

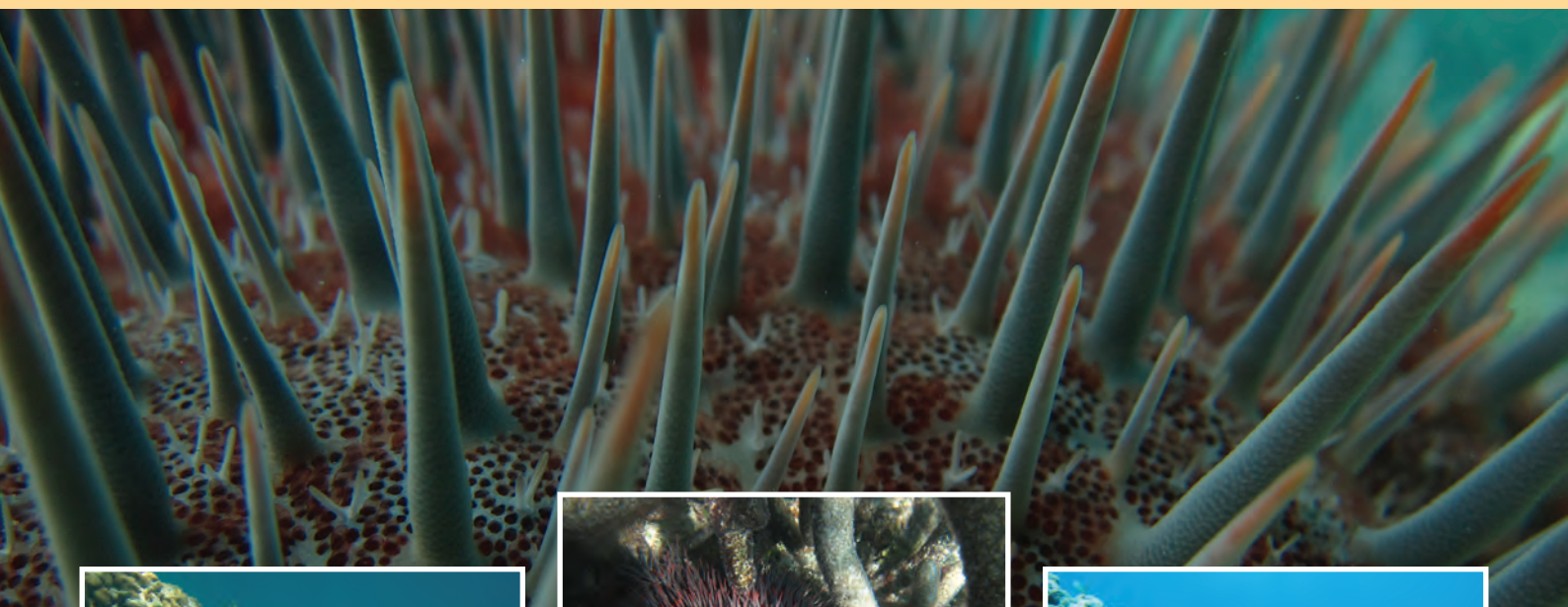


National Environmental
Research Program

TROPICAL ECOSYSTEMS *hub*

Technical Report

The status of crown-of-thorns starfish populations on the Great Barrier Reef from AIMS surveys



Ian Miller and Hugh Sweatman



Australian Government

Department of Sustainability, Environment,
Water, Population and Communities



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Acronyms Used In This Report

GBR	Great Barrier Reef
NERP.....	National Environmental Research Program
COTS	Crown-of-thorns starfish
AIMS	Australian Institute of Marine Science
TC.....	Tropical Cyclone
STC.....	Severe Tropical Cyclone

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Main findings:

Crown-of-thorns starfish

- Outbreaks densities of crown-of-thorns starfish (COTS), *Acanthaster planci*, were recorded on 30% of reefs surveyed in 2012-13, the highest proportion since surveys began in 1986. However the majority were Incipient Outbreaks which suggests that the numbers of starfish that are visible on these reefs may increase. The overall mean density of COTS on the Great Barrier Reef (GBR) remains below historic levels (see [here](#)).
- COTS densities have increased dramatically on reefs in the Cooktown-Lizard Island sector and are at the highest level recorded from this sector since surveys began in 1986.
- Recent increases in COTS abundance in the Cooktown-Lizard Island sector provide further evidence that the source of COTS outbreaks on the northern and central GBR is located in this sector.
- Outbreak densities of COTS were recorded on far southern reefs in the Capricorn-Bunker sector for the first time in 2012 and 2013.
- COTS remain active on far-northern reefs with outbreaks recorded in Princess Charlotte Bay and Cape Grenville sectors.

Coral cover

- Coral cover has varied considerably in the different sectors and current coral cover reflects the sum of the various impacts that have affected reefs in each sector.
- The highest average coral cover was recorded from reefs in the Cape Grenville sector in 2013.
- The lowest average coral cover was recorded from reefs in the Innisfail sector in 2013.
- Though COTS numbers were generally low for a period until the last two years, storm damage from a number of severe tropical cyclones has led to a strong overall decline in coral cover on the GBR in recent years.
- There have been marked declines in coral cover on reefs from the Whitsunday sector south, due mainly to the effects of Severe Tropical Cyclone (STC) Hamish (category 4/5) in March 2009. This intense system uniquely tracked southwest along the GBR reef tract, unlike most cyclones which track from East to West and affect far fewer reefs.
- Coral recovery on reefs in the Innisfail sector has been hampered by a number of cyclones including STC Larry (category 4) in March 2006, Tropical Cyclone (TC) Ellie (category 2) in February 2009 and STC Yasi (category 5) in January 2011.

Introduction

This report provides a summary of the findings from broadscale surveys of the Great Barrier Reef (GBR) using manta tows in the 2012-13 field season. A more detailed summary on the current status of crown-of-thorns starfish status on the GBR from broadscale surveys since 1986 is available on the AIMS Reef Monitoring [web page](#), where details for each sector and for the most recently surveyed reefs in each sector are also available.

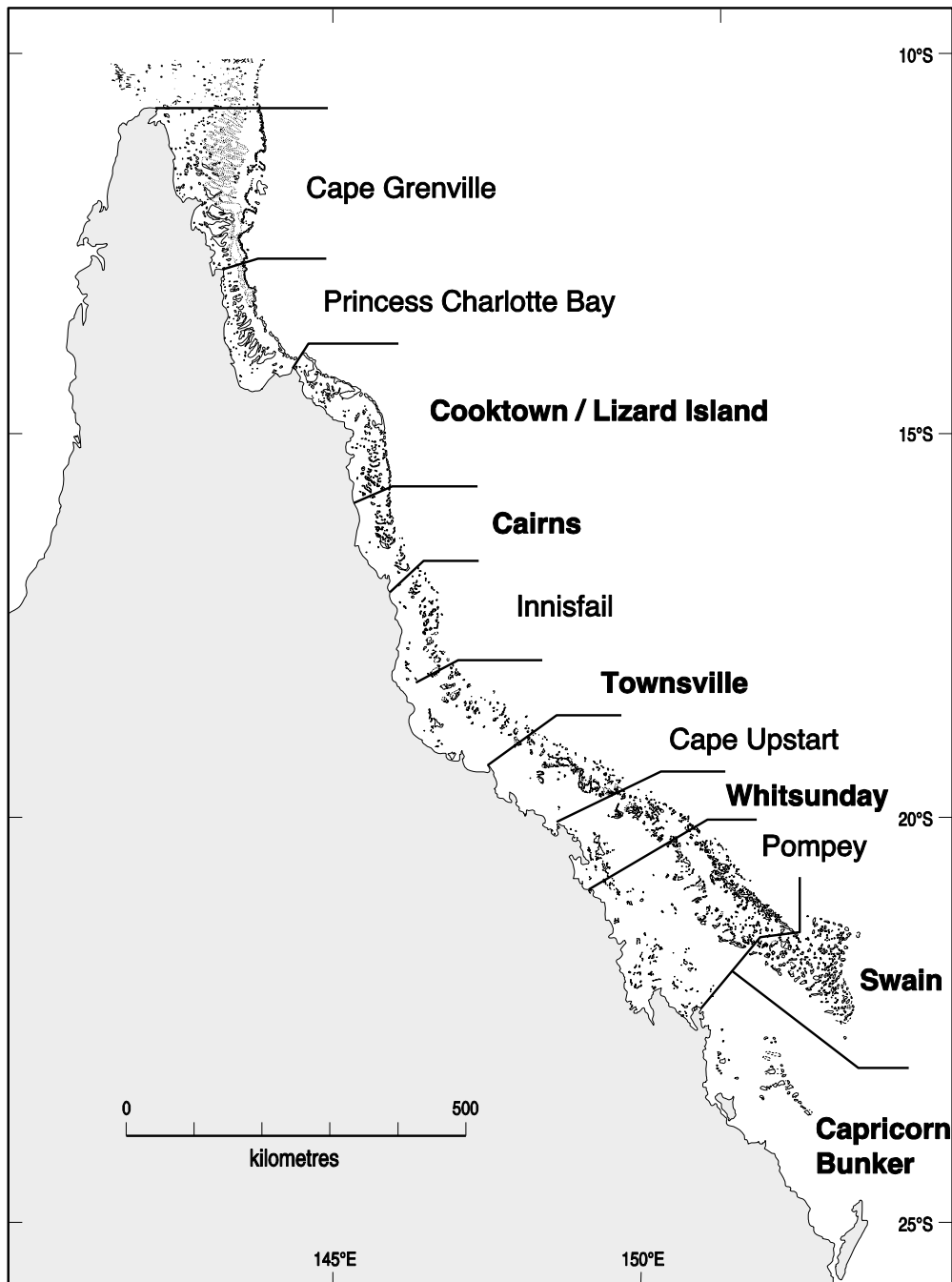


Figure 1 Coast of Queensland showing the Great Barrier Reef and the locations of sectors surveyed by AIMS using manta tows.

Survey Methods

Manta tows were used to survey reefs for COTS. This involves a snorkeler with a manta board (hydrofoil) being towed behind a tender at low speed for periods of two minutes. The tow path generally follows the reef edge and aims to scan a 10m wide swathe of reef slope and starting just below the reef crest. After two minutes the boat stops and idles while the observer records the number of starfish and the number of feeding scars seen, as well as estimates of living coral cover and recently dead standing coral seen in the past two-minute period (using a 10-point scale). For a full description, see Miller et al. (2009).

In principle, *A. planci* populations are described as outbreaks when they reach densities such that the starfish are likely to consume coral tissue faster than the corals can grow. There are various ways of estimating this density, but when starfish numbers seen on a reef with normal levels of coral cover average one starfish per manta tow, the coral cover will certainly be reduced; this is referred to as an "Active Outbreak". Average densities as low as 0.22 starfish per tow can cause damage to coral cover on reefs with average coral cover (~30%); this is referred to as an "Incipient Outbreak."

The status of crown-of-thorns starfish populations

Cape Grenville sector:

Historic trends

For the sector as a whole, coral cover has generally been high (30-50%) since surveys began in 1986 (Figure 2). Low level COTS activity has been observed on reefs in this sector in every year of survey, with outbreak levels recorded in 1996 and in 2013. A steady increase in sector-wide coral cover during the initial years of survey was followed by a decline from 2003 to 2006. This was likely due to storm damage from the effects of STC Ingrid (category 4) in March 2005. COTS may also have contributed to the observed decline; an Incipient Outbreak was recorded at Quoin Island (Fisons Reef) in 2006, even though COTS were below outbreak levels for this sector as a whole. Surveys in 2013 found an overall increase in coral cover on reefs in this sector over the past seven years.

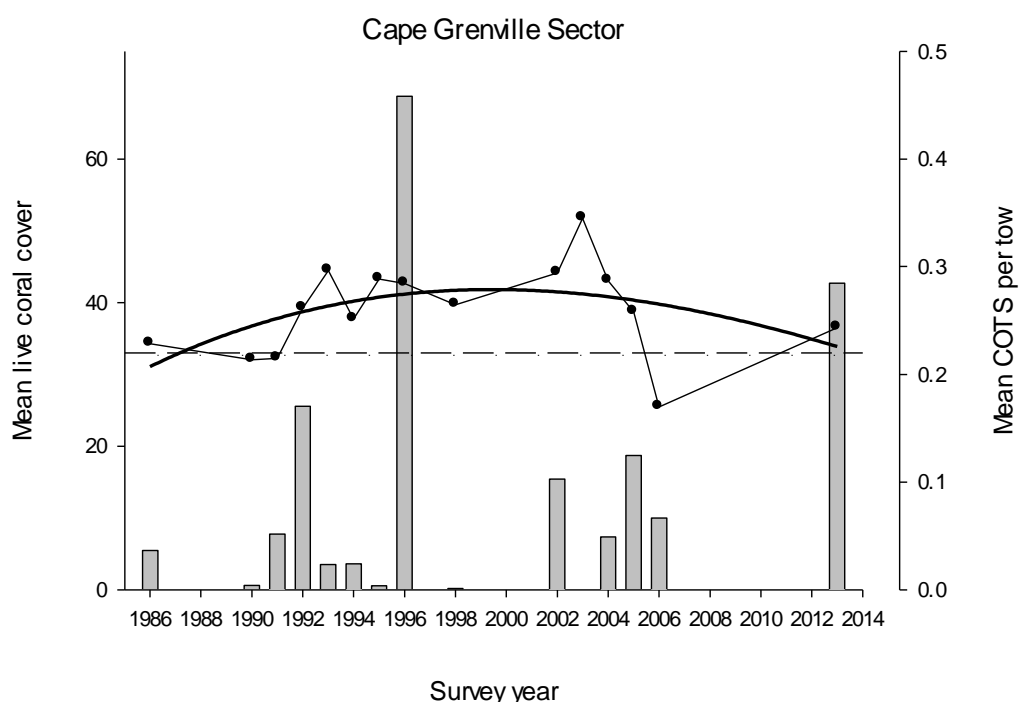


Figure 2 Average coral cover on reefs (line plot; left hand axis) and average density of COTS (bar chart; right hand axis) recorded during manta tow surveys of reefs in the Cape Grenville sector since 1986. Symbols on line plot indicate survey years. Dashed line indicates level at which COTS densities may be expected to have an impact on live coral cover. The smooth solid line represents a cubic function fitted to the values for coral cover.

Recent surveys

Eleven Reefs were surveyed in 2013 (Table 1). COTS were active on reefs in this sector and at the highest level recorded since 1996 (Figure 2). Average densities of COTS on all reefs surveyed in the sector were at an Incipient Outbreak level which can be expected to reduce living coral cover. COTS outbreaks were recorded at four reefs in 2013, with the highest number of COTS recorded from Quoin Island (Fisons Reef) that was reclassified as an Active Outbreak. Kay Reef, Sir Charles Hardy (1) and Sir Charles Hardy (2) were all classified as Incipient Outbreak. There was no general trend in coral cover on the reefs surveyed in 2013, though cover had declined at a number of reefs since the last survey, including Ashmore Banks (1), Ashmore Banks (3) and Middle Banks (3). In February 2013 there was evidence of mechanical damage to hard corals suggesting recent storm damage.

Table 1 Summary of manta tow survey results for eleven reefs in the Cape Grenville sector in 2013 (click on the reef names for more information).

Reef	Shelf Position	Tows	COTS	COTS per tow	Median % Live Coral Cover	Median % Dead Coral Cover	Median % Soft Coral Cover	Reef Status
KAY	Inner	63	16	0.25	50 to 63	0 to 5	0 to 5	IO
CURD	Inner	32	3	0.09	30 to 40	0 to 5	0 to 5	RE
SIR CHARLES HARDY (1)	Mid	19	17	0.89	50 to 63	0 to 5	0 to 5	IO
SIR CHARLES HARDY (2)	Mid	23	14	0.61	40 to 50	0 to 5	0 to 5	IO
PEARSON (Forty Winks)	Mid	35	3	0.09	20 to 30	0 to 5	0 to 5	NO
MIDDLE BANKS (2)	Mid	10	1	0.1	63 to 75	0 to 5	0 to 5	NO
MIDDLE BANKS (3)	Mid	11	1	0.09	30 to 40	0 to 5	0 to 5	NO
ASHMORE BANKS (1)	Mid	11	0	0	20 to 30	0 to 5	0 to 5	NO
ASHMORE BANKS (2)	Mid	14	0	0	20 to 30	0 to 5	0 to 5	NO
ASHMORE BANKS (3)	Mid	12	0	0	20 to 30	5 to 10	0 to 5	NO
FISONS (Quoin Island)	Mid	7	7	1	5 to 10	0 to 5	0 to 5	AO

Princess Charlotte Bay sector:

Historic trends

Reefs in the Princess Charlotte Bay sector had low level COTS activity in the majority of survey years. Coral cover has remained generally moderate (20-30%) on reefs in this sector but has shown a small decline in the late eighties and in recent years (Figure 3). The shallow decline in sector-wide coral cover during the late eighties was likely due to persistent COTS that exceeded Incipient Outbreak levels for the sector as a whole in 1989 and also the effects of TC Ivor (category 3) that passed through this region in March 1990. Slow recovery in coral cover through to 2001 came to a halt as COTS numbers built up once more in the sector, exceeding Active Outbreak levels in 2004. The ensuing decline in sector-wide coral cover was likely driven by high COTS numbers. However STC Ingrid (category 4) that passed through the northern part of the sector in March 2005 may have contributed to the decline in coral cover seen in 2006. There was subsequently a long gap in surveys until 2013 when sector-wide coral cover had recovered to moderate levels. COTS remain active on reefs in this sector in 2013 but generally below outbreak levels.



Figure 3 Plot showing average coral cover on reefs (line plot; left hand axis) and average density of COTS (bar chart; right hand axis) recorded during manta tow surveys of reefs in the Princess Charlotte Bay sector since 1986. Symbols on line plot indicate survey years. Dashed line indicates level at which COTS densities may be expected to have an impact on live coral cover. The smooth solid line represents a cubic function fitted to the values for coral cover.

Recent surveys

Thirteen reefs were surveyed using manta tows in 2013 (Table 2). Coral cover was moderate (10-20%) on the majority of reefs; the highest cover was recorded at Grub Reef (40-50%). For those reefs with a history of survey, reef-wide live coral cover was similar to that recorded when they were last surveyed. The exception was Osborne Reef where coral cover had declined markedly from a high 30-40% in 2005 to a moderate 10-20% in 2013. Mechanical damage to hard corals visible at the time of survey suggests that storms may have been responsible, though the long interval between surveys makes any attribution speculative.

For the remaining reefs surveyed in 2013 (Pelican Island Reef, Clack Island Reef and Reef 13-124) coral cover was high (30-40%). Coral cover had increased on all three of these reefs since they were last surveyed. In the case of Clack Reef this was despite being classified as an Active Outbreak and that COTS have been present in most past surveys. Reef 13-124 also has a long history of low level COTS activity and COTS were present below outbreak levels in 2013. No COTS were recorded at Pelican Island Reef. Celebration Reef had moderate coral cover and appears to be in the process of recovering from past COTS and storm damage. Coral cover at Morris Reef was similar to that in 1986 but there is no information on how coral cover changed over the intervening period. Reef 13-093, Corbett Reef, Hedge Reef, Magpie Reef, Ogilvie Reef were all surveyed for the first time and all had moderate coral cover (10-20%). COTS were recorded on all of these reefs except for Magpie Reef. Corbett Reef had Incipient Outbreak densities.

Table 2 Summary of manta tow survey results for reefs in the Princess Charlotte Bay sector in 2013 (click on the reef names for more information).

Reef	Shelf	Tows	COTS	COTS per tow	Median % Live Coral Cover	Median % Dead Coral Cover	Median % Soft Coral Cover	Reef Status
OSBORNE	Inner	48	0	0	10 to 20	0 to 5	0 to 5	NO
PELICAN IS	Inner	41	0	0	30 to 40	0 to 5	0 to 5	NO
CLACK	Inner	78	19	0.24	30 to 40	0 to 5	0 to 5	AO
CELEBRATION	Mid	47	1	0.02	10 to 20	0 to 5	0 to 5	NO
BLANCHARD	Mid	109	1	0.01	10 to 20	0 to 5	0 to 5	RE
MORRIS IS	Mid	78	0	0	10 to 20	0 to 5	0 to 5	NO
13-124	Mid	62	4	0.06	30 to 40	0 to 5	0 to 5	NO
GRUB †	Mid	78	1	0.01	40 to 50	0 to 5	0 to 5	NO
OGILVIE *†	Mid	61	1	0.02	20 to 30	0 to 5	0 to 5	NO
MAGPIE *†	Mid	59	0	0	10 to 20	0 to 5	0 to 5	NO
13-093 *†	Mid	40	2	0.05	10 to 20	0 to 5	10 to 20	NO
HEDGE *†	Mid	98	6	0.06	10 to 20	0 to 5	5 to 10	NO
CORBETT *†	Mid	105	24	0.23	10 to 20	0 to 5	0 to 5	IO

* denotes a reef that was surveyed for the first time in 2013. † denotes a reef where only part of the perimeter was surveyed.

Cooktown-Lizard Island sector:

Historic trends

The Cooktown Lizard Island sector has an extensive and complex COTS history since the beginning of surveys in 1986 when sector-wide COTS were at Incipient Outbreak levels. This sector is particularly interesting as the last two (1979 -1991 and 1994-2007) and likely a third (2009 - ?) series of COTS outbreaks on the northern and central GBR have been spawned from reefs in this sector. Coral cover has remained generally moderate (10-30%) for this sector (Figure 4) as impacts due to COTS and cyclones have set back recovery of coral cover as they have occurred.

Initial surveys of reefs in this sector in 1986 revealed outbreak levels of COTS that subsequently declined. Coral cover also declined likely due to COTS feeding activity. Coral cover subsequently increased before declining once more in 1990 due to TC Ivor (category 3) that passed to the north of the sector in March 1990. Sector-wide coral cover then increased until 1995, when there was a build-up of COTS numbers to reach outbreak levels by 1997. Coral cover subsequently declined once more as a result of COTS. Subsequent recovery of coral cover stalled in 2005 due to the effects of STC Ingrid (category 4) that passed to the north of the sector and had a big impact on coral cover on exposed outer-shelf reefs and to a lesser extent to TC Fritz (category 1) that passed through the sector in February 2004. Since that time there has been little change in coral cover that has remained moderate. The latest survey in 2013 indicates a rapid build-up of COTS on reefs in this sector to the highest levels yet recorded. This rapid increase in COTS numbers will have major implications for reefs further to the south in coming years

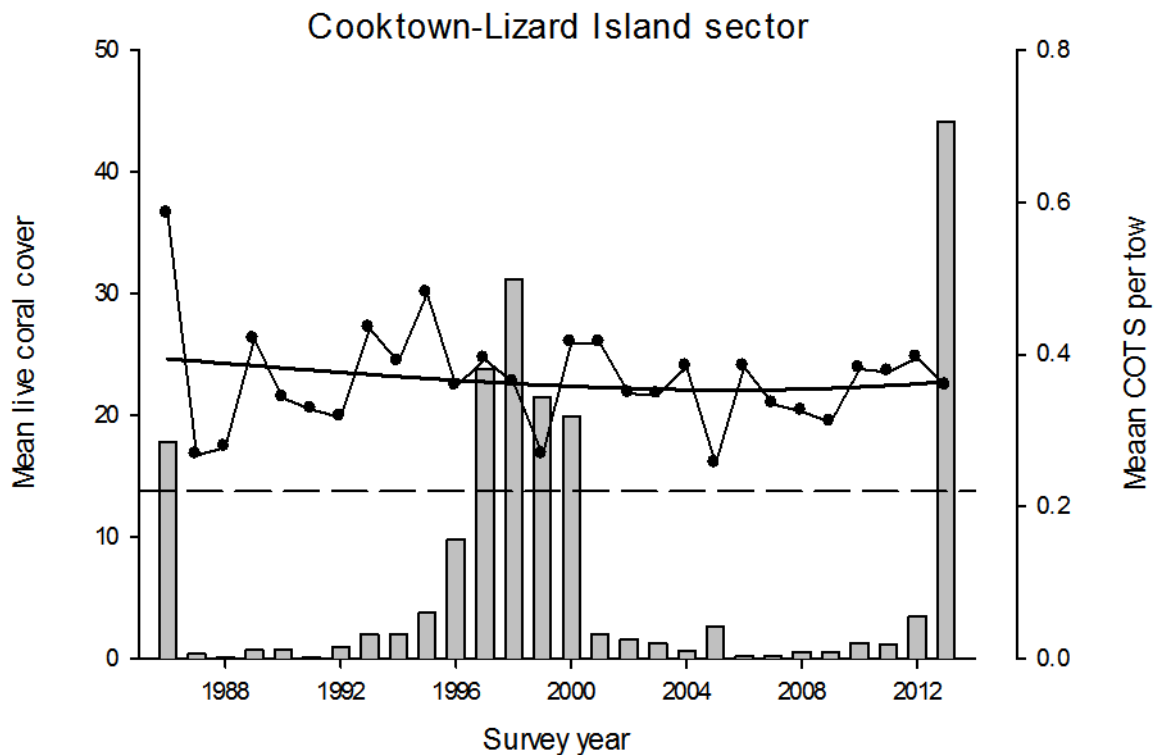


Figure 4 Average coral cover on reefs (line plot; left hand axis) and average density of COTS (bar chart; right hand axis) recorded during manta tow surveys of reefs in the Cooktown-Lizard Island sector since 1986. Symbols on line plot indicate survey years. Dashed line indicates level at which COTS densities may be expected to have an impact on live coral cover. The smooth solid line represents a cubic function fitted to the values for coral cover.

Recent surveys

Surveys in 2013 indicate that there has been a rapid increase in COTS populations on reefs in this sector (Figure 4) and starfish densities are at the highest level since surveys began in 1986. Active Outbreaks (>1.0 COTS per two minute tow, meaning that COTS feeding activity is almost certain to reduce coral cover) were recorded at Two Isles Reef, Forrester Reef, Startle East Reef, Irene Reef and South Direction Island Reef. These included both inshore and mid-shelf reefs. The highest density of COTS was at Two Isles Reef (mean of 2.7 COTS per tow). Eleven reefs were classified as having Incipient Outbreaks (between 0.22 – 1.0 COTS per tow) in 2013. Incipient Outbreak densities mean that COTS activity is likely to reduce coral cover substantially in the future. All outer-shelf reefs and one mid-shelf reef (Reef 15-047) were classified as 'No Outbreak'. Startle-East was the only reef of those surveyed in 2013 that had a recorded COTS outbreak (Incipient) during the previous survey. The status of the majority of the reefs during the previous survey was 'No Outbreak', though some reefs (Eyrle, Irene, Ribbon #6 and Three Isles) had not been surveyed within the previous five years. Three reefs (Helsdon, Lizard Island and MacGillivray) were still classified as 'Recovering' from a previous outbreak when last surveyed in 2010.

Low but gradually increasing numbers of COTS have been recorded on reefs in the Cooktown-Lizard Island sector since 2006. Observations at the start of the previous wave of outbreaks (1994 on) suggested that numbers build up on reefs in this region over a number of years until populations reach densities that produce very large numbers of larvae that colonize and reach outbreak densities on reefs immediately to the south. This now appears to be occurring with the recorded numbers of COTS

already greater than those recorded during the 1990s. The high proportion of relatively small starfish recorded suggests that the populations on these reefs will continue to increase in the next few years, with a substantial loss of coral from present levels, and the likely initiation of a wave of outbreaks that will pass southwards through the central GBR over the next decade.

Table 3 Summary of manta tow survey results for the Cooktown-Lizard Island sector in 2013 (click on the reef names for more information).

Reef	Shelf Position	Tows	COTS	COTS per tow	Median % Live Coral Cover	Median % Dead Coral Cover	Median % Soft Coral Cover	Reef Status
MARTIN	Inner	67	34	0.51	20 to 30	0 to 5	0 to 5	IO
LINNET	Inner	35	34	0.97	30 to 40	0 to 5	0 to 5	IO
TWO ISLES	Inner	25	69	2.76	30 to 40	0 to 5	0 to 5	AO
THREE ISLES	Inner	26	12	0.46	40 to 50	0 to 5	0 to 5	IO
BOULDER	Inner	73	50	0.68	20 to 30	0 to 5	0 to 5	IO
MACGILLIVRAY	Mid	19	5	0.26	30 to 40	0 to 5	0 to 5	IO
LIZARD IS	Mid	86	64	0.74	10 to 20	0 to 5	0 to 5	IO
EYRIE	Mid	67	57	0.85	20 to 30	0 to 5	0 to 5	IO
HELSDON	Mid	48	46	0.96	20 to 30	0 to 5	0 to 5	IO
NORTH DIRECTION IS	Mid	21	15	0.71	20 to 30	0 to 5	0 to 5	IO
SOUTH DIRECTION IS	Mid	45	55	1.22	10 to 20	0 to 5	0 to 5	AO
FORRESTER	Mid	73	152	2.08	10 to 20	0 to 5	0 to 5	AO
MARX	Mid	32	15	0.47	20 to 30	0 to 5	0 to 5	IO
STARTLE (EAST)	Mid	40	49	1.23	10 to 20	0 to 5	0 to 5	AO
15-047	Mid	48	5	0.1	10 to 20	0 to 5	0 to 5	NO
15-077	Mid	41	15	0.37	10 to 20	0 to 5	0 to 5	IO
IRENE	Mid	55	62	1.13	10 to 20	0 to 5	0 to 5	AO
CARTER	Outer	81	0	0	5 to 10	0 to 0	0 to 5	NO
YONGE	Outer	81	0	0	10 to 20	0 to 0	0 to 5	NO
NO NAME	Outer	54	0	0	10 to 20	0 to 5	0 to 5	NO
RIBBON NO.6	Outer	61	0	0	10 to 20	0 to 0	0 to 5	NO
15-034	Outer	32	0	0	10 to 20	0 to 5	0 to 5	NO

Cairns sector:

Historic trends

Reefs have been surveyed in this sector since 1986 (Figure 5) and coral cover has generally been moderate (10-30%). The initial years of survey saw a small decline in sector-wide coral cover, though this could not be explained by COTS or cyclone activity. There was a general increase in overall coral cover on reefs in this sector from 1990 through to 2000, despite the passage of TC Rona (category 2) in February 1999 and persistent low levels of COTS. By 2000 COTS had reached Incipient Outbreak levels and sector-wide coral cover declined through to 2002. The decline was strongly linked to COTS, though TC Steve (category 2) passed through the sector in March 2000. Coral cover subsequently increased up until 2010 before decreasing due to the combined impact of TC Olga (category 1) in January 2010 and STC Yasi (category 4) that passed well to the south in February 2011. Manta tow surveys in 2013 found a recent build-up of COTS (Figure 5).

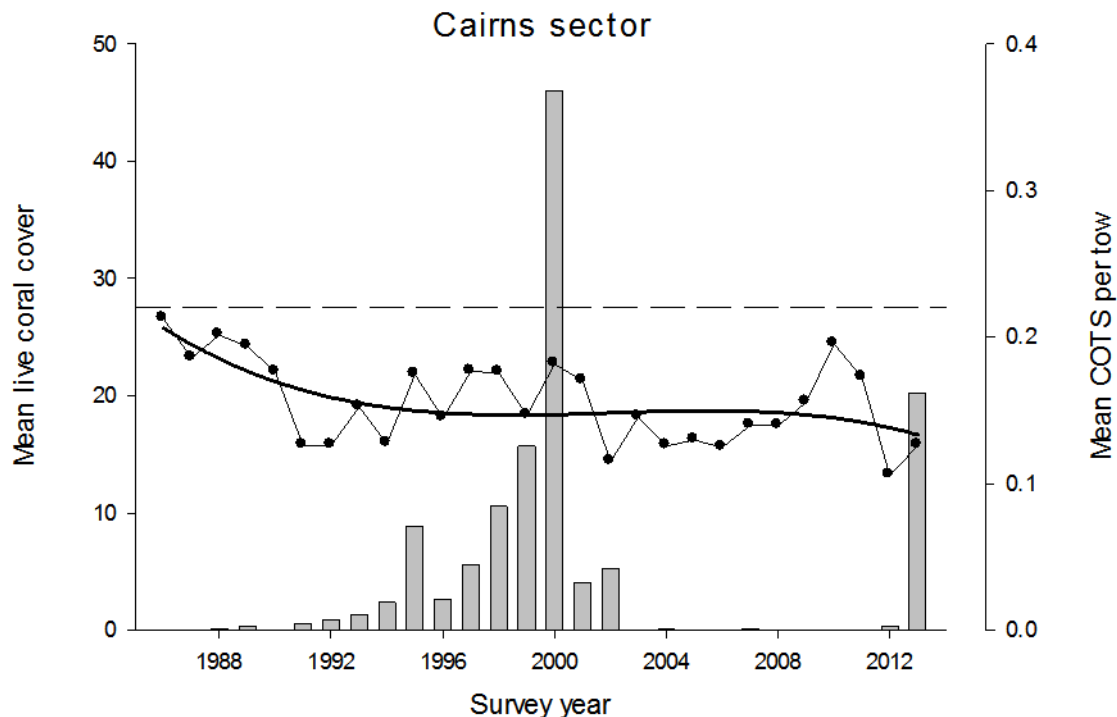


Figure 5 Average coral cover on reefs (line plot; left hand axis) and average density of COTS (bar chart; right hand axis) recorded during manta tow surveys of reefs in the Cairns sector since 1986. Symbols on line plot indicate survey years. Dashed line indicates level at which COTS densities may be expected to have an impact on live coral cover. The smooth solid line represents a cubic function fitted to the values for coral cover.

Recent surveys

Eleven reefs were surveyed in 2013 using manta tows (Table 4). Coral cover on the majority of reefs was moderate (10-30%); the highest cover was recorded at Mackay Reef. A substantial proportion of reefs had low coral cover (0-10%) with the lowest values recorded from Green Island and Michaelmas Reef. Crown-of-thorns starfish were recorded on seven of the eleven reefs that were surveyed. Starfish reached Incipient Outbreak densities on two reefs (Green Island and Reef 16-017) Coral cover on Green Island Reef has declined from 5-10% in 2012 to 0-5% in 2013, most likely due to COTS feeding activity. Coral cover on Reef 16-017 has also declined, from a high 30-40% in 2010 to the current 10-20%. While COTS certainly contributed, the decline is also likely to be partly due to STC Yasi (category 4) that passed some 200km to the south in February 2011.

Coral cover had also declined at three other reefs since the last surveys: at Reef 16-024 cover declined from 20-30% in 2010 to 10-20% in 2013, at Opal(2) Reef cover declined from 20-30% in 2011 to 10-20% in 2013, and cover declined from 10-20% in 2009 to 0-5% in 2013 at Michaelmas Reef. The most recent previous survey of each of these reefs was prior to STC Yasi, so this is likely to have contributed to the decline. No recent changes in coral were recorded on the remaining reefs; these were last surveyed by manta tow in 2012 (except for Middle Cay (B) Reef that was last surveyed in 2007).

The last wave of outbreaks (beginning in 1994) greatly reduced coral cover on reefs in the northern and central GBR. Then, COTS numbers built up on reefs in the Cooktown-Lizard Island region over a number of years. These populations subsequently reached densities that produced very large numbers of larvae that were transported by

prevailing currents and colonized and reached outbreak densities on reefs immediately to the south. In this way, outbreaks cascaded through the central GBR. Recent observations in the Cairns sector are consistent with this pattern being repeated. The high proportion of relatively small starfish seen during scuba searches and the large and increasing number of COTS recorded on reefs immediately to the north suggests that starfish populations on reefs in the Cairns sector will continue to increase in the next few years. Substantial loss of coral cover will follow, and spawning by these populations is likely to generate a wave of outbreaks that will pass southwards through the central GBR over the next decade.

Table 4 Summary of results of manta tow surveys of reefs in the Cairns sector in 2012-13 (click on the reef names for more information).

Reef	Shelf Position	Tows	COTS	COTS per tow	Median % Live Coral Cover	Median % Dead Coral Cover	Median % Soft Coral Cover	Reef Status
GREEN IS	Inner	56	32	0.57	0 to 5	0 to 5	5 to 10	IO
MACKAY	Mid	25	4	0.16	20 to 30	0 to 5	5 to 10	RE
REEF 16-017	Mid	17	15	0.88	10 to 20	0 to 5	0 to 5	IO
REEF 16-024	Mid	46	2	0.04	10 to 20	0 to 5	0 to 5	RE
MIDDLE CAY (B)	Mid	38	1	0.03	5 to 10	0 to 5	5 to 10	NO
HASTINGS	Mid	38	0	0	10 to 20	0 to 0	5 to 10	RE
MICHAELMAS	Mid	127	1	0.01	0 to 5	0 to 0	5 to 10	NO
THETFORD	Mid	40	2	0.05	10 to 20	0 to 5	5 to 10	RE
AGINCOURT NO.1	Outer	33	0	0	5 to 10	0 to 0	0 to 5	NO
ST. CRISPIN	Outer	88	0	0	5 to 10	0 to 0	0 to 5	NO
OPAL (2)	Outer	65	0	0	10 to 20	0 to 0	10 to 20	RE

Innisfail sector:

Historic trends

Manta tow surveys of reefs in this sector show that coral cover increased over the initial years of survey (Figure 6). This increase was driven by two inshore reefs (Normanby and Mabel Islands, and Round and Russell Islands) that had a high (30-50%) coral cover in 1990. Increases in coral cover from 1991 reflect recovery of coral cover on mid shelf reefs affected by COTS outbreaks before 1986 when surveys began. Coral cover on reefs in this sector peaked at this time as there was then a rapid build-up of COTS numbers that continued through to 2000. Coral cover on the reefs in this sector dropped to a low level (0-10%) by 2003 as a result of COTS feeding activity and a major coral bleaching event in 1998. Subsequent recovery in coral cover has been interrupted by a number of cyclones in following years: STC Larry (category 4) in March 2006, TC Ellie (category 2) in February 2009 and STC Yasi (category 5) in January 2011.

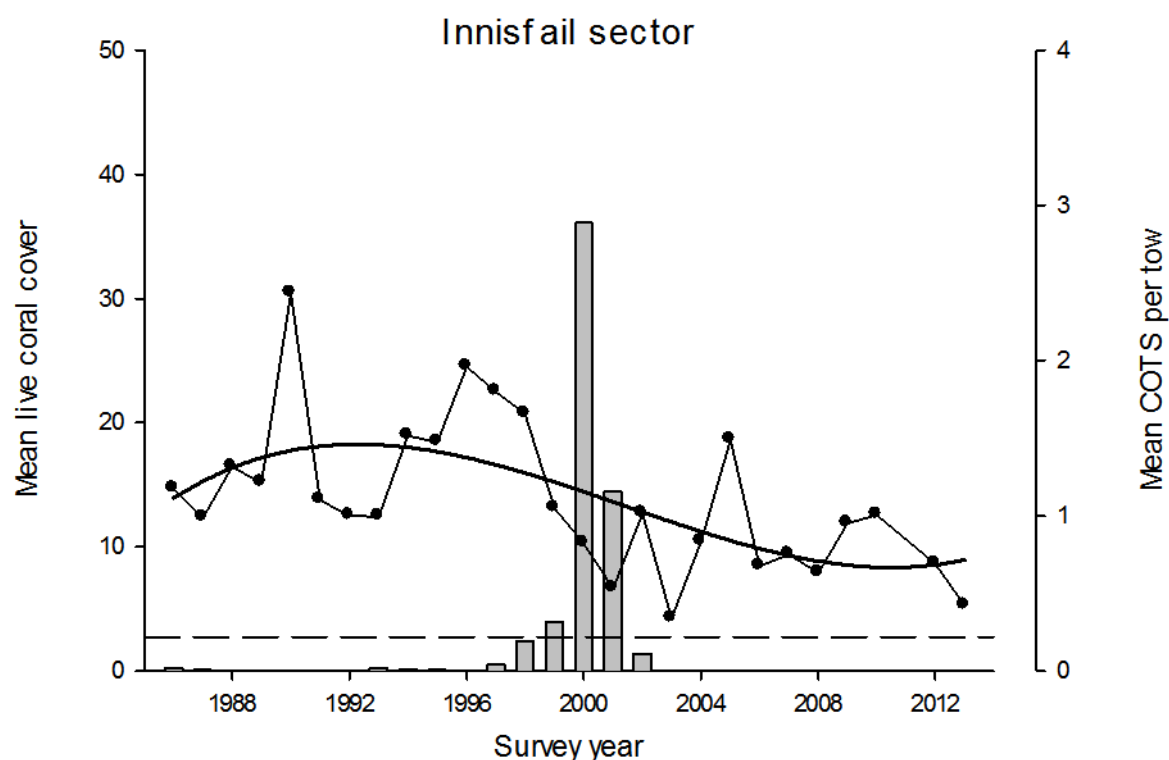


Figure 6 Average coral cover (line plot; left hand axis) and average density of COTS (bar chart; right hand axis) recorded in manta tow surveys of reefs in the Innisfail sector since 1986. Symbols on line plot indicate survey years. Dashed line indicates level at which COTS densities may be expected to have an impact on live coral cover. The smooth solid line represents a cubic function fitted to the values for coral cover.

Recent surveys

Two inshore reefs, Normanby and Mabel Islands and Jessie and Kent Islands, were surveyed in the Innisfail sector in 2013 (Table 5). Six more reefs in this sector will be surveyed in June 2013. No crown-of-thorns starfish were recorded at either reef. Coral cover on these reefs was low (0-10%) and similar to the last survey (2007 and 2002 respectively). STC Yasi (category 4) passed just 20km to the south of Jessie and Kent Islands in February 2011 and most likely caused loss of coral cover there (currently low (0-5%)). Similarly STC Yasi passed 70km to the south of Normanby and Mabel Islands and probably also reduced coral cover at that reef. In both cases the long interval between surveys means that any coral recovery prior to the cyclone cannot be assessed.

Table 5 Summary of results of manta tow surveys of reefs in the Innisfail sector in 2013. More reefs are scheduled for survey in June 2013 (click on the reef names for more information).

Reef	Shelf	Tows	COTS	COTS per tow	Median % Live Coral Cover	Median % Dead Coral Cover	Median % Soft Coral Cover	Reef Status
NORMANBY & MABEL IS	Inner	16	0	0	5 to 10	0 to 5	0 to 5	NO
JESSIE AND KENT IS'S	Inner	19	0	0	0 to 5	0 to 0	0 to 5	NO

Townsville sector:

Historic trends

Changes in coral cover since 1986 strongly reflect patterns of COTS outbreaks on reefs in the Townsville sector (Figure 7). A rapid decline in sector-wide coral cover from 1986 through 1991 was associated with persistent COTS outbreaks with numbers at or exceeding Active Outbreak levels for the sector through to 1992. STC Aivu (category 4) passed through this sector in April 1989 and likely contributed to the decline. There was a subsequent recovery in coral cover through the 1990s until another series of COTS outbreaks beginning in 1990 reduced coral cover again. This decline, though strongly linked to COTS activity, may have been exacerbated by the effects of TC Tessi (category 2) in April 2000. Sector-wide Active Outbreak levels of COTS persisted until 2006. Coral cover began to recover after this time but has been subsequently hampered by the effects of STC Yasi that passed to the north of this sector prior to surveys in 2011. All benthic communities surveyed in the Townsville sector in 2011 had been damaged by storm waves from STC Yasi. Coral destruction was widespread although damage to corals was patchier on inshore reefs. Evidence for cyclone effects included fragmented and rolled corals, exfoliation of the reef matrix, redistribution of old and new coral rubble and the appearance of new underwater ramparts of rubble.

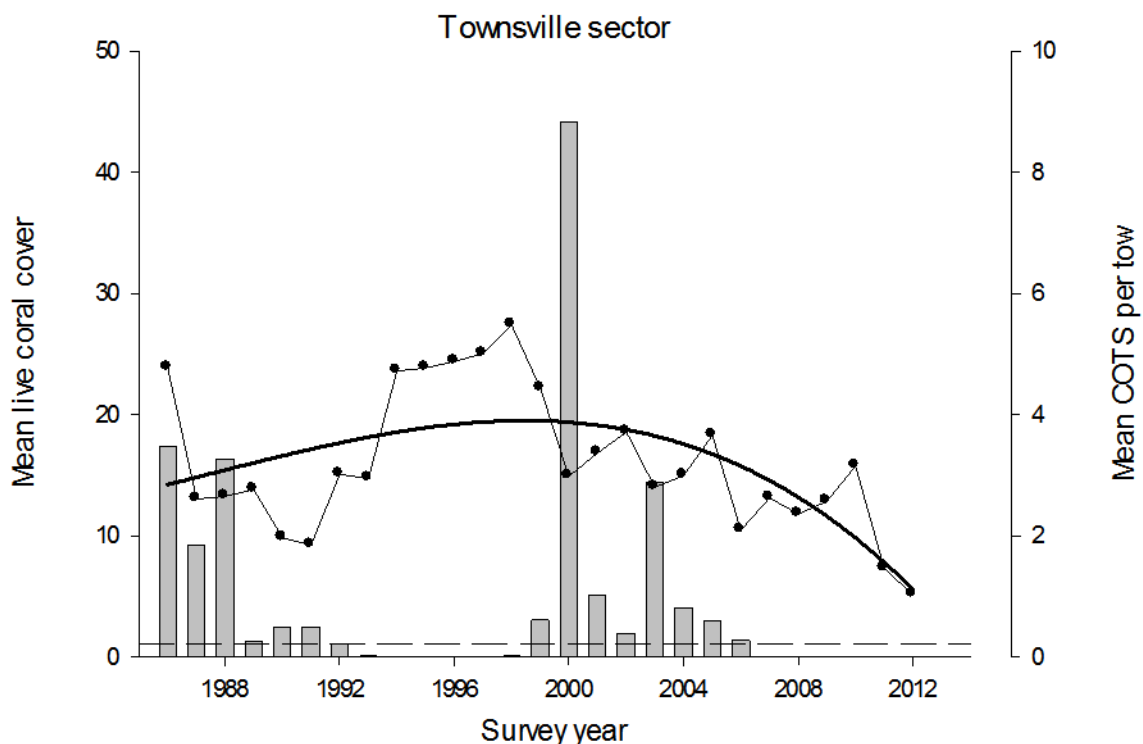


Figure 7 Average coral cover on reefs (line plot; left hand axis) and average density of COTS (bar chart; right hand axis) recorded during manta tow surveys of reefs in the Townsville sector since 1986. Symbols on the line plot indicate survey years. Dashed line indicates level at which COTS densities may be expected to have an impact on live coral cover. The smooth solid line represents a cubic function fitted to the values for coral cover.

Recent surveys

The most recent surveys were of nine reef perimeters using manta tow (Table 6) in 2012 (10 reefs remain scheduled to be surveyed in June 2013). The median reef-wide

live coral cover was very low (<5%) on eight of the reefs. Little Kelso Reef had the highest median reef-wide coral cover at a low 5-10%. While these reefs have historically had low coral cover as a result of major COTS outbreaks before 2006, the declines in hard coral cover recorded in 2012 were attributed to storm damage. STC Yasi (category 4) passed north of the Townsville sector in February 2011, and surveys found evidence of patchy storm damage on most reefs in the Townsville sector, generally on the northern and eastern facing areas of each reef. Median reef-wide coral cover had been reduced from moderate levels (20-30%) to very low levels observed on Helix, Knife, Fork and Roxburgh reefs and reductions from low (5-10%) to very low levels were recorded on Grub and Rib reefs. Coral cover remained the same at three reefs (Chicken, Fore & Aft and Little Kelso). Chicken Reef was surveyed in 2011 prior to Yasi and a year later coral cover had decreased from low to very low levels. Fore & Aft Reef had not been surveyed by manta tow since 2008.

Table 6 Summary of manta tow survey results for reefs in Townsville sector in 2012 (click on the reef names for more information).

Reef	Shelf	Tows	COTS	COTS per tow	Median % Live Coral Cover	Median % Dead Coral Cover	Median % Soft Coral Cover	Reef Status
LITTLE KELSO	Mid	32	0	0	5 to 10	0 to 5	0 to 5	RE
RIB	Mid	34	0	0	0 to 5	0 to 5	0 to 5	RE
ROXBURGH	Mid	20	0	0	0 to 5	0 to 0	0 to 5	NO
FORE AND AFT	Mid	52	0	0	0 to 5	0 to 0	0 to 5	RE
HELIX	Mid	14	0	0	0 to 5	0 to 5	0 to 5	RE
GRUB	Mid	42	0	0	0 to 5	0 to 0	0 to 5	NO
KNIFE	Outer	28	0	0	0 to 5	0 to 0	0 to 5	RE
FORK	Outer	34	0	0	0 to 5	0 to 0	0 to 5	RE
CHICKEN	Outer	41	0	0	0 to 5	0 to 0	0 to 5	RE

Cape Upstart sector:

Historic trends

As in the Townsville sector, changes in coral cover in the Cape Upstart sector strongly reflect the patterns of COTS outbreaks on those reefs. From 1986 coral cover decline with sector-wide outbreak levels of COTS recorded through to 1991. Coral cover recovered somewhat over the ensuing decade, despite the passage of TC Celeste (category 3) through the sector in January 1997, before declining once more as COTS numbers increased from 2003. A further decline in coral cover recorded in 2011 was attributed to the effects of Severe Hamish (category 5) in March 2009 and STC Yasi (category 4) that passed to the east and the north of this sector respectively in January 2011 prior to surveys.

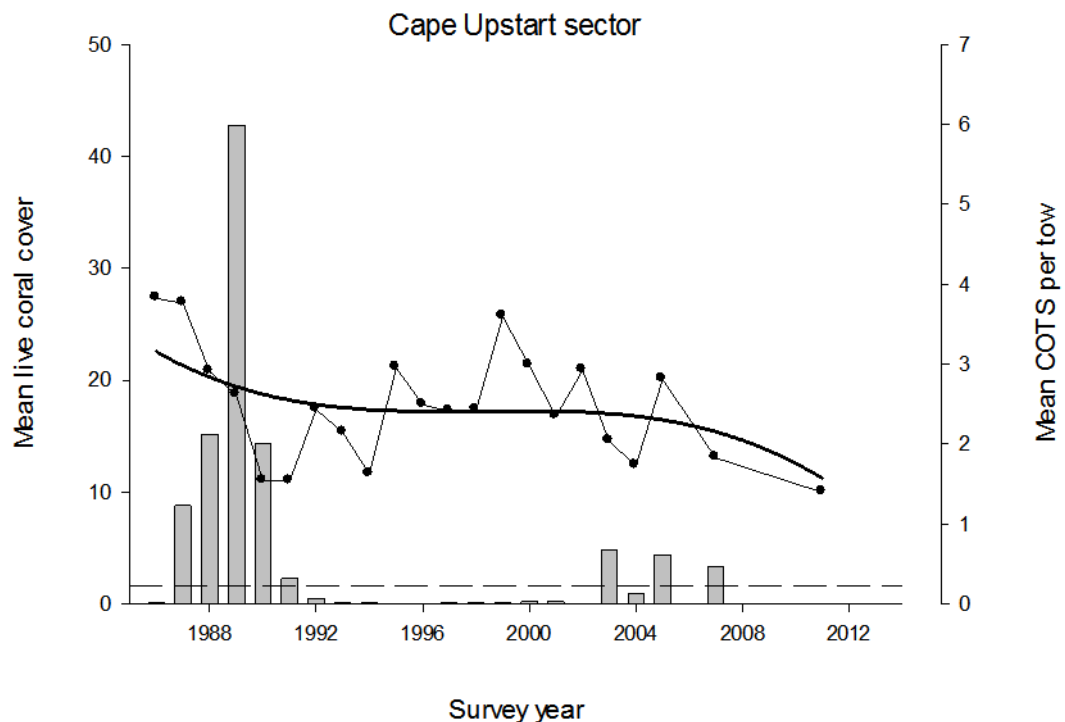


Figure 8 The average coral cover on reefs (line plot; left hand axis) and average density of COTS (bar chart; right hand axis) recorded during manta tow surveys of reefs in the Cape Upstart sector since 1986. Symbols on line plot indicate survey years. Dashed line indicates level at which COTS densities may be expected to have an impact on live coral cover. The smooth solid line represents a cubic function fitted to the values for coral cover.

Recent surveys

The last time this sector was surveyed using manta tows was in 2011 when two reefs were surveyed (Table 7). Six reefs remain scheduled to be surveyed in 2013. No COTS were recorded during these surveys. Coral cover was low (5-10%) at both reefs. Coral cover at Viper Reef had declined substantially since it was last surveyed in 2005 (from 30-40% to 5-10%). This decline may be partly attributable to STC Yasi (category 4) January 2011 given the obvious signs of wave damage to the benthos (similar to that observed in the Townsville sector). Coral cover at Bowden Reef had remained relatively stable since the last survey in 2007.

Table 7 Summary of manta tow survey results for two reefs in the Cape Upstart sector in 2011 (click on the reef names for more information).

Reef	Shelf	Tows	COTS	COTS per tow	Median % Live Coral Cover	Median % Dead Coral Cover	Median % Soft Coral Cover	Reef Status
BOWDEN	Mid	77	0	0	5 to 10	0 to 5	0 to 5	RE
VIPER	Outer	27	0	0	5 to 10	0 to 0	0 to 5	NO

Whitsunday sector:

Historic trends

Overall coral cover has declined in this sector since surveys began in 1986 (Figure 9). This long term decline has been due to a variety of factors. The initial decline in sector-

wide coral cover corresponded to high COTS populations between 1989 and 1992. Coral cover was also affected by the passage of TC Justin (category 1) in March 1997. Recovery was further hampered by a bleaching event in 2002. Surveys since 2007 have seen a precipitous decline in coral cover on reefs in this sector (Figure 9). This decline has been partially due to COTS activity on some reefs, but it is mainly due to the effects of STC Hamish (category 5) in March 2009 and TC Ului (category 3) in March 2010.

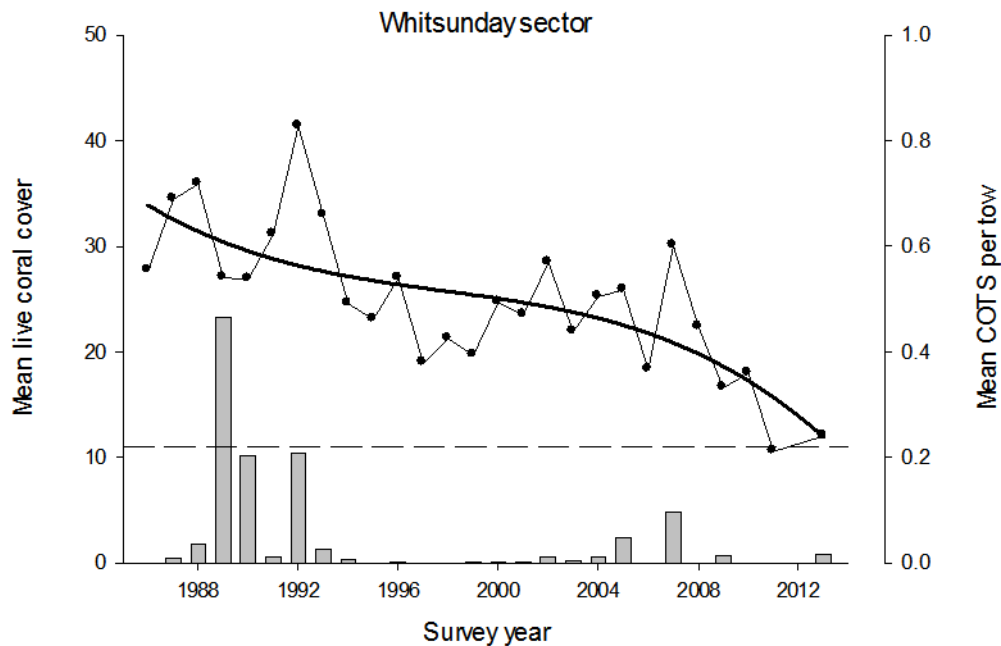


Figure 9 Average coral cover on reefs (line plot; left hand axis) and average density of COTS (bar chart; right hand axis) recorded during manta tow surveys of reefs in the Whitsunday sector since 1986. Symbols on line plot indicate survey years. Dashed line indicates level at which COTS densities may be expected to have an impact on live coral cover. The smooth solid line represents a cubic function fitted to the values for coral cover.

Recent surveys

Nine reefs were surveyed using manta tow (Table 8). All outer shelf reefs had very low coral cover (0-5 %). These reefs are in the early stages of recovery after being stripped of most of their live coral cover by the full impact of STC Hamish (category 5) that passed within 30km of these reefs in March 2009. Inner and midshelf reefs were less damaged by STC Hamish than the outer shelf reefs were. All reefs in this sector were also affected by TC Ului, a category 2 storm that passed through this sector in March 2010. Coral cover on mid-shelf reefs was moderate in 2013 (10-20%) and similar to the value recorded in the last survey in 2011. Coral cover had increased at one reef (20-104), the first signs of recovery in coral cover on a reef that had previously been affected by COTS (2005-2007), STC Hamish (2009) and TC Ului (2010). The waters around the inshore reefs were unusually clear, which allowed three reefs to be surveyed by manta tow for the first time since 2005. Coral cover on all three of these inshore reefs had declined since they were last surveyed. Coral cover at Border Island and Langford and Bird Island has declined from 10-20% in 2005 to 5-10% in 2013. Coral cover at Hayman Island declined similarly from 20-30% in 2005 to 10-20% in 2013. Given the eight year break between surveys, the reason for the decline is not known with any certainty. However the major declines in coral cover at both Border Island and Hayman Island and to a lesser extent at Langford and Bird Islands, occurred on exposed

parts of the reef, which suggests storm damage from the cyclones that have affected this region in recent years (particularly TC Ului that passed through the Whitsunday islands in March 2010) and these have likely played a major role in the observed decline.

COTS were seen on two of the nine reefs that were surveyed by manta tow (Table 8). One COTS was observed on the back of Reef 20-104. Though this constituted a localised Incipient Outbreak, a lack of feeding scars suggested that starfish densities were unlikely to be a threat to reef-wide live coral cover in the immediate future. Similarly three large COTS were seen on the back reef at Langford and Bird Island, this was also enough to constitute a localised Incipient Outbreak. Though the large size and number of COTS suggest that they may have some impact on coral cover on this part of the reef, overall this density of COTS would not be considered to be a threat to coral cover at the reef level.

Table 8 Summary of results of manta tow surveys of reefs in the Whitsunday sector in 2013 (click on the reef names for more information).

Reef	Shelf Position	Tows	COTS	COTS per tow	Median % Live Coral Cover	Median % Dead Coral Cover	Median % Soft Coral Cover	Reef Status
HAYMAN IS	Inner	30	0	0	10 to 20	0 to 5	10 to 20	NO
LANGFORD & BIRD IS'S	Inner	30	3	0.1	5 to 10	0 to 0	10 to 20	NO
BORDER ISLAND A	Inner	58	0	0	5 to 10	0 to 0	20 to 30	NO
19-131	Mid	49	0	0	10 to 20	0 to 5	0 to 5	NO
19-138	Mid	31	0	0	10 to 20	0 to 5	0 to 5	RE
20-104	Mid	22	1	0.05	10 to 20	0 to 0	0 to 5	RE
SLATE REEF	Outer	38	0	0	0 to 5	0 to 0	0 to 5	NO
HYDE	Outer	50	0	0	0 to 5	0 to 0	0 to 5	NO
REBE	Outer	37	0	0	0 to 5	0 to 0	0 to 5	NO

Pompey Sector:

Historic trends

For many years (1986 to 2008), reefs in the Pompey sector had high (30-50%) coral cover (Figure 10). No Active Outbreaks were recorded in this sector in early surveys through to 1992. Only one reef (21-155) was surveyed in 1992, and that had an Active Outbreak, so the high coral cover and high COTS numbers recorded during that year is unlikely to reflect patterns in the sector as a whole. In general, small numbers of COTS (well below outbreak levels) have been recorded from this sector in the majority of survey years. Between 2004 and 2006 there was an increase in COTS activity in this sector that peaked in 2008 at levels that would be expected to impact sector-wide coral cover. From 2008 coral cover declined precipitously. This was due to the impact of STC Hamish (category 5) in March 2009. This system caused extensive damage to reefs in this sector. Coral destruction was widespread including fragmented and rolled corals, exfoliation of the reef matrix, redistribution of old and new coral rubble and the presence of new underwater ramparts of rubble. More recent surveys show that COTS remain active in this sector despite the widespread removal of coral cover.

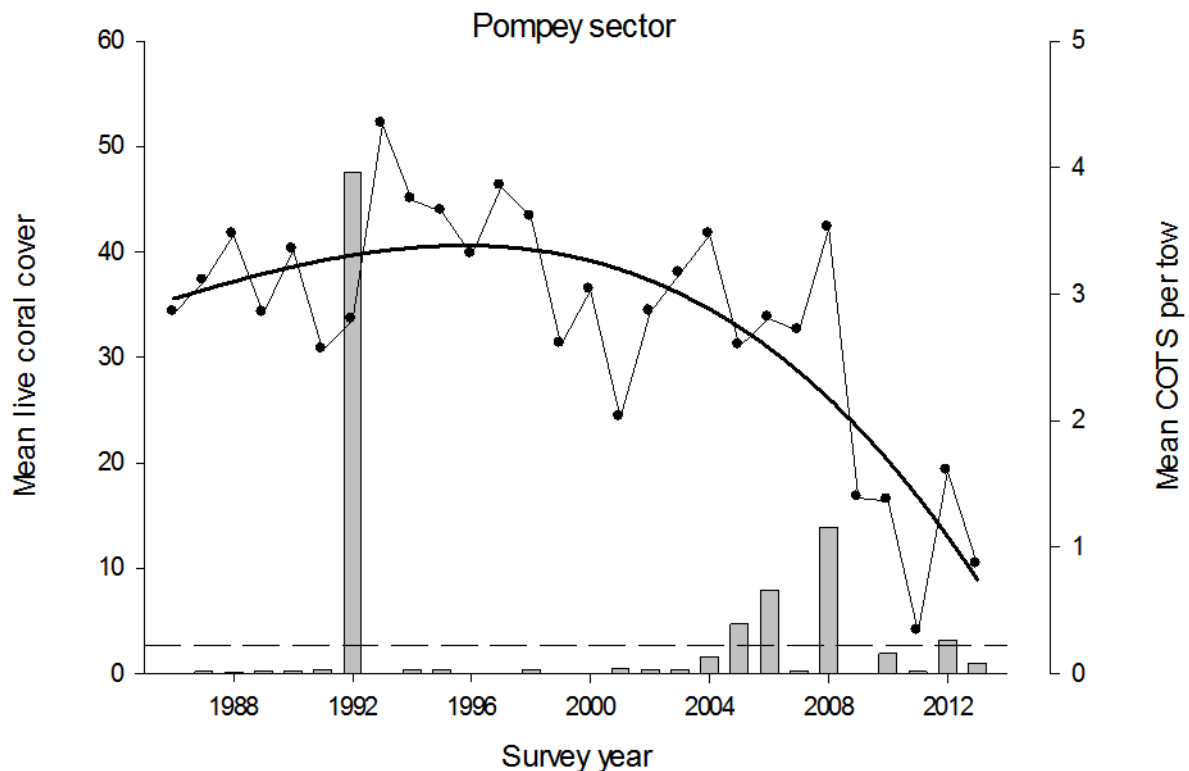


Figure 10 Average coral cover on reefs (line plot; left hand axis) and average density of COTS (bar chart; right hand axis) recorded during manta tow surveys of reefs in the Pompey sector since 1986. Symbols on line plot indicate survey years. Dashed line indicates level at which COTS densities may be expected to have an impact on live coral cover. The smooth solid line represents a cubic function fitted to the values for coral cover.

Recent surveys

Perimeters of six reefs in the Pompey sector were surveyed using manta tow in 2013 (Table 9). COTS were only recorded at Creal Reef, but in numbers high enough for this reef to be reclassified as having an Incipient Outbreak. COTS had only been recorded in very low numbers on three occasions at Creal Reef since surveys began in 1986. The COTS were aggregated along one of the few sections of reef where large branching corals had escaped the ravages of STC Hamish in 2009. As such the prognosis for rapid recovery of this section of Creal Reef is poor. Reefs in the Pompey sector continue to be a centre for COTS activity, with outbreaks of COTS recorded at six reefs in this sector since 2008. This may represent the tail of the third wave of outbreaks that was first seen on reefs north of Cooktown in 1994.

Median reef-wide live coral cover was low (<10%) on all but one reef, due either to past COTS outbreaks (one reef) or the devastating effects of STC Hamish at the others. Coral cover was high at Packer Reef (30-40%), because Packer Reef consists of two emergent reefs separated by a narrow deeper channel that lie within a larger reef complex. The reef was therefore partially sheltered from the effects of STC Hamish, so the protected edges of the channel retained much of their coral cover. There was a stark difference between the lush coral growth in the channel, where coral cover was close to 100%, and the pulverized coral skeletons covered by turf algae in nearby sections of reef that had been exposed to cyclonic waves.

Table 9 Summary of manta tow survey results for the Pompey sector in 2013 (click on the reef names for more information).

Reef	Shelf Position	TOWS	COTS	COTS per tow	Median % Live Coral Cover	Median % Dead Coral Cover	Median % Soft Coral Cover	Reef Status
CONDER	Mid	69	0	0	0 to 5	0 to 0	0 to 5	NO
EDGELL	Mid	80	0	0	5 to 10	0 to 0	0 to 5	NO
PACKER	Mid	30	0	0	30 to 40	0 to 5	0 to 5	NO
CREDLIN	Mid	51	0	0	5 to 10	0 to 0	0 to 5	RE
CREAL	Mid	21	10	0.48	0 to 5	0 to 5	0 to 5	IO
BEN	Outer	12	0	0	0 to 5	0 to 0	0 to 5	NO

Swain sector

Historic trends

Sector-wide there has been a long-term decline in coral cover from high levels (30-50%) when surveys began in 1986 to moderate levels (10-30%) in recent years (Figure 11). For the first two decades COTS were numerous on reefs in this sector; Active Outbreak levels of COTS recorded in nearly every year of survey. The decline in coral cover initially was due to the combined effects of COTS and TC Fran (category 1) in March 1992 and TC Rewa (category 2) January 1994. From 1999 to 2003 COTS activity on reefs in this sector was high, exceeding Active Outbreak levels across the sector, with an associated decline in coral cover. COTS activity has declined since 2004. 2007 was the first survey year that no Active Outbreaks of COTS have been recorded from this sector, though some residual COTS activity remained. In March 2009 STC Hamish

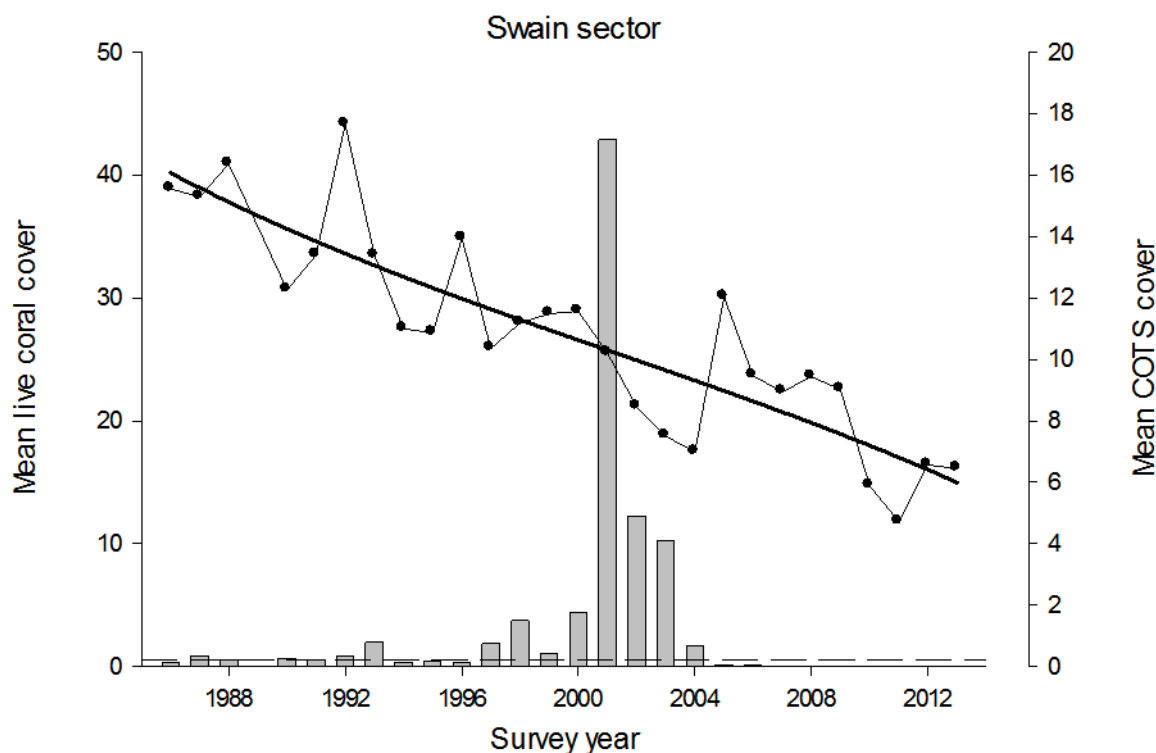


Figure 11 Average coral cover on reefs (line plot; left hand axis) and average density of COTS (bar chart; right hand axis) recorded during manta tow surveys of reefs in the Swain sector since 1986. Symbols on line plot indicate survey years. Dashed line indicates level at which COTS densities may be expected to have an impact on live coral cover. The smooth solid line represents a cubic function fitted to the values for coral cover.

(category 4) caused widespread destruction and a further decline in coral cover on reefs across the sector.

Recent surveys

Perimeters of seven reefs in the Swain sector were surveyed using manta tow in 2013 (Table 10). COTS were recorded in very low numbers during manta tow surveys at Chinaman Reef and East Cay. Median reef-wide live coral cover was low (<10%) on four reefs: Reef 21-529, Gannet Cay and Snake Reef, all of which were recovering from major coral mortality caused by either STC Hamish in 2009 or COTS outbreaks prior to 2006 (Horseshoe Reef and Gannet Cay). The other three reefs had moderate coral cover (10 to 30%). Coral cover on all reefs had changed little in the two years since the last survey.

Table 10 Summary of manta tow survey results for the Swain sector (click on the reef names for more information).

Reef	Shelf Position	TOWS	COTS	COTS per tow	Median % Live Coral Cover	Median % Dead Coral Cover	Median % Soft Coral Cover	Reef Status
21-529	Mid	30	0	0	0 to 5	0 to 0	0 to 5	NO
GANNET CAY	Mid	19	0	0	5 to 10	0 to 5	0 to 5	RE
SNAKE	Mid	95	0	0	5 to 10	0 to 0	0 to 5	NO
CHINAMAN	Mid	31	4	0.13	20 to 30	0 to 5	5 to 10	NO
HORSESHOE	Mid	77	0	0	5 to 10	0 to 0	0 to 5	RE
EAST CAY	Outer	63	2	0.03	20 to 30	0 to 5	5 to 10	NO
TURNER CAY	Outer	51	0	0	10 to 20	0 to 5	0 to 5	RE

Capricorn-Bunker sector:

Historic trends

Coral cover was initially very high (50-75%) on reefs in this sector at the beginning of surveys. A dramatic decline in coral cover from 1988 through to 1995 was considered to be driven by cyclones (Figure 12). These reefs are particularly prone to storm damage as many are exposed to oceanic conditions of the Coral Sea where large swells can remove corals on exposed reef faces even though storms may not pass directly through the sector. Cyclones that are likely to have affected the reefs in this period include TC Greg (category 2) in March 1990, TC Betsy (category 2) in January 1992, TC Fran (category 2) in March 1992, TC Roger (category 2) in March 1993 and TC Violet (category 3) in March 1995. Following these events and in the absence of any major disturbance, coral cover recovered remarkably to reach high levels by 1999. Cover remained high through to 2005 sector-wide coral cover then declined precipitously through to 2009, once more due to storm damage. Storms that affected the area in that period included TC Harvey (category 1) in February 2005, an un-named hybrid low (equivalent to a category 2 cyclone) in March 2006, another similar hybrid low in January 2008 and STC Hamish (category 4) in March 2009. COTS activity has increased in recent years and the first the first Active Outbreak was recorded on a reef in this sector in 2012.

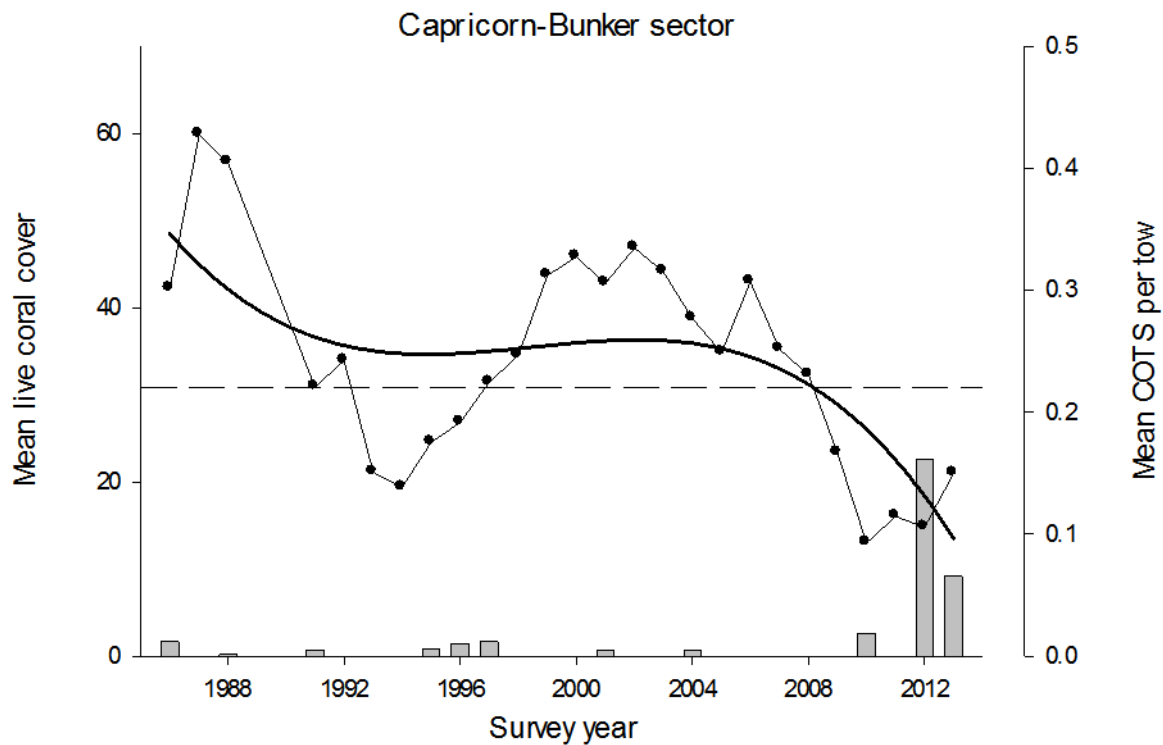


Figure 12 Average coral cover on reefs (line plot; left hand axis) and average density of COTS (bar chart; right hand axis) recorded during manta tow surveys of reefs in the Capricorn-Bunker sector since 1986. Symbols on line plot indicate survey years. Dashed line indicates level at which COTS densities may be expected to have an impact on live coral cover. The smooth solid line represents a cubic function fitted to the values for coral cover.

Recent surveys

Perimeters of four reefs were surveyed using manta tow (Table 11) in 2013. COTS were recorded at Lady Musgrave Island in numbers sufficient to constitute an Incipient Outbreak. COTS have been recorded at this reef on several occasions since manta tow surveys began in 1986, but only in low numbers. This is the second outbreak to be recorded from this sector in as many years; a larger Active Outbreak was recorded on Fairfax Island reef just to the north of Lady Musgrave Island in 2012. No COTS have been recorded on the other three reefs surveyed in the sector. These are the first two COTS outbreaks to be recorded from reefs in this sector in nearly thirty years of surveys.

Median reef-wide live coral cover ranged from 5 to 10% on one reef, 10-20% on two reefs and 20-30% on one reef (Table 11). In general, coral cover had remained relatively stable on reefs in this sector since last surveyed one to two years ago. The variability in coral cover among reefs reflects differences in exposure to the damaging waves from offshore storms from 2005 to 2008 and from STC Hamish in 2009. Large numbers of coral recruits were observed during scuba searches at all reefs, suggesting that recovery in coral cover was well underway. One caveat is the increase in COTS activity that will almost certainly hamper any recovery of coral cover on affected reefs.

Table 11 Summary of manta tow survey results for the Capricorn-Bunker sector (click on the reef names for more information).

Reef	Shelf Position	Tows	COTS	COTS per tow	Median % Live Coral Cover	Median % Dead Coral Cover	Median % Soft Coral Cover	Reef Status
BROOMFIELD	Outer	55	0	0	20 to 30	0 to 5	0 to 5	NO
WRECK IS	Outer	41	0	0	10 to 20	0 to 0	0 to 5	NO
ONE TREE IS	Outer	64	0	0	10 to 20	0 to 0	0 to 5	NO
LADY MUSGRAVE IS	Outer	61	16	0.26	5 to 10	0 to 0	0 to 5	IO

Discussion

Two patterns are apparent in the distribution of outbreaks of COTS on the GBR: waves of outbreaks start at intervals on inshore and midshelf reefs north of Cairns and spread south through the central GBR. A second unsynchronised cycle of outbreaks originates and remains in the offshore Swain reefs in the southern GBR. Starfish numbers are generally low on Swains reefs at present, while a fourth wave of outbreaks appears to be underway in the north. It will be interesting to see if the low coral cover in the region to the south of Cairns following Cyclone Yasi affects the rate of spread of the wave of outbreaks through the central GBR.

References

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