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Supplementary Materials for

Climate-driven regime shift of a temperate marine ecosystem

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Materials and Methods

Study Area

This study took place in Western Australia, where the Leeuwin Current carries warm water down the coast from the tropical Ningaloo Reef (23°S) to the temperate kelp forests of Australia's south coast. Here, we focus on changes in the abundance and composition of reef associated marine life in the midwest region (approx. 27.7-30.3°S) since 2001. The midwest region has experienced significant warming over the past 4 – 6 decades, at an average rate of 0.013°C year-1 (*19*). In addition to the gradually increasing mean temperatures, summer ocean temperatures from 2011 – 2013 were the warmest on record. The hottest of these years, 2011, resulted in an unprecedented marine heatwave, where ocean temperatures along >2,000 km coastline soared to >2 °C above the long term mean temperature for >10 weeks, exceeding anything recorded in the previous 215 years (*17, 18, 24*).

Kelp Loss

The extent of kelp loss (Fig. 1) was determined by combining measurements of kelp (*Ecklonia radiata*) cover at different latitudes before and after the 2011 marine heatwave with detailed spatial modeling of kelp distribution (Table S1). Latitudinal patterns in kelp cover were determined by conducting extensive benthic surveys at 36 reefs across 4 evenly spaced locations in 2005 (*8, 31*) and 52 reefs across 10 locations (*cf.* Fig. 1) in 2012/13, from Kalbarri (27.7 ºS) to Cape Leeuwin (34.2 ºS). The 52 reefs sampled in 2012/13 included the original 36 reefs. To best characterize latitudinal patterns, physically similar, wave exposed reefs at similar depth (8 – 12 m) were randomly selected >1 km apart. A scuba diver swam six 25 × 1 m non-overlapping transects at each reef (following *31*), recording the benthic cover (%) of kelp. In 2005, there were no differences in kelp cover across the 4 locations ($p > 0.05$, *8, 31*). Relative kelp loss was calculated as the change in cover between surveys. Extensive searches were undertaken on each reef in Kalbarri (n=6), Port Gregory (80 km south, n=6) and Horrocks (110 km south, n=6) where no kelp was recorded in 2012/13, with 3 – 4 divers additionally swimming specifically to search for kelps for >30 minutes. Latitudinal kelp loss patterns were modelled using a 3rd order polynomial regression (proportion kelp remaining = $0.0062 x^3 + 0.5618 x^2 + 16.815 x + 166$, $r^2 = 0.962$, n = 10, x = latitude).

A full coverage map of kelp distribution for Australia's west coast was developed through species distribution modelling (see *32*), using the Australian national bathymetry grid (approximately 250 m × 250 m resolution, *33*), bathymetry derived terrain variables and geo-referenced towed video data collected along the west coast between 2000 and 2009 (*32, 34, 35*). Kelp distribution between Kalbarri and Cape Leeuwin out to 30 m water depth was extracted from the kelp distribution raster in ArcGIS (Esri ® ArcGIS TM 10.2) to produce a new raster specifically for the area of study. A raster of the 3rd order polynomial relationship between kelp loss and latitude was created for the study area and then multiplied by the kelp distribution raster, generating a spatially explicit representation of predicted kelp loss along the west coast of Australia. The number of pixels with kelp present at each latitudinal interval was calculated and multiplied by the predicted kelp loss at that same latitude and size of the pixel, to give an estimate of the potential area loss of kelp forest. These estimates were summed within each half a degree of latitude.

Time series of kelp forest and turf seaweed cover (Fig. 2C) were constructed from 15 years of observations and sampling at the same three reefs in Kalbarri between 2001 to 2015. These reefs were a subset of those visited to assess proportional kelp loss (see above) and community changes (see below). In 2005, abundances were estimated within $6 \times 1\ m^2$ quadrats per reef. In 2006 – 2009, abundances were estimated within $4 \times 3.14\ m^2$ circular plots per reef and after 2011 within $10 \times 0.25\ m^2$ quadrats per reef. All reefs were visited in December 2001, where the kelp forests were 'extensive and dense' (*36*, Fig. 2A) and December 2010, but no kelp data collected; nothing unusual about the canopy cover was noted and, consequently, these dates are represented by the mean (± SE) across all other pre-2011 sampling dates. Reefs in Cape Leeuwin, Perth, Jurien Bay, Port Gregory and Kalbarri were revisited several times each year for additional surveys in 2014 and 2015.

Community Changes

We contrasted changes to fish and seaweed communities in the midwest region with tropical northwest (Ningaloo Reef) and temperate southwest (Perth) regions, these being 500 – 600 km farther north and south, respectively. In each region, we sampled 3 – 6 distinct reefs >1 km apart. In the southwest and midwest, these were 8 – 12 m depth rocky reefs. In the northwest, reefs were 3 – 5 m deep coral reef lagoon (dominated by limestone pavement) sites, as these are extensive and the main seaweed habitats for fish in the region. Sampling, as described below, was undertaken between late austral spring and early autumn (October to May) by experienced researchers. Seasonal differences in sampling time are unlikely to have influenced the observed patterns as previous studies have shown seasonal changes in both seaweed (*37*) and fish communities (*38*) to be subtle compared to those occurring across this latitudinal gradient. Similarly, observer and depth biases are unlikely to have influenced the observed changes in fish communities, as demonstrated by the highly consistent results obtained by Underwater Visual Censuses (UVC) and Diver Operated stereo Videography (stereo DOV) (Fig. 3B *vs.* Fig. S3).

To determine changes in seaweed community structure (Fig. 3), we collected all foliose seaweeds within $6 \times 0.25\ m^2$ quadrats, a standard protocol previously used in both temperate (*37*) and tropical (*39*) habitats. This was done in November 2005 (southwest, midwest before, Kalbarri), November 2010 (northwest), (*39*) and in May 2013 (midwest after, Kalbarri). All seaweeds were harvested and then identified in the laboratory. Fishes were quantified using UVC's, following Holmes et al. (*40*). A SCUBA diver counted and identified all fishes along three 25 × 5 m belt transects (*38*). In the southwest (Perth) and midwest (Kalbarri) fishes were sampled in October 2006, March 2007, June 2007 and October 2007 (38), and in the northwest (Ningaloo) in February 2008. In the midwest (Kalbarri), fishes were resampled again ('after' the 2011 marine heatwave) in March and November 2013, and August 2015. In addition, fish abundance and biomass changes (using known length-weight relationships, *41, 42, 43*) were also determined independently using stereo DOVs following standardized methods in all three regions (*40*). Stereo DOVs used two underwater video cameras, separated by 700 mm on a base bar, facing inward at an angle of 8 degrees to enable accurate measurement of fish lengths (*44*). Twelve 25 × 5m transects were performed on each of six reefs in the midwest (Port Gregory) in July 2006 on exposed reefs between 6 – 10 m depth (*cf. 45*). These transects were repeated in June 2013 at the exact same coordinates using the same methodology. In 2013, an additional six reefs from the northwest region (Ningaloo) and six reefs from the southwest (Perth) were sampled at similar depth and wave exposure to act as tropical and temperate reference regions respectively. Video footage obtained by stereo DOVs was analysed using the software 'EventMeasure (Stereo)' (SeaGIS Pty Ltd). All fish observed were identified to the lowest taxonomic level possible, and counted. *Kyphosus bigibbus*, *K. sydneyanus* and *K. gladius* were not distinguishable on all transects, and therefore the three species were conservatively pooled for the analysis of community structure (Fig. S3). Feeding assays were however filmed at closer range and distinguished between these species (*10*). Initial phase (IP) *Scarus ghobban* and *S. schlegeli* were also not distinguishable on all transects and were, therefore, pooled, as IP individuals constituted the majority of the parrotfish abundance. Non-metric Multidimensional Scaling (nMDS) based on Bray-Curtis dissimilarities calculated from Ln[x+1] transformed data was used to illustrate multivariate patterns of seaweed and fish community structure. Analyses of similarity percentages (SIMPER) identified which species were driving differences in community structure in the midwest before and after the warm summers of 2011 – 2013 (see *46* for technical details on these methods).

Changes in mobile and sessile invertebrate communities over the past decade, before and after the 2011 heatwave, were quantified within the midwest region only as no data prior to 2011 were available for the northwest and southwest (Fig. 4). Mobile invertebrates (large gastropods and sea urchins) were sampled at six reefs in Jurien Bay (30.3 °S) by counting all individuals along six 1 × 5m belt transects in summer 2004 and 2005 (before) (*47, 48*) and again in 2012 and 2013 (after). Transects were pooled for each sampling year and averaged for each reef and time period. We restricted the analyses to common species, defined as those with an average abundance of more than one individual recorded per reef per time period. Hermatypic corals were sampled at 23 reefs distributed across four midwest locations (Cervantes, Jurien Bay, Green Head and Dongara, 30.6 – 29.3°S) by counting and measuring (maximum linear length) all individual colonies along three 1 × 5m belt transects in 2005/06 (before) (*49*) and again in 2013 (after). All transects were pooled for each sampling period and location, standardized for total sampling area and averaged across locations for each sampling period. We restricted analyses to small colonies (< 6 cm maximum linear length) which would have recruited and/or grown during the census period. For both mobile invertebrates and hermatypic corals, data were Ln[x+1] transformed for calculation of changes in abundances in order to match the SIMPER outputs for seaweeds and fishes.

Seaweeds, fishes and invertebrates were classified according to their affinity for either cool or warm water, based on their predominant distribution south (cool) or north (warm) relative to the midwest coast region or their functional ecology (e.g., *Sargassum* spp., Table S2). A third category, 'ambiguous', was used to describe cosmopolitan species and unresolved taxa with species representatives in opposite climes. Sources for all classifications can be found in Tables S2, S3, S4 and S5. To test if the direction of change in abundance (decrease vs increase) of taxa in the community was related to their temperature affinity (cool vs warm) all observations (Fig. 3C,D and Fig. 4) were categorized and their frequency of association tested in 2 × 2 contingency tables using

Fisher's exact method for each taxon and all combined. To be conservative we included ambiguous species, and species with no change, as responding opposite to expectation. Due to the low number of observed taxa for mobile invertebrates and corals ($n = 5$ and $n = 7$, respectively) we pooled these into one test of responses of 'invertebrates'.

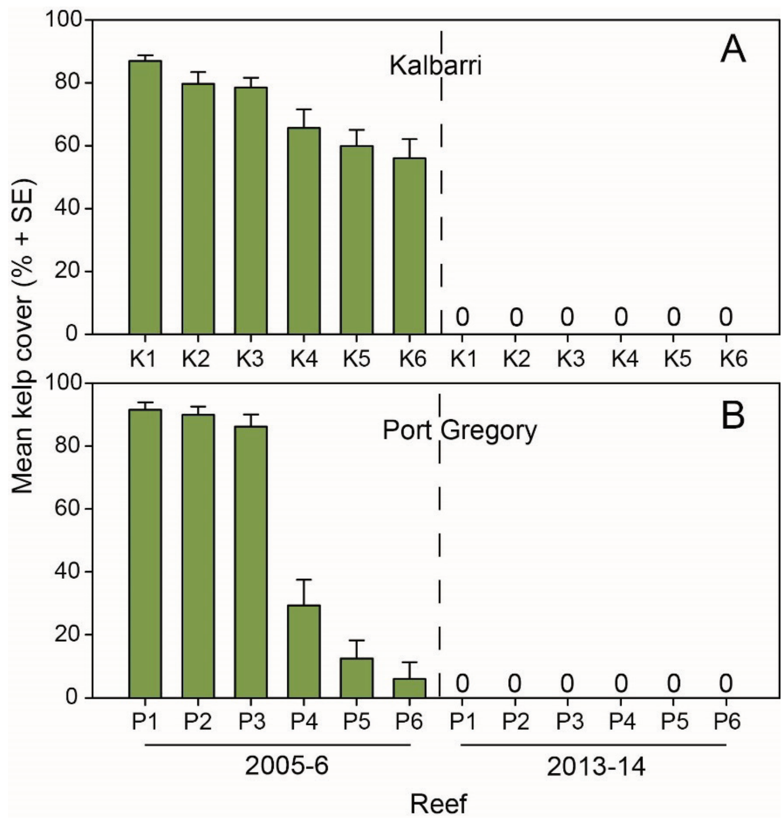

Fig. S1.

Landscape-scale cover of kelp forests (*Ecklonia radiata*) at two locations in the midwest before and after the 2011 marine heatwave. In Kalbarri (27.7 ºS, A), kelp forests covered 71% (mean ± 5 SE, n = 6 reefs) of reefs in 2005, and were not different (p > 0.05) to similar reefs in Jurien Bay (30.3 ºS), Perth (31.8 ºS) and Cape Leeuwin (34.2 ºS) sampled at the same time (8, 31). In Port Gregory (28.2 ºS, B), kelp forests covered 52% (mean ± 16 SE, n = 6 reefs) in 2006. Bars represent reefs >1 km apart, sampled along 25 m transects (n = 10 and 12, respectively). No kelps were seen in either region, at any of the 12 reefs (or elsewhere) during extensive searching in 2013, 2014 and 2015.

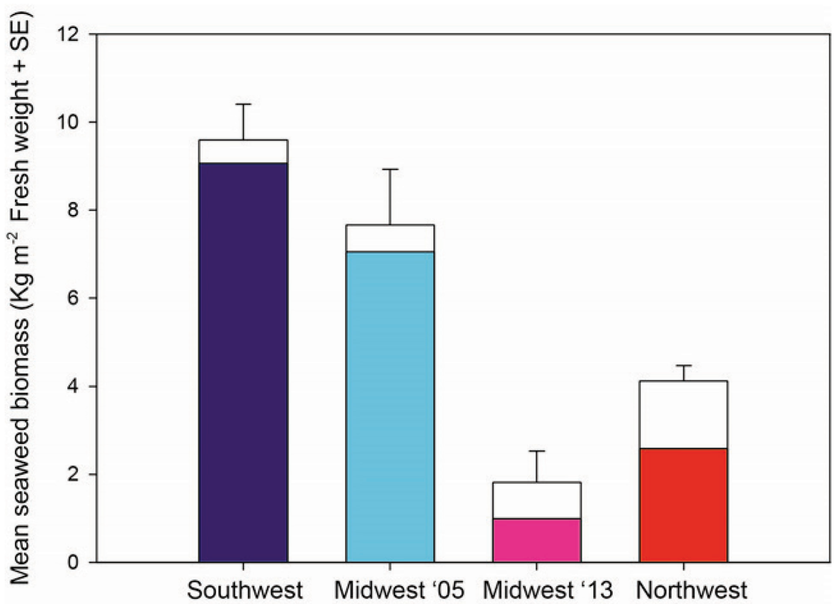

Fig. S2

Total standing seaweed canopy (colored bars) and understory (open bars) biomass in the southwest (Perth, 2005), northwest (Ningaloo, 2010) and midwest (Kalbarri, 2005, 2013) regions before and after the 2011 marine heatwave. Each bar represents an average of six reefs >1 km apart, where seaweeds were harvested by scuba divers within six 0.25 m^2 quadrats. Canopy seaweeds are kelps and fucoids larger than ~25 cm.

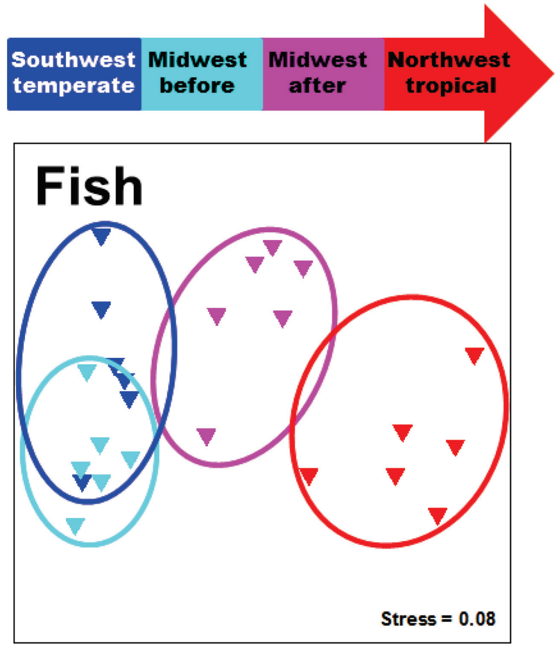

Fig. S3

Ordination (nMDS) based on diver operated video analysis showing changes in fish communities in the midwest (Port Gregory, 28.1 – 28.3ºS) between 2006 (light blue) and 2013 (pink) relative to the southwest (Perth, 2006, dark blue) and the northwest (Ningaloo, 2013, red). The video-captured data clearly shows a shift in community structure from strong resemblance of the temperate communities farther south towards a greater similarity to the tropical communities farther north. Points represent reefs >1 km apart, sampled by twelve 25 m transects where species abundances were converted to biomass using known length-weight relationships (*10*). Transects were averaged for each reef and data Ln[x+1]-transformed for analysis.

Table S1.

Summary of sampling methods, locations and sites. Details on analyses are provided in the Materials and methods section.

Data	Location(s)	Years	Basic sampling design
Kelp extent and loss (Fig, 1)			
	Map of kelp distribution, west coast	2000 – 2009	Species distribution modelling, using bathymetry derived terrain variables and geo-referenced towed video data (*32-35*). Color heat (proportion kelp forest lost) generated by applying the 3rd order polynomial relationship between kelp loss and latitude obtained from surveys in 2005 and 2012 – 13.
	Proportion kelp loss, Kalbarri (27.7ºS) Port Gregory (28.2ºS) Horrocks (28.4ºS) Dongara (29.3 ºS) Jurien Bay (30.3ºS) Lancelin (31.0ºS) Perth (31.8ºS) Warnbro Sound (32.3ºS) Cape Naturaliste (33.5ºS) Cape Leeuwin (34.2ºS)	 2005, 2013 2013 2013 2013 2005, 2013 2013 2005, 2013 2012 2012 2005, 2013	4 – 12 reefs surveyed per location. 6 – 10 replicate 25 × 1 m belt transects per reef recording kelp cover. Reefs selected to be >1 km apart, physically similar: 8-12m depth, wave exposed, initially (2005) dominated by kelps (>50% cover) (*8, 31*). Proportional kelp loss with latitude fitted by polynomial regression.
	Area of kelp loss, west coast	2005 to 2013	There were no differences in reef kelp cover or biomass between locations in 2005 (*8, 31*). The number of pixels with kelp was calculated for each latitudinal interval and multiplied by proportional loss to give an estimate of the area loss of kelp forest
Kelps and turf (Figs. 2, S1)			
	Kelp and turf abundance (Fig. 2), Kalbarri (27.7ºS)	2001 to 2015	Abundances quantified at the same three reefs (a subset of those described above) each time, within randomly positioned sampling units: 6 × 1 m^2 quadrats (2005), 4 × 3.14 m^2 circular plots (2006 – 2009) or 10 × 0.25 m^2 quadrats per reef (post 2011). Values for 2001 and 2010 were estimated from *in situ* observations and the mean of all other pre-2011 measurements.
	Kelp loss (Fig. S1), Kalbarri (27.7ºS) Port Gregory (28.2ºS)	 2005, 2013, 2014, 2015 2006, 2013, 2014, 2015	Landscape-scale cover of kelp forests measured along 25 m transects at six reefs in each location. In Kalbarri (n = 10 transects per reef) a scuba diver recorded cover in situ (*8, 31*). In Port Gregory (n = 12 transects per reef) transects were filmed by DOV (*40*) and cover estimated subsequently. No kelps were seen in either region, at any of the surveyed reefs (or elsewhere) during extensive searching in 2013, 2014 and 2015.

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Data	Location(s)	Years	Basic sampling design
<u>Community change (Figs. 3, 4, S2, S3)</u>			
	Seaweeds (Figs. 3A, C, S2), Ningaloo (23 – 21°S, northwest) Kalbarri (27.7ºS, midwest) Perth (31.8ºS, southwest)	 2010 2005, 2013 2005	All foliose seaweeds were collected within 6 x 0.25 m^2 quadrats at each of six reefs, and identified and weighed in the laboratory (*37, 39*).
	Fishes (Figs. 3B, D), Ningaloo (23 – 21°S, northwest) Kalbarri (27.7ºS, midwest) Perth (31.8ºS, southwest)	 2008 2006 – 2007, 2013, 2015 2006– 2007	Underwater Visual Censuses (UVCs, *40*), where a SCUBA diver counted and identified all fishes *in situ* along three 25 × 5 m belt transects at each reef, were undertaken. Eight reefs were sampled in Ningaloo, six in Kalbarri before and after the 2011 marine heatwave and three in Perth (*38*). Samples from different times were averaged per reef before and after 2011.
	Fishes (Fig. S3), Ningaloo (23 – 21ºS, northwest) Port Gregory (28.2 ºS, midwest) Perth (31.8ºS, southwest)	 2013 2006, 2013 2013	Diver Operated stereo Videos (stereo DOVs, *40*), enabling accurate measurement of fish lengths (*44*) were recorded on each of six reefs (n = twelve 25 x 5m transects per reef) per region. All reefs were randomly selected, exposed to swells and between 6 – 10 m depth. Video footage obtained by stereo-DOVs was analysed using EventMeasure software and species abundances were converted to biomass using length – weight relationships from Western Australian Fisheries research reports, primary literature (*41, 42*) or FishBase (*43*).
	Mobile invertebrates (Fig 4A), Jurien Bay (30.3ºS)	 2004, 2005, 2012, 2013	Common large gastropods and sea urchins were sampled at six reefs by counting all individuals along six 1 × 5m belt transects (*47, 48*). Transects were pooled for each sampling year and averaged for each reef and time period.
	Corals (Fig 4B), Cervantes (30.6 ºS) Jurien Bay (30.3ºS) Green Head (30.1ºS) Dongara (29.3ºS)	 2005/06, 2013 2005/06, 2013 2005/06, 2013 2005/06, 2013	Small (<6cm) hermatypic corals were sampled at 23 reefs distributed across four midwest locations by counting and measuring (maximum linear length) all individuals along three 1 × 5m belt transects per reef (*49*). All transects were pooled for each sampling period and location.

Table S2.

Seaweeds contributing most to changes in assemblage structure in the midwest (Kalbarri) before (2005) and after (2013) the warm summers of 2011 – 2013 (Fig. 3A), and their biogeographical affinities. Mean fresh weight [grams] per 1.5 m^2 (SE, n = 6 reefs). Top 20 species as identified by SIMPER. In order of declining biomass change (cf. Fig. 3C). Distribution records downloaded from The Atlas of Living Australia (http://www.ala.org.au/) on 14 October 2015. 30.3°S (Jurien Bay) represents the southern end of the midwest coast and observed impacts (17). Species names checked on Algaebase (http://www.algaebase.org/) and current as of 15 Dec 2015.

Species	Before	After	Affinity and distribution
Sargassum spp.[§]	324 (196)	989 (276)	Warm; wide-spread genus. Species difficult to separate. Characteristic and dominant element of tropical coral reefs and lagoons, including Ningaloo Reef in the northwest of Australia (*39*).
Lobophora variegata	3 (2)	422 (89)	Warm; widespread, mostly tropical to warm-temperate, characteristic and dominant of tropical coral reefs (*50*) incl. Ningaloo Reef in the northwest (*39*). 52.4% of 559 records north of 30.3˚S.
Zonaria spiralis	0 (0)	52 (32)	Cool; 99.3% of 307 records south of 30.3˚S.
Small geniculate coralline algae	10 (6)	39 (17)	Ambiguous; species of *Corallina*, *Haliptilon* and *Jania;* polyphyletic functional group. All genera widespread across Australia.
Padina spp.	0 (0)	20 (16)	Warm; widespread but generally a tropical genus. Characteristic of tropical reefs and lagoons including Ningaloo Reef in the northwest of Australia (*3*). 70.8% of 1040 records north of 30.3˚S.
Stypopodium sp.	0 (0)	17 (14)	Warm; 80% of 115 records north of 30.3˚S.
Asparagopsis taxiformis	0 (0)	14 (9)	Warm; Rottnest Island around northern Australia, cosmopolitan warm-water species (*50*). 74.3% of 393 records north of 30.3 ˚S.
Callophycus serratus	0 (0)	12 (9)	Warm; wide-spread in warmer waters (*50*). 82.8% of 29[#] records north of 30.3˚S.
Tricleocarpa cylindrica	0 (0)	4 (2)	Warm; Cape Leeuwin around northern Australia (*50*). 73.5% of 117 records north of 30.3˚S.
Myriodesma spp.	10 (8)	4 (3)	Cool; 83.3% of 474 records south of 30.3˚S.
Hennedya crispa	35 (29)	29 (29)	Cool; midwest coast around southern Australia (*50*). 69.5% of 275 records south of 30.3˚S.
Zonaria turneriana	11 (6)	2 (2)	Cool; midwest coast south to Tasmania and Victoria (*50*). 93.4% of 806 records south of 30.3˚S.
Pterocladia lucida	17 (13)	2 (1)	Cool; midwest coast around southern Australia (*50*). 90.9% of 1107 records south of 30.3˚S.
Halopeltis australis	16 (10)	1 (1)	Cool; midwest coast around southern Australia (*50*). 78.0% of 601 records south of 30.3˚S.
Rhodopeltis australis	17 (6)	0 (0)	Cool; midwest coast south to Victoria (*50*). 93.2% of 133 records south of 30.3˚S
Callophycus oppositifolius	73 (51)	32 (32)	Cool; midwest coast south to South Australia (*50*). 74.5% of 216 records south of 30.3˚S.
Amphiroa anceps	197 (63)	114 (59)	Cool; Australia-wide(*50*) but not common in the northwest (e.g., *39*). 77.5% of 831 records south of 30.3˚S.
Delisea pulchra	95 (41)	0 (0)	Cool; midwest coast, around the south coast to southern Queensland (*50*). 76.0% of 437 records south of 30.3˚S.
Plocamium preissianum/mertensii	120 (58)	0 (0)	Cool; midwest/northwest around the south coast (*50*). Species not differentiated. 95.6% of 1617 records south of 30.3˚S.
Ecklonia radiata	5569 (1419)	0 (0)	Cool; midwest coast, around the south coast and Tasmania to southern Queensland (*50*). Characteristic and dominant on the south coast (*51*). 95.7% of 843 records south of 30.3˚S.

[#] Sparsely recorded. Affinity and distribution from these records should be interpreted with caution.

[§] Includes *Sargassopsis decurrens* (formerly *Sargassum decurrens*).

Table S3.

Reef fishes contributing most (top 20) to changes in fish assemblage structure in the midwest (Kalbarri) before (2006 – 2007) and after (2013, 2015) the warm summers of 2011 – 2013 (Fig. 3B), and their biogeographical affinities. Mean number of individuals per 125 m2 (SE, n = 3 reefs). Top 20 species as identified by SIMPER. In order of declining biomass change (cf. Fig. 3D). Species names checked on World Register of Marine Species (http://www.marinespecies.org/) and current as of 15 December 2015.

Species	Before	After	Affinity and feeding mode
Siganus canaliculatus & fuscescens	0 (0)	6.9 (3.2)	Warm; species difficult to separate, sub-tropical to tropical, browser (*10, 43, 52*).
Parma occidentalis	0.1 (0.1)	2.6 (0.4)	Warm; subtropical, grazer§ (*10, 43*).
Parupeneus spilurus	0 (0)	2.4 (0.4)	Warm; tropical, carnivore (*10, 43, 52*).
Thalassoma septemfasciatum	0 (0)	0.8 (0.2)	Warm; subtropical to tropical, carnivore (*10, 43*).
Plectorhinchus flavomaculatus	0.2 (0.1)	0.9 (0.2)	Warm; subtropical to tropical, carnivore (*10, 43*).
Coris auricularis	1.6 (0.4)	2.3 (0.8)	Ambiguous; temperate to subtropical, carnivore (*10, 43, 52, 53*).
Scarus ghobban	0 (0)	0.6 (0.2)	Warm; tropical to subtropical, scraper§ (*10, 43*).
Kyphosus sydneyanus	0.2 (0.2)	0.8 (0.6)	Cool; temperate, browser (*54, 55*)
Pomacentrus milleri	0 (0)	0.6 (0.3)	Warm; tropical, grazer (*10, 43*).
Scarus schlegeli	0.1 (0.1)	0.5 (0.3)	Warm; tropical, scraper§ (*10, 43*).
Choerodon rubescens	0.01 (0.01)	0.4 (0.1)	Warm; subtropical, carnivore (*10, 43, 53*).
Chaetodon assarius	0 (0)	0.4 (0.1)	Warm; subtropical to tropical, carnivore (*43, 52*).
Kyphosus cornelii	0.1 (0.1)	0.4 (0.2)	Ambiguous; temperate to tropical grazer (*10, 54*).
Notolabrus parilus	0.2 (0.1)	0.4 (0.1)	Cool; temperate to subtropical, carnivore (*10, 43, 52, 53*).
Thalassoma lunare	0.2 (0.2)	0.2 (0.1)	Warm; tropical to warm temperate, carnivore (*10, 43, 52*).
Pseudolabrus biserialis	0.3 (0.1)	0 (0)	Cool; temperate, carnivore (*43*)
Parma mccullochi	0.8 (0.3)	0 (0)	Cool; temperate, grazer§ (*45*)
Pempheris klunzingeri	2.0 (1.3)	0.9 (0.8)	Cool; temperate to subtropical, (*43, 52*).
Chromis klunzingeri	1.5 (1.5)	0 (0)	Cool; temperate, planktivore (*52*).
Schuettea woodwardi	12.6 (6.6)	0.1 (0.1)	Cool; temperate, planktivore (*43, 52*).

§ Here we distinguish the more specific feeding modes, in the text, however, we refer to grazers, scrapers and excavators under one name (‘grazers’) as they all ultimately remove substratum, turfs and microscopic kelps, limiting the kelp recovery process.

Table S4.

Common (mean >1 per site in either time period) mobile invertebrates on reefs in the midwest (Jurien Bay) before (2005, 2011) and after (2013, 2014) the warm summers of 2011 – 2013. Mean number of individuals per 30 m2 (SE, n = 6 reefs). In order of declining density change (cf. Fig. 4A). Distribution records were downloaded from The Atlas of Living Australia (http://www.ala.org.au/) on 14 October 2015. 30.3˚S (Jurien Bay) represents the southern end of the midwest coast and observed impacts (17). Species names checked on World Register of Marine Species (http://www.marinespecies.org/) and current as of 15 December 2015.

Species	**Before**	**After**	**Affinity and distribution**
Centrostephanus tenuispinus	0.2 (0.2)	4.2 (1.3)	Warm; warm-temperate, range-limit at Shark Bay (25.3 ˚S), least abundant at most temperate latitudes (*47, T. Wernberg pers. obs.*)[ǂ]. Family characteristic of tropical reefs (*56*); 28.3% of 11[#] records north of 30.3˚S
Tripneustes gratilla	0 (0)	2.0 (1.7)	Warm; tropical, northern Australia (*56*), 68.8% of 288 records north of 30.3˚S.
Phyllacanthus irregularis	1.9 (1.0)	0.6 (0.3)	Cool; temperate (*56*), 70% of 20[#] records south of 30.3˚S.
Lunella torquatus	2.6 (1.2)	1.2 (0.6)	Cool; temperate (*56*), 87.4% of 372 records south of 30.3˚S.
Heliocidaris erythrogramma	8.3 (1.7)	5.9 (1.7)	Cool; temperate (*56*), 92.3% of 607 records south of 30.3˚S.

§ Extensive searches in 2014 and 2015 did not discover a single individual at any of the reefs sampled for seaweed and fish in Kalbarri (27.7 °S), the species' range-limit prior to the heatwave and where it was previously common (*48*).

ǂ An unpublished survey of 90 identical transects across 18 similar reefs between South Australia (Adelaide) and Jurien Bay in 2005/06 did not find a single *C. tentuispinus* on these southern reefs (T. Wernberg unpublished data).

Very sparsely recorded. Affinity and distribution from these records should be interpreted with caution.

Table S5.

Small (< 6 cm) hermatypic corals on reefs in the midwest (Cervantes to Dongara) before (2005/05) and after (2013) the 2011 marine heatwave. Mean number of colonies per 1000 m^2 (SE, n = 4 regions). In order of declining density increase (cf. Fig. 4B). Hermatypic (reef building) corals are the key foundation-species of tropical coral reefs, and while some species are frequently found at temperate latitudes, their core distributions are tropical (cf. data below) and as a group they are characteristic of warm and tropical environments. Distribution records were downloaded from The Atlas of Living Australia (http://www.ala.org.au/) on 2 October 2015. 30.3˚S (Jurien Bay) represents the southern end of the midwest coast and observed impacts (*17*). Species names checked on World Register of Marine Species (http://www.marinespecies.org/) and current as of 15 December 2015.

Species	**Before**	**After**	**Affinity and distribution**
Plesiastrea versipora	60 (4)	338 (83)	Warm; widespread; 81.3% of 283 records north of 30.3˚S
Alveopora fenestrata	0 (0)	10 (5)	Warm; 93.4% of 76 records north of 30.3˚S
Turbinaria mesenterina	0 (0)	6 (5)	Warm; widespread; 97.6% of 381 records north of 30.3˚S
Turbinaria reniformis	0 (0)	2 (3)	Warm;94.7% of 337 records north of 30.3˚S
Coelastea aspera	0 (0)	2 (3)	Warm; 97.7% of 299 records north of 30.3˚S
Pocillopora damicornis	6 (3)	5 (5)	Warm; widespread; 97.5% of 1088 records north of 30.3˚S
Montipora capricornis	2 (3)	0 (0)	Warm; subtropical; 90.0% of 10[#] records north of 30.3˚S
All species combined	68 (6)	365 (94)	
Species richness	3	6	

[#] Very sparsely recorded. Affinity and distribution from these records should be interpreted with caution.

Table S6.

Comparison of mean feeding rates by herbivorous fishes in the current study and rates reported in the coral reef literature. Seaweed browsing bite rates were standardized by herbivore biomass (kgH), seaweed assay biomass (kgA) available for consumption and by the period of exposure (hr). Coral reef feeding rates were only used where the seaweed assay was placed onto coral dominated areas (primarily reef crest or outer reef flat), where grazing rates are highest. All reported grazing rates were obtained by standardized video methods, following Hoey and Bellwood (*57*).

Feeding rates on the benthos by herbivorous fishes were standardized by the grazing area and time ($1\ m^2\ hr^{-1}$). For studies where bite rates per unit area were not reported, values were estimated based on the reported percentage of reef area grazed per unit time using mean bite sizes reported in the literature ($16\ mm^2$, equivalent to a 10 – 15cm, TL, *Scarus rivulatus*) (*58*). Note that feeding rates by scrapers reported in the literature were not standardized by fish biomass. All values were extracted from the literature using 'Data Thief' software. Where the feeding rates of multiple species were individually reported, all reported species were summed to determine the total mean grazing pressure. Table modified from details in (*10*). Species names checked on World Register of Marine Species (http://www.marinespecies.org/) and current as of 15 December 2015.

Region	Mean bite rate	Dominant herbivores	References
Seaweed browsing (bites $kg_H^{-1}\ kg_A^{-1}\ hr^{-1}$) (*Ecklonia radiata*, *Sargassum* spp.)			
Port Gregory, midwest, WA	3836	*Kyphosus bigibbus*	(*10*)
Great Barrier Reef (5 locations)	459 (30 – 1251)	*Siganus canaliculatus* *S. doliatus* *Kyphosus vaigiensis* *Naso unicornis,*	(*59-62*)
Ningaloo Reef (5 locations)	163 (54 – 199)	*Kyphosus vaigiensis* *K. bigibbus* *Scarus* spp *Naso unicornis*	(*63*)
Fiji	189-787*	*Naso lituratus* *N. unicornis*	(*64*)
Seychelles	688*	*Siganus puelloides*	(*65*)
Seaweed turf grazing (bites $m^2\ hr^{-1}$) (epilithic algal matrix/turf)			
Port Gregory, midwest, WA	172 ± 50	*Scarus ghobban* *Siganus fuscesens*	(*10*)
Great Barrier Reef (3 locations)	61* (45* – 1685)	*Scarus rivulatus* *Scarus* IP *Scarus psittacus* *Siganus* spp	(*66-68*)
Abrolhos Archipelago, NE Brazil	315	*Acanthurus bahianus*	(*69*)
Florida Keys, USA	59	n/a	(*70*)
Fiji	258	*Acanthurus nigricauda* *Ctenochaetus striatus* *Scarus* spp.	(*64*)

* Unstandardized bite rates as mass standardized bite rates not reported in the study.

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