outer barrier reef slope, off western New Caledonia, in water depths 65–350 m (Adrian Flynn, unpublished data)—cont'd

Scientific name	English name	French name
Sharks		
Heptranchias perlo	Sharpnose sevengill shark	Requin perlon
Centrophorus moluccensis	Endeavour dogfish	Saumonette
Hydrolagus sp.	Chimera	Chimère

2012). In the southwest Coral Sea, other important genera targeted by mid-water trawling include alfonsino *Beryx* spp., blue-eye trevalla and boarfish (family Pentacerotidae).

6.2.2 Impacts

Formal stock assessments for deepwater fisheries in the Coral Sea have been hampered by the lack of reliable fisheries data and poor understanding of the biology of most species. Exceptions include assessments of the trawl fishery in the southwest Coral Sea that indicate that alfonsino are not overfished (Woodhams et al., 2012) and the simple depletion models that used explor-atory fishing data from PNG, the Solomon Islands, Vanuatu and New Cale-donia to estimate maximum sustainable yields (MSY) for the deepwater fish complex in each country, based on the length of the 200 m isobath (Dalzell and Preston, 1992). These estimates of MSY are considered highly uncertain (Williams et al., 2012b), and recent research has revealed that life histories of deepwater fishes in the Coral Sea are characterised by extended longevity, slow growth rates, late maturity and low rates of natural mortality (Fry et al., 2006; Williams et al., 2013). For example, longevity has been estimated at 47 years for eightbar grouper *Hyporthodus octofasciatus*, 40 years for crimson jobfish *Pristipomoides filamentosus*, 35 years for ruby snapper *Etelis carbunculus*, 18 years for flame snapper *Etelis coruscans* and 19 years for saddle-back snapper *Paracaesio kusakarii* (Andrews et al., 2011, 2012; Fry et al., 2006; Wakefield et al., 2013; Williams et al., 2013). As such, many exploited deepwater species in the Coral Sea are assumed to have exceptionally low production potential and are likely to be vulnerable to overexploitation (Williams et al., 2012b).

6.3. Pelagic fish

Knowledge of large pelagic fishes in the Coral Sea has benefited from a sig-nificant amount of fisheries research, but virtually no fishery-independent

research exists. Many of these species use the Coral Sea during critical periods of their life cycles. Genetic data suggest that there is no partitioning of yellowfin *Thunnus albacares* and bigeye tuna *Thunnus obesus* stocks in the western and central Pacific Ocean (Grewe and Hampton, 1998; Ward et al., 1994), though tagging data indicates weak connectivity between equatorial regions and the western Coral Sea (Campbell, 2011b). Larvae of these species are found extensively across the subtropical ocean all year round, suggesting widespread and continuous spawning, although in the northwestern Coral Sea, these species aggregate and spawn over periods of the full moon during October–January (McPherson, 1991a). Albacore tuna *Thunnus alalunga* is considered a single stock across the South Pacific (Hoyle et al., 2012), although recent analyses suggest genetic heterogeneity (Montes et al., 2012). Striped marlin *Kajikia audax* and broadbill swordfish *Xiphias gladius* are believed to constitute separate stocks within the southwest Pacific (Alvarado-Bremer et al., 2005; McDowell and Graves, 2008), with seasonal spawning well into the southern Coral Sea (Young et al., 2003). Black and blue marlins *Makaira indica* and *Makaira mazara* are believed to comprise single stocks across the entire Pacific.

Black marlins congregate in the northwest Coral Sea to spawn from September to December and subsequently disperse to unknown regions. This is the only known spawning aggregation of black marlin in the world (Domeier and Speare, 2012). There is evidence of southward movement of juvenile black marlin in eastern Australia from game fish tagging data (Pepperell, 1990), representing strong connectivity between coastal resources (as juveniles feed and migrate on the GBR shelf) and the wider Coral Sea. Tagging studies off eastern Australia show that smaller fish can disperse large distances (>8000 km), but 'homing' behaviour has also been shown (Domeier and Speare, 2012). Detailed information on the sex structure of black marlin caught around the Coral Sea rim, particularly in areas influenced by the New Guinea Coastal Undercurrent, could greatly help resolve the possibility of sex-dependent migration patterns.

6.4. Pelagic fisheries

6.4.1 Catch

Pelagic fisheries in the Coral Sea form part of the world's largest tuna fishery in the Western and Central Pacific Ocean, which in 2011 caught in excess of 2.2 million tonnes or ~55% of the global tuna catch (Williams and Terawasi, 2012). However, for most species, the catch in the Coral Sea itself is small compared with catches further north (Figure 4.12). Tunas and billfishes

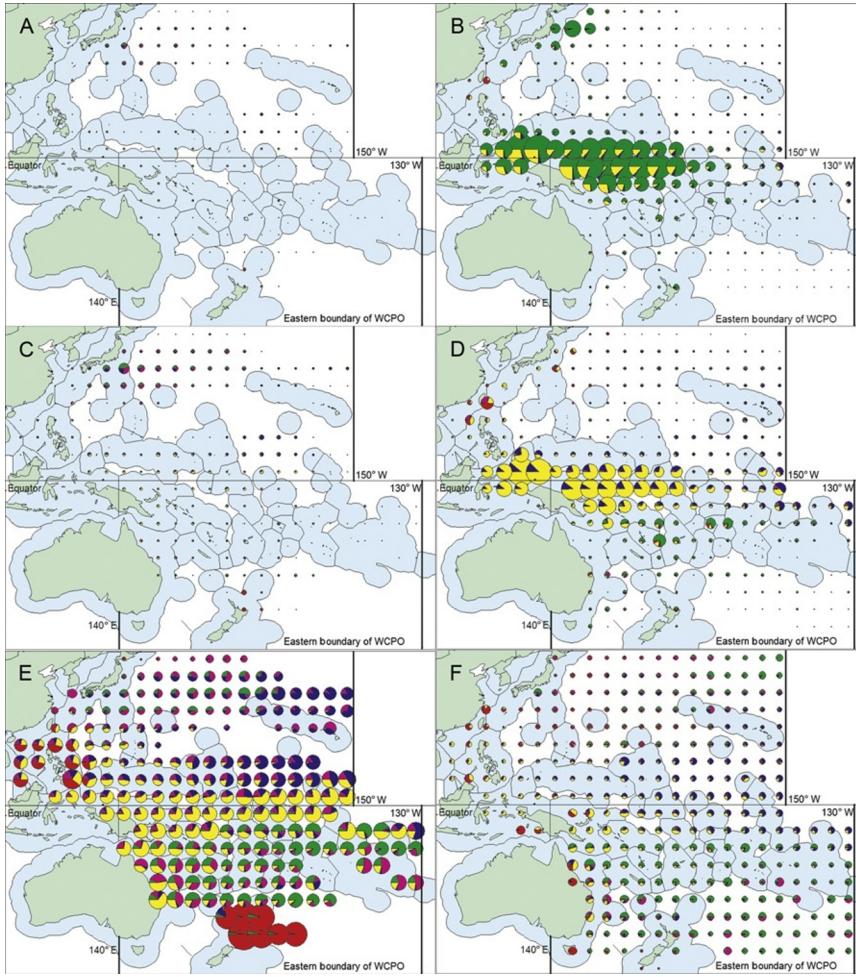

Figure 4.12 Catch data from the WCPO pelagic fisheries. (A) Total catch (longline, purse seine and pole line) by 5×5 degree cells for the decade 1950–1959, (B) and for the decade 2000–2009, (C) longline-only catch by 5×5 degree cells for the decade 1950–1959, (D) and for the decade 2000–2009, (E) longline nominal CPUE by 5×5 degree for the decade 1950–1959, (F) and for the decade 2000–2009. Note: Data used for these figures are public-domain data published by the Western Central Pacific Fisheries Commission. Pie charts show skipjack tuna (dark green), albacore tuna (light green), bigeye tuna (blue), yellowfin tuna (yellow), billfish (pink) and others (red).

account for by far the greatest proportion of the total regional fisheries catch, although xiphiids (swordfish), coryphaenids (mahi-mahi, or dolphinfish) and sharks are also targeted. In the Coral Sea, the primary fishery method is longlining, targeting adult albacore, yellowfin and bigeye tunas and swordfish. Catch and effort statistics for the Coral Sea region (defined as 10–30° S, 140–170° E) were collated from both aggregate annual and quarterly $5° \times 5°$ data covering the western and central Pacific Ocean (Figure 4.12). Since longline fishing began in the Coral Sea in 1952, yellowfin tuna (36%) and albacore tuna (30%), followed by skipjack tuna *Katsuwonus pelamis* (18%), have been the dominant species taken by all methods combined. Catch methods are dominated by longlining (78%), followed by purse seine (18%). Apart from pole and line, effort has increased substantially since the late 1990s. Annual catches also show concomitant increases over the past decade, with the mean annual catch of the eight main tuna and billfish species shown since 2000 (36,901 mt) being double that taken during the 1990s (18,524 mt; Figure 4.12).

Over the past decade, the annual catch of albacore, yellowfin, bigeye and skipjack tuna caught in the Coral Sea (~39,100 mt) was only a small proportion (~1.7%) of the total catch of these species in the western and central Pacific Ocean, amounting to 11.1%, 2.5%, 1.5% and 0.7%, respectively, for the individual species. For other species, however, the proportion of the catch taken from the single stock within the South Pacific Ocean is much higher: 19.2% for albacore, 23.6% for striped marlin and 16.4% for swordfish.

Recreational anglers and spearfishers have caught tunas and billfishes and other large pelagics off eastern Australia since the early 1900s (Anon, 2000), whilst artisanal fishers in Vanuatu and the Solomon Islands may have been targeting these species much earlier. The recreational fishery that targets pre-spawning aggregations of black marlin in the Cairns/Lizard Island region off northeastern Australia is internationally renowned, regularly yielding world record fish. Boutique charter operations in the Coral Sea for spearfishing of pelagic predators have also emerged in recent years. Due to a lack of logbook data from these fisheries, the level of take in the recreational sector is unknown.

6.4.2 Impacts

For yellowfin tuna, the most recent assessment (Langley et al., 2011) indicates that the stock in the Western and Central Pacific Ocean is only moderately depleted, whilst bigeye tuna (Davies et al., 2011) is more heavily depleted and currently at 40% of its unfished biomass. The assessment for skipjack, South Pacific albacore, southwest Pacific striped marlin and

broadbill swordfish is not spatially disaggregated, making it difficult to infer the fishery impacts on these species within the Coral Sea alone. Assessments for blue and black marlin have not yet been completed. However, a total abundance index based on Japanese longline catch and effort shows large declines for each of the three marlin species over the past 50 years in the Coral Sea (Figure 4.12).

Alongside the target species, ~100 non-target or bycatch species are caught by longline fishing in the Coral Sea, some of which are kept (especially mahi-mahi, wahoo and opah), whilst others are discarded and usually die at sea (e.g. lancet fish and oilfish). There are some interactions with seabirds and turtles in the New Caledonia EEZ, but more frequent interactions with sharks. Shark finning was a common practise until the beginning of the 2000s, but has decreased and was declared illegal since the New Caledonia EEZ was declared a shark sanctuary in 2013; shark finning was banned in Australian waters in 2000 (Clarke, 2011).

7. ICONIC AND PROTECTED SPECIES

The Coral Sea has a rich diversity of iconic and protected species (Appendix 3; see supplementary material in the web version of this chapter), and the southwestern edge of the Coral Sea is a global hotspot of predator biodiversity (Worm et al., 2003). A number of species listed under national or international agreements or legislative documents for special protection because of their rarity, migratory habits, restricted habitats or other characteristics exist in the Coral Sea, but their exact distribution and abundance are poorly known. Even seabirds and turtles, whose populations have been relatively well monitored, have not been documented except at a few individual Coral Sea cays (Figure 4.13).

7.1. Marine mammals

At least 27 species of dolphins and whales frequent the Coral Sea (Borsa, 2006; Garrigue, 2007; Garrigue and Poupon, 2013). There are indications that the Coral Sea hosts dwarf minke whales *Balaenoptera acutorostrata*, humpback whales *Megaptera novaeangliae* and sperm whales *Physeter macrocephalus* (Arnold et al., 2005; Borsa, 2006), but patterns of colonisation and population exchanges between the Coral Sea and other regions remain poorly understood (Oremus and Garrigue, 2013). The Coral Sea is an important migration corridor and breeding habitat for humpback whales (Constantine et al., 2012). Whaling logbook records from the nineteenth

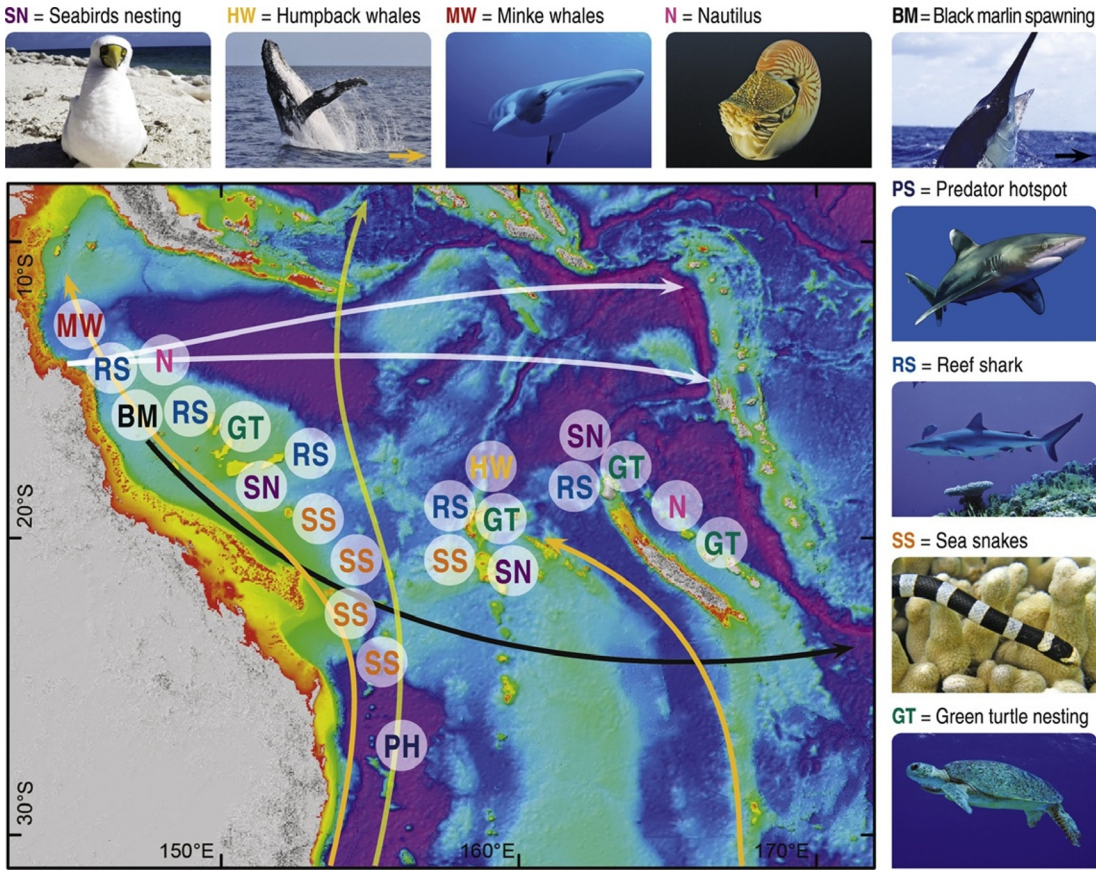

Figure 4.13 Iconic and protected species and their key habitats in the Coral Sea. Individual images: grey reef shark, masked booby, green turtle: Daniela Ceccarelli oceanic whitetip shark: ©Secretariat of the Pacific Community copyright; *Nautilus*, minke whale: John Rumney, Eye to Eye Marine Encounters; endemic sea krait *Laticauda saintgironsi*: Philippe Borsa humpback whale: Claire Garrigue; black marlin: © John Ashley/OceanwideImages.com.

century indicate that the Chesterfield archipelago was one of the main whaling grounds for humpback whales in the South Pacific (Townsend, 1935; Bourne et al., 2005). In the late 1950s and early 1960s, whaling reduced the ~10,000 population to an estimated 500 individuals, and recovery since the 1963 humpback whaling ban has been slow (Vang, 2002).

A long-term study has followed the dynamics of a population of dwarf minke whales on the northern GBR, which most probably extends into the western Coral Sea (Arnold et al., 2005). There are seasonal trends in the occurrence of sperm whales and, possibly, year-round occurrence of pygmy sperm whales *Kogia breviceps* (Borsa, 2006). Studies on depredation of longline catches by toothed whales suggest there may be long-term fluctuations in populations of false killer whales *Pseudorca crassidens* and short-finned pilot whales *Globicephala macrorhynchus* in the Coral Sea (McPherson et al., 2003). Despite limited information, it appears that toothed whales congregate around the black marlin spawning aggregation in the northwestern Coral Sea between October and December (McPherson et al., 2003).

7.2. Seabirds

The Coral Sea cays host at least 18 species of nesting seabirds (Borsa et al., 2010; Bourne et al., 2005; Robinet et al., 1997). The Australian cays host a significant proportion of Australia's breeding population of several species, including the red-footed booby *Sula sula*, lesser frigate bird *Fregata ariel*, great frigate bird *Fregata minor* and red-tailed tropicbird *Phaethon rubricauda*. The d'Entrecasteaux, Chesterfield–Bampton and Bellona cays host large nesting colonies of red-footed and brown boobies *Sula leucogaster*, lesser frigate birds and great frigate birds *Fregata minor*, wedge-tailed shearwater *Puffinus pacificus*, sooty tern *Onychoprion fuscata* and black *Anous minutus* and brown *Anous stolidus* noddies (Borsa et al., 2010; Bourne et al., 2005; Robinet et al., 1997). They also host a few dozen breeding pairs of the New Caledonian fairy tern (*Sternula nereis exsul*; Barré et al., 2012; Rancurel, 1976), which is a significant proportion for this rare species.

Seabird populations have remained mostly stable, except for dramatic declines in populations of frigate birds and black noddies on the Herald Cays (Wilcox et al., 2007) and an increase in brown boobies in the Chesterfield Islands (Borsa et al., 2010). Causes for the changes have been attributed to a complex set of changes in food sources, suitable nesting habitat, SST and other climatic conditions since the 1997/1998 El Niño event (Devney et al., 2009; Wilcox et al., 2007). Seabirds provide the key link between

terrestrial and marine habitats on oceanic cays, preying on fish in surface waters and nesting and roosting on cay vegetation, transporting seeds in their plumage, causing vegetation disturbance, but also contributing to soil development and fertilisation through their guano and carcasses (Batianoff et al., 2010). These links are even more important for unvegetated cays, where ephemeral fauna and microbial communities are sustained largely by seabird carrion (Heatwole, 1971).

7.3. Turtles

Six of the world's seven species of sea turtles are found in the Coral Sea: green *Chelonia mydas*, hawksbill *Eretmochelys imbricata*, loggerhead *Caretta caretta*, leatherback *Dermochelys coriacea*, flatback *Natator depressus* and olive ridley *Lepidochelys olivacea* turtles. The annual monitoring of nesting green turtles on the Coringa–Herald Cays between the early 1990s and 2005 found high regional fidelity, with 75% of tagged nesting females returning within a 4–6-year period (Harvey et al., 2005). Green turtles that nest in the Coral Sea form a distinct genetic group, targeted by fisheries in their foraging grounds in PNG and the Torres Strait (Moritz et al., 2002). Individuals from other populations cross the Coral Sea during their breeding migration, and loggerhead turtles travel from islands surrounding the Coral Sea to nest on the Queensland coastline and in New Caledonia (Limpus et al., 1992). Leatherback and olive ridley turtles travel through the Coral Sea to forage in Australian waters. Major ocean currents play an important role in the migration of hatchlings (Boyle et al., 2009).

7.4. Sea snakes

In the Coral Sea, Guinea (2002) reported 31 sea snake species in Australian waters, 21 in southern PNG and 14 in New Caledonia. Sea snakes play a significant role as predators of fishes on coral reefs (Brischoux et al., 2011; Ineich and Laboute, 2002). *Laticauda saintgironsi* and *Hydrophis laboutei* are Coral Sea endemics, with the former found only in New Caledonia and the latter found only in the Chesterfield lagoon (Ineich and Laboute, 2002), and the understanding of patterns of endemicity may evolve with further sampling and ongoing genetic analysis (Sanders et al., 2013). Available information suggests a decline in sea snake abundance on some Coral Sea reefs over the past 20 years, but causes are poorly understood, although some cases of commercial catches for skins are reported (Lukoschek et al., 2010).

Recent surveys indicate that the southwestern Coral Sea has unusually high sea snake abundance, with numbers averaging 1 animal per 500 m^2 on the Saumarez, Marion, Kenn, Frederick, Cato and Wreck reef systems, but with no snakes observed on more northern Coral Sea reefs or on the southern Elizabeth and Middleton Reefs (Appendix 4; see supplementary material in the web version of this chapter). Surveys using Reef Life Survey transect methodology (Edgar and Stuart-Smith, 2009) on the GBR indicated numbers over an order of magnitude lower (0.03 per 500 m^2).

7.5. Elasmobranchs

Estimates of species composition, distribution and abundance of elasmobranchs (sharks and rays) in the Coral Sea can be obtained from fisheries data (mainly longline and trawl catches), coral reef surveys and dedicated sampling by trawls or video-based surveys. Based on commercial fishing catch and bycatch records, the most abundant pelagic sharks in the Coral Sea are blue sharks *Prionace glauca* and shortfin mako sharks *Isurus oxyrhynchus*. Recently, trophic studies have contributed important new information on the role of sharks in pelagic ecosystems of the Coral Sea (Revill et al., 2009). While most pelagic predators have dietary overlap, the shortfin mako shark has the most specialised diet (with a high proportion of large teleost prey) and therefore a unique role in the pelagic system of the Coral Sea (Young et al., 2010).

Other sharks are more sporadically associated with the pelagic ecosystems of the Coral Sea, undertaking regular movements between coastal and oceanic habitats. Tiger sharks *Galeocerdo cuvier* travel between oceanic islands and coastal waters (Fitzpatrick et al., 2012), and juveniles have been sighted at depths of up to 360 m in the Coral Sea around aggregations of Eteline snappers (Lindsay et al., 2012). The great white shark *Carcharodon carcharias* is a winter visitor to the Coral Sea (Bonfil et al., 2010; Tirard et al., 2010), with peak abundance around New Caledonia coinciding with that of humpback and sperm whales (Tirard et al., 2010). Sightings of whale sharks *Rhincodon typus* have been reported offshore of the GBR, associated with lantern fish, tuna and black marlin aggregations in October and November (Colman, 1997).

Reef sharks in the Coral Sea include resident species and sporadic visitors (Smith et al., 2008). Coral reefs of the Queensland Plateau also host at least three species of shallow-water rays (Ceccarelli et al., 2009). Despite their largely sedentary nature and fidelity to one reef, reef sharks can undertake

long-range movements, with one grey reef shark *Carcharhinus amblyrhynchos* tracked as it travelled between Osprey Reef and the GBR, a distance of 134 km (Heupel et al., 2010). Because reef shark numbers increase with protection from fishing (Ayling and Choat, 2008), densities of reef sharks are often used as an indicator of the general health of reef populations (Sandin et al., 2008). Habitat structure and prey availability are most probably equally important for supporting healthy shark populations, with higher abundances of sharks on large and networked coral reefs (e.g. Lihou Reef, Ceccarelli et al., 2009) than on small, isolated reefs (e.g. Coringa–Herald, Ceccarelli et al., 2008). Deepwater sharks dwell on the plateaux, slopes and rises of the Coral Sea (Compagno and Stevens, 1993). A number of deepwater skates, rays and stingarees have been recorded from the deep slopes and plateaux, some of which are known only from there (e.g. Iglesias and Levy-Hartmann, 2012; Seret and Last, 2003). Last and White (2011) also note the relatively high number of microendemic sharks and rays despite the paucity of surveys. Some 57% of shark and ray species from slope waters off central Queensland appear to be endemic to this region.

7.6. Nautilus

Several species of chambered *Nautilus* are found around coral reefs of the Indo-Pacific and have been relatively well-studied on Osprey Reef, in the northwestern Coral Sea (Dunstan et al., 2011a,b). The Coral Sea population of *Nautilus pompilius*, a member of the cephalopod class between 1 and 5 million years old and capable of extremely deep dives (~400 m), is genetically distinct from the GBR population. This suggests that despite their ability to undertake deep dives, their horizontal movements may be more restricted (Sinclair et al., 2007). Furthermore, the species found in New Caledonian and Vanuatu waters, *Nautilus macromphalus*, is endemic to this eastern portion of the Coral Sea. The Loyalty Islands and Vanuatu stand out as places where *Nautilus* spp. can be found in relatively shallow waters at night (Dunstan et al., 2011b).

8. ECOSYSTEM LINKAGES AND HOTSPOTS IN THE CORAL SEA

Interactions between topographic complexity, oceanographic patterns and animal movements determine the broadscale ecological processes, trophic structure and the direction, strength and timescale of connectivity between different ecosystems in the Coral Sea. A useful classification of

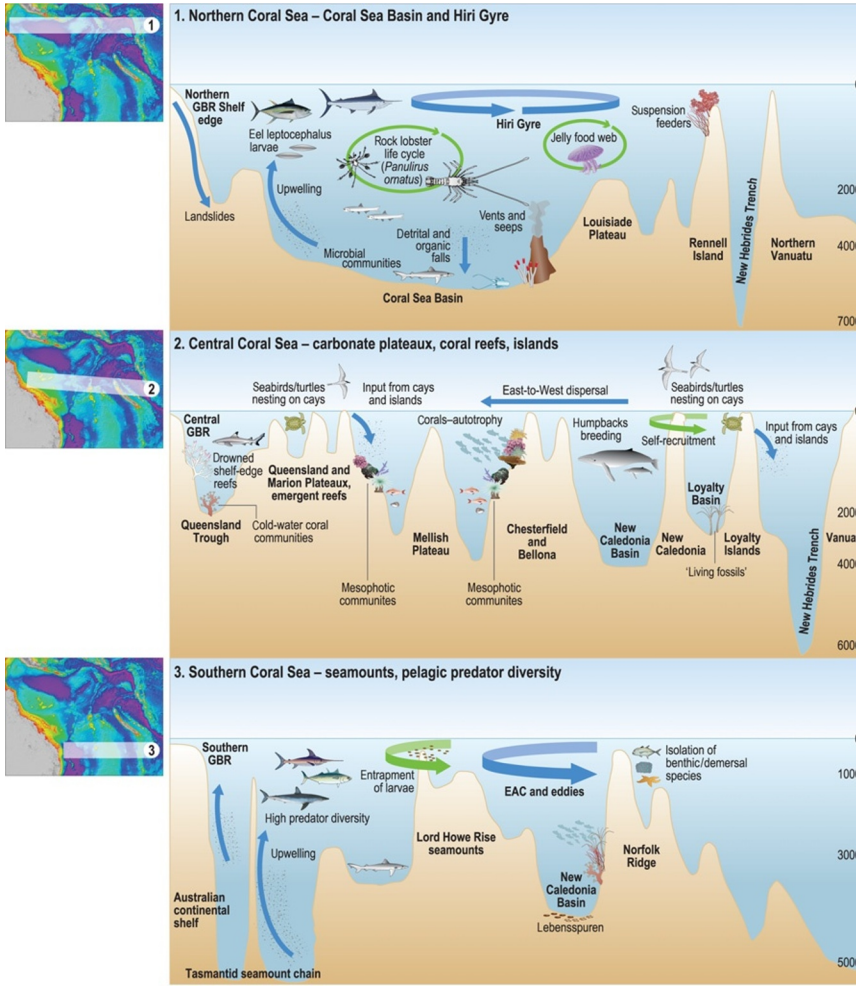

Figure 4.14 Schematic diagram of key features and defining characteristics of the northern, central and southern Coral Sea. Cross-section profiles were adapted from bathymetry data provided by Robin Beaman

the Coral Sea is based on the major structural features, which vary among the northern, central and southern sectors (Figure 4.14). The northern Coral Sea is predominantly an open-water habitat (>4000 m), with the Hiri Gyre having a strong influence on pelagic ecology. The central Coral Sea hosts the highest density of coral reefs and islands, creating a network of stepping stones between the Australian coast and GBR in the west and the islands of New Caledonia and Vanuatu in the east. The southern Coral Sea is

characterised by three prominent rises with abundant seamounts, separated by deep basins and trenches (>3500 m) and influenced by the proximity of the oceanographic boundary of the Tasman Front. The following sections highlight the ecological features and linkages typical of the three Coral Sea sectors.

8.1. Northern Coral Sea

The Hiri Gyre, which flows from the northern arm of the bifurcation of the SEC at the Australian continental margin, plays a major role in the northern Coral Sea's oceanography and in the life cycle of species such as the rock lobster (*Panulirus ornatus*; Figure 4.14). Rock lobster breeding areas in the eastern Gulf of Papua, on the shelf edge of the far northern GBR and along the east coast of Queensland, produce larvae that are entrained into the Hiri Gyre, where they develop, and settle in the Torres Strait and the northern GBR (Dennis et al., 2001). Also, a high density and diversity of eel leptocephalus larvae have been collected from the northwestern Coral Sea, with larvae of at least 40 species (Miller, 2009). This area may represent a spawning ground for eels that migrate from freshwater systems >1000 km away. Eel leptocephali and the larvae of tunas feed on pelagic tunicates and jellyfishes, which are an important part of the 'jelly food web' typical of this region (see Section 4.3). The question of whether the Hiri Gyre enhances connectivity through the area, or acts as a barrier to dispersal, remains unanswered, and it may play different roles for different species. The Coral Sea basin appears to be the Coral Sea's most prominent topographic barrier to larval dispersal between shallow-water habitats at its margins (Mora et al., 2012).

Another prominent element of the northern Coral Sea is the 'Cairns hot spot', featuring myctophid spawning grounds (Flynn and Paxton, 2012), possible spawning and mating grounds for yellowfin and bigeye tuna (McPherson, 1991b), and the world's only known black marlin spawning aggregation (Domeier and Speare, 2012). A lunar periodicity in aggregations of tuna and billfishes noted in Japanese catches is thought to be related to changes in current strengths, which may create a deep turbulence that generates an upwelling or doming effect. Church and Boland (1983) suggested that plankton swept southward by the surface EAC may be carried northward at a later stage by an undercurrent, influenced by the bathymetry of the area. Myctophid populations in the Queensland Trough may be carried southward during the night and returned northward by the deeper undercurrent during the day.

Further east, the Louisiade Plateau, Rennell and Bellona Islands, the New Hebrides Trench and the islands of northern Vanuatu are perhaps the least known of the Coral Sea's ecosystems. Fisheries catches of yellowfin and skipjack tuna tend to be higher in this region than in the rest of the Coral Sea (Figure 4.12), suggesting high productivity.

8.2. Central Coral Sea

The central region hosts potentially the highest biodiversity of the Coral Sea, given its abundance of coral reefs, and a high proportion of research on the Coral Sea's shallow-water habitats comes from this central region. Small islands and cays are a negligible proportion of the Coral Sea's surface area, but these are concentrated in the central Coral Sea, providing resting, feeding and nesting habitat for migratory species such as seabirds and turtles. This region is also likely to have the highest benthic productivity and is the region of major transport from east to west by the prevailing jets of the SEC (Figure 4.14).

Population and genetic connectivity of coral reefs in the Coral Sea is a key issue, since oceanic coral reefs are generally vulnerable to overexploitation and climate change impacts and may rely on self-seeding or sporadic external sources for recruitment. Isolation and high exposure to cyclones make Coral Sea reefs more vulnerable to natural catastrophic impacts than the continuous reef systems of New Caledonia or the GBR (Graham et al., 2006). Models of dispersal-driven connectivity suggest that links across the Coral Sea are weak, depend on a long larval duration, and are stronger during El Niño years (Treml et al., 2008), whilst other research highlights the stepping stone role of Coral Sea reefs in the dispersal of shallow-water taxa (e.g. van Herwerden et al., 2009). However, the role of oceanographic patterns is still unclear; gyres can form over individual plateaux (e.g. the Marion Plateau), potentially entraining species and their larvae and enhancing the probability of endemism (Middleton et al., 1994).

Most research on mesophotic reefs and deepwater corals (e.g. the Gloria Knolls) has been in this central section of the Coral Sea, generating hypotheses about the role of deeper-water communities as refugia for the recovery of shallow habitats that are at greater risk of disturbance from storms and coral bleaching (Bongaerts et al., 2011). Coral Sea reefs may also have had a role as refugia during periods of lower sea levels; they may act as refugia again as reefs closer to human populations become increasingly degraded.

8.3. Southern Coral Sea

A cross-section of the southern Coral Sea reveals a series of three rises and ridges, punctuated by seamounts and separated by deep basins (Fig. 14.3). Some of the seamounts (especially the northernmost ones) are crowned by emergent reefs and islands, but most are submerged and serve as isolated habitat patches for deep-sea biota. Communities are influenced by localised upwelling, eddies driven by the flow of the EAC, and the proximity of the Tasman Front. Benthic communities in this region have received little attention, and new species of both vertebrates and invertebrates have been collected in the past decade (Bruce, 2009; Imamura and Knapp, 2009; Last and Yearsley, 2002; Poutiers, 2006).

Links between the central and eastern parts of this region to New Zealand (e.g. through genetics of sessile and demersal taxa) and the Southern Ocean (e.g. through migrating whales) are strong. For fish, strong faunal relationships exist between the northern ends of the seamount chains and more northern regions of the Coral Sea and the Queensland continental shelf, whilst fishes in the southern half of the seamounts relate more closely to New Zealand (Zintzen et al., 2011). Invertebrate affinities are more complex and may occur at a finer scale (Williams et al., 2006); ophiuroids from waters >150 m are more closely related to New Zealand and New Caledonia deep-sea faunas than to Australian fauna. Migrating humpback whales traverse the area annually (Garrigue et al., 2011), as do freshwater eels migrating from spawning grounds in northern Coral Sea to New Zealand and southeastern Australia (McDowall et al., 1998).

9. BIOGEOGRAPHY AND CONNECTIVITY WITHIN AND BEYOND THE CORAL SEA

The Coral Sea is at the interface of a number of large biogeographic regions, including the Coral Triangle and the GBR, which contain the highest marine biodiversity in the world. For invertebrates and fishes, connectivity between habitats and regions depends on the interaction of ocean currents with larval behaviour, swimming ability, survival and successful settlement on suitable habitats (Cowen and Sponaugle, 2009). For larger, more mobile fauna, behaviour and seasonal migrations determine patterns of connectivity.

The complex geological history of the Coral Sea and the varied topography of today's seabed have contributed to its current biogeographic

complexity. The evolution of species in the Coral Sea may have been driven by the separation of plateaux, ridges and island chains from the Gondwanan continent, by the appearance and disappearance of islands and by large sea-level fluctuations (Pelletier, 2006). For instance, as recently as 20,000 years ago, during the Last Glacial Maximum, sea level was >120 m below that of today. Conversely, during warmer periods, sea levels rose by ~100 m in more recent times, drowning reefs and shoals and forcing shallow-water species to re-colonise elsewhere. Effects of plate tectonics and fluctuating sea levels resulted in greater numbers of, and more closely spaced, emergent reefs, island chains and shallow ridges, providing stepping stones for the potential dispersal of species. Many marine, terrestrial and freshwater species common to New Caledonia, Australia, PNG and surrounding islands are likely a result of these historic connections (Pelletier, 2006).

The level of functional connectivity between the main coral reef areas of the Coral Sea remains poorly characterised. However, several gene flow studies have used Coral Sea samples in a larger Indo-Pacific context (e.g. sea snake *Aipysurus laevis*; fishes *Scomberomorus commerson*, *Cephalopholis argus* and *Triaenodon obesus*; echinoderms *Linckia laevigata* and *Acanthaster planci*; and a variety of algae), but few have focused on the Coral Sea itself. Patterns and processes vary widely and may be subjected to frequent modifications with larger sampling efforts (e.g. Lester and Ruttenberg, 2005). The Chesterfields, for example, are isolated from the GBR to the west and New Caledonia to the east by basins 3500 m deep, restricting dispersal of many demersal species, which are often limited to narrow bathymetric 'bands'. However, high connectivity in coral reef fishes may be assisted by their lengthy larval duration (typically 28–35 days), although historical changes in connectivity with fluctuating sea levels make the relationship between larval duration and genetic relatedness inconsistent. Dispersal capability of demersal species may also be facilitated along ridges such as the Norfolk Ridge or across areas of shallow habitats. For instance, several western Australian echinoderm populations were more closely related to Pacific populations than those in the Indian Ocean (Benzie, 1998), suggesting possible pathways between the Coral Sea and the Arafura and Timor Seas through the Torres Strait (Mirams et al., 2011). Alternatively, the link between these populations could pre-date the collision of the Australian plate with Southeast Asia (~50 Mya) (Andreakis et al., 2012).

Dispersal pathways from eastern PNG southeast along the Solomon Islands, Vanuatu and New Caledonia island chains and from PNG southward to the GBR across the Torres Strait are likely for some species, given

the proximity of available habitats (Benzie, 1998). On the other hand, isolated reefs such as those throughout the central Coral Sea appear to be largely reliant on self-seeding (Ayre and Hughes, 2004), and species with limited larval dispersal capabilities have developed genetically distinct populations at short spatial scales (Planes et al., 2001).

Larval transport of shallow benthic invertebrates (e.g. sponges and clams) may have occurred westward from the Pacific, with reefs forming stepping stones across the Coral Sea (Benzie, 1998; Treml et al., 2008). Jets of the SEC may therefore provide both the connectivity pathways between eastern and western reefs and a dispersal barrier between north and south. Conversely, the EAC enhances connectivity between the central Coral Sea and temperate waters to the south, and the North Queensland Current provides a northern pathway from the Coral Sea into the Solomon Sea. At a finer scale, separation is indicated in the marine flora of the Chesterfield and Bellona Plateau, the Loyalty Islands and the New Caledonian coastal reefs and lagoons, with less than 25% of species in common (Claude Payri, unpublished data).

Fisheries tagging research or large-scale biodiversity sampling (Census of Marine Life, Lifou 2000, Santo 2006, Niugini 2012, etc.) can highlight critical locations and habitats across multinational boundaries. Pelagic apex predators exploit their environment in predictable ways, returning regularly to key feeding and breeding grounds (Block et al., 2011) and displaying some degree of regional fidelity (Evans et al., 2011). Great white sharks move from New Zealand waters to more equatorial latitudes of the southwestern Pacific (including the Coral Sea), presumably following the migration pathways of humpback whales (Tirard et al., 2010). Leatherback turtles travel from southeastern Australia to the Solomon Sea and then across the Pacific to the California Current Large Marine Ecosystem (Block et al., 2011). Tagged tunas and billfishes regularly travel from the Coral Sea to the equatorial, northern and eastern Pacific (Campbell, 2011a).

Movements of large animals link not just geographic areas but also different ecosystems (McCauley et al., 2012). In the Coral Sea, seasonal movements of tunas, marlin, swordfish and pelagic sharks form a key link between temperate regions (the Tasman Sea) and tropical areas (the Coral Sea; Hobday et al., 2011; Stevens et al., 2010). Much less is known about dispersal and connectivity in deep-sea habitats, and depth stratification appears more significant than geographic distance for some species, even across locations as widely separated as Australia, New Zealand and Chile (Miller et al., 2011). Such comparisons have yet to be carried out between deep-sea benthos of the Coral Sea and other locations connected by deeper water masses.

10. RESEARCH AND MANAGEMENT PRIORITIES

Despite at least seven decades of research in the Coral Sea, there remain large knowledge gaps that hinder the understanding of ecosystem processes (Table 4.1). Here, we highlight the most significant areas that could help prioritise future research and argue that there is a need for a more integrated management approach.

10.1. Species inventories

At the most basic level, species inventories are still needed for most habitats; even coral reef communities, which have perhaps been the best studied, still lack the geographic scope to aid the definition of patterns of biodiversity, endemism, community structure and species composition. Species-level inventories have an important role in establishing the foundations of ecosystem functioning (Vermeulen, 2013) and ultimately informing management decisions that focus on biodiversity conservation (Dunstan et al., 2012). Several taxa are well studied (e.g. coral reef fish and algae), but gaps remain. The discovery of new species in the last decade, even in shallow waters, suggests that visual census and sampling by collection are likely to be of great value, especially in areas that remain undersampled (e.g. the northeastern Coral Sea). Existing knowledge suggests a number of biogeographic provinces within the Coral Sea, but without the characterisation of species composition throughout the area, these are not yet defined. Similarly, fine-scale endemism cannot be resolved without more intensive sampling. It is also important that taxonomic descriptions keep pace with ecological research; integrative taxonomy (using morphological and molecular data) will help uncover cryptic species and address broader questions of phylogeography and evolutionary ecology.

In areas difficult to access due to remoteness or depth, the use of habitat proxies or surrogates has shown promising results for inferring biodiversity patterns. In deep-sea environments, physical seabed characteristics can be good predictors of taxonomic composition and the proportional cover of benthic taxa (Anderson et al., 2011; Dunstan et al., 2012). Trails, burrows and other traces of life (lebensspuren) are a useful indicator of assemblage structure in the Coral Sea (Dundas and Przeslawski, 2009). Biophysical surrogates and lebensspuren can both be sampled remotely, and the development of remote sampling devices for the collection of images or actual samples has advanced rapidly in recent years (e.g. Lindsay et al., 2012).

10.2. Movement, migration and connectivity

Ecological connectivity at all scales remains poorly known. Patterns of connectivity have crucial conservation and sustainability implications, especially given the position of the Coral Sea in relation to biodiversity hotspots in the Coral Triangle and on the GBR. Connectivity is vital to communities for larval replenishment and the exchange of genetic material to maintain resilience and diversity, especially after periods of stress or disturbance (Bernhardt and Leslie, 2013; Thrush et al., 2013). Molecular markers (Baco and Cairns, 2012), numerical simulation (Treml and Halpin, 2012) and trace elemental fingerprinting (Thorrold et al., 2007) have been the primary methods emerging during the past decade, but usually, these studies have focused on one or two species, rather than assemblage-level investigations (Lopez-Duarte et al., 2012). Understanding connectivity at the level of multispecies assemblages would give insight into the recovery potential of communities in a time of increasing disturbance (Thrush et al., 2013). Management decisions increasingly rely on establishing source and sink populations and connectivity pathways, and the ongoing development of genetic tools is improving the ability to locate these pathways.

There is little knowledge of migration routes and residency of threatened and endangered species, as most studies on the movement of large oceanic species have focused on fishes and sharks of commercial importance. It is increasingly understood that large, mobile marine animals link different regions and ecosystems through their movements (McCauley et al., 2012). Genetic analyses, satellite tags and acoustic arrays have provided insights into movement of individual animals and could be coupled with visual surveys and mapping techniques to identify multispecies pathways.

10.3. Temporal dynamics and ocean observation

We know relatively little about the natural variability of Coral Sea ecosystem structure and processes. Long-term studies are critical for understanding ecological responses to physical changes in the environment, detecting ecosystem processes over long (e.g. decadal) timeframes and providing data to support population models, multidisciplinary research and management decisions (Lindenmayer et al., 2012). Only fishes of commercial importance and species that make some use of terrestrial environments (seabirds and turtles) have been the subject of dedicated monitoring in the Coral Sea (Baker et al., 2005; Harvey et al., 2005).

In a time of rapidly changing environmental conditions, describing 'baseline' conditions against which to measure change is increasingly difficult. With relatively low anthropogenic impact, the Coral Sea represents a tropical sea close to its environmental baseline. Long-term datasets are increasingly available through remote sources (e.g. satellite imagery), but the links between remotely sensed parameters and biological responses are theoretical at best and unknown for most species. There needs to be a concerted effort in the Coral Sea to collect baseline biological data.

10.4. Ecosystem modelling for a whole-of-system understanding

Ecosystem models are increasingly used for strategic assessment of broad management strategies and for exploring marine ecosystem function and structure (Plagányi, 2007; Travers et al., 2007). 'Whole-of-system' models have been used to: (1) integrate extensive amounts of system information and highlight major gaps in knowledge; (2) increase understanding of system dynamics and identify major processes, drivers and responses; and (3) simulate alternative options for management (including monitoring schemes and the potential cumulative effects of anthropogenic impacts; Fulton et al., 2011). For example, ecosystem models such as Ecopath with Ecosim have been formulated to evaluate the role of squid and micronekton fish under various climate impact scenarios in the region (Griffiths et al., 2010).

A whole-of-system model for the Coral Sea currently in development (CSIRO, Australia) using the Atlantis framework (Fulton et al., 2011) faces major challenges associated with data availability. Once complete, this model should provide improved understanding of the ecosystem dynamics and major processes and allow evaluation of the consequences of different management approaches.

Qualitative models can be used as an initial step to describe the system using available expert knowledge and identify key inconsistencies and gaps, before the full implementation of any quantitative modelling exercise (Dambacher et al., 2009). A key output for informing management in this case would be an outline of key uncertainties and a 'value of information analysis' of what data and information are critical for management of the Coral Sea. Given the lack of understanding of system dynamics, any large-scale ecosystem modelling would be more of a 'proof of concept' and as an initiative would at best evaluate broad questions, which could,

for example, consider large-scale climate-related impacts or strategic questions such as the potential effects of MPAs on the system as a whole. The development of models that could evaluate the value of management actions is still some way off, given the uncertainties in data, system processes and ecosystem function, although initiatives are under way to use models of intermediate complexity (Plagányi et al., 2012).

10.5. Human use and impacts

Despite relatively low human impact in the Coral Sea, the area has a history of fishing, shipping and other low-impact human uses (e.g. tourism and research). Fisheries activities beyond the continental shelf span at least 70 years, and some have been well documented (e.g. longline tuna fisheries). However, even for these fisheries, unanswered questions remain regarding, amongst others, population connectivity and migration pathways between the Coral Sea and adjacent regions, the relationship between fish movement and climate and oceanography, biological parameters of bycatch species, and spawning and residency times. Artisanal and boutique charter fisheries that may range beyond the continental shelves, and recreational fisheries (especially in Australian waters), are poorly documented. For instance, the numbers of boutique game fishing and spearfishing charters to Coral Sea reefs from the Australian coastline have increased in the past decade, but there is no information on species composition or magnitude of the catch. Given the isolated nature of Coral Sea reefs, serial depletion of stocks of target species on individual reefs is a real possibility.

A major shipping lane crosses the Coral Sea between southeastern Australia and Southeast Asian ports, but the risks to the environment of commercial shipping have not been assessed. Further high-impact human uses, such as mining, have yet to occur in the Coral Sea, although there has been some petroleum exploration within the New Caledonia EEZ (Brodien et al., 2003). Plastic pollution is a pervasive problem throughout the world's oceans and has yet to be quantified for the Coral Sea. There is a need to understand how a changing climate and increased seafood demand, vessel traffic and marine debris may affect the Coral Sea.

10.6. International collaboration on research and management

EEZs of five nations lie in the Coral Sea, but the only joint research programmes have been French–Australian–New Zealand collaborations and cruises in the southern regions of the Coral Sea. International workshops

have considered aspects of the Coral Sea, but until a recent meeting (Brisbane, March 2013), there have been no specific workshops focused on the region as a whole. There is a desire from scientists and managers to better coordinate the management of the Coral Sea, particularly between Australia and New Caledonia in the context of the potential co-management of a future large marine protected area.

Investment in research and management should reflect the scale of the Coral Sea, including collaboration and capacity building, as necessary, for the bordering countries. Key transboundary issues include ecologically significant and migratory species, seamounts, coral reefs and human pressures on those environments (including fisheries); these will need to be managed at regional (or even global) scales to be effective. Useful focal points for collaboration on science and management include the sharing, collation and synthesis of existing datasets; the standardisation of data collection and storage methods; the development of a bioregional profile that includes all five EEZs; and the sharing of technical expertise and equipment. A series of shared, multidisciplinary and multinational voyages tackling some of the issues raised in this chapter would substantially improve our knowledge of the Coral Sea and provide the foundation for improved management. A regional conference on current research in the Coral Sea could help stimulate collaboration.

11. CONCLUSIONS

The Coral Sea is an important component of the southwestern Pacific, with particular significance because of its relatively unimpacted state. It connects the tropical centre of marine biodiversity with subtropical and temperate seas, and its oceanography influences Pacific-wide climate dynamics. It contains critical spawning and breeding habitats for wide-ranging pelagic species whose movements link it to Antarctic waters and to the eastern and northern Pacific. The Coral Sea's character changes latitudinally in response to oceanographic–topographic interactions. The reefs and islands have unique assemblages that show varying degrees of connectivity within the Coral Sea, links to the western Pacific, individual sectors of the GBR and the wider Indo-Pacific beyond.

This synthesis of current knowledge has allowed the identification of a number of key areas of global and regional significance, most of which require further investigation. The Coral Sea offers a rare opportunity to

explore a tropical sea as close to its 'baseline' condition as any marine area in the world. As the exploitation of living and nonliving marine resources expands, this opportunity may be lost. Collaboration across EEZ boundaries has already led to the streamlining of research interests and the foundation for complementary management. This chapter provides the platform from which key knowledge gaps can be addressed across the entire Coral Sea, enhancing the ability to manage and assess the impacts of future human activities.

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