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State of the Reef Report

Environmental Status of the Great Barrier Reef:

Macroalgae (Seaweeds)

Report to the Great Barrier Reef Marine Park Authority

by

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Environmental Status: Macroalgae (Seaweeds)

Condition

Overview and Introduction

Macroalgae is a collective term used for seaweeds and other benthic (attached to the bottom) marine algae that are generally visible to the naked eye. Larger macroalgae are also referred to as seaweeds, although they are not really "weeds". In this report, macroalgae are treated as marine plants because they are photosynthetic (convert sunlight into food) and have similar ecological roles to other plants. However, macroalgae differ from other marine plants such as seagrasses and mangroves in that macroalgae lack roots, leafy shoots, flowers, and vascular tissues. They are distinguished from microalgae (e.g. diatoms, phytoplankton, and the zooxanthellae that live in coral tissue), which require a microscope to be observed.

Macroalgae take a wide range of forms, ranging from simple crusts, foliose (leafy), and filamentous (threadlike) forms with simple branching structures, to more complex forms with highly specialised structures for light capture, reproduction, support, flotation, and attachment to the seafloor. The size of coral reef macroalgae ranges from a few millimetres to plants up to 3-4 m high (e.g. *Sargassum*, Fig. 1). With few exceptions, macroalgae (seaweeds) grow attached to hard surfaces, such as dead coral or rock; most species can not grow in mud and sand because, in contrast to seagrasses, they lack roots to anchor them to the sediment. Compared to higher (vascular) plants, macroalgae have quite complex life cycles, and a wide variety of modes of reproduction; most algae reproduce by releasing sexually or asexually produced gametes and/or spores (propagules) and by vegetative spread and/or fragmentation (breaking off of plant pieces to produce new individuals).

Fig. 1. Seaweeds are marine plants that play important roles on both healthy and degraded reefs. This photo shows the brown seaweed *Sargassum* growing amongst corals on the inshore Great Barrier Reef.

Macroalgae play important roles in the ecology of coral reefs. They are the major food source for a wide variety of herbivores and are the basis of the reef food-web, they are major reef formers, and they create habitat for invertebrates and vertebrates of ecological and economic importance. They also play critical roles in reef degradation, when abundant corals are often replaced by abundant macroalgae. This may result from over-fishing of herbivorous fish, or from pollution by excess nutrients and sediments. In this sense, macroalgae are distinctly different from other groups, such as corals, fishes or seagrasses, where usually "more is better". Increased macroalgae on a coral reef is often undesirable, indicating reef degradation, although this depends on the type of algae.

Diversity of Great Barrier Reef Macroalgae

The macroalgae of the Great Barrier Reef (the Reef) are a very diverse and complex group of species and forms. They occupy a variety of habitats, including shallow and deep coral reefs, inter-reefal areas, sandy bottoms, seagrass beds, mangrove roots, and rocky intertidal zones. Some algae are even endolithic, living inside the skeletons of corals, and other reef substrata.

Taxonomic diversity

Macroalgae include members of four different phyla (Figs. 2-6), with very different evolutionary histories. This systematic classification is mostly based on the composition of pigments involved in photosynthesis:

- Rhodophyta (from the Greek "rhodo" meaning "red rose" and "phyton" meaning "plant"): Red algae
- Ochrophyta (Class Phaeophceae, from the Greek "phaios" meaning "brown" or "dark"; previously classified as Phaeophyta and Heterokontophyta): Brown algae
- Chlorophyta (from the Greek "chloro" meaning "green"): Green algae
- Cyanophyta (from the Greek "cyanos" meaning "dark blue"): Blue-green algae or cyanobacteria.

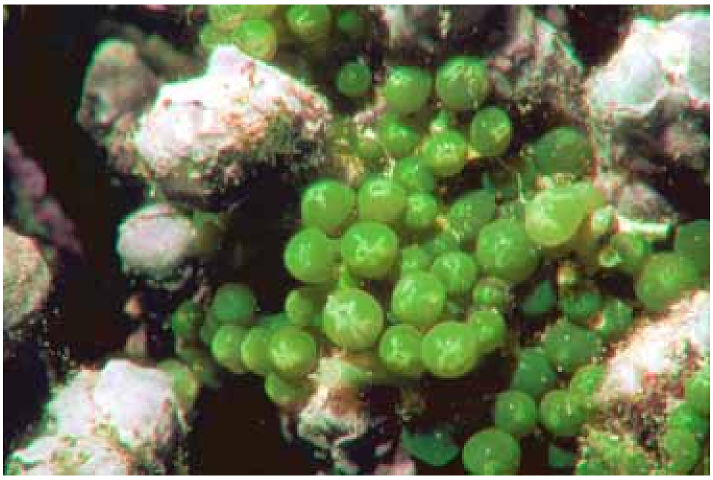


Fig. 2. The green macroalga *Caulerpa racemosa* is common in shallow zones of reefs of the Great Barrier Reef, but may occur down to 45m.

Fig. 3 & 4. Brown macroalgae are diverse and abundant on inshore reefs of the Great Barrier Reef. *Sargassum* (Fig. 3) and *Lobophora variegata* (Fig. 4) are amongst the most common brown seaweeds in inshore reefs.

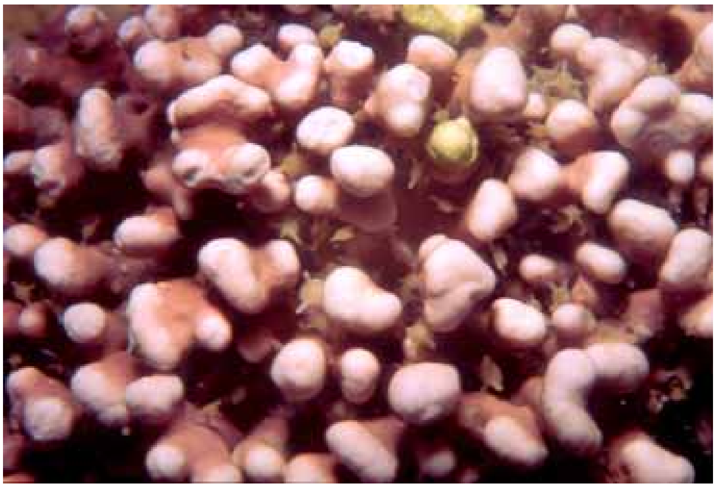


Fig. 5. Red algae include various forms of crustose calcareous algae CCA which are abundant on offshore reefs of the Great Barrier Reef.

Fig. 6. Blue-green algae, such as the tangles of thread-like filaments shown here, have been poorly studied on the Great Barrier Reef, but play a critical role in nitrogen fixation on the reef.

There are approximately 600-700 species of benthic algae on the Great Barrier Reef. The most complete database of the taxonomy and diversity of Australian marine macroalgae (the Australian Marine Algal Name Index) lists 629 species [20]. This is a significant number, since it accounts for nearly 32 per cent of the total species recorded for the continent (Table 1).

However, it is important to note that this estimate is very preliminary, being based on limited collections, and it is likely that the number is significantly higher, and will increase with future field surveys and floristic studies of the Reef. The macroalgal flora of the Reef, indeed of the entire northern Australian coast, are very poorly known [26, 27, 43, 63, 64, 97]. There is no adequate field guide for the identification of the macroalgae of the Great Barrier Reef, and available material only includes particular taxonomic groups [e.g. red [23] brown algae [107] or green algae [75]] or functional groups [e.g. turfs [111]], or are limited to specific localities [21, 24]. The paucity of information on the diversity of macroalgae in the Reef contrasts with that for temperate Australia, which has been well studied, and for which comprehensive illustrated identification guides are available [147, 152].

Table 1. Estimated diversity of species of marine macroalgae of the Great Barrier Reef, compared to the entire Australian coast and worldwide.

Macroalgae	**Species numbers (marine only)**		
	World-wide	**Australia** [(e)]	**Great Barrier Reef** [(e)]
Red algae	3900[(a)]-9500 [(b)]	1253	323
Brown algae	1500 [(c)]-2151[(6)]	373	111
Green algae	>800 [(c)] – 1597 [(f)]	350	195
Total	6200-13248 [(d,f)]	1976	432[(f)] - 629[(e)]

[a] ref 149; [b] ref 145; [c] ref 110; [d] ref 130; [e] ref 20; [f] ref 64; Algae Base: <www.algaebase.org/>.

Of the four Phyla, the Rhodophyta is the most diverse on the Reef, with 323 species known so far, in 131 genera, of which the most speciose include *Laurencia* (27 species), *Polysiphonia* (19) and *Ceramium* (16). There are 111 species of brown algae in thirty-two genera recorded from the Reef, of which more than 50per cent belong to only two genera, *Sargassum* (47 species) and *Dictyota* (11). The green algae of the Reef include 195 species in 51 genera, of which *Caulerpa* (36), *Halimeda* (23), and *Cladophora* (19) contain the most species [20]. The true diversity of Great Barrier Reef macroalgae is likely much higher as these figures are only estimates, based on limited collections and taxonomic work.

Functional group diversity

Instead of systematic and taxonomic classification, macroalgae may also be classified into different "functional form" groups, based on ecological characteristics and growth form (Table 2). This approach considers key plant attributes and ecological

characteristics, such as the form of the plant, size, toughness, photosynthetic ability and growth, and resistance to grazing. Functional groups help us to understand the distribution of algal communities and responses to environmental factors, since algae with similar ecological characteristics have similar responses to environmental pressures, whereas taxonomically related algae often have quite different ecological properties and responses. This functional approach is also particularly useful because algae are often very difficult to identify to species level in the field, and so the approach has been widely used to characterize algal communities in ecological studies on coral reefs. The scheme is summarised in Table 2.

Table 2. Categories and functional groups of benthic algae present in the Great Barrier Reef [83, 84, 135].

ALGAL CATEGORIES		**FUNCTIONAL GROUPS**		**EXAMPLES OF COMMON GENERA IN THE GREAT BARRIER REEF**
Algal turfs (< 10 mm height)		Microalgae		*Lyngbya, Oscillatoria*
		Filamentous		*Cladophora, Polysiphonia*
"Upright " macroalgae (> 10 mm height)	Fleshy	Foliose	Membranous	*Ulva, Anadyomene*
			Globose	*Ventricaria, Dictyosphaeria*
			Corticated	*Dictyota, Lobophora*
		Corticated		*Laurencia, Acanthophora*
		Leathery		*Sargassum, Turbinaria*
	Calcareous	Calcareous articulated		*Halimeda, Amphiroa*
Crustose algae		Crustose- Fleshy		*Ralfsia, Lobophora (one form)*
		Calcareous		*Porolithon, Hydrolithon*

- Algal turfs: assemblages or associations of many species of minute algae, mainly filamentous, with fast growth and high productivity, and high colonization rates. Turfs have low biomass[LM1]) per unit area, but dominate a surprisingly large proportion of reef area, even on healthy reefs. Analogous to grasslands in terrestrial environments, turfs often persist because constant grazing by herbivores prevents their overgrowth by larger, fleshy seaweeds (Fig. 7).
- Fleshy macroalgae or seaweeds: large algal forms, more rigid and anatomically more complex than algal turfs, which are abundant in zones of low herbivory, such as intertidal reef flats. Seaweeds often produce chemical compounds that deter grazing by fishes (Figs. 3-4).
- Crustose algae: hard plants that grow as crusts, adhering closely to the substrate (reef surface), with an appearance more like a painted layer than a typical plant; generally slow growth rates. Like corals, some crustose algae produce calcium carbonate (limestone) and may have important roles in cementing the reef framework together (Fig. 5).

The term "epilithic algal community" or EAC is often used to refer collectively to the algal assemblage that grows on the reef surface; usually this refers to an assemblage dominated by filamentous algal turfs [78].

Ecological roles

Macroalgae play several critical, but very different roles on the coral reefs of the Great Barrier Reef, including major contributions to primary production, construction and cementation of reef framework, bioerosion, facilitation of coral settlement, and creation of habitats for other reef species. They may also contribute to coral reef degradation. In the next paragraphs we discuss some of these ecological roles.

Contribution to primary production

During photosynthesis, plants convert energy from sunlight into organic matter (carbohydrate food), using inorganic carbon dioxide and water. Primary production is the overall amount of this organic matter produced in the ecosystem, and forms the basis of food-webs. On coral reefs, a large proportion of the primary production comes from benthic algae, particularly algal turfs (Fig. 7; Box 1). Planktonic microalgae and algal symbionts of scleractinian corals (zooxanthellae) also contribute to reef productivity, but to a lesser degree [1]. Most of this organic matter (carbohydrate) enters the reef food chain by several paths. Many algae are consumed by herbivorous fishes, crabs, sea urchins and zooplankton, but algae also "leak" organic carbon into the water, where it is consumed by bacteria, in turn consumed by a variety of filter feeders [10]. Significant amounts of organic matter are exported to adjacent ecosystems, such as seagrass meadows, mangroves or the sea floor, by currents and tides. Rates of transfer of energy from reefs to other ecosystems have been poorly investigated for the Great Barrier Reef [142].

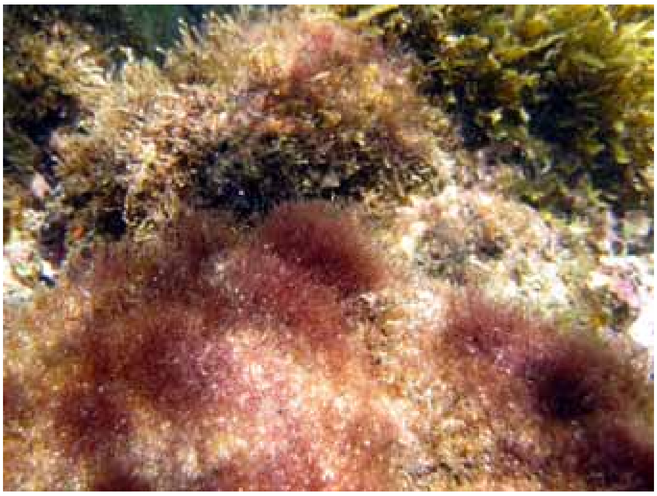


Fig. 7. Macroalgae play important roles in the ecology of coral reefs. Algal turfs, such as these filamentous red algae are a major food source for a variety of herbivores (turf height is approximately 1 cm).

Box 1: Primary production by algae on the Reef:

There is little information on rates of primary production on the Reef, although the available information suggests that it varies considerably in time, space and with the functional group of algae (Table 4). On reef flats in the central GBR, estimated production by algal turfs ranged between about 150 g C m^{-2} yr^{-1} on an inshore reef to 500 g C m^{-2} yr^{-1} on offshore reefs [72]. Macroalgal production decreases with depth [probably due to reduced light and water movement [118]] and varies with season, being highest in summer and lowest in winter, but no apparent latitudinal gradient has been observed. Preliminary work indicates that production by fleshy macroalgae and crustose algae are also important in the Reef [[16, 123]; Table 3].

Table 3. Estimated net primary production of benthic algae on coral reefs of the Great Barrier Reef. Data are standardised to area.

Macroalgae	Primary production (g C m-2 day-1)	Primary production (g C m-2 yr-1)	Source
Algal turfs	0.3 – 1.37	109 – 500	72, 118
Fleshy macroalgae (*Sargassum*)	0.4 – 3.0	146 – 1095	123
Crustose coralline algae	0.2 – 1.3	73 – 475	16

Nitrogen fixation

Organic nitrogen is an important nutrient in any ecosystem. Its an essential component of proteins, DNA and other compounds required by all biological systems. Although inorganic nitrogen is the most common element in the atmosphere, organic nitrogen is often a limiting nutrient in ecosystems. Nitrogen fixation is the process by which atmospheric (inorganic) nitrogen is converted (fixed) into organically available nitrogen, usually by blue-green algae (Fig. 8). Much of the organic nitrogen in coral reefs is fixed by filamentous blue-green algae, which are common components of algal turf communities. These blue-green algae have rapid growth rates, but are intensely grazed, so that the fixed nitrogen is rapidly distributed throughout the reef ecosystem [10, 56]. Rates of nitrogen fixation on the Reef appear high, particularly on substrates exposed to fish grazing [10, 77, 143, 144].

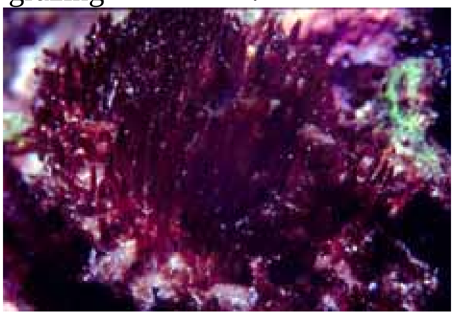


Fig. 8. Some blue-green algae, such as those shown here, fix atmospheric nitrogen, which is then used by other reef organisms.

Construction

Many macroalgae make important contributions to the construction of the reef framework by depositing calcium carbonate ($CaCO_3$ or limestone). Crustose calcareous algae (CCA, especially the Order Corallinales: e.g. *Porolithon*) are considered important in building and cementing the carbonate framework of coral reefs. CCA bind adjacent substrata and provide a calcified tissue barrier against erosion (Fig. 9)[81]. This process is particularly important on many reef crests of the Great Barrier Reef, where crustose coralline algae are dominant [22]. Estimates of calcification rates of CCA at Lizard Island indicated significant annual deposition rates [1 to 10.3 kg $CaCO_3$ m^2 yr^1; [15]]. Non-coralline CCA (e.g. *Peyssonnelia*) are also important in deep areas (between 80 and 120 m) at the edge of the continental platform in the southern Reef, where they form large algal frameworks several meters high [28].

Fig. 9. Crustose calcareous red algae have important roles in coral reef construction and cementation.

Upright calcareous algae, predominantly the green algae *Halimeda* (Fig. 10), but also including *Udotea* (green alga), *Amphiroa* and *Galaxaura* (both red algae) contribute to the production of marine sediments that fill in the spaces within the reef structure. The eroded calcium carbonate skeletons of *Halimeda* are major contributors to the white sand of beaches and reef lagoons [29, 86]. Estimated production is around 2.2 kg $CaCO_3$ m^2 yr^1 [40]. Calcium carbonate is deposited as aragonite, calcite and high magnesium calcite in the algal tissues. Calcification may be a defensive adaptation to inhibit grazing, resist wave shock, and provide mechanical support. Calcification may also enhance light harvesting ability.

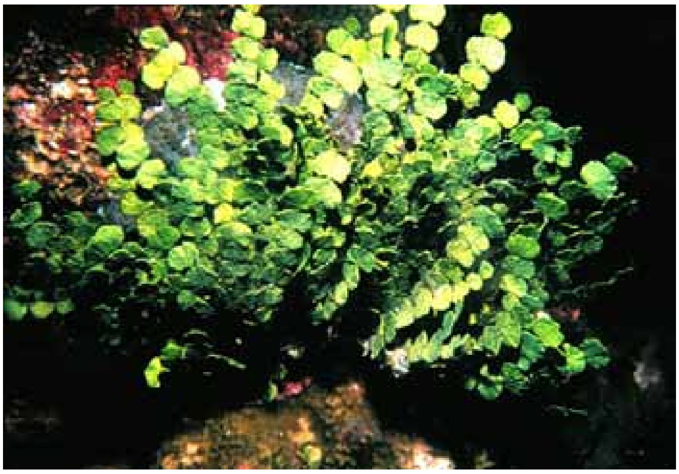


Fig. 10. The green seaweed *Halimeda* contributes to the production of marine sediments including beach sand in the Reef. Unique deep-water banks of *Halimeda* have been discovered in the Great Barrier Reef and northwestern Australia.

Facilitation of coral settlement

Crustose coralline algae are suggested to induce settlement of coral larvae on the Reef [59]. Recent experimental studies have demonstrated that the crustose coralline alga *Titanoderma prototypum* is one of the most preferred substrates for coral settlement. Larvae settlement rates on this alga were 15 times higher than on other CCA [54], but the significance of this facilitation at the level of the ecosystem remains unclear.

Bioerosion

Endolithic algae are algae that live within the skeletons of healthy and dead corals and in other calcareous substrates; these algae contribute to reef erosion and destruction. Such algae are generally filamentous and microscopic but may appear as a thin dark green band visible to the naked eye underneath the coral tissue. Examples of carbonate-boring algae include the green algae *Ostreobium* spp, the cyanobacteria *Mastigocoleus testarum*, *Plectonema terebrans*, and *Hyella* spp. and some red algae [48, 50, 51, 80]. By physical and chemical processes, endolithic algae penetrate and dissolve the calcium carbonate, weakening the calcareous reef framework and hastening erosion. There have been few studies of rates of bio-erosion by endolithic algae; preliminary estimates range between 20 – 30 g m^{-2} yr^{-1} at One Tree Island in the Great Barrier Reef [139]. *Ostreobium* is an unusual alga as its filaments, after penetrating the carbonate, deposit calcium carbonate within its cells, as well as on the surface of the alga. Endolithic algal communities are also important in that they provide an alternative source of energy to corals; this may be particularly important during coral bleaching [47]. This group of algae needs much more taxonomic and ecological research.

Roles in reef degradation

In addition to the "positive" roles, macroalgae also play critical roles in reef degradation, particularly in ecological "phase shifts" where abundant reef-building corals are replaced by abundant fleshy macroalgae [39, 62, 91, 94]. Reductions in herbivory due to overfishing, and increases in nutrient and sediment inputs causing eutrophication, may result in the replacement of abundant corals by abundant macroalgae, in turn leading to reef degradation (Fig. 11). Coral disturbances such as bleaching, crown-of-thorns starfish outbreaks, extreme low tides, coral diseases, cyclones, etc, kill corals, which are rapidly colonised by diverse algal communities [33, 35, 53, 65, 108]. On healthy reefs, dominance by algae may be gradually reversed, as corals recover and recruit into the disturbed area. But on reefs with reduced resilience, macroalgae may develop into thick mats, which overgrow coral remnants, exclude coral recruitment, favour pathogens that damage corals, and decrease the aesthetic value of reefs [8, 62, 95, 103, 133, 136]. The outcome may be a failure of reef recovery, and long-term reef degradation [94].

Fig. 11. Macroalgae play important roles in reef degradation, particularly during "phase shifts" when abundant corals are replaced by fleshy macroalgae.

It is important to note that while such disturbances, particularly due to climate change, may lead to an overall increase in the total amount of macroalgae [33], this does not mean that all macroalgae benefit: some types, groups or assemblages of algae may thrive [122], but others may decline markedly, in response to the direct impacts, or as a result of exclusion by more successful forms [37].

Spatial and temporal patterns of abundance and distribution

Biogeography

The marine benthic algal flora of Australia has been divided into 4 biogeographical provinces [64, 101, 147]:

1. Damperian Province, including Western Australia and northern Australia to Torres Strait.
2. Solanderian Province, comprising the mainland coast from Torres Straight south to southern Queensland, including the Great Barrier Reef.
3. Peronian Province, from the southern coast of Queensland along the New South Wales coast.
4. Flindersian Province, comprising the southern coast of Australia.

Based on the limited information available, the algal flora of the Great Barrier Reef (Solanderian province) appears less diverse than that of the southern Australian flora, the Flindersian province of Victoria, Tasmania, South Australia and south-western Australia. Endemism is low, since most Great Barrier Reef species are apparently widely distributed in the Indo-West Pacific biogeographical region. Many genera and species of coral reef algae occurring in the Great Barrier Reef are even thought to be present in the tropical Atlantic. However, a recent genetic analysis examined morphologically similar seaweeds of the genus *Halimeda*, thought to be the same species in the Indo-Pacific and Atlantic. The results showed that many were actually different species that had evolved independantly [73]. This may be the case for many other tropical seaweeds, so that a reliable assessment of the extent of endemism of the Reef algal flora really requires more such genetic analyses.

Tropical algal floras are widely considered to be less diverse than those of cold and temperate regions [64]. However, this difference may in part be because research effort in the tropics has been much less intense, there has historically been a lack of suitably trained phycologists (experts in algae), and a lack of research funding for tropical algal floras [43, 97].

Spatial distribution:

Algal communities on the Reef are highly variable, with marked differences in species composition[GDP2] and abundance from north to south, from inshore to offshore areas across the continental shelf, and between zones and habitats within reefs. In addition to this spatial variability, many reef macroalgae are highly seasonal. Notwithstanding this variability, data from ecological studies of benthic communities of GBR coral reefs show that macroalgae of some form (including turfs, fleshy macroalgae and crustose algae) are widespread and abundant on most reefs, covering between 30 – 80 per cent of the reef substrate [71, 72, 98].

Although macroalgae are critically important to reef ecology (as discussed above), there is a serious lack of information on the structure and composition of algal communities and on species distributions. There are no published estimates of the extent of macroalgal cover in the Great Barrier Reef World Heritage Area

(GBRWHA), even at the level of larger functional groups. Few descriptive accounts dealing with the algal communities of the Reef are available [93, reviewed by 96, also 116, 117, 123], and there is limited information on the processes which determine the patterns of algal distributions. The best available dataset, which addresses latitudinal (north-south), cross-shelf (inshore-offshore) and within reef variability, comes from a series of surveys between 1995 and 2001 [93, 96, 98]. Although limited in taxonomic resolution to genus, these provide a valuable baseline for algal distributions, summarised in the following section.

Cross-shelf distributions

Offshore reefs

Cross shelf differences in seaweed composition are marked. Offshore reefs (Fig. 12) usually have low abundance of fleshy macroalgae and high cover of crustose calcareous algae, relative to inshore reefs (Fig. 13). Some fleshy macroalgae do occur on offshore reefs, but most are red algae and large brown algae such as *Sargassum* are virtually absent. Species of green fleshy macroalgae, such as *Caulerpa*, *Chlorodesmis*, *Halimeda*, and the reds *Laurencia*, *Spyridia*, *Galaxaura* and *Liagora* are often present but in low abundance [93, 116].

Fig. 12. Offshore reefs usually have low abundance of fleshy macroalgae but high cover of algal turfs and crustose calcareous algae. Although the corals are most noticeable, much of the area between the corals in this scene is occupied by turf and crustose algae, and the calcareous green alga, *Halimeda*.

Algal turfs are widespread and abundant, and are the dominant functional group in several reef zones [see “Within reef distribution” section below; [72]]. Their cross-shelf distribution is influenced by fish grazing and water quality. Territorial damselfishes exert a strong influence on the species composition of algal turfs, by defending patches of turfs from grazers and maintaining communities that are distinct from the surrounding undefended substratum [12, 13]. The composition of algal turfs across the continental shelf varies significantly, with offshore algal turfs often dominated by the red alga *Ceramium punctatum* and blue-green algae of the family Nostococaceae [33, 128].

Crustose calcareous algae are abundant and diverse on offshore reefs, where they may play significant roles in reef construction [45, 98, 114]. Abundant taxa on offshore reefs include *Neogoniolithon*, *Lithophyllum* and *Porolithon* species [134]. Surveys of CCA along and across the Reef suggest that grazing and sediment deposition have large impacts on the distributions of CCA [45].

Inshore reefs

Inshore reefs usually have abundant and conspicuous stands of large, fleshy macroalgae (Fig. 13). In particular the tall fleshy brown macroalga *Sargassum*, together with other seaweeds from the Order Fucales (*Hormophysa*, *Turbinaria* and *Cystoseira*) form dense and highly productive beds of up 2-4 m height [87, 98, 109, 123, 140]. These beds provide habitat and food for numerous invertebrates, many of commercial interest [88] and are likely to be important as fish nurseries. Other fleshy brown macroalgae, including *Dictyota*, *Lobophora variegata*, *Colpomenia*, *Chnoospora* and *Padina*, and the red alga *Asparagopsis*, may also be abundant on shallow inshore reefs [33, 98, 117]. The leafy brown alga, *Lobophora variegata* can be particularly abundant in deep zones of inshore reefs, especially between branches of corals [66] and has recently overgrown extensive areas of bleached corals in the southern Reef (Diaz-Pulido & McCook pers obs, Aug. 2006). Crustose calcareous algae are common in the understorey of *Sargassum* beds.

The high abundance of *Sargassum* on inshore reefs has been shown to be due to the lower intensity of grazing by herbivorous fish in these areas, rather than the direct enhancement of algal growth by higher nutrients in coastal waters [89]. It had previously been suggested that the abundance of fleshy macroalgae on inshore reefs is unnaturally high and is a sign of eutrophication and reef degradation, due to increased sediment and nutrient inputs from the land (or loss of large herbivores). However, in the absence of good historical data, it is still uncertain to what extent current abundances are natural or result from human activities. While local increases in algal abundance have been reported on some reefs, there is no strong evidence whether or not macroalgal cover is generally increasing on fringing inshore reefs.

The turf algae of inshore reefs are dominated by different species to those on offshore reefs. Common species include the green algae *Acetabularia calyclus* and *Cladophora fascicularis*, the filamentous brown algae *Sphacelaria* spp. and the *Falkenbergia* stage of the red alga *Asparagopsis taxiformis*.

Fig. 13. In contrast to offshore reefs, inshore reefs often have seasonally abundant fleshy seaweeds.

Within reef distribution

Within a reef, the composition and abundance of benthic macroalgal vegetation varies with depth (related to light quality and quantity), wave exposure and grazing by herbivores [90]. These factors result in zones or bands of different algae. Algal zonation is usually quite distinct on rocky intertidal coasts but is often more diffuse on subtidal reefs, where algal communities tend to vary gradually and continuously along environmental gradients such as depth or wave exposure. There are relatively few studies describing the zonation of macroalgae within reefs of the Great Barrier Reef, at the level of species [10, 24, 25, 102, 111] or functional groups [72]. A number of reef zones can be recognised in a cross section of an offshore reef from shallow to deep areas (Table 4):

- Intertidal: Diverse, but often sparse, fleshy macroalgal communities; reduced grazing by large animals; intense solar radiation.
- Reef lagoon: Limited algal growth due to sandy bottom; occasional cyanobacterial mats and rhizophytic algae[GDP3].
- Reef flat (or back reef): Diverse fleshy macroalgal communities, reduced grazing (Fig. 14).
- Reef crest: Abundant CCA and algal turfs; intense grazing.
- Reef front and upper reef slope: The abundance and diversity of macroalgae decreases with increasing depth; algal communities dominated by turfs and CCA. Poorly developed fleshy macroalgal populations.
- Walls: Low algal cover and high coral cover; some upright calcareous macroalgae (e.g. *Halimeda*) can be locally abundant.
- Particular microhabitats, such as crevices and damselfish territories, play

important roles in locally increasing algal diversity.

Table 4. Generalised zonation of benthic algae in the Great Barrier Reef [7, 10, 24, Based on 102, 134 and personal observations].

Zones	Crustose corallines	Common fleshy macroalgae		
		Reds	Browns	Greens
Upper Reef Slope and Reef Front:	*Porolithon* *Neogoniolithon* *Hydrolithon*	*Predaea*	*Lobophora*	*Chlorodesmis*
Reef Crest:	*Porolithon* *Neogoniolithon* *Lithophyllum*	*Laurencia*		*Caulerpa*
Reef Flat		*Acanthophora,* *Laurencia* *Gelidiella* *Hypnea*	*Dictyota, Padina* *Sargassum* *Hydroclathrus* *Chnoospora*	*Caulerpa* *Chlorodesmis* *Halimeda* *Dictyosphaeria*
Lagoon[1]			*Hydroclathrus*	*Halimeda* *Caulerpa*
>10 m Deep and *Cryptic	**Lithothamnium* **Mesophyllum* *Neogoniolithon*	Turfs[2] *Melanamansia*	*Lobophora*	*Rhipilia* *Halimeda* *Caulerpa*

[1]Often dominated by blue-green algae.
[2]Usually dominated by red algae, but include other taxa.

Fig. 14. Inshore reef flats provide habitat for many species of seaweeds.

Inter-reef areas

Seaweeds are surprisingly abundant in the deepwater, inter-reefal areas of the northern part of the World Heritage Area. Large mounds formed by the calcareous green alga *Halimeda* are estimated to cover up to 2,000 km^2 in this region, and may be up to 20 m high [41, 86, 105]. These *Halimeda* meadows occur principally in the northern sections of the Reef, at depths between 20 to 40 m, but there are also some in the central and southern sections, where they have been found at depths down to 96 m [41]. The World Heritage Area apparently contains the most extensive actively calcifying *Halimeda* beds in the world, although little is known about the true extent of such meadows in other areas. The presence of extensive, deep (30-45 m) *Halimeda* meadows is apparently due to the injection of nutrient-rich water by “tidal jets”: when localized upwelling of deep ocean water on the edge of the continental shelf strikes the barrier of the Ribbon Reefs, the nutrient-rich water is pushed through gaps in the reef, causing “jets” of nutrient-rich water along the seafloor, apparently enhancing the growth and productivity of the *Halimeda* in these habitats [40, 146].

Surveys of deepwater seagrass beds by the Queensland Department of Primary Industry in the northern Reef, found a surprising amount and diversity of macroalgae associated with these habitats [17], although information on the species composition of the algae is limited. Many of these macroalgae are exceptions to the rule that most algae can not attach on sand or mud seafloors. Several taxa of green macroalgae, particularly *Halimeda*, *Caulerpa* and *Udotea*, have adapted to such environments by developing special anchoring features. Special filaments grow into the sediment and bind sand into a lump anchoring the plant into the sediment bottom (these “rhizoids” are not true roots, which both anchor the plant and absorb nutrients). Algae also grow in seagrass beds by attaching to the seagrass leaves, growing as “epiphytes”. Although there is little information on the epiphytic algae of inter-reefal habitats, they likely play important roles, as food for invertebrates and vertebrates.

Temporal variability

The abundance, growth and reproduction of many Reef macroalgae are highly variable in time, in particular showing strong seasonal changes in biomass (size) and reproduction, and strong changes in response to reef disturbances. A study of 84 species from a range of functional groups suggested that the Reef flora may be as strongly seasonal as that in temperate areas [109]. Large seaweeds like *Sargassum* are strongly seasonal, growing luxuriant canopies and reproducing during the summer but then dying back to a few stumpy branches during the winter [36, 87, 140]. A large proportion of the benthic algal species recorded for the Great Barrier Reef grow actively only during the Australian autumn (March to May), winter (June to August), and spring. Extensive blooms of fleshy brown macroalgae, such as *Chnoospora* and *Hydroclathrus*, have been observed on shallow reef flats only during winter (pers. obs.; Fig. 15). The causes of such large changes in algal abundance through time are not well understood [11], although it is likely that factors such as water temperature and day length are involved. Variability in grazing pressure has also been related to seasonal changes in algal turf abundance and productivity [71, 72].

Macroalgal communities often experience dramatic changes in response to disturbances which cause coral mortality, such as mass bleaching [33, 37], crown of thorns starfish outbreaks [65] or cyclones [32, 53]. Generally, the dead coral substrate will be colonised initially by diatoms, then filamentous algal turfs and fast-growing coralline algae, with potential subsequent overgrowth by larger, fleshy seaweeds [33]. Importantly, such disturbances may also contribute to declines in some other types, groups or assemblages of algae [37]. The long-term impacts of coral mortality events on algal condition, abundance and composition on the Reef are unknown.

Fig. 15. Seasonal blooms of fleshy macroalgae occur on many inshore reefs. The brown macroalga *Chnoospora* (pictured) blooms on the reef flat of Great Palm Island during winter.

Current condition of Reef macroalgae

Status and quantitative monitoring programs

There is very limited information available on the condition of any population of macroalgae on the Reef, on long-term trends in macroalgal diversity, or on possible impacts of pressures on population or community characteristics. The Long Term Monitoring Program of the Australian Institute of Marine Science (AIMS Reef Monitoring Status Report number 7) provides the only data set that allows identification of long-term trends in per cent cover of macroalgae on the Reef as part of general benthos surveys. However, the taxonomic resolution of the data set is highly limited, and quantification focuses on the cover of large functional groups, using algal categories such as “fleshy macroalgae”, “algal turfs” or “coralline algae” [97]. Thus, current knowledge only allows interpretation of the general patterns described in the previous section (Fig. 16).

On inshore reefs, the high abundance of fleshy macroalgae compared to the offshore reefs has been suggested as a symptom of recent widespread decline of those reefs, apparently in response to anthropogenic nutrient enrichment and increased sedimentation from the land. However, given the proximity of inshore reefs to natural terrestrial inputs, it is likely that these areas have always had a different algal flora from the offshore reefs [96] (see below). Extensive beds of the large brown seaweed

Sargassum are abundant on the inshore Reef but there is no reliable information indicating changes over time. Similarly, there is no information available on trends in abundance or composition of either crustose calcareous or turf algae. Recent algal surveys on inshore reefs of the Great Barrier Reef along water quality gradients in two regions with contrasting agricultural land use suggested that red and green macroalgal abundance increased with increasing nutrients on the northern reefs [46, McCook, Unpublished data]. These results suggest algal communities on inshore reefs are influenced by present-day water quality conditions but, without detailed long term data on the algal flora, we can not determine the extent to which the current abundance of algae is natural or the consequence of human impacts.

Despite the lack of information on current trends in algal condition, major changes in distribution, abundance and composition of algae are expected to occur as a result of mass coral bleaching and mortality due to climate change; these changes will be of major significance to reef resilience [37, 94]. There is a need to improve the taxonomic and quantitative detail of monitoring of reef algae, in order to understand the nature of these changes.

Rare / endangered species

There are no macroalgae from the Reef currently listed in the *Environment Protection and Biodiversity Conservation Act 1999 (www.environment.gov.au/epbc/index.html).* However, scientists currently consider it impossible to prepare a list of rare and threatened macroalgal species for the country (and for the Great Barrier Reef) due to the lack of relevant data on the diversity and systematics of Australian algae [43, 107]. Although much is still to be done before it is possible to identify any endangered or threatened macroalgal species, the cosmopolitan nature of most tropical marine algae suggests this specific risk is less significant than large-scale changes in distribution and composition of algal assemblages.

Fig. 16. *Chlorodesmis* or "Turtle weed", a green alga that is common and easily noticed on both inshore and offshore reefs.

Pressure

Pressures are factors, processes, activities or phenomena that modify the distribution, abundance and functioning of organisms. Three main types of pressures affect Reef macroalgae: environmental factors, resource supply and biological interactions. Environmental factors (or conditions) influence the physiology or ecology of seaweeds and include water temperature, salinity, water movement (waves and currents, known as hydrodynamics), and pollutants. Resources are things organisms

require to survive and grow. As photosynthetic organisms, macroalgae require light, carbon dioxide (CO_2) and mineral nutrients; they also require space, and most benthic algae specifically require hard substrate on which to attach and grow: unlike seagrasses and terrestrial plants, most macroalgae don't have roots to anchor them to soft substrates such as mud or sand. Other pressures include biological interactions such as herbivory and competition, both of critical importance to overall reef status.

Pressures may be direct or indirect. For example, herbivory causes a direct change in the abundance of algae. Indirect effects cause changes in macroalgae by modifying other resources or conditions. For example, a decrease in coral abundance, due to coral mortality by bleaching or crown-of-thorns starfish outbreaks, will modify the availability of space (a resource), leading to an increase of some types of algae and an overall change in the abundance and composition of the algal communities.

Assessing the pressures on the macroalgae of the Reef is more complex than for groups such as corals or fish. Because increases in macroalgae are often associated with reef degradation, factors which increase macroalgae (e.g. over-fishing or nutrient increases) may in fact cause degradation of the ecosystem: more algae is not necessarily better. Indeed, such increases in overall abundance of macroalgae will be detrimental not only to corals, but also to the natural composition of the algal flora: some, naturally-occurring types of macroalgae will be displaced by the unnatural growth. From a management perspective, such changes clearly exert pressure on the natural ecosystem. This section focuses on pressures relevant to management, and includes pressures which alter the natural balance in macroalgal abundance and composition, especially those leading to high abundance of macroalgae and algal blooms.

Natural pressures

Marine plants are affected by numerous natural pressures, including light, temperature, nutrient availability, water movement, biological interactions such as competition and herbivory, and disturbances such as cyclones. Of these, this section considers storms, herbivory and competition as most relevant to management of the Reef.

Storms and cyclones

Storms and cyclones are natural phenomena that occur along and across the entire Reef, particularly during the summer-autumn months. They are considered one of the most important disturbances for coral communities, and are therefore critical to reef ecology (see Coral Reef chapter). However, there are very few specific examples of either direct or indirect impacts of storms on macroalgal communities of the Reef.

The most important impact of cyclones and storms on macroalgal communities is an indirect effect: storm damage to corals from storms will result in major increases in area of algal turfs and other macroalgae [14, 32, 53]. Algal colonization of dead and stressed corals is the near-universal outcome of coral mortality (Diaz- Pulido and McCook 2002, 2004). Cyclones also cause re-suspension of sediments, releasing

nutrients into the water column, potentially increasing growth of turf algae which is passed rapidly to the next trophic level (i.e. herbivores [119]).

Direct impacts of storms and cyclones can include effects of waves, strong surge, currents or abrasion by sand and coral rock, and may cause severe damage to fleshy macroalgal communities, often detaching fragments or entire plants. When tropical cyclone Fran passed over Heron Reef in March 1992, it caused immediate and substantial changes in macroalgal cover on the reef flat. Species of *Sargassum* decreased in cover in the year following the cyclone, and had not fully recovered to their pre-cyclone abundance 42 months after the storm. The green alga *Caulerpa cupressoides* was almost completely removed by the cyclone. Differences in brown algae such as *Lobophora variegata, Colpomenia* spp. *Padina* spp. and *Chnoospora implexa* and in green algae before and nine months after the cyclone were smaller and not statistically significant [116, 117]. Impacts of cyclones on algal turfs and CCA have not been evaluated so far. However, when violent tropical cyclones pass over a reef, there are changes in the physical environment, such as breakage of hard substrate and movements of sand and coral rubble, that certainly will affect these algal groups. Surveys immediately after Cyclone Larry, in 2006, found that most fleshy algae had been dislodged from reefs, but that pre-existing turf and CCA were little affected. However, there was an immediate bloom of benthic diatoms on newly exposed substrate and broken corals [32].

Recovery of macroalgal communities after cyclone disturbance largely depends on the species and functional forms. Immediate impacts on fleshy macroalgae may be devastating, but most will recover substantially within one year; large seaweeds, such as *Sargassum*, may require longer (3-4 years[4, 116, 117]).

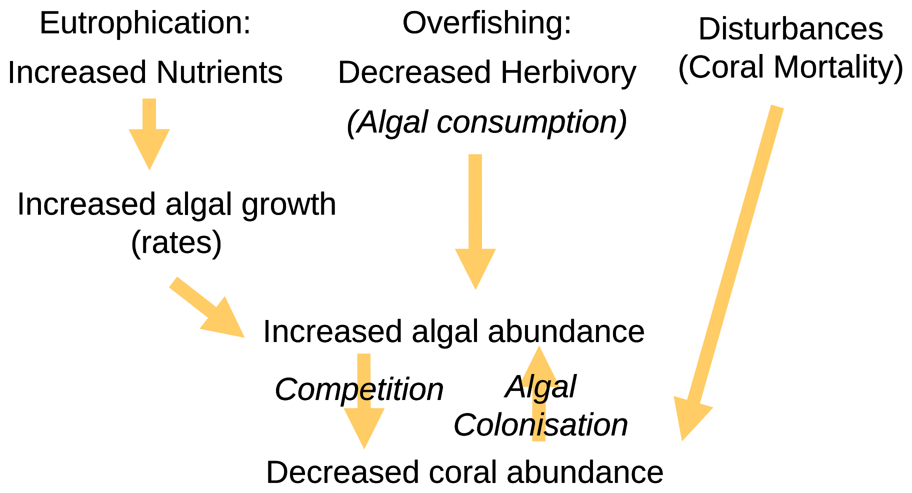
Herbivory

Grazing by herbivores, especially herbivorous fish, is one of the most important and widespread ecological processes directly affecting macroalgal productivity [72, 119], distribution [34, 62, 67, 89, 90], and abundance and composition [57, 128] on the Reef [91, see review in 96]. In most circumstances, herbivore grazing only removes part of the algal tissue, which allows for rapid future regeneration of the plant. The effects of grazing on an alga depend on the functional group (turfs, CCA, etc) and characteristics of the alga (toughness, chemical defences, etc) and the herbivores involved (crustaceans, molluscs, echinoderms, fish or megafauna such as dugongs; Fig. 17). For example, fleshy macroalgae are generally more susceptible to fish grazing than crustose calcareous algae, although many fleshy macroalgae have chemical compounds that deter feeding by fish but not by invertebrates such as sea slugs. Algal turfs are usually intensively grazed, particularly on offshore reefs, although they may compensate by increased growth rates [72]. Although herbivory has received considerable attention from scientists on the Reef, there are still many unanswered questions, particularly regarding the relative impacts of different groups of herbivores on the different functional groups of algae.

Fig. 17. Grazing by herbivorous fish, such as these parrotfish, is one of the most important ecological processes affecting the distribution and abundance of macroalgal communities on the Great Barrier Reef. Herbivores prevent macroalgae from overgrowing corals.

Studies on the Reef have suggested that herbivory has a stronger direct impact on the distributions and abundance of fleshy macroalgae than does nutrient supply. Transplant experiments have shown that fish grazers reduced the survival of *Sargassum* on offshore reefs and on inshore reef slopes, while differences in water quality had no detectable effect on survival [89, 90]. This is because grazing is more intense on offshore than on inshore reefs, and more intense on reef crests than reef flats, restricting the occurrence of high biomass[LM4]) seaweeds to inshore reef flats. Simultaneous herbivore and nutrient manipulations on inshore and offshore reefs have shown that grazers have a stronger impact than nutrients in controlling the abundance of both early stages and adult seaweeds (see Box 2) [34, 57, 67].

Box 2: Control of algal and coral abundance on coral reefs: “Phase shifts”



Adapted from McCook, 1999

Most space on a coral reef is occupied by either corals or macroalgae, whether algal turfs, crustose algae or larger fleshy seaweeds. Corals and macroalgae compete for space; if the abundance of macroalgae increases, the algae may outcompete and replace corals, resulting in a reef dominated by macroalgae, instead of corals: a degraded reef. Scientists call the shift from coral to algal dominance a “phase shift”. On healthy reefs, abundant herbivorous fish act like lawnmowers, eating the algae as fast as they can grow, and preventing overgrowth.

If the growth of macroalgae is limited by nutrients, then increasing nutrient supply may increase growth *rates* of the algae. However, increased growth rates will only lead to increased amounts of macroalgae if the extra growth accumulates: if herbivores are abundant, the extra growth will be consumed before it can accumulate (just as fertilizing a lawn will not make the grass grow long if the lawn is mown every few days).

However, when herbivores are over-fished, or are naturally less abundant (apparently the case on the inshore Reef), they may be unable to consume the extra algal growth. In these circumstances, increased nutrients may result in marked increases in the amount (or biomass[LM5]) of macroalgae on the reef, potentially giving the algae a competitive advantage.

Herbivores and nutrients tend to regulate *the biomass of algae within an area of reef*. However, the greatest changes *in area of reef covered by algae* are often due to disturbances which kill or stress corals, resulting in their rapid colonisation by algal turfs. Although this process also results in more algae and less coral, there is an important difference in the causes: in this case the increase in algae is the consequence, not the cause, of the decrease in corals. Such changes are becoming more frequent as the result of mass-bleaching of corals due to climate change.

Competition

Competition for space (or light), between hard corals and macroalgae is fundamental to the overall status of coral reefs, because the relative amounts of corals and algae determine the condition of the reef (Box 2; Fig. 18). Degradation of reefs during "phase shifts" amounts to an imbalance in coral-algal competition [61, 62, 91, 95, 136]. Under healthy reef conditions, corals are often competitively superior to algae, but when corals are stressed, disturbed (e.g. by bleaching) or killed, algae rapidly overgrow the corals: that is, algae are released from competitive pressure by corals and grow freely [33, 35, 98]. Similarly, fleshy algae such as *Sargassum* or the leafy brown alga *Lobophora variegata* (Fig. 18), may become competitively superior to corals when grazing pressure is reduced (e.g. by overfishing). In these circumstances, fleshy macroalgae grow unchecked by herbivores and can potentially overgrow and kill coral tissue [62, 66, 67].

Fig. 18. Competition between corals and macroalgae is widespread in reefs of the Great Barrier Reef. The fleshy macroalga *Lobophora variegata* can overgrow the coral *Porites cylindrica* on inshore reefs, particularly when herbivory is low. The alga was removed from the coral branch on the right to show the dead coral skeleton underneath.

Experimental evidence from the Great Barrier Reef shows that there is considerable variability in the outcomes of coral-algal competition, variability that largely depends on the properties of the macroalgae. For example, mixed filamentous turfs apparently have relatively minor effects on healthy corals, as do the larger filamentous "Turtle Weed" *Chlorodesmis fastigiata*, common on Indo-Pacific reefs, and the corticated red alga *Hypnea pannos*a, frequently observed living within colonies of the branching coral *Porites cylindric*a [68, 69, 92]. In contrast, the turfing filamentous red algae *Corallophila huysmansii* and *Anotrichium tenue* are able to overgrow and kill live coral tissue, apparently due to chemical toxins produced by the algae (an effects known as allelopathy; Jompa & McCook 2003a, b). Much of this variability can be explained in terms of functional form groups: the (physical, biological, or chemical)

properties that determine competitive outcomes are often those used to distinguish functional groups [95].

Human pressures

Water quality

One of the major current human impact on macroalgal communities arises from changes in water quality, as a result of land use and agricultural practices adjacent to the Reef. Direct human impacts include inputs of pollutants such as nutrients, sediments and toxic compounds (see Environmental Status - Water Quality), which have been shown to negatively affect marine plants such as mangroves and seagrasses, although the effects on macroalgae are less clear [91, 126]. These impacts are most pronounced on inshore reefs, reflecting their proximity to the sources of terrestrial inputs.

Increased nutrients

Coral reef macroalgae, like any plants, require minimum levels of nutrients to grow. Natural sources of background nutrients for coral reef macroalgae include upwelling of nutrient-rich, deep waters, flood-plumes from coastal rivers, resuspension during storms and cyclones, and nitrogen fixation by blue-green algae. However, problems arise when human activities add nutrients far in excess of natural levels, disturbing the balance of these nutrient dynamics. This effect is known as eutrophication, and potentially leads to increases in algal growth and ultimately to overgrowth of corals and reef degradation.

Increased nutrients are probably the most important human impact on the macroalgae of the Reef at the current time. Run-off of nutrients from agriculture and grazing lands has been suggested to be causing increases in biomass and shifts in species composition of the natural macroalgal flora in the inshore Reef, in turn resulting in replacement of corals by algae, and damaging the ecological and aesthetic value of reefs [5]. Available evidence for nutrient impacts on macroalgae suggests that the processes involved are complex [91, reviews in 96, 126]. Laboratory studies have shown increased growth of several coral reef seaweeds in response to increased nutrients [121, 125], but this increased growth may not result in increased biomass or abundance in the field (Box 2). The ENCORE (Enrichment of Coral Reefs) project found no significant effects of increased nutrients on biomass of algal turfs at One Tree Island [74, 79]. Experiments that have simultaneously manipulated nutrients and herbivory have shown that effects of herbivores are consistently greater than those of nutrient supply (Box 2), often because grazers consume the excess of algal biomass production [34, 57, 67, 91](discussed in previous Herbivory section). However, herbivores are relatively scarce on inshore areas of the Reef, where human derived nutrients are highest, so that these reefs are likely to be most vulnerable.

Increases in nutrients may also have important impacts on the pool of species occurring at a particular site, and may contribute to algal dominance after disturbances. Recent surveys of fleshy macroalgae have shown that cover and

diversity of genera of red algae and cover of green algae on inshore reefs increased along a water quality gradient from lowest to highest nutrient concentrations [46]. Nutrient impacts on algae appear most critical after disturbances such as mass bleaching or cyclone damage, when dead coral is colonised by algae, and herbivore control may be reduced. In such circumstances, increased algal growth due to nutrients may seriously inhibit recruitment and recovery of corals [99]. These effects may be exacerbated by negative effects of nutrients on corals. High nutrient levels may stress corals, or inhibit their recovery after disturbances, thus enhancing algal colonisation.

Increased nutrient loading may also have harmful direct effects on some macroalgae. Some nutrient enrichment experiments with Reef seaweeds have found that high nutrient concentrations caused reductions in photosynthetic rates in *Sargassum baccularia* [98, 124] and of reproductive tissue of *Sargassum siliquosum* [36]. High nutrient levels have also been shown to inhibit early life-history stages of temperate seaweeds, but the mechanisms behind that inhibition remain unclear [38, 70].

The capacity of some macroalgae to rapidly take up nutrients makes them useful indicators for nutrient pulses and eutrophication. For example, the fleshy red algae *Gracilaria edulis* and *Catenella nipae* have been used to detect nutrient pulses [18] and to assess the efficacy of nutrient removal in sewage treatment plants in southern Queensland [19]. Overall, the variety and complexity of macroalgal responses to nutrients, combined with the lack of good historical data on the natural composition of macroalgal flora on inshore reefs, makes it difficult to assess the extent to which this pressure is affecting Reef macroalgae [96].

Sediment deposition

Sedimentation may have both direct and indirect impacts on macroalgal communities. Indirect effects include colonisation of seaweeds following coral mortality due to sediment accumulation, the inhibition of coral recruitment by sediments trapped in algal mats [9], or decreased light due to increased turbidity. Direct deposition of sediments on plants may block physiological processes such as photosynthesis, and gas and nutrient exchange, although some seaweeds may benefit from organic matter settled on their thalli [120]. Sediments may come from natural processes (e.g. storms and cyclones) or as the result of human activity, from increased run-off or dredging operations. Experimental additions of sediments to *Sargassum* populations on an inshore reef (Magnetic Island) reduced the density and growth of young plants and affected recruitment [137]. Sediment smothering has also been related to reduction in cover of crustose coralline algae [45]. The impacts of sedimentation on algal turfs have been poorly studied on the Reef, but are probably minor compared to impacts on fleshy and crustose algae, because turf algae have relatively rapid growth and recovery. Some turf algae appear able to grow sufficiently to keep pace with sediment deposition [112, 113].

Toxic compounds

Recent studies have found that inshore areas of the Reef are exposed to significant levels of organic pollutants, including herbicides and polycyclic aromatic hydrocarbons. Although there is little direct evidence on the effects of these chemicals on macroalgae, the nature of the pollutants as herbicides suggests strong impacts [42, 100, 129]. The only available study testing the effects of herbicides on macroalgae from the GBR found significant inhibition of photosynthesis and mortality of crustose coralline algae when exposed to the herbicide diuron [55]. Heavy metals, such as zinc, copper, cadmium, nickel, lead and mercury, may have negative effects on processes such as reproduction, photosynthesis, etc [85], although there is again little direct evidence available for Great Barrier Reef macroalgae. Baseline studies of heavy metals in 48 species of macroalgae performed 20 years ago found low levels of contamination [30].

Coastal development and habitat destruction

Coastal development, such as ports, marinas, jetties or breakwaters, may have serious direct effects on macroalgal communities through habitat destruction, sediment burial and smothering, and indirectly, especially through damage to corals, with consequent shifts in macroalgal composition. However, impact assessments of such developments typically focus on other groups, such as corals and seagrasses, so that there is little direct evidence available to assess impacts on macroalgae specifically. Further information about water quality and coastal development on the Great Barrier Reef is described in the chapter Environmental Status - Water Quality.

Trawling

Trawling may directly affect deepwater inter-reefal macroalgae (see Environmental Status Inter-reefal and Lagoonal benthos and Seagrasses). Trawl nets may cause removal and mortality of fleshy sand-dwelling macroalgae. However, knowledge of inter-reefal algal communities is even more limited than for seagrasses, so that the nature and extent of such impacts, and any recovery, are unknown and require research. For more information on trawling in the Great Barrier Reef, see Environmental status – inter-reefal and lagoonal benthos and Management status – fisheries.

Overfishing

Overfishing of herbivorous fish is not currently considered a threat on the Reef, but, were it to develop, it would have major impacts on the ecology of macroalgae, particularly on the balance between abundant corals and large fleshy macroalgae. Experience on coral reefs in South-east Asia and the Caribbean [61], along with recent experimental studies on the Great Barrier Reef [62, 89, 91] has unequivocally demonstrated that overfishing of herbivorous fish results in sustained algal blooms that continue to the present. These algal blooms have contributed to the long-term loss of corals, and resultant “phase-shifts” or reef degradation. These changes involve not only massive increases in amount of macroalgae on a reef, but major shifts in the type

of algae, from dominance by algal turfs and crustose coralline algae to large fleshy seaweeds. Although fishing pressure on small herbivores, such as parrotfish and surgeonfish, is currently minimal on the Reef, hunting of large herbivores, such as dugongs and sea turtles, has caused serious declines in their population densities since European colonisation [6, 106]. It is reasonable to assume that such declines have contributed to changes in the ecology of Reef macroalgae, and associated habitats, but evidence for, or against, such long-term changes in algal abundance and composition is lacking.

Harvesting

Harvesting of seaweeds for uses as food, extracts or fertilizers is minimal within the Reef, although widespread in many parts of the world. A permit from the Department of Primary Industries is required to collect any marine plants, including seaweeds (www.dpi.qld.gov.au/).

Other pressures

Climate change

Global climate change is causing critical changes in marine habitats, with serious consequences for organisms, such as corals and macroalgae, in those habitats. The Intergovernmental Panel on Climate Change (IPCC: www.ipcc.ch/) and CSIRO [3] have identified a number of possible outcomes, many of which will have direct or indirect effects on macroalgal communities of the Reef (see Table 5). Although the exact nature of these effects is largely unknown, and there is little direct evidence [37], some impacts are relatively certain. Ocean acidification will cause declines in coralline algae [76]. Perhaps the major impact will be the indirect consequence of increased frequency and severity of coral bleaching and mortality, resulting in large-scale algal colonisation and dominance of reef habitats (Box 3, Figs. 19-21). As such disturbances become more frequent [60], recovery of corals will be reduced, leading to large-scale phase shifts and general declines in coral reefs [8, 37, 94].

Table 5. Potential and probable outcomes of Global Climate change for Reef macroalgae from [37].

Stress	Predicted and Potential Outcomes
Increase in sea surface temperature	Indirect effects: large scale shifts in composition due to coral mortality. Change in algal distributions.
More severe cyclones and storms	Indirect effects resulting from coral mortality leading to increases in algal abundance and shifts in composition. Direct disturbance to fleshy macroalgae but rapid to moderate (3 yrs) recovery.
Sea level rise	Increased colonisation of all macroalgal groups.
Increases in land sourced inputs, precipitation, and run-off	Shifts in species composition.
Changes in ocean chemistry, particularly carbon dioxide concentrations and consequent ocean acidification (reduction of pH)	Reduced abundance and calcification by calcareous algae: e.g *Halimeda*, CCA, *Amphiroa*. Increased primary productivity.
Changing ocean circulation	Species introductions (i.e. range expansions). Changes in species distributions and abundances.
Increased UV light	Increased physiological stress for shallow species.
Increased substrate availability due to coral mortality (Box 3)	Increased algal abundance and shifts in species composition.
Increase susceptibility to diseases	Potential increase, e.g. Coralline Lethal Orange Disease.
Increased air temperature	Limited impact - intertidal macroalgae only.

Box 3. Case study: what happens after coral bleaching?

The 1998 mass bleaching of corals was one of the most severe disturbances to coral reefs world-wide. Researchers on the Great Barrier Reef documented the outcome of coral bleaching on *Porites* corals, as shown in these photographs and graphs (Figs. 19-21). In some cases, coral tissue regained their symbiotic zooxanthellae, and recovered. In other cases, the bleached coral died, and was overgrown by a sequence of algae. As shown in the graphs, the more severely bleached corals were more likely to die, and to be overgrown by algae (Fig. 21).

The usual outcome of coral mortality is algal colonisation: repeated and severe bleaching will result in reefs dominated by various forms of macroalgae. This means that the recovery of reefs, which depends on the settlement and successful growth of coral larvae, may be seriously inhibited by the dominance of fleshy algae (Fig. 22).

Fig. 19. A massive *Porites* coral after the 1998 mass bleaching at Orpheus Island on the Great Barrier Reef. Bleached tissue appears white; dead tissue has been overgrown by algae and appears grey-brown.

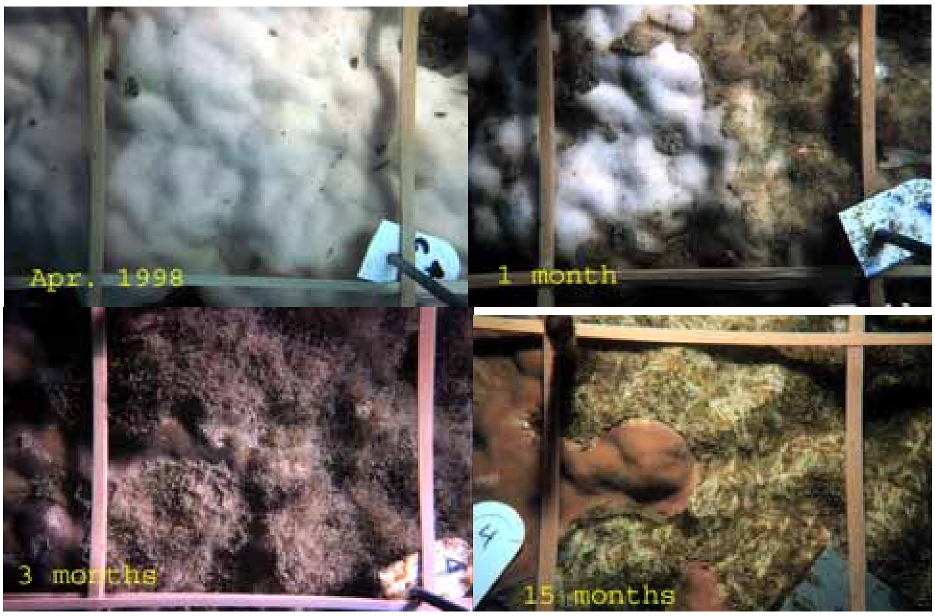


Fig. 20. Series of close-up photographs of bleached coral following the 1998 mass bleaching. Some coral tissue recovered, whereas the more severely damaged coral died, and was overgrown by filamentous algal turfs (turfs at 15 months show the effects of grazing by parrotfish).

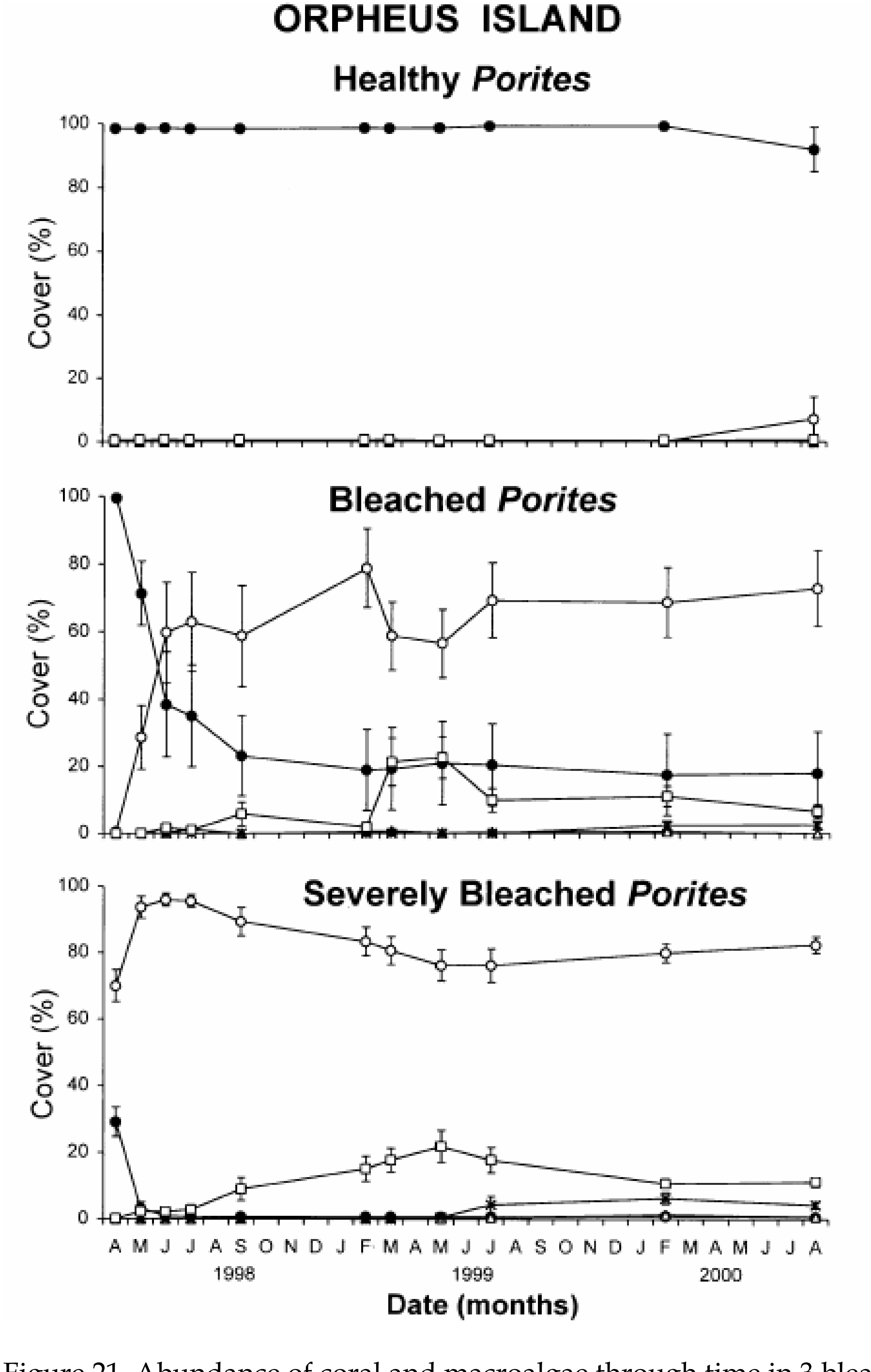


Figure 21. Abundance of coral and macroalgae through time in 3 bleaching categories at Orpheus Island. All areas had 100 per cent live coral cover before the bleaching event. (•) coral; (O) algal turfs; (Δ)fleshy macroalgae; (X) crustose calcareous algae; (□) bare substratum (From Diaz-Pulido & McCook 2002).

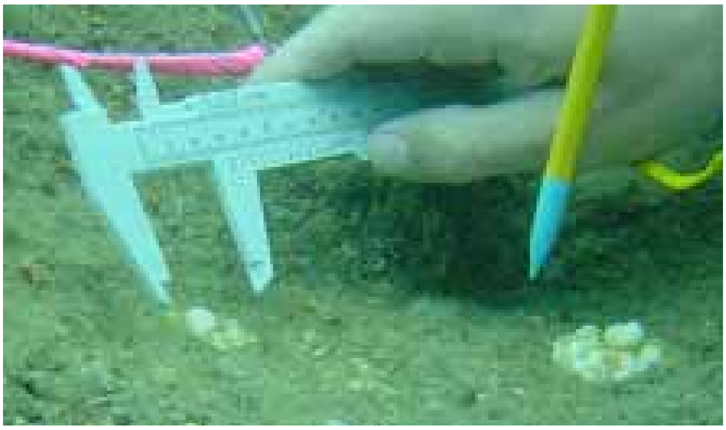


Fig 22. Coral recruits settled on a closely cropped algal turf. The nature of the algal community dominating the substrate will have a major effect on the success of the coral recruits [8].

Diseases, invasive species and species outbreaks

There is very little information available on the threats posed by diseases, invasive species and outbreaks to the macroalgae of the Great Barrier Reef. The only available study of algal diseases on the Reef documented "Coralline Lethal Orange Disease" (CLOD, Fig. 23), on crustose coralline algae, and "*Peyssonnelia* Yellow Band disease" (PYBD) on the calcifying red algae *Peyssonnelia* on offshore reefs of the central Reef[31]. CLOD disease has affected a number of CCA species across reefs in the Pacific [82]. PYBD has only been observed in the Great Barrier Reef and the Caribbean but is apparently quite rare [31].

Fig. 23. The "Coralline lethal orange disease" has been observed on crustose algae on the Great Barrier Reef. Very little is known about the incidence, causes and consequences of diseases of macroalgae on the Great Barrier Reef.

The introduction of invasive and exotic (alien) species is often considered to be one the most serious threats to biodiversity in marine ecosystems [104, 141], but their impacts on the reefs and flora of the Great Barrier Reef is unknown. Coral reefs are vulnerable to introduction of exotic seaweeds, because they can become ecological dominants,

overgrowing corals and displacing native algae, with resultant shifts in community structure and food webs. Introduction of exotic seaweeds elsewhere has resulted from ship hull fouling, shipping ballast water, accidental introduction during shellfish aquaculture and from deliberate introductions for cultivation and harvesting, aquarium use, and research.

Examples of seaweed introductions to coral reefs include the fleshy seaweeds *Kappaphycus alvarezii* and *Gracilaria salicornia*, brought for aquaculture purposes to Hawaiian reefs, and the recent introduction of *Caulerpa brachypus* to Florida, apparently discharged by an aquarium hobbyist. These seaweeds have spread across the reefs and caused coral death and reductions in diversity of natural macroalgae [49, 115, 131, 132]. Several exotic seaweeds have been introduced to temperate Australia, including the Asian kelp *Undaria pinnatifida* to Tasmania and Victoria, and the green seaweed *Caulerpa taxifolia* to New South Wales. Both have had serious impacts on the marine flora and fauna [52, 58, 127, 138, 141, 153].

Despite the potential impacts of species introductions, there are no studies directly addressing this issue in the GBR. The CSIRO has developed the National Introduced Marine Pest Information System (www.marine.csiro.au/crimp/nimpis/Default.htm), which includes lists of marine species introduced to Australian waters. These lists include at least 55 species of seaweeds that may have been introduced into Australia. Of these, 23 occur in the Great Barrier Reef World Heritage Area, but there is considerable uncertainty whether these records represent genuine introductions or simply taxonomic misidentifications. This uncertainty largely reflects the lack of research on these species.

Coral reefs are also subject to the harmful effects of outbreaks or blooms of naturally occurring species. For example, blooms of the toxic blue-green alga *Lyngbya majuscula* have caused concern, as this alga can overgrow other marine plants, causing ecological shifts and potential harm to human health. Strains of the algae have toxic effects on the skin, eyes and respiratory tract. South of the Reef, increasingly frequent outbreaks of *Lyngbya* have been reported in Deception Bay since 1990 and in other parts of Moreton Bay since 1997. In late 2002, five areas along the Queensland coast showed signs of *Lyngbya* blooms (Hinchinbrook Island, Hardy Reef, Shoalwater Bay, Great Keppel Island and Moreton Bay; 4/5 are Great Barrier Reef areas), but the magnitude and impact were not clear [44]. Whether the increase in abundance of such blue-green algae is an indicator of widespread environmental changes, such as degrading water quality, is unknown. However, the minimal available evidence does suggest outbreaks of *Lyngbya* blooms are associated with run-off of dissolved iron and phosphorus from human activity on land [2].

Response

The GBRMPA uses a range of management approaches, which reduce direct and indirect impacts on macroalgal communities. These approaches include the marine park zoning, which designates areas for particular activities, the application of permit conditions associated with specific activities, the establishment of guidelines and codes of conduct, and the development of research and monitoring programs to assess impacts and monitor ecosystem condition.

The new Great Barrier Reef Marine Park Zoning Plan 2003 (www.gbrmpa.gov.au/corp_site/management/zoning/index.html), established to better protect the biodiversity and ecological functions of the GBRWHA, provides varying degrees of protection to representative portions of all the major bioregions in the marine park. This provides some protection to seaweed communities, directly through no-take zones, and indirectly, by protecting overall ecological functions and ecosystem resilience. Importantly, this includes both reefal and inter-reefal habitats, such as deepwater *Halimeda* beds.

All marine plants, including seaweeds, are specifically protected under the Queensland Fisheries Act 1994. Approval is required for any works or activities that could disturb, destroy or damage them.

Response to water quality issues

The impacts of run-off and coastal development on the Great Barrier Reef are being addressed principally through the Reef Water Quality Protection Plan (www.deh.gov.au/coasts/pollution/reef/). This plan, released in October 2003, aims to halt and reverse declining water quality in the Great Barrier Reef within ten years, and is a joint initiative of the Australian Government and the Queensland Government. The development of the Plan included a comprehensive review of the scientific information on water quality in the Great Barrier Reef (www.deh.gov.au/coasts/pollution/reef/science/index.html), which concluded that there is presently a serious risk to the long-term future of inshore reef habitats, and that immediate action is required to avoid further damage and facilitate recovery of affected habitats.

Under the Reef Plan, regional working groups are being established to:

- Address land use practices and water quality issues in each catchment
- Identify and establish nutrient sensitive zones, to allow programs to minimise the impact of nutrients on the reef
- Protect and rehabilitate riparian and wetland areas
- Develop and implement local water quality improvement plans in high-risk high-priority catchments
- Develop water quality targets for Reef catchment waterways.

The GBRMPA has also focused on point sources of pollution that discharge directly into the marine park, including sewage discharges, aquaculture and shipping.

For more information about the management of water quality issues, see Environmental Status - water quality (www.gbrmpa.gov.au/corp_site/info_services/publications/sotr/water_quality/index.html) and the GBRMPA Annual Report 2005-2006

Response to coastal development and habitat degradation

Although management of activities in the catchment and coastal regions adjacent to the Marine Park are the responsibility of the Queensland Government, the GBRMPA provides advice to the Queensland Government on coastal developments and activities that may affect habitats in the Marine Park, including macroalgal communities. In particular, the *Great Barrier Reef Marine Park Act1975* and *Environment Protection and Biodiversity Conservation Act 1999* include provisions to assess and manage the environmental impact of coastal development and activities such as dredging.

Response to trawling

Strategies for minimising impacts of trawling on inter-reefal habitats, including *Halimeda* beds and other algal assemblages, include the Great Barrier Reef Marine Park Zoning Plan 2003 (discussed above; www.gbrmpa.gov.au/corp_site/management/zoning/index.html) and the *East Coast Trawl Fishery (ECTF) Management Plan*. Under the ECTF Management Plan, limits have been placed on the potential further expansion of trawled area, and on the amount of trawling effort. Under the *Environment Protection and Biodiversity Conservation Act 1999*, the ecological sustainability of the Queensland east coast trawl fishery is being assessed.

For more information on responses to trawling see Environmental status: Seagrasses (www.gbrmpa.gov.au/corp_site/info_services/publications/sotr/seagrasses/index.html) and Environmental Status: Inter-reefal and Lagoonal benthos (www.gbrmpa.gov.au/corp_site/info_services/publications/sotr/benthos/). See also Management Status: Fisheries for details of trawl fishery (www.gbrmpa.gov.au/corp_site/info_services/publications/sotr/fisheries/).

Response to climate change

Climate change is a global problem that is beyond the scope of the GBRMPA to manage directly; nevertheless the GBRMPA is committed to addressing climate change issues as they relate to the Reef. The GBRMPA has developed a Climate Change Response Program to investigate the potential impacts of climate change on the animals, plants and habitats of the Reef, and to identify strategies to mitigate these impacts. These strategies include minimising the impacts of other pressures on Great Barrier Reef habitats, thereby maximising the resilience of habitats in the face of climate change, or other emerging threats.

Response to diseases and invasive species

There is currently insufficient knowledge regarding the impacts of macroalgal diseases and invasive species on macroalgal communities. Nevertheless, the GBRMPA works closely with other regulatory agencies and the shipping industry on a range of ship safety and pollution-prevention measures in the Marine Park to reduce

the risk of introductions of invasive species. For further information, see Management Status: Shipping and Oil Spills (www.gbrmpa.gov.au/corp_site/info_services/publications/sotr/latest_updates/shipping).

In response to the outbreak of *Lyngbya* in Moreton Bay, the *Lyngbya* Steering Committee, part of the Moreton Bay Waterways and Catchments Partnership, published a management strategy in 2002 [44].

Managing for resilience

The GBRMPA is committed to ensuring that the overall resilience of the Marine Park habitats is not degraded by human activities, thereby maximising the capacity of the ecosystem to withstand or recover from the combined effects of existing and emerging pressures. For example, declining water quality, increased coastal development, or loss of biodiversity, will affect the ability of macroalgal communities to cope with the effects of climate change. Minimising these pressures through the Zoning plan (www.gbrmpa.gov.au/corp_site/management/zoning/index.html), the Reef Water Quality Protection Plan (www.deh.gov.au/coasts/pollution/reef/index.html) and improved fisheries management, will help to ensure that macroalgal communities and coral reefs cope better with climate change.

Summary

- The Great Barrier Reef World Heritage Area has a highly diverse macroalgal flora.
- Macroalgal communities strongly vary in composition from inshore to offshore, and show pronounced seasonal changes.
- Macroalgae play critical roles in both the maintenance of reef health and in the degradation of reefs.
- It is difficult to assess the condition of macroalgal communities due to a lack of detailed monitoring programs, although the Long Term Monitoring Program from AIMS provides some coarse information on trends.
- Assessing the impacts of pressures is more complex for macroalgae than for groups such as corals or fish, because macroalgae are more diverse, and much more complex in function, than most other groups.
- Natural pressures such as cyclones may have major direct impacts on macroalgal communities.
- Grazing by herbivores strongly regulates the abundance, distribution and composition of macroalgae on the Reef and helps to maintain competitive dominance by reef building corals.
- Pressures causing coral mortality and stress, such as cyclones, coral bleaching, outbreaks of crown-of-thorns starfish and coral diseases, have indirect effects on macroalgal communities leading to increases in algal abundance and shifts in species composition. Macroalgal communities are vulnerable to such shifts in species composition.
- A major human impact on macroalgal communities arises from water quality changes caused by land use and agricultural practises, but there is considerable

uncertainty as to whether the current algal abundance is natural, or a result of those changes in water quality.

- The major impact of global climate change on macroalgae is likely to involve the indirect effects of increased frequency and severity of coral bleaching, followed by coral mortality, algal colonisation of dead coral, and consequent increases in macroalgal abundance. Such shifts may have negative impacts on the overall condition of current macroalgal communities.
- Ocean acidification due to increases in carbon dioxide as a consequence of human activities may reduce the calcification of calcareous algae with potential negative consequences for reef ecology.
- Macroalgae, and other marine plants, are protected under the *Queensland Fisheries Act 1994*, which requires approval for any works or activities that could disturb, destroy or damage them.
- The *Great Barrier Reef Marine Park Zoning Plan 2003* will help to ensure the ecological viability and resilience of coral reefs and macroalgal communities, by protecting the full range of reef and inter-reefal habitats, in a network of protected areas. This network will help protect biodiversity, maintain ecosystem function and preserve interconnectivity both within and between coral reefs and other habitats.
- Increasing run-off of nutrients, sediments and toxic compounds is being addressed through a variety of management provisions, including the *Reef Water Quality Protection Plan*.

Further Reading:

Information about macroalgae of the Great Barrier Reef and *Halimeda*

- General information on macroalgae of the Great Barrier Reef by the CRC-reef: www.reef.crc.org.au/discover/plantsanimals/algae/index.html
- Research on coral reef resilience and climate change: www.pewoceanscience.org/fellows/lmccook/fellows-dir-project.php?pfID=10267
- *Halimeda* banks of the Great Barrier Reef: home.austarnet.com.au/edrew1/atlas/spums/halbank.htm#s7
- *Halimeda* Ecosystems from the Timor Sea: www.aims.gov.au/pages/reflib/bigbank/pages/bb-08.html

Information about the macroalgae of Australia

- Australian Marine Algal Name Index: www.anbg.gov.au/abrs/online-resources/amani/
- Marine Plants Project WA: florabase.calm.wa.gov.au/marineplants/project
- Information on Australian macroalgae at the Royal Botanic Gardens, Sydney: www.rbgsyd.nsw.gov.au/information_about_plants/botanical_info/marine_algae

- Australasian Society for Phycology and Aquatic Botany ASPAB: www.aspab.cjb.net/

Information on Legislation relevant to macroalgae from the Great Barrier Reef

- Legal protection of marine plants, Department of Primary Industries and Fisheries: www.dpi.qld.gov.au/cps/rde/xchg/dpi/hs.xsl/28_1239_ENA_HTML.htm
- List of CITES species for Australia: www.deh.gov.au/biodiversity/trade-use/lists/cites/pubs/cites.pdf
- Zoning: www.gbrmpa.gov.au/corp_site/management/zoning/index.html

Information on macroalgal blooms and invasive macroalgae on Australia and around the world

- Blooms of blue-green algae: *Lyngbya majuscula*: www.epa.qld.gov.au/publications/p01425aa.pdf/iLyngbya/i_Update_Synthesis_of_resultstodate_of_the_iLyngbya/i_scientific_tasks.pdf
- National Introduced Marine Pest Information System (NIMPIS): www.marine.csiro.au/crimp/nimpis/Default.htm
- Algae threaten great coral reef: news.bbc.co.uk/2/hi/science/nature/3237294.stm
- Invasive Algae Database: www2.bishopmuseum.org/algae/index.asp
- Invasive algae smothering Florida coral reefs: www.flmnh.ufl.edu/FISH/southflorida/news/invasivealgae.html

General information about the biology of macroalgae

- General information about seaweeds and phycology: www.freakinfucus.co.uk/index.htm
- Internet sites of interest to phycologists: www.upe.ac.za/botany/pssa/pssanet.htm
- The world of algae: www.botany.uwc.ac.za/algae/
- General information on all aspects of seaweeds: www.seaweed.ie/
- Taxonomic Catalogue of Benthic Marine Algae of the Indian Ocean - P.C. Silva: ucjeps.berkeley.edu/rlmoe/tioc/ioctoc.html
- International database of information on algae: www.algaebase.org/
- General information on macroalgae, Smithsonian Institution: www.nmnh.si.edu/botany/projects/algae/
- Macroalgae from Hawaii: www.botany.hawaii.edu/ReefAlgae/

Monitoring programs

- AIMS Reef Monitoring Status Report number 7: www.aims.gov.au/pages/research/reef-monitoring/ltm/mon-statrep7/statrep7.html

State of the environment of Australia, relevant to algae

- State of the Environment 2003 Queensland – EPA: www.epa.qld.gov.au/environmental_management/state_of_the_environment/state_of_the_environment_2003/main_report/
- The State of the Marine Environment Report for Australia: www.deh.gov.au/coasts/publications/somer/annex1/index.html
- State of the Environment, Queensland 2003: www.epa.qld.gov.au/register/p01258bt.pdf

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