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Significance of *Halimeda* bioherms to the global carbonate budget based on a geological sediment budget for the Northern Great Barrier Reef, Australia

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Abstract Since the correlation between carbon dioxide (CO₂) levels and global temperatures was established in the ice core records, quantifying the components of the global carbon cycle has become a priority with a view to constraining models of the climate system. The marine carbonate budget is still not adequately constrained and the quantitative significance of the calcareous green alga *Halimeda* still remains particularly poorly understood. Previously, it has been suggested that *Halimeda* bioherms on the shelf of the Great Barrier Reef may contain a volume of carbonate equal to or greater than that contained within the shelf edge coral reefs. This study uses published datasets to test this hypothesis in the Northern Great Barrier Reef (NGBR) province. It is estimated that *Halimeda* bioherms on the outer shelf of the NGBR contain at least as much (and up to four times more) CaCO₃ sediment as the adjacent ribbon reef facies. Globally, if these findings are even only partially applicable, that contribution of shallow water carbonate sediments to the global carbon budget based on coral reefs alone is currently substantially underestimated.

Keywords *Halimeda* bioherms · Holocene · Calcium carbonate budget

Introduction

Carbonate budgets

The role of neritic carbonate within the global carbon cycle is yet to be adequately quantified (Ridgwell and Zeebe 2005). Documenting the loci and rates of carbonate production and accumulation during the Holocene is the key to quantifying the shallow water carbonate budget (Milliman 1993). Recently, it has been estimated that coral reefs have accumulated approximately 7,970 Gt CaCO₃ over the last 10,000 years before present (kyr BP; i.e. 0.8 Gt CaCO₃ year⁻¹; Rees 2006). It is widely accepted that the calcareous green alga *Halimeda* is a prominent contributor of carbonate to reef sediment facies in the tropics, but the significance to the global carbonate budget of distinct *Halimeda* bioherms, independent of coral reefs, is poorly known (Hillis-Colinvaux 1980; Drew and Abel 1983; Phipps et al. 1985; Milliman 1993; Freile et al. 1995; Hillis 1997; Steneck and Testa 1997).

Milliman (1993) estimated that modern *Halimeda* bioherms accumulate approximately 0.15 Gt CaCO₃ year⁻¹ globally. This figure was based on estimated numbers of *Halimeda* meadow crops per year and the assumption that, globally, bioherms cover an area of 5×10^4 km². Hillis (1997) attempted a first budget for modern day *Halimeda* meadows using the estimates for lagoon, ridge and bioherm area and *Halimeda* crops per year taken from the studies of Smith and Kinsey (1976), Smith (1978) and Milliman (1993). On this basis, Hillis (1997) calculated a modern global *Halimeda* bioherm production of 0.4 Gt CaCO₃ year⁻¹, approximately 83% of coral reef carbonate production. Despite these early attempts to determine a *Halimeda* carbonate budget, the global distribution, aerial extent and role of *Halimeda* in the global carbon cycle have yet to be precisely quantified for both the present day and the past (Milliman 1993; Rees et al. 2005).

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Halimeda

Halimeda is a genus of macroscopic calcareous green algae (Order Caulepales; Chlorophyta; Hillis 1997; Heyward et al. 1997). The bushy plants are composed of numerous calcified (60–80% CaCO_3) flat segments between 0.5 and 3 cm wide that are joined at un-calcified nodes (Drew 1993). The calcified segments are shed as part of the growth and senescence cycle by disintegration of the nodes (Drew 1993; Hillis 1997). *Halimeda* are found in a variety of habitats from mangrove prop roots to the reef front zone on coral reefs, and *Halimeda* meadows create complex habitats that serve as refuges, nursery grounds and food for a variety of organisms (Hillis-Colinvaux 1986a; Hillis 1997; Steneck and Testa 1997; Heyward et al. 1997). *Halimeda* originated in the Cretaceous and are thought to have contributed to reef sediments for at least the last 65 million years (Elliot 1965; Johnson 1969; Hillis-Colinvaux 1980; Hillis 1997). In fact, it has been proposed that modern bioherms are reminiscent of phylloid algal bioherms of late Paleozoic reefs that presently act as hydrocarbon reservoirs (Ball et al. 1977; Wray 1977; Drew and Abel 1988; Kirkland et al. 1993). A variety of terms have been used to describe the range of different structures created by *Halimeda* sediments (Table 1).

Halimeda bioherms

Significant accumulations of *Halimeda* debris have been found worldwide. Actively accreting *Halimeda* bioherms have been described in exposed and protected environments in the Eastern Java Sea, Indonesia on Kalukalukang Bank (K bank) (Roberts et al. 1987a, b, 1988; Phipps and Roberts 1988). These bioherms are approximately 20–30 m thick, locally 50 m high and are commonly 10 km wide. Vibrocores reveal that these structures are composed of *Halimeda* packstone with foraminifera-rich carbonate mud and exhibit rapid accumulation rates in the region of 3–6 m kyr^{-1} (Roberts et al. 1987a, b; Roberts and Phipps 1988). Similarly, Hine et al. (1988) discovered extant *Halimeda* bioherms 20–30 m in height (some reaching as high as 140 m) that form an almost continuous band, approximately 125 km long, in water depths of 40–50 m in the Southwest Caribbean (Nicaraguan Rise, Miskito Channel). These

banks are composed of coarse poorly cemented packstones and grainstones of dead disarticulated *Halimeda* segments with a living veneer on top. *Halimeda* rich gravel deposits up to 15 m in relief with accumulation rates averaging 0.2 m kyr^{-1} have also been described on the Fly River Delta, Gulf of Papua New Guinea (Harris et al. 1996). A series of eight submerged carbonate platforms, that range in size from 0.05 to 40 km^2 , in the Timor Sea, North Western Australia are dominated by *Halimeda* bank deposits (Heyward et al. 1997). Cores from these banks reveal that over 80% of the total sediment is *Halimeda* debris.

Coral reefs

Ribbon reefs are the barrier reefs along the edge of the Australian continental shelf, they form an almost continuous narrow high wall interrupted by narrow channels. For the purpose of this study a ribbon reef is defined as a three-dimensional structure comprised of calcium carbonate sediment (rock, sands and muds) generated by scleractinian coral and coralline algae calcification occurring in a tropical environment which remains as solid CaCO_3 and is not dissolved (Rees et al. 2005). This definition excludes terrigenous sediments and non-reef habitats including banks, platforms and carbonate dominated embayments. Reefs within the Great Barrier Reef (GBR) province vary considerably in size and form, Holocene reef growth is represented by only a thin veneer, 10–20 m thick, commonly on top of karstified Pleistocene substrates (Davies et al. 1977; Hopley 1982). These investigations reveal that the Holocene ribbon reefs of the Lizard Island and Cooktown regions are approximately 9.5 and 15 m thick, respectively.

Study area

The GBR, a high energy epi-continental shelf edge reef system, is the largest reef system in the world covering an area of approximately 49,000 km^2 and comprises nearly 3,000 individual reefs (Fig. 1; Davies and Marshall 1980; Spalding et al. 2001). The northern province of the GBR extends from 9°S to 16°S, is generally narrow, between 24 and 60 km wide and is the shallowest

Table 1 Terms used to describe *Halimeda* sediment formations

Term	Definition	Reference	Year
Bioherms	Mounds which have relief above the sea floor but which do not exhibit a clear framework and which exist in a relatively low energy environment	Davies and Marshall	1985
Meadow	Inter-reefal areas of luxuriant <i>Halimeda</i> vegetation	Drew and Abel	1988
Mounds or banks	Discrete circular mounds of <i>Halimeda</i> debris that sometimes coalesce into ridges	Drew and Abel	1988
Drapery	Vertical meadow of loose sprawling plants that hang over the cemented escarpment ledges	Freile et al.	1995

Fig. 1 a Australia showing location of the Great Barrier Reef (GBR) (modified after Flood 1984). b The GBR. The majority of *Halimeda* meadows are located between the latitudes of 10°30'S and 15°35'S (Far Far North GBR to Northern Great Barrier Reef)

part of the GBR with depths commonly < 40 m below sea level (Maxwell 1968; Orme and Flood 1980; Orme 1985). This region of the Northern Great Barrier Reef (NGBR) is characterised by an almost continuous line of shelf edge ribbon reefs, varying from 3 to 26 km in length and between 300 and 450 m wide (Orme and Flood 1977, 1980; Kinsey 1979; Flood 1984). The Lizard Island region is located approximately 270 km north of Cairns (Fig. 2; Flood 1984). This area of the GBR province has a north-south trending line of granite continental islands (Lizard Island; North Direction Island and South Direction Island) which are surrounded by fringing reefs. The Cooktown region lies directly east of Cooktown itself and 180 km north of Cairns, it is characterised by a line of ribbon reefs along the shelf edge and platform reefs of various shapes and sizes across the shelf (Fig. 3).

Halimeda bioherms of the GBR

Maxwell (1968) estimated that approximately 10–30% of the reef surface in the GBR is composed of *Halimeda*

rubble and that 5–65% of the inter-reefal sediments are derived from *Halimeda*. The majority of *Halimeda* bioherms are located between the latitudes of 10°30'S and 15°35'S (Far Far North GBR to NGBR) on the outer shelf at depths of between 20 and 40 m below sea level (Fig. 1b; Drew and Abel 1983, 1988). Seismic profiling studies have revealed the absence of *Halimeda* bioherm deposits in the Princess Charlotte Bay and Bathurst Bay areas, just north of Lizard Island (Fig. 1b; Orme 1983, 1985). Further north, however, seismic profiles reveal the presence of bioherms in the region adjacent to Lloyd Bay and the Lockhart River, between North Lloyd Island and Hibernia Entrance and between Restoration Island and Second Small Reef (12°47'S, Fig. 1b; J.S. Jell, personal communication). *Halimeda* deposits, 1.5–14 m thick, have also been found within the Swains Reef Complex (20°53'S–22°24'S) of the Southern GBR (Maxwell 1973; Searle and Flood 1988). Radiocarbon dating of sediments from the top 4.3 m of the Swains Reef bioherms reveal accretion rates of between 2 and 3.5 m kyr⁻¹ during the last 5,000 years (Searle and Flood 1988).

Halimeda bioherms have been investigated in detail using seismic profiling, echo sounding, vibro and piston coring and grab sampling in two regions of the Northern GBR, Lizard Island and Cooktown (Figs. 2, 3; Orme et al. 1978; Orme 1985; Davies and Marshall 1985; Phipps et al. 1985; Orme and Salama 1988; Marshall and Davies 1988). Seismic investigations in the Lizard Island region (between latitudes of 14°27'S and 15°02'S) reveal extensive *Halimeda* bioherms behind the ribbon reefs. These bioherms are up to 6 km wide, 100 km long and can reach thicknesses of 18.5 m at a depth of 25 m below sea level (Fig. 2; Orme et al. 1978; Orme 1983; Flood and Orme 1988; Orme and Salama 1988). The bioherms are composed of *Halimeda* packstones and wackstones, reach maximum thickness of 18.5 m in the east but are less well developed in the west. The bioherms in the Lizard Island region are formed of ridges and mounds separated by hollows and channels and living *Halimeda* vegetation is found on the tops of the bioherms. Radiocarbon dating of a peat surface immediately below the bioherms reveals that they were formed during the Holocene (radiocarbon age of a peat sample 10,070 ± 180 years BP) and growth was initiated some 1,500 years before the nearby ribbon reefs (Orme 1985).

On the outer shelf east of Cooktown (between latitudes 15°10'S and 15°46'S) discrete biohermal complexes are found lying 1–2 km directly behind the ribbon reefs (Fig. 3; Davies and Marshall 1985; Marshall and Davies 1988). Individual bioherms can cover an area of several kilometres square and are composed of numerous sub-conical mounds (100–250 m wide) of unconsolidated sediments between 15 and 20 m in relief (Marshall and Davies 1988; Wolanski et al. 1988). The tops of the bioherms are covered by a forest of green algae (*Caulopora* and *Halimeda*) which effectively traps and stabilises the sediment. Radiocarbon dating of vibrocored sedi-

Fig. 2 Lizard Island region, Northern Great Barrier Reef. Area enclosed by grey dashed lines indicates the extent of *Halimeda* bioherms revealed by seismic profiling (adapted from Orme et al. 1978; Orme 1983; Orme and Salama 1988), the grey stippled area indicates the area of bioherm coverage which averages 10 m thickness and was used in the calculations herein (modified after Admiralty Chart Aus 373)

Fig. 3 Cooktown region, Northern Great Barrier Reef, grey stippled areas indicate locations of *Halimeda* bioherms; North Bank and Ribbon Banks 2–5 (modified after the Great Barrier Reef Marine Park Authority Map BRA Q 155 February 1992)

ments reveals that the bioherms are still actively accreting and that vertical accretion rates have ranged between 1 and 3 m kyr⁻¹ during the last 5,000 years. The bioherms are composed dominantly of *Halimeda*.

Cores extracted from the bioherms reveal a carbonate content averaging 75%, the remaining 25% is comprised fine grained terrigenous material (Marshall and Davies 1988).

In summary, the *Halimeda* bioherms of the NGBR are restricted to outer shelf areas, have thicknesses, accretion and productivity rates comparable to and cover areas larger than individual coral reefs (Davies and Marshall 1979; Drew 1983; Drew and Abel 1983; Marshall and Davies 1988). It has been suggested that the mass of CaCO_3 sediment within the *Halimeda* bioherms may be greater than those of the adjacent shelf edge reefs (Flood 1984; Hillis 1997).

Mechanism of formation

The mechanisms of *Halimeda* bioherm formation are still debated. The *Halimeda* bioherms in the NGBR are thought to have been formed because jets of up-welled nutrient-rich oceanic water intruded onto the outer shelf through the narrow passages between the ribbon reefs and formed eddies in the relative shelter behind the reefs (Drew and Abel 1985; Marshall and Davies 1988). The absence of *Halimeda* bioherms in the Princess Charlotte Bay region is probably related to the input of fluvial mud from the Normandy River system, which reduces light levels and smothers vegetation (Drew and Abel 1988). In the Southern GBR *Halimeda* deposits in the Swains Reef Complex have been associated with an influx of nutrient-rich water onto the platform as a result of convergence of the ocean currents from the Capricorn Channel and the Coral Sea (Maxwell 1968; Searle and Flood 1988).

Materials and methods

To quantify the relationship between *Halimeda* and coral reef-derived carbonate accumulated during the Holocene on the outer shelf of the NGBR this study used data derived from seismic profiling, reef drill cores and *Halimeda* bioherm piston and vibrocore cores taken from the published literature (Orme et al. 1978; Davies and Hopley 1983; Davies et al. 1985; Davies and Marshall 1985; Orme 1985; Marshall and Davies 1988; Orme and Salama 1988; Wolanski et al. 1988). The volume of carbonate sediment within *Halimeda* bioherms was compared with the adjacent ribbon reefs for the following reasons. The presence of ribbon reefs is believed to be essential for *Halimeda* bioherm development within the NGBR (Wolanski et al. 1988). It would not be appropriate to compare the volume of carbonate sediment within mid-shelf reefs with that within the *Halimeda* bioherms because mid-shelf reefs contain variable volumes of terrigenous sediment whereas the ribbon reefs contain little terrigenous sediment. To extrapolate the proportion of carbonate within the *Halimeda* bioherms to the rest of the NGBR it was necessary to select a reef type which is a consistent feature of the NGBR. The number and type of mid-shelf reef varies considerably within that NGBR province whereas ribbon reefs are a consistent feature of the NGBR.

Reef calcium carbonate

The mass of CaCO_3 for the ribbon reefs in each region was estimated using Eq. 1.

$$M = ((A \times T) \times 2) \times D \times P \times C \quad (1)$$

where M is the mass of carbonate sediments; A is reef area (km^2) estimated using a 1-km^2 grid (Fig. 4); T is the average thickness of the Holocene ribbon reefs (m); 2 is the factor used to correct reef mass for material exported to the leeward accretionary wedge and lagoon facies (Ryan et al. 2001). D is the density of coral reef CaCO_3 (2.9 g cm^{-3} ; Kinsey and Hopley 1991); P is the average porosity of coral reef sediments (50%; Ryan et al. 2001); C is the average carbonate content of coral reef sediments, this term can effectively be ignored because the carbonate content of coral reefs is assumed to be 100%. The mass of ribbon reef CaCO_3 estimated by Eq. 1 is shown in Table 2.

Reef area and thickness

A 1-km^2 grid was used to estimate the area of the ribbon reefs in both the Lizard Island and Cooktown regions from the GBR Marine Park Authority map BRA Q 155 February 1992 (Figs. 2, 4). The areas of the ribbon reefs in the Lizard Island and Cooktown regions were esti-

Fig. 4 Schematic diagram showing the estimation of the area covered by the *Halimeda* bioherms and the coral reefs in the Lizard Island region using a 1-km^2 grid. The grey dashed line indicates the area on the outer shelf where *Halimeda* bioherms are present, the grey stippled area indicates the area where the bioherms are at least 10 m thick. The black heavily stippled areas indicate the shallow coral reef flats

Table 2 Dimensions and mass of ribbon reef CaCO₃

Region	Ribbon reef	Reef area (km ²)	Thickness (m)	Mass CaCO ₃ (Gt)
Lizard Island	Day	5.75	9.5	0.16
	Carter	5.75	9.5	0.16
	Yonge	6.75	9.5	0.19
Total		18.5		0.52
Cooktown	Ribbon 5	5	15	0.22
	Ribbon 4	5	15	0.22
	Ribbon 3	4.5	15	0.2
	Ribbon 2	5	15	0.22
	15-072	0.25	15	0.01
	15-073	0.75	15	0.03
Total		20.5		0.92

mated to be 18.5 and 20.5 km², respectively (Fig. 4; Table 2).

Drilling, radiocarbon dating and seismic profiling investigations across the outer ribbon reefs, Carter and Yonge (15 km east of Lizard Island) have revealed that these reefs reached modern sea level by approximately 5,800 and 5,200 years BP, respectively, and that modern sea level was reached by 5,500 years BP (Harvey 1977a; Hopley 1994). The Holocene–Pleistocene unconformity lies at approximately 19.3 m below the reef flat of the back reef at Yonge Reef and 19 m below the reef flat of the leeward edge of Carter Reef (Harvey 1977a, b; Hopley 1977, 1994). Seismic profiling also has revealed discontinuity surfaces at about 10 m below the reef flat on the windward margins of Carter reef and two mid-shelf reefs, Nymph and Three Isle (Figs. 2, 3; Harvey 1977a, b; Orme et al. 1978).

Immediately east of Cooktown itself, a transect of reefs has been drilled including Boulder Reef, Williamson Reef and Ribbon Reef 5 (Fig. 3; Davies et al. 1985; International Consortium for Great Barrier Reef Drilling 2001). Radiocarbon dating has indicated that reef growth in this region was initiated between 6,300 and 8,400 years BP on Pleistocene foundations at depths ranging from 15 to 17 m below the reef flat. Modern day sea level was established in this region by 6,500 years BP and the reefs reached modern day sea level between 5,900 and 6,700 years BP (Thom and Chappell 1975; Stoddart et al. 1978; Chappell et al. 1983).

The thickness of the Holocene ribbon reefs was estimated from drill cores for the Cooktown region (Davies et al. 1985) and from both drill cores and seismic profiling studies in the Lizard Island region (Davies et al. 1977; Hopley 1977, 1994). These studies reveal that the average thickness of the Holocene ribbon reefs is 15 and 9.5 m for the Cooktown and Lizard Island regions, respectively.

Halimeda calcium carbonate

The mass of *Halimeda* bioherm CaCO₃ for both regions was estimated using Eq. 2.

$$M = A \times T \times D \times P \times C \quad (2)$$

where M is the mass of carbonate sediments; A is bioherm area (km²); T is the average thickness of the *Halimeda* bioherms (m); D is the average density of CaCO₃ (2.9 g cm⁻³; Kinsey and Hopley 1991); P is the porosity of the bioherm sediment which is assumed to be 50%; C is the average carbonate content of the *Halimeda* bioherms (75%; Orme 1985; Marshall and Davies 1988).

Lizard Island region bioherm area and thickness

To estimate the mass balance of *Halimeda* bioherm CaCO₃ it was necessary to approximate their area using data from seismic profiling, echo sounding and grab sampling studies of the Lizard Island area (Orme et al. 1978; Orme 1985) and Cooktown regions (Davies and Marshall 1985; Phipps et al. 1985; Marshall and Davies 1988; Wolanski et al. 1988). The area covered by the bioherms in the study area is harder to assess because they form a series of sinuous ridges and banks that effectively blankets the outer shelf. Thicknesses of sediment vary from 4 to 19 m over relatively short distances but the majority of the bioherms are between 10 and 19 m thick, averaging 14.5 m thick (Orme et al. 1978; Orme 1985; Orme and Salama 1988). Estimating the areal extent of the bioherms is also hampered by the sparsity of published seismic profiles. A 1-km² grid was used to estimate the area of bioherms which are consistently reported to have a thickness of 10 m or more (Figs. 2, 4). It is estimated that the areas occupied by *Halimeda* bioherms are at least 184 and 118 km² for the Lizard Island and Cooktown regions, respectively (Fig. 4; Table 3). It is conservatively assumed that the average thickness of the *Halimeda* deposits in the Lizard Island region is 10 m (Table 3).

Cooktown region bioherm area and thickness

Halimeda bioherms in the Cooktown region appear to form more or less discrete mounds behind each of the ribbon reefs. The average thickness of each bioherm in the Cooktown region was estimated from seismic and echo sounding profiles and descriptions in the published literature (Fig. 5; Davies and Marshall 1985; Phipps et al. 1985; Marshall and Davies 1988). To interpret the seismic profiles which display the thickness of sediment in milliseconds, a figure of 1,500 ms⁻¹ was used to represent the velocity of the acoustic pulse following the methods of previous authors (Orme et al. 1978; Ryan et al. 2001). The thickness of each of the bioherms is not uniform. To take into account the variation in bioherm thickness, the bioherms were spilt into boxes (Fig. 5). For example, half of the area of a bioherm may be approximately 11.25 m thick, whereas the other half may be only 3.75 m thick (Ribbon Bank 3; Table 3). The mass of sediment was calculated by assuming that the

Table 3 Dimensions and mass of *Halimeda* bioherm CaCO₃

Region	Bioherm complex	Area (km ²)	Thickness (m)	Mass CaCO ₃ (Gt)
Lizard Island	Lizard Island region	184	10	2.06
Total		184		2.06
Cooktown	Ribbon 5a	8.4	8.25	0.07
	Ribbon 5b	9.1	3.75	0.04
	Ribbon 4a	21	6	0.14
	Ribbon 4b	14	3.75	0.06
	Ribbon 3a	12.5	11.25	0.16
	Ribbon 3b	12.5	3.75	0.05
	Ribbon 2a	20	11.25	0.25
	Ribbon 2b	20	3.75	0.08
Total		118		0.86

bioherm sediments approximate a box shape with the area of each bioherm (width × length) multiplied by the corresponding thickness (Fig. 5). Some bioherms were split into two boxes to estimate the appropriate volume

of the bioherms as a whole, e.g. Ribbon 3a, 2b (Fig. 5; Table 3).

Carbonate content

The carbonate content of the bioherms has been investigated by vibrocoring studies in both the Lizard Island and Cooktown regions (Orme 1985; Marshall and Davies 1988). Marshall and Davies (1988) estimated, from twenty 5-m vibrocores taken in the Cooktown region, that the carbonate content within the bioherms averages approximately 75%. Four vibrocores from the Lizard Island region revealed that the carbonate content (acid soluble) within the top 4 m of the bioherms varies between 73 and 99% (Orme 1985). A fifth core taken from the edge of one of the bioherms revealed that the carbonate content of the bioherms increases progressively upwards above the peat substratum, varying between 20 and 90% (core 92; Orme 1985). This core is marginal

Fig. 5 **a** Seismic profile of *Halimeda* bioherm, Ribbon Bank 3, behind Ribbon Reef 3 in the Cooktown region [modified from Marshall and Davies 1988 (Fig. 2, profile b)]. The black dashed rectangles (3a and 3b) outlines how Ribbon Bank 3 was split into two boxes in order to calculate the volume of carbonate sediment. **b** The mass of sediment was conservatively estimated by assuming that the bioherm sediments approximate a box shape with the area of each bioherm ($L \times W$) multiplied by the corresponding thickness (T). **c** The volume of 3a was calculated by multiplying the area ($L_a \times W$; 12.5 km²) by the thickness of the bioherm (T , 11.25 m; Table 3). **d** The volume of 3b was calculated by multiplying the area ($L_b \times W$; 12.5 km²) by the thickness of the bioherm (T_b , 3.75 m; Table 3). The volume of Ribbon Bank 3 is calculated as the sum of boxes 3a and 3b

therefore it is assumed that the carbonate content of the bioherms is 75% throughout.

Results

Reef and bioherm calcium carbonate

This study estimates that the ribbon reefs of the Lizard Island and Cooktown regions cover areas of approximately 18.5 and 20.5 km² and comprise approximately 0.52 and 0.92 Gt CaCO₃, respectively (Table 2). The *Halimeda* bioherms of the Lizard Island and Cooktown regions cover areas of approximately 184 and 118 km² and comprise approximately 2.06 and 0.86 Gt CaCO₃, respectively (Table 3).

Thus, the ratio of ribbon reef to *Halimeda* bioherm CaCO₃ is approximately 1:4 and 1:1 for the Lizard Island and Cooktown regions, respectively (Fig. 6; Table 4).

Discussion

Reefs versus bioherms

The *Halimeda* bioherms contain at least as much (and up to four times more) CaCO₃ sediment as the adjacent ribbon reefs in the NGBR (Table 4). This finding is in agreement with assertions that *Halimeda* bioherms contain more carbonate sediment than the adjacent reef platforms (Flood 1984; Hillis-Colinvaux 1986b; Marshall and Davies 1988; Freile and Hillis 1997). The ratio of reefal to bioherm CaCO₃ varies within the NGBR province from 1:1 in the Cooktown region to 1:4 in the Lizard Island region. The variation in the ratio is a consequence of the differences in the thicknesses and extent of the bioherms in the two regions. For example, in the Lizard Island region the bioherms form a series of

Fig. 6 Mass of carbonate sediments accumulated within the ribbon reefs and *Halimeda* bioherms of the Lizard Island and Cooktown regions of the Northern Great Barrier Reef

large ridges which traverse most of the outer shelf, with an average thickness of 10 m (maximum 19 m) and an area of at least 184 km². Whereas the Cooktown region bioherms form discrete mounds behind each ribbon reef with maximum and minimum thickness of 11.25 and 3.75 m, respectively, they cover a combined area of approximately 118 km². The size differences in the *Halimeda* bioherms in these two regions is the result of the morphology of the shelf affecting the growth potential of the *Halimeda*. The formation of the bioherms is related to up-welling of nutrient-rich waters from the Coral Sea. The timing and amount of water intruding onto the shelf during the Holocene is controlled by sea level rise and the dimensions of the reef passes (bathymetry and width). For example, Wolanski et al. (1988) suggest that *Halimeda* Ribbon Bank 5 is small because it only received nutrients from one reef passage whereas the larger banks (bioherms) behind Ribbon Reefs 2, 3 and 4 were each fed by two passages (Fig. 3). The absence of bioherms behind Ribbon Reef 1, Lena Reef, Ribbon Reef 6 and Pearl Reef is attributed to the channels being either too wide or too shallow to induce sufficient upwelling to support bioherm development. Wolanski et al. (1988) suggested that the presence of ribbon reefs at least 4 km long and reef passages <1 km wide and 40–45 m deep are necessary for the development of bioherms.

Halimeda distribution

The extent of *Halimeda* bioherm formation within the GBR province has yet to be adequately assessed. Detailed bathymetric sampling has revealed that *Halimeda* sediments make up to 5–65% of the inter-reefal sediments on the outer shelf of the GBR province (Maxwell 1968). Drew and Abel (1983) estimated that 2,000 km² of the GBR province seabed is carpeted with *Halimeda* vegetation. Standard monochrome aerial photographs of the far NGBR (between 12.3°S and 13.5°S) reveal the presence of dark circular patches approximately 300 m in diameter. These patches were initially interpreted as submerged reefal shoals, however, it has also been suggested that they could be *Halimeda* bioherms (Hopley 1978; Drew and Abel 1988). Seismic profiling transects of the NGBR (from Lloyd Island to Hibernia Entrance and from Restoration Island to Second Small Reef) in the region adjacent to Portland Roads and the Lockhart River reveal the presence of substantial *Halimeda* bio-

Table 4 Mass of CaCO₃ accumulated by the ribbon reefs and *Halimeda* bioherms of the Lizard Island and Cooktown regions during the Holocene

Region	Reef CaCO ₃ (Gt)	<i>Halimeda</i> CaCO ₃ (Gt)	Ratio of reef: <i>Halimeda</i> CaCO ₃
Lizard Island	0.52	2.06	1:4
Cooktown	0.92	0.86	1:1

herms on the outer shelf in this region (J.S. Jell, personal communication). Given reports of luxuriant *Halimeda* meadows principally at 20–40 m below sea level on the GBR (Drew 1983; Drew and Abel 1985), Hillis (1997) suggested that it is likely that additional *Halimeda* bioherms will be discovered.

Previous studies have indicated that the *Halimeda* bioherms may have begun to develop prior to the initiation of reef colonization of topographic highs on the shelf (Marshall and Davies 1988). It has been suggested that the locus of carbonate deposition on the NGBR shelf shifted from bioherm development (between 10 and 8.5 kyr BP) when the shelf was initially flooded, to coral reef development when the eroded karst remnants of the Pleistocene ribbon reefs were transgressed and served as sites for Holocene reef colonization (Hopley 1994). The common delay in reef colonization of newly flooded topographic highs within the NGBR is probably related to high nutrient levels which would have favoured *Halimeda* growth (Davies et al. 1985; Marshall and Davies 1988; Hopley 1994). It has been proposed that changes in oceanic circulation or climate then favoured the development of coral reefs, on topographic highs, between 8,000 and 4,000 years BP (Davies et al. 1985). *Halimeda* bioherm development may have been reduced during the main phase of reef growth. Once the Holocene ribbon reefs had attained a sufficient height in relation to sea level, the area behind the ribbon reefs would have again become sufficiently sheltered enough to allow *Halimeda* bioherm development which continues to this day (Davies and Marshall 1985; Marshall and Davies 1988; Hopley 1994). If this model of Holocene shelf evolution is correct, *Halimeda* calcification within the NGBR may have released a pulse of CO₂ to the early Holocene atmosphere.

Carbonate budget

Rees (2006) estimated that the coral reefs of the GBR (North and Northeastern Australia) accumulated 1,709 Gt CaCO₃ (205 Gt C) over the last 10,000 years. This mass balance of CaCO₃ was estimated using the reef area estimate of 4.492×10^4 km² calculated using Spalding et al.'s (2001) reef area estimate for Australia minus the area of Ningaloo Reef, the Houtman Abrolhos Islands, Christmas Island and Cocos-Keeling Islands (Sheppard and Wells 1988). If it is assumed that 0.6 mol of CO₂ is available for release to the atmosphere per mole of CaCO₃ deposited in the marine environment (Ware et al. 1991; Zeebe and Wolf-Gladrow 2001), the *Halimeda* bioherms of the Lizard Island and Cooktown regions had the potential to release 0.54 and 0.23 Gt CO₂ to the atmosphere during the last 10 kyrs, respectively.

Assuming that the conservative ratio of ribbon reef to *Halimeda* bioherm CaCO₃ calculated here for the Cooktown region (1:1) holds true for the entire NGBR, it is possible to estimate the approximate mass of car-

bonate sediments within the *Halimeda* bioherms of the whole NGBR. Using Kinsey and Hopley's (1991) estimate of the total area covered by the GBR ribbon reefs (approximately 1,081 km²) and conservatively assuming the thickness of the ribbon reefs to be 10 m, this study estimates that the ribbon reefs and hence the *Halimeda* bioherms of the NGBR may have accumulated at least 32 Gt CaCO₃ during the Holocene. Indeed *Halimeda* bioherms have been found to have similar accretion and production rate compared to coral reefs (Table 5). It is important to note that ribbon reefs are mainly restricted to the NGBR hence these calculations are restricted to the northern province of the GBR and that this estimate is confined to the *Halimeda* bioherms behind the ribbon reefs, it does not include *Halimeda* bioherms in the Swains Reef complex (Southern GBR).

While the mass of carbonate contained within the *Halimeda* bioherms of NGBR (~32 Gt CaCO₃; 3.9 Gt C) is small in comparison to that contained within the reefs of the GBR as a whole (1,709 Gt CaCO₃; 205 Gt C) or globally (Table 6; Rees 2006) this perspective mis-represents the likely wider importance of *Halimeda* within the carbon budget because the true extent of this sedimentary facies is probably vastly underestimated (Table 6). It is important to note that *Halimeda* sediments contribute significantly to coral reef and lagoonal facies and can constitute up to 77% of lagoonal sediments on Pacific and Caribbean reefs (Hillis-Colinvaux 1980).

This study provides support for the contention that because bioherms have been found to produce and accumulate carbonate at similar rates to coral reefs, their importance in global carbon cycles is currently underestimated and merits further investigation. The global distribution and areal extent of *Halimeda* deposits are unknown, however the discovery of significant accumulations of *Halimeda* carbonate including; Miskito Channel (SW Caribbean Sea; a band 125 km long reaching thicknesses of 20–30 m), K Bank (Java Sea; approximately 20–52 m thick, covering an area of at least 1,300 km²) and Big Bank Shoals (Timor Sea; a series of 13 submerged banks range from 0.05 to 40 km² with thicknesses up to 55 m), requires that their contribution to the global carbonate budget be better quantified (Roberts et al. 1987a; Hine et al. 1988; Heyward et al. 1997). If the ratio of *Halimeda* bioherm to coral reef carbonate on the shelf of the NGBR established here is even partially applicable globally then the accurate assessment of *Halimeda* distribution, through seismic profiling and vibrocoreing, is a prerequisite to a comprehensive understanding of the marine carbon cycle.

This study estimates the ratio of reefal to *Halimeda* bioherm CaCO₃ within the Northern GBR to fall somewhere in the range 1:1–1:4. Assuming that thick emergent areas of coral reef covers approximately 300×10^3 km² globally, *Halimeda* bioherm carbonate, of Holocene age, could rival the total carbonate derived from Holocene coral reefs alone (Spalding et al. 2001).

Table 5 Comparison of *Halimeda* and coral reef productivity and accumulation rates during the Holocene

Location	Accretion rate (m kyr ⁻¹)	Reference	Year
<i>Halimeda</i>			
NGBR Cooktown Big Bank bioherms ^a	0.75–2	Marshall and Davies	1988
NGBR Lizard Island bioherm core 92 ^a	0.22	Orme	1985
SGBR Swains reef bioherm ^a	2–3.5	Searle and Flood	1988
K Bank bioherm, Java Sea ^a	1.2–5.9	Roberts et al.	1987a
Western Great Bahama bank ^b	2–4	Freile et al.	1995
Bight of Abaco, Bahamas, lagoon ^b	2–3	Neumann and Land	1975
Coral reef			
NGBR Lizard Island ^a	1.1	Rees	2006
NGBR Macgillivray reef ^a	1.4–1.9	Rees	2006
NGBR Yonge ribbon reef ^{c,d}	15.8	Hopley	1994
NGBR Ribbon reef 5 ^{a,c}	1.3–14.2	Davies et al.	1973
GBR windward reefs	4–6	Davies and Hopley	1983
GBR reefs ^{a,c}	1–4.4	Rees	2006
Global reef ^{a,c}	1.16	Rees	2006
Location	Productivity (kg CaCO ₃ m ⁻² year ⁻¹)	Reference	Year
<i>Halimeda</i>			
GBR	2.2	Drew	1983
Moorea Island lagoon, Tahiti ^e	2.3	Freile et al.	1995
Western Great Bahama Bank ^{b,f}	2.4	Freile and Hillis	1997
Pico Feo, San Blas, Panama ^b	2.3	Freile and Hillis	1997
Coral reef			
Seaward reef flat ^e	4	Smith and Kinsey	1976
GBR reefs ^e	2.4	Kinsey and Hopley	1991
GBR ribbon reefs ^e	3	Kinsey and Hopley	1991
Lizard Island reef ^e	4	LIMER	1975

GBR Great Barrier Reef, NGBR Northern Great Barrier Reef, SGBR Southern Great Barrier Reef

^aHolocene mean accretion rates calculated from radiometrically dated cores

^bEstimated from present day values biomass, percent cover, density and crops per year

^cMean Holocene accretion rates

^dEstimated from seismic profile thicknesses and assumed date of transgression (10 kyr before present)

^eEstimated using alkalinity anomaly technique

^fEstimated by extrapolating modern productivity values into Holocene

Table 6 Comparison of *Halimeda* carbon mass balance with other natural reservoirs during the Holocene (adapted from Rees 2006)

Reservoir	Mass carbon (Gt)	Reference	Year
Present day atmosphere as CO ₂	720	Powlson	2005
Deep ocean dissolved inorganic carbon	38,000	Sigman and Boyle	2000
Sediments and crust (Ca, Mg) CaCO ₃	48,000,000	Sigman and Boyle	2000
Terrestrial	2,100	Sigman and Boyle	2000
Present day soil reservoir (organic carbon)	1,500	Powlson	2005
Present day carbon in vegetation	600	Powlson	2005
Global coral reef CaCO ₃	956	Rees	2006
GBR coral reef CaCO ₃	205	Rees	2006
Global <i>Halimeda</i> ^a	576	Hillis	1997
Global <i>Halimeda</i> bioherms ^b	180	Hillis	1997
NGBR <i>Halimeda</i> bioherms ^c	3.9	This study	
NGBR coral ribbon reefs ^c	3.9	This study	

^aCarbon in *Halimeda* sediments, including bioherms, reef lagoons, ridge, fore reefs, reef slopes, banks and bays

^bCarbon in *Halimeda* bioherm sediments

^cEstimated using Kinsey and Hopley's (1991) ribbon reef area of 1,081 km² and the ratio of coral reef: *Halimeda* bioherm carbonate within the Northern Great Barrier Reef (NGBR) of 1:1 established in this study

The areal extent of the *Halimeda* bioherms needs to be better quantified before a confident mass balance for neritic carbonate of Holocene age can be established for the NGBR. However, if the ratio of *Halimeda* bioherm to coral reef carbonate on the shelf of the NGBR established here is even partially applicable globally then

this study concludes that current global budgets for shallow water CaCO₃ sediments, that are based on coral reefs alone, are significantly underestimated.

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