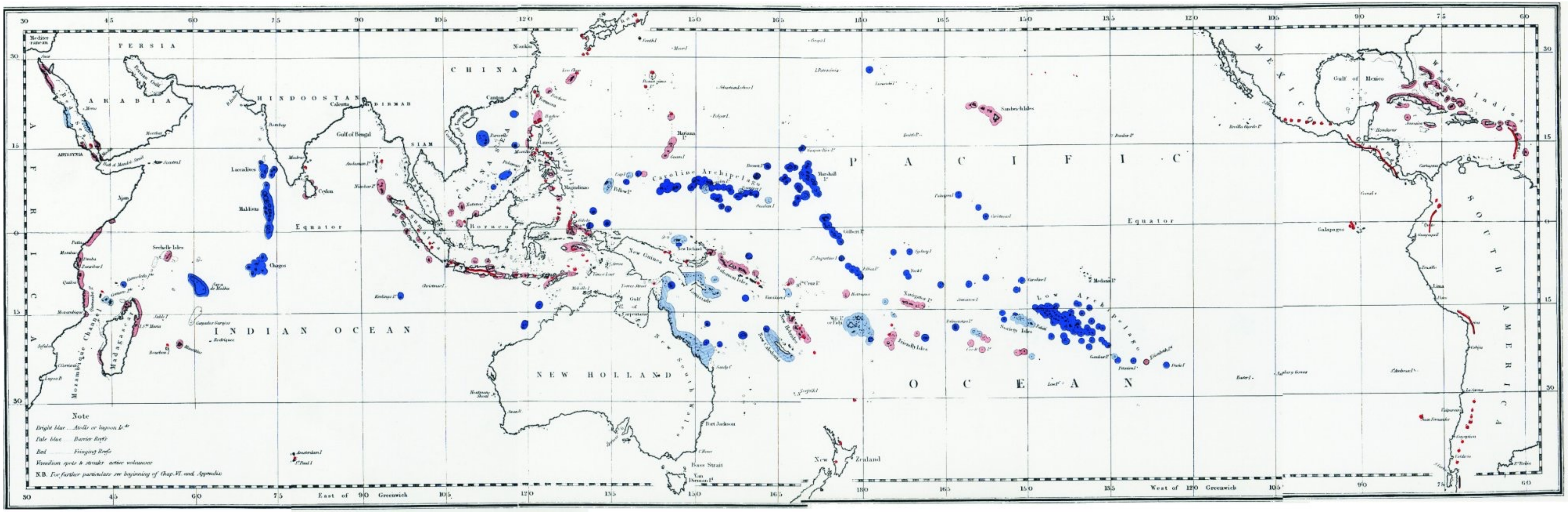
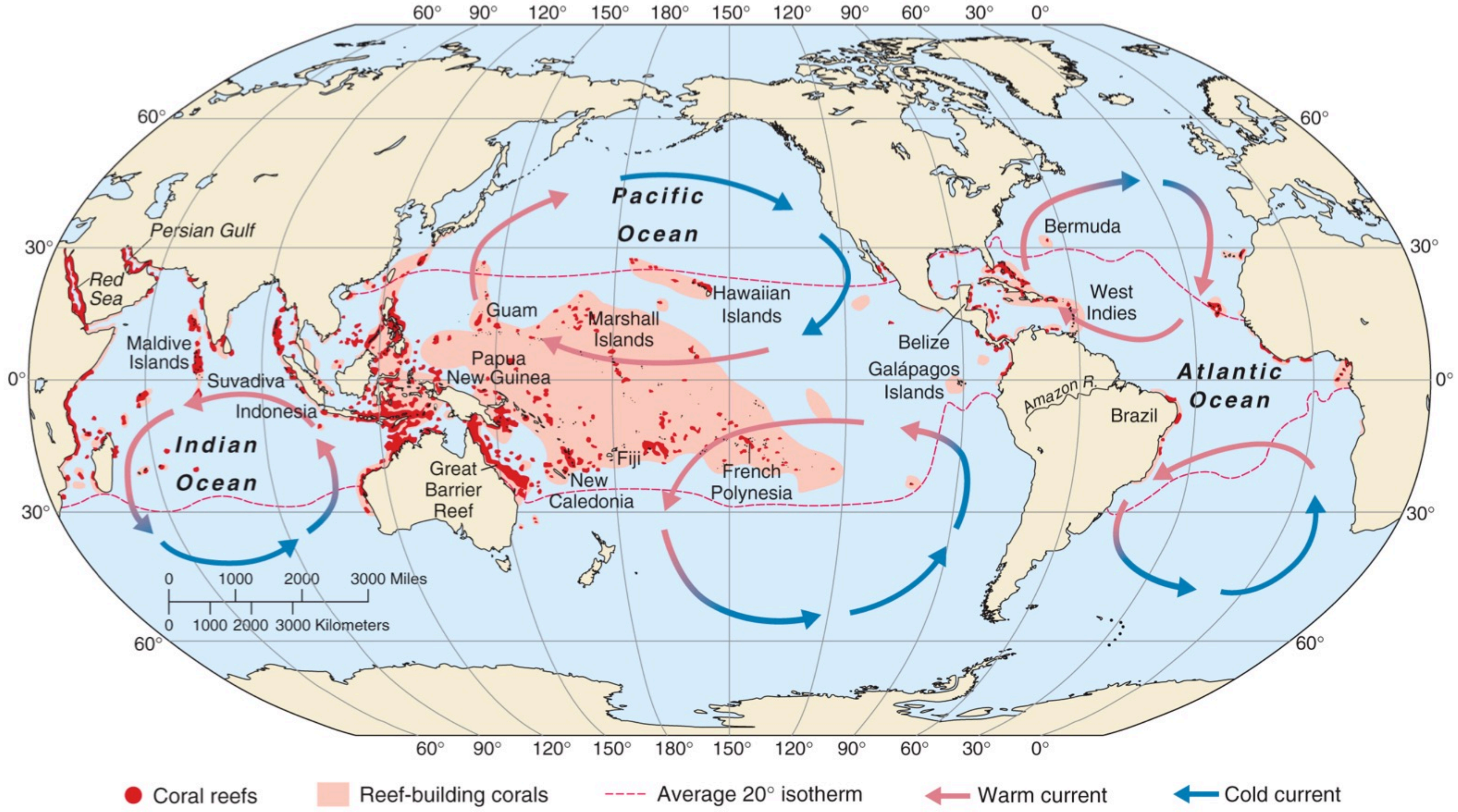
Coral Reefs

Distribution of coral reefs

Charles Darwin (1809-1882)
1831-1836: Circumnavigation with HMS *Beagle*
1839: “Voyage of the *Beagle*”
1842: “The structure and distribution of coral reefs”
1859: “The origin of species”

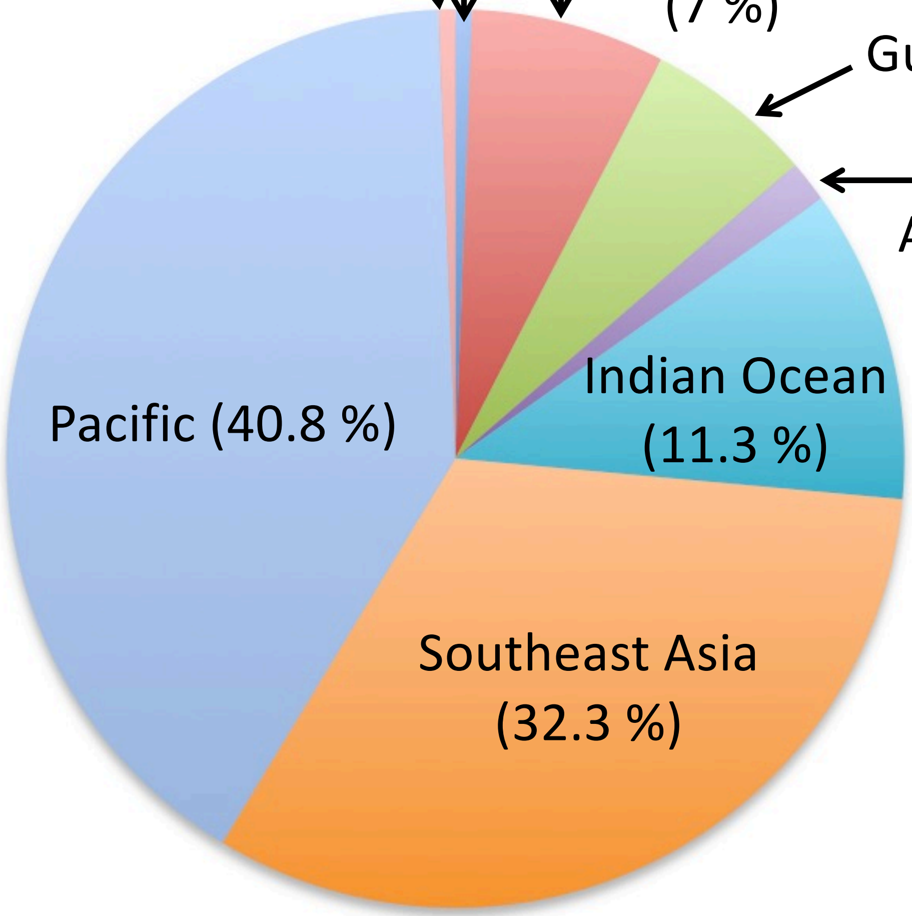


Distribution of coral reefs



Castro & Huber (2010)

Distribution of coral reefs

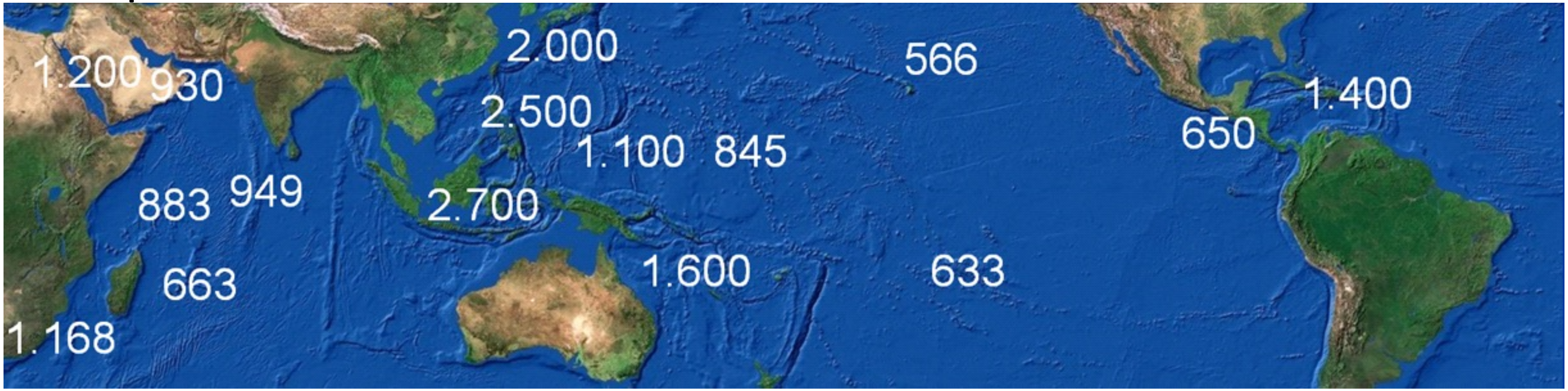


Estimates of global coral reef area:

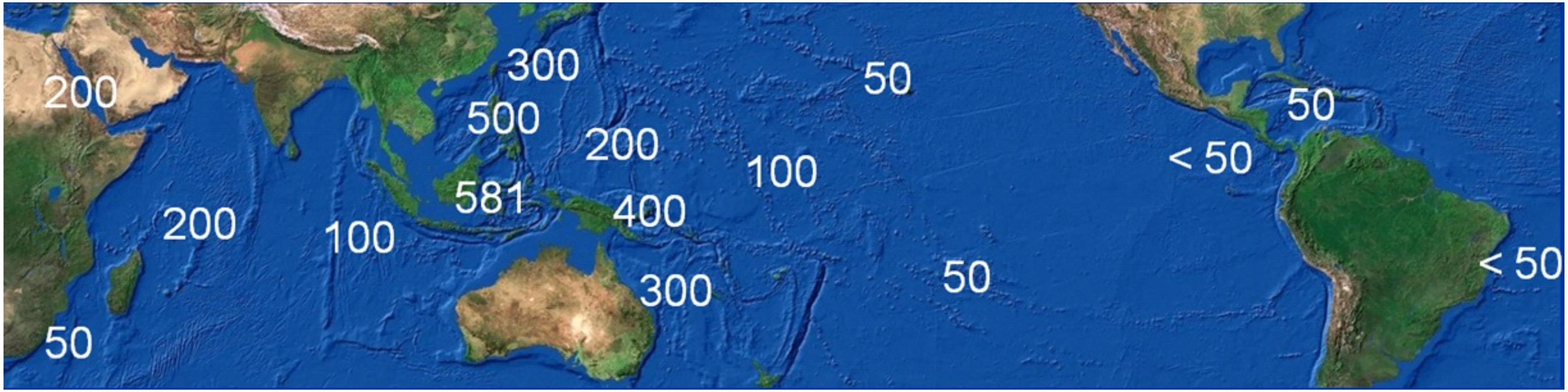
- Smith (1978): 617,000 km^2
- Spalding & Grenfell (1997): 255,000 km^2
- Spalding et al. (2001): 284,300 km^2

Coral reef biodiversity

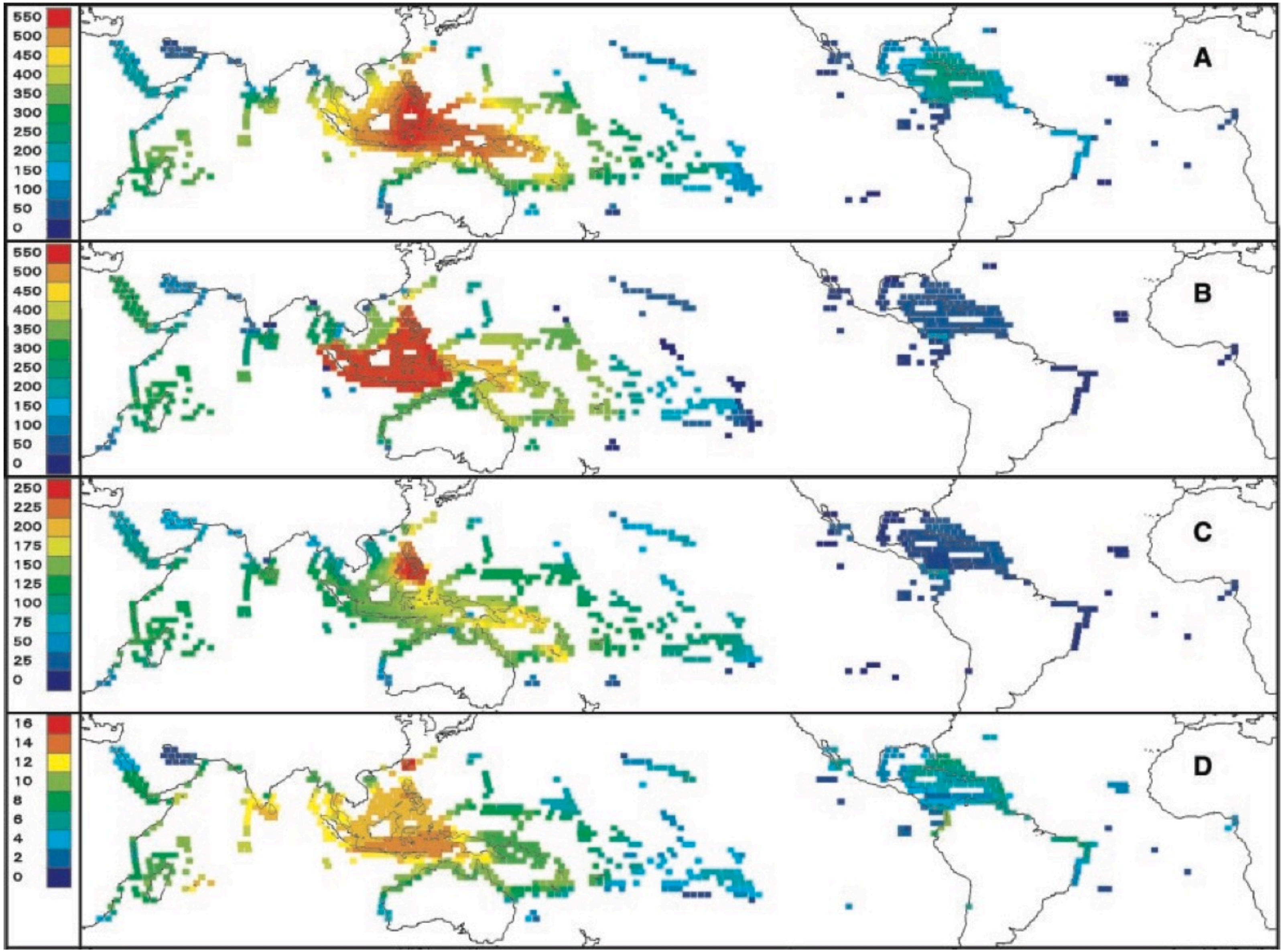
Fish species



Scleractinian coral species



Coral reef biodiversity



Fish: species richness based on 1700 species (40 % of all known species)

Scleractinian corals: species richness based all known 804 species

Snails: species richness based on 662 species of cone shells, cowries and volutes

Lobsters: species richness based on 69 species from 7 families

Roberts et al. (2002)

Coral reef biodiversity

Coral reefs cover only 0.089 % of the world's oceans (Spalding et al. 2001), but:

- about 70,000 described species life on coral reefs
  = 30 % of all marine species
  = 5 % of all species
- estimated number of species: 830,000 (Fisher et al. 2015)

Center of coral reef biodiversity in the **Coral Triangle** (Southeast Asia):

- centre-of-origin hypothesis: species evolve in the centre and disperse
- centre-of-overlap hypothesis: overlap of fauna from several biogeographic provinces
- centre-of-accumulation hypothesis: speciation in peripheral areas and dispersal to the centre
- centre-of-survival: species get extinct elsewhere

Coral reef biodiversity: regional-scale assembly rules in fish and corals

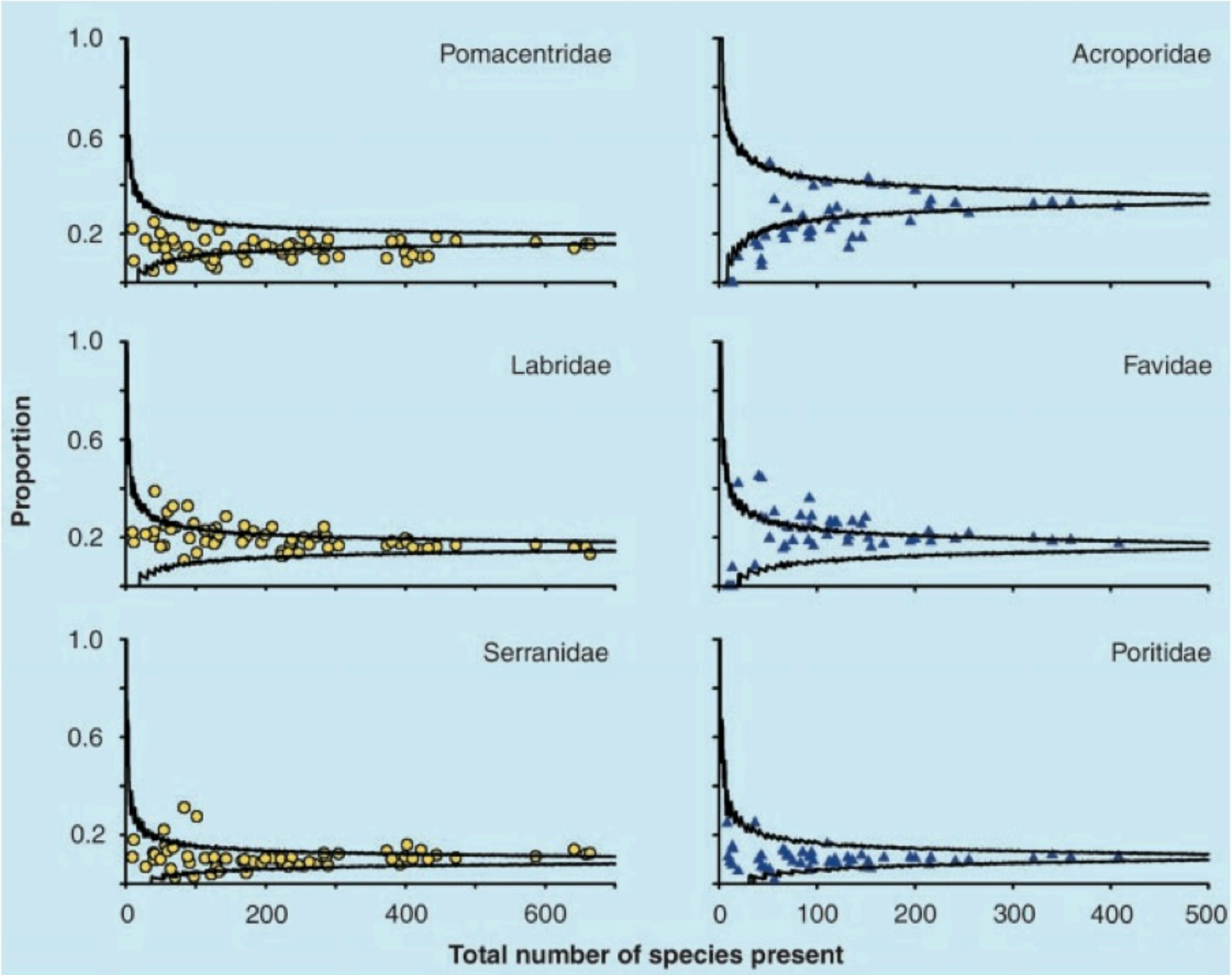


Fig. 2. Contribution to the total species pool of the three most abundant fish and coral families across a range of total species richnesses. Upper and lower lines are bootstrapped 95% confidence limits based on random selection of species from the total species pool (*13*). Other families show similar patterns (compare Fig. 3).

Bellwood and Hughes (2001)

Coral reef biodiversity: regional-scale assembly rules in fish and corals

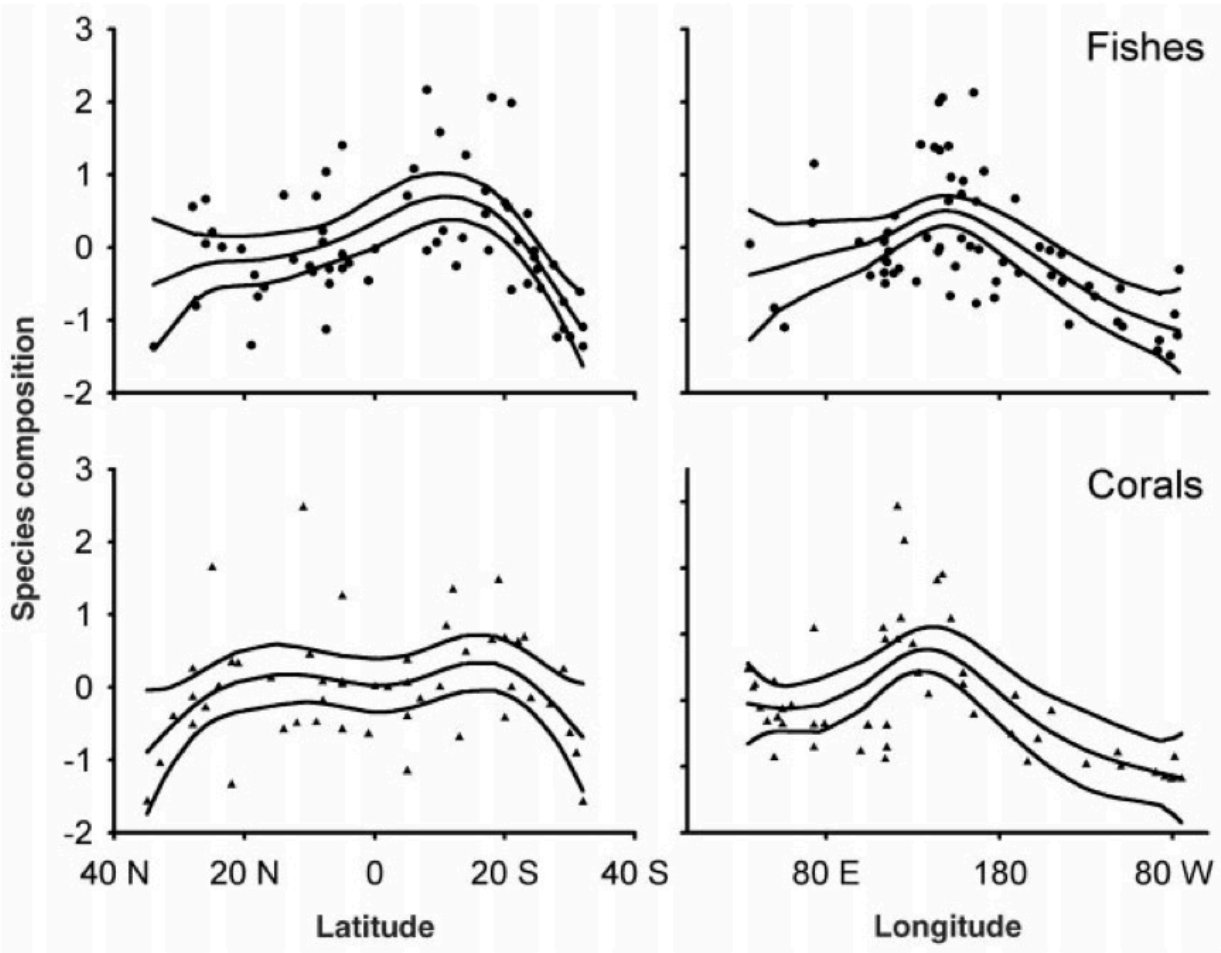


Fig. 3. Latitudinal and longitudinal changes in the taxonomic composition of fishes and corals. Taxonomic composition is expressed as the score on the first axis (PC1) of a principal components analysis (*40*), which provides a quantitative description of the degree of taxonomic similarity between fish or coral assemblages at different locations (Fig. 1). Two locations with the same PC1 score share similar species richness in those families that account for the greatest variation among sites. Latitude and longitude values are given in degrees from the equator or degrees east or west of Greenwich. Lines indicate the mean ± 2 SEM.

Bellwood and Hughes (2001)

Coral reef biodiversity: regional-scale assembly rules in fish and corals

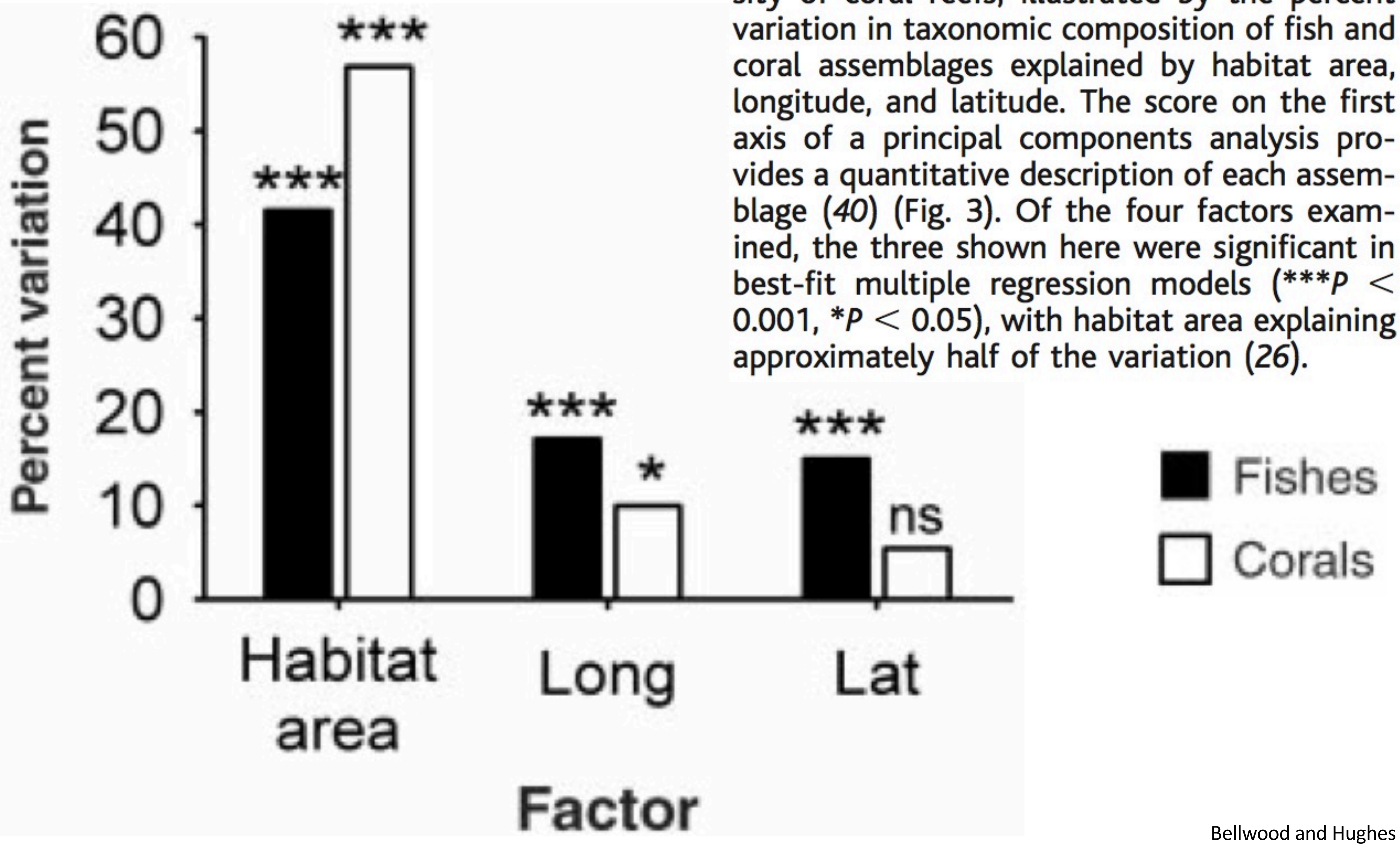
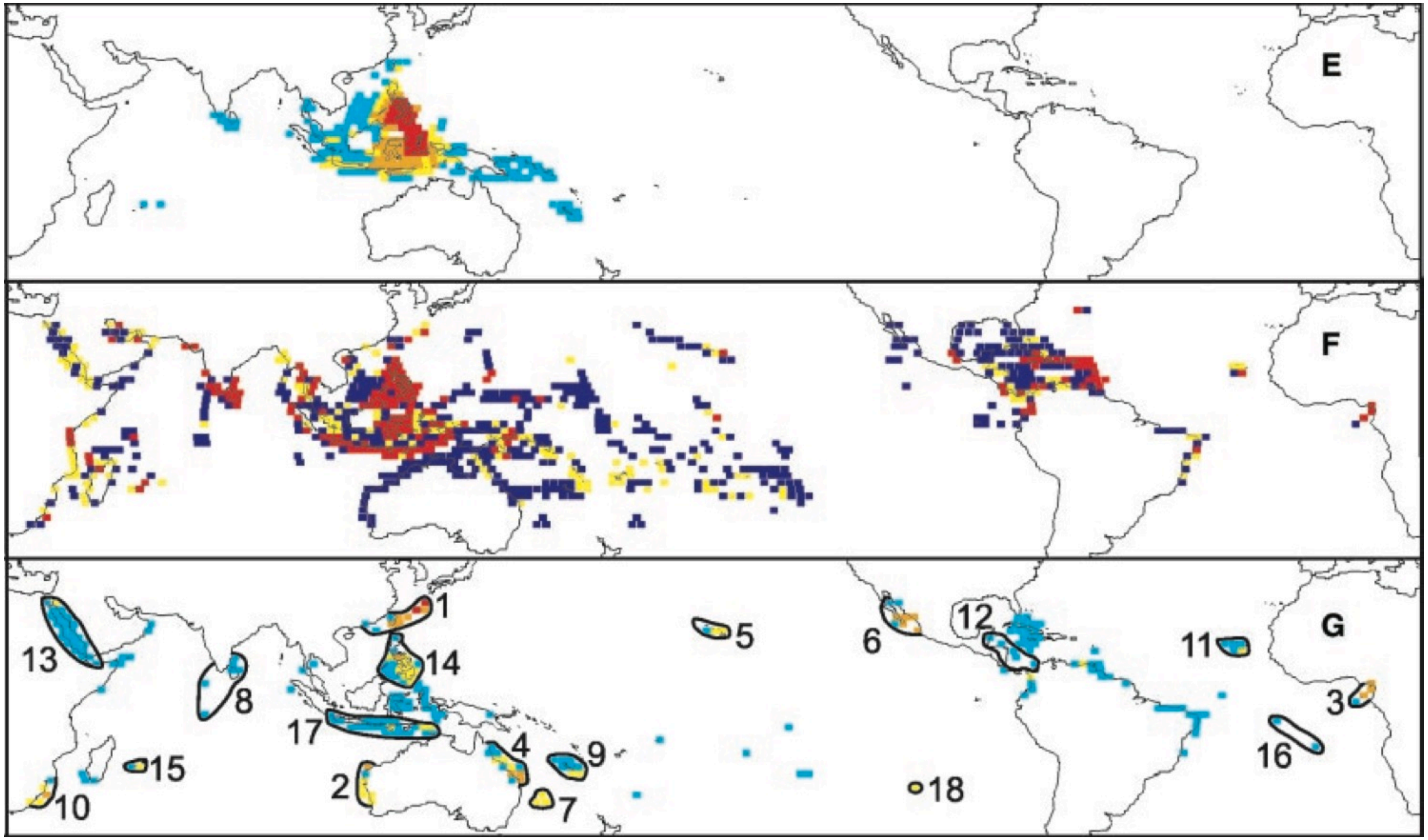


Fig. 4. Analysis of factors influencing biodiversity of coral reefs, illustrated by the percent variation in taxonomic composition of fish and coral assemblages explained by habitat area, longitude, and latitude. The score on the first axis of a principal components analysis provides a quantitative description of each assemblage (*40*) (Fig. 3). Of the four factors examined, the three shown here were significant in best-fit multiple regression models (***$P < 0.001$, *$P < 0.05$), with habitat area explaining approximately half of the variation (*26*).

Bellwood and Hughes (2001)

Coral reef biodiversity: threats



Concordance of top 10 % most species-rich cells:
- red: 4 taxa
- orange: 3 taxa
- yellow: 2 taxa
- blue: 1 taxon

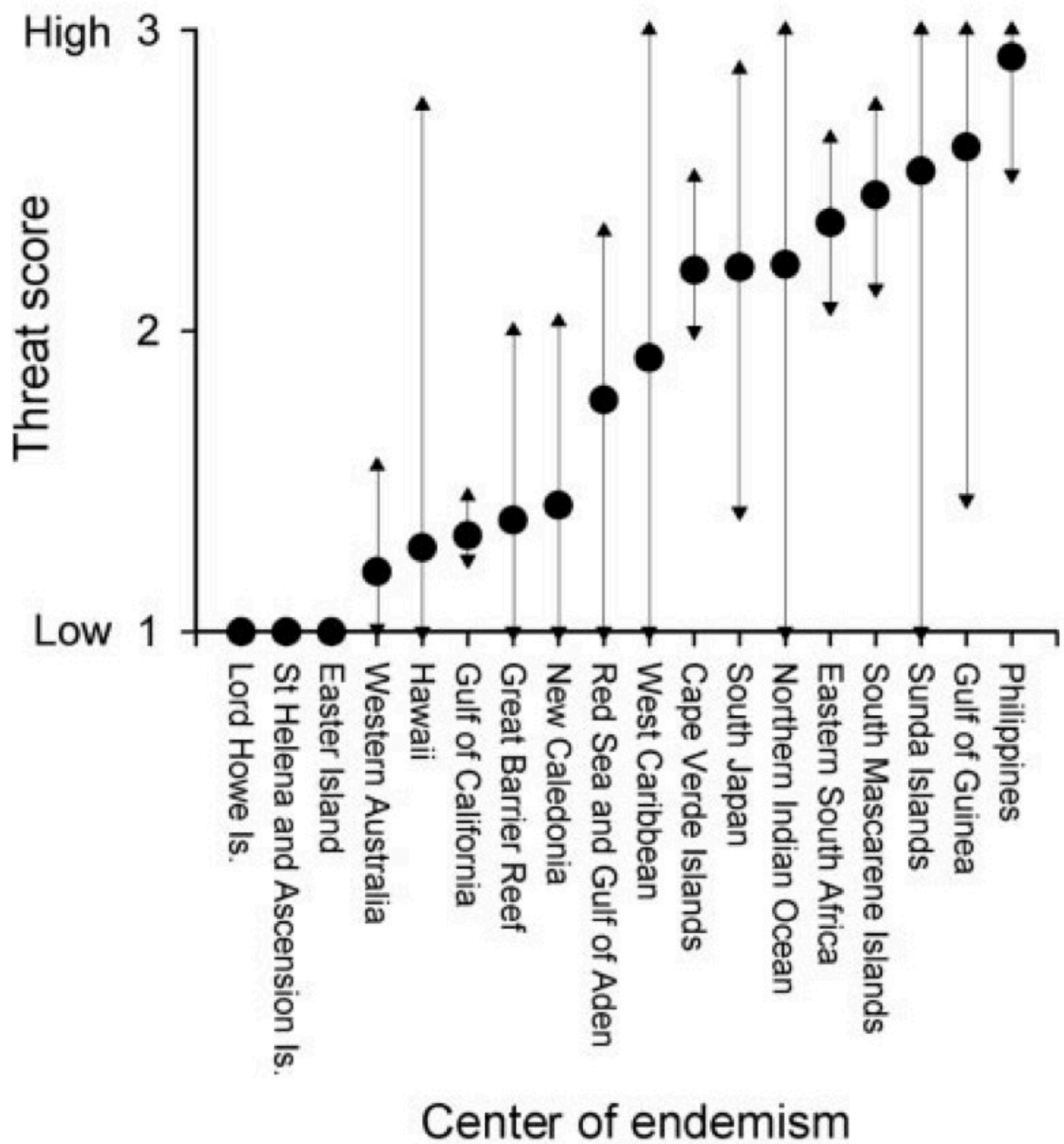
Threats to reefs in each grid cell:
- blue: low risk
- yellow: medium risk
- red: high risk

Concordance in patterns of range rarity among the top-scoring 10 % of cell for each taxon (colour codes are as in E). Places outlined show multitaxon centres of endemism

1	South Japan	4	Great Barrier Reef	7	Lord Howe Island	10	Eastern South Africa	13	Red Sea	16	St. Helena and Ascension Islands
2	Western Australia	5	Hawaiian Islands	8	North Indian Ocean	11	Cape Verde Islands	14	Philippines	17	Sunda Islands
3	Gulf of Guinea	6	Gulf of California	9	New Caledonia	12	West Caribbean	15	South Mascarene Islands	18	Easter Island

Roberts et al. (2002)

Coral reef biodiversity: threats



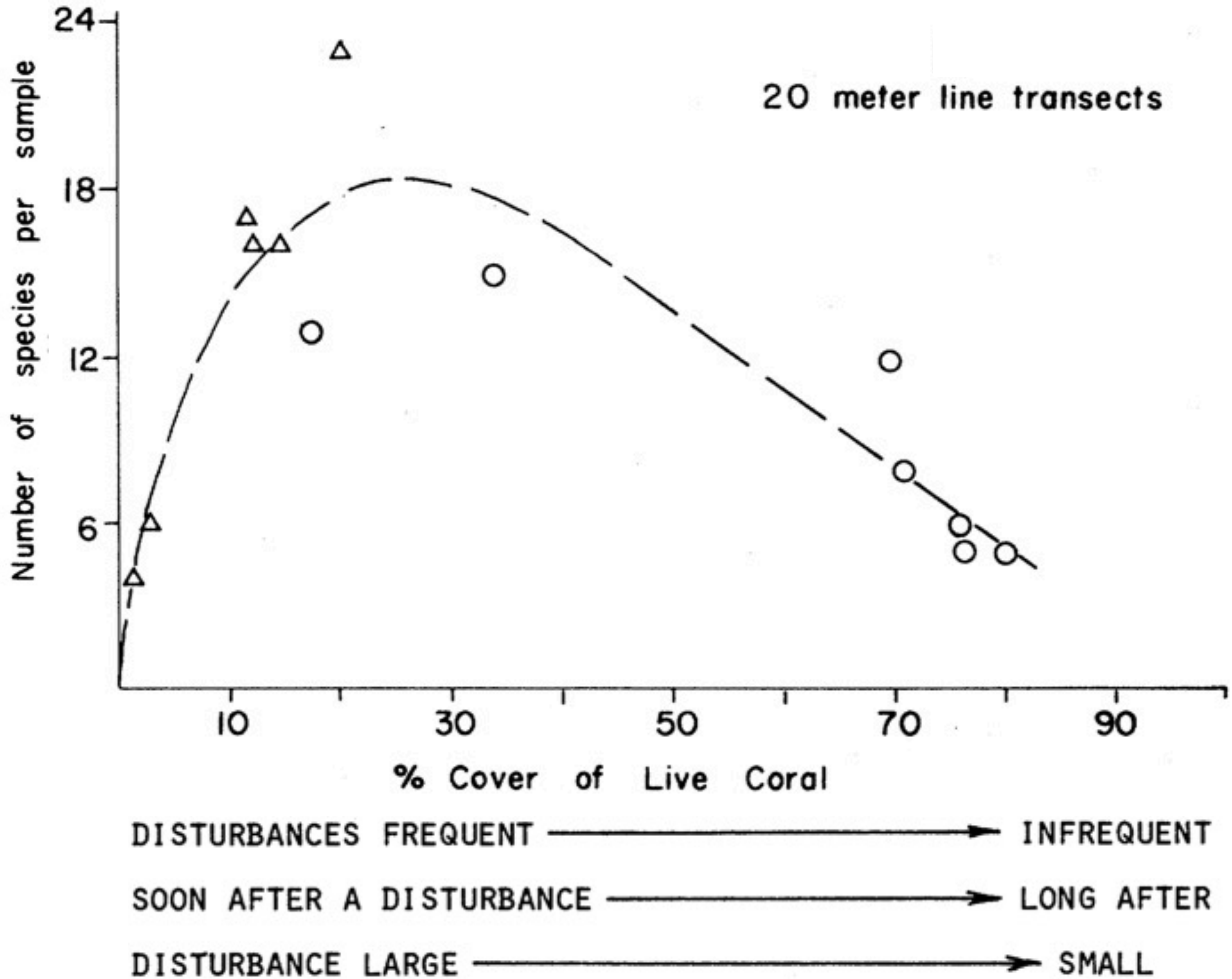
- between 7.2 and 53.6 % of each taxon (fish, corals, snails and lobsters) have highly restricted ranges
  ➔vulnerable to extinction

- 10 richest centres of endemism cover 15.8 % of the world's coral reefs, but include between 44.8 and 54.6 % of the endemic species

Fig. 3. Threats to reefs in centers of endemism. The figure shows mean (circles), maximum, and minimum threat scores for grid cells included within each center of endemism, calculated with data from Bryant *et al.* (*3*, *13*).

Roberts et al. (2002)

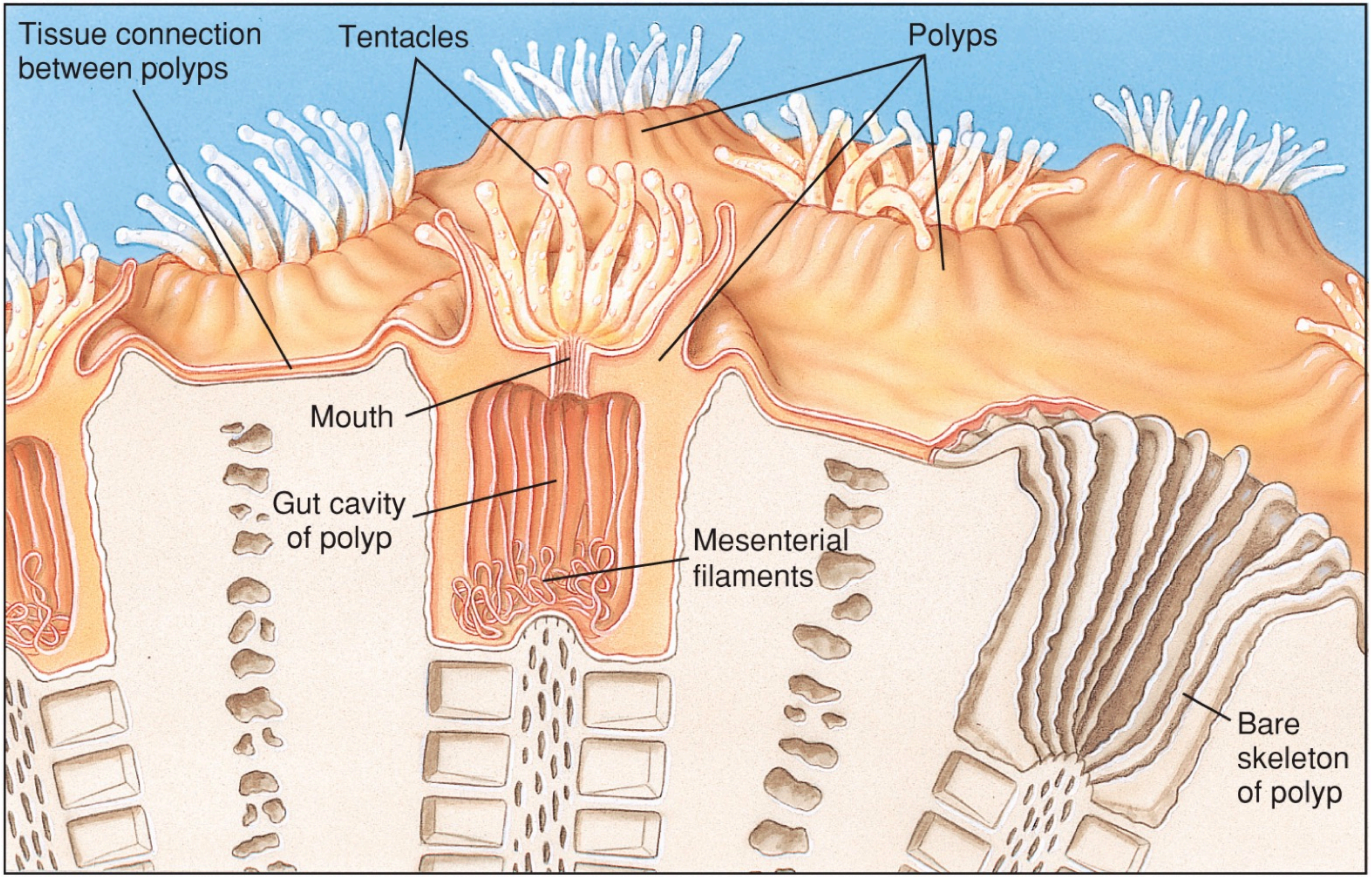
Coral reef biodiversity: intermediate disturbance hypothesis



Connell (1978)

Coral anatomy

Castro & Huber (2010)



Coral anatomy: zooxanthellae

Castro & Huber (2010)

Zooxanthellae

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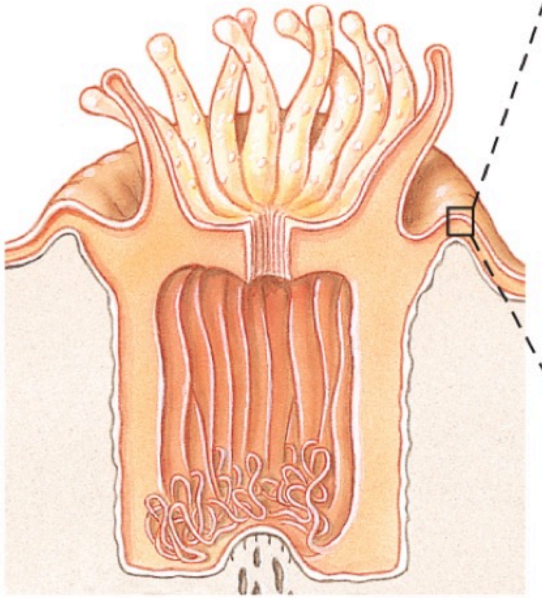
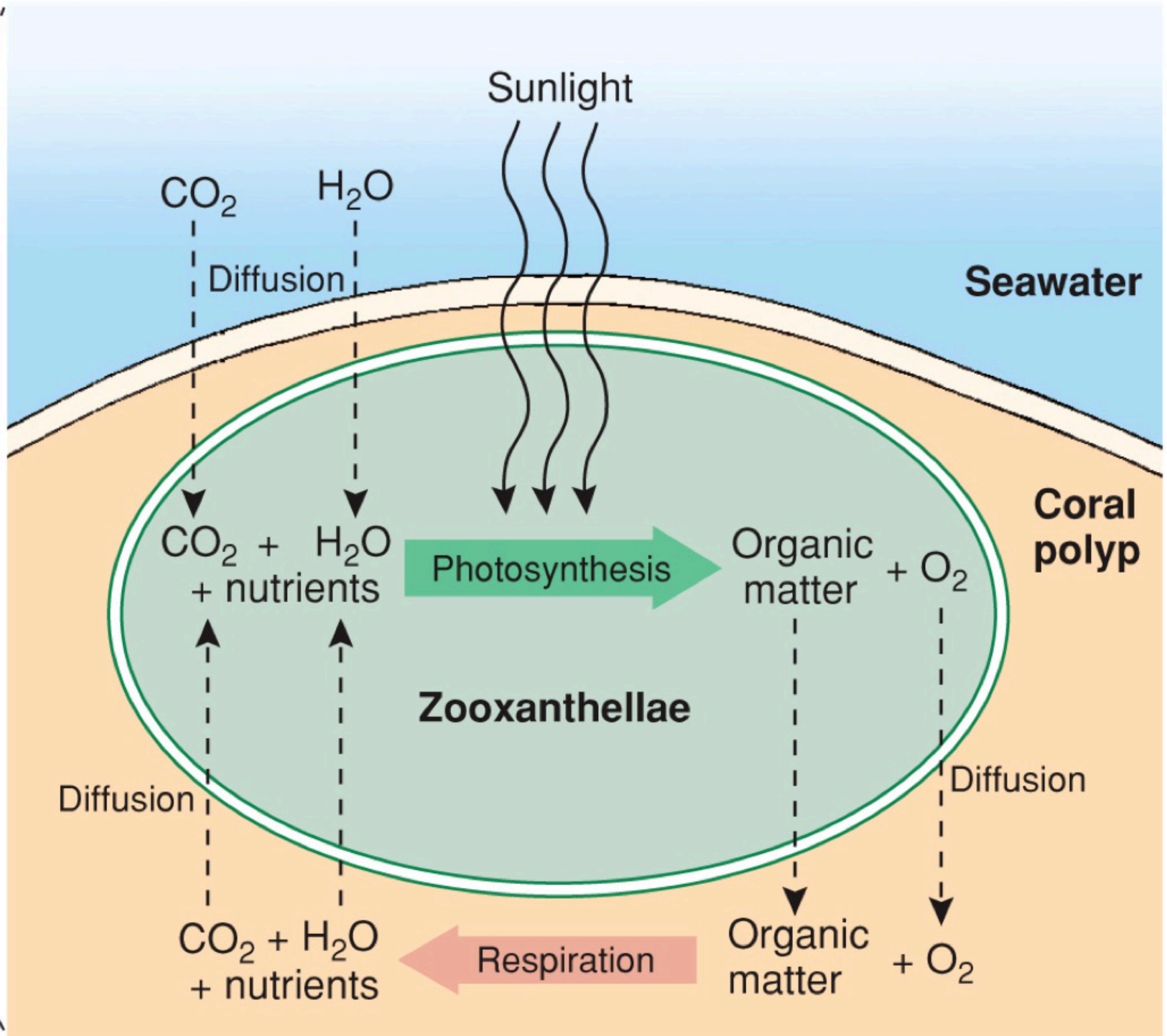




Coral anatomy: calcification

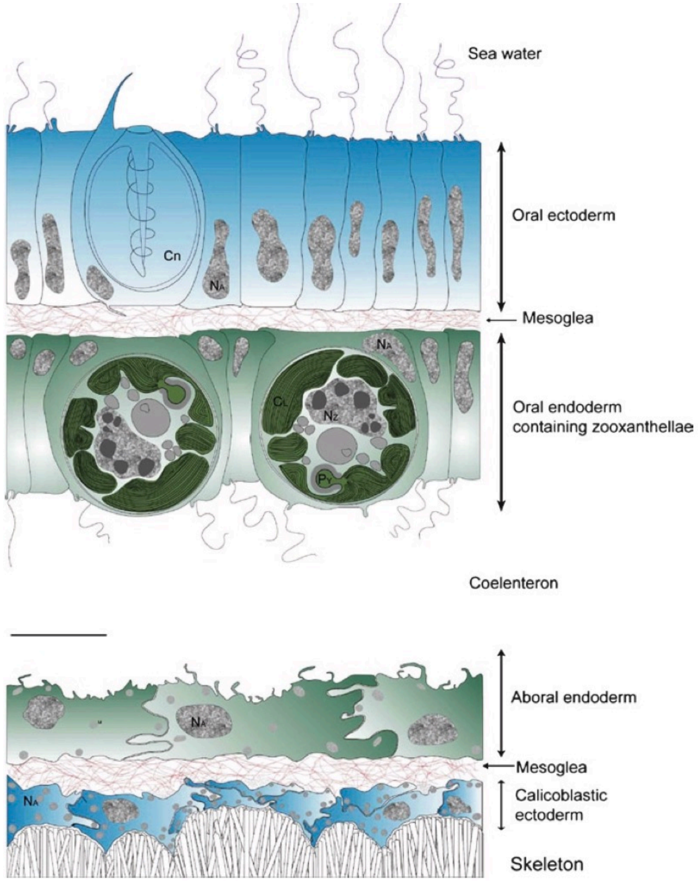


Fig. 2 Schematic section of the histology of a coral across its coenenchyme. Cn cnidocyte, N_A animal cell nucleus, N_V zooxanthella cell nucleus, C_L chloroplast, P_Y pyrenoid. The small gray spots inside the cells are mitochondria. Scale bar: 5 µm

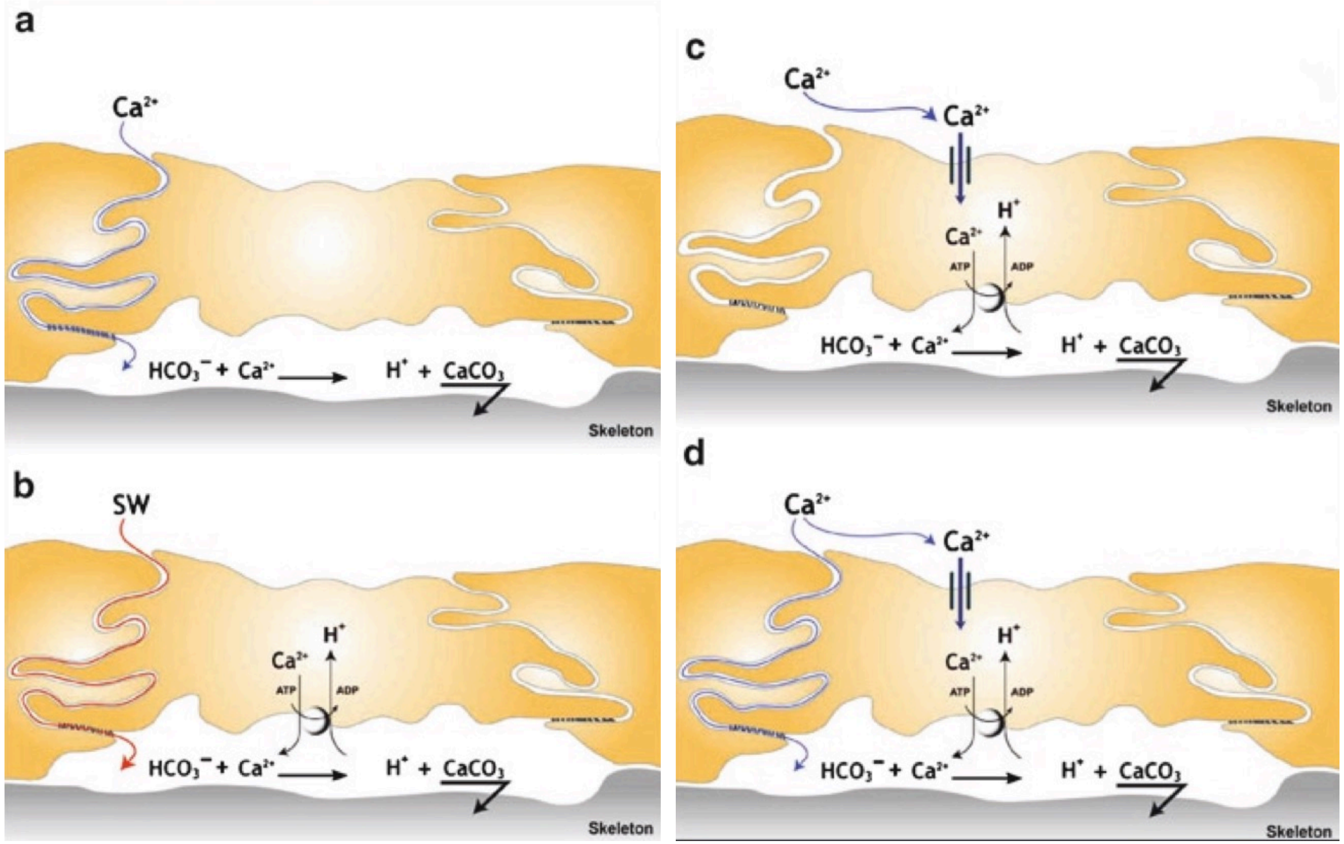
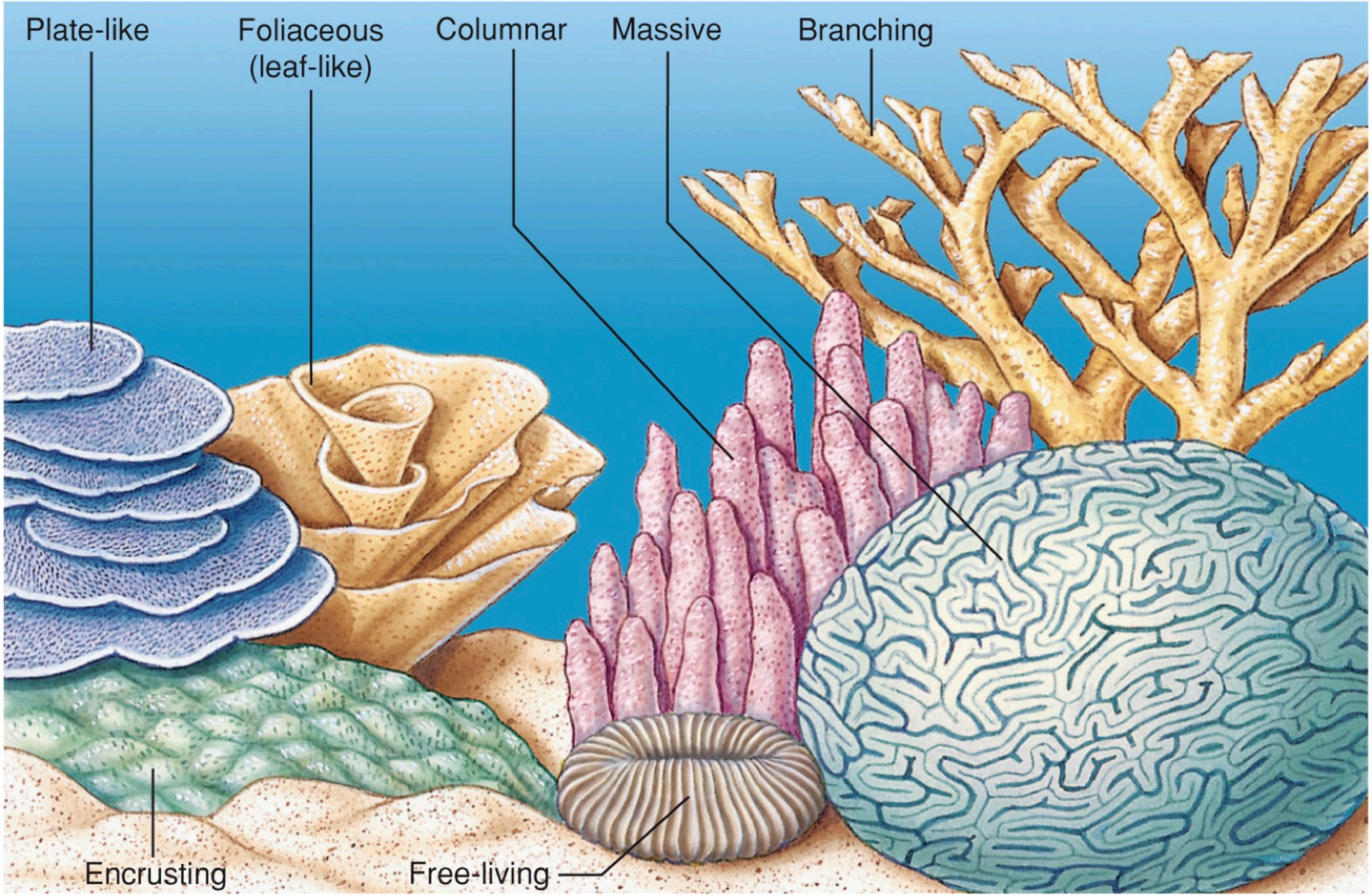


Fig. 4 Schematic view of the four hypotheses explaining transfer across the calicodermis to supply ions to the subcalicoblastic extracellular calcifying medium: (**a**) ions are provided by a passive paracellular pathway between calicoblastic cells, (**b**) bulk seawater provides the essential of ions by a paracellular pathway, (**c**) ions are supplied by an active transcellular pathway through calicoblastic cells, (**d**) combination of (**a**) and (**c**) where calcium ions are provided by both a transcellular and a paracellular pathway

Allemond et al. (2011)

Coral anatomy: growth forms

Castro & Huber (2010)



Coral anatomy: growth forms

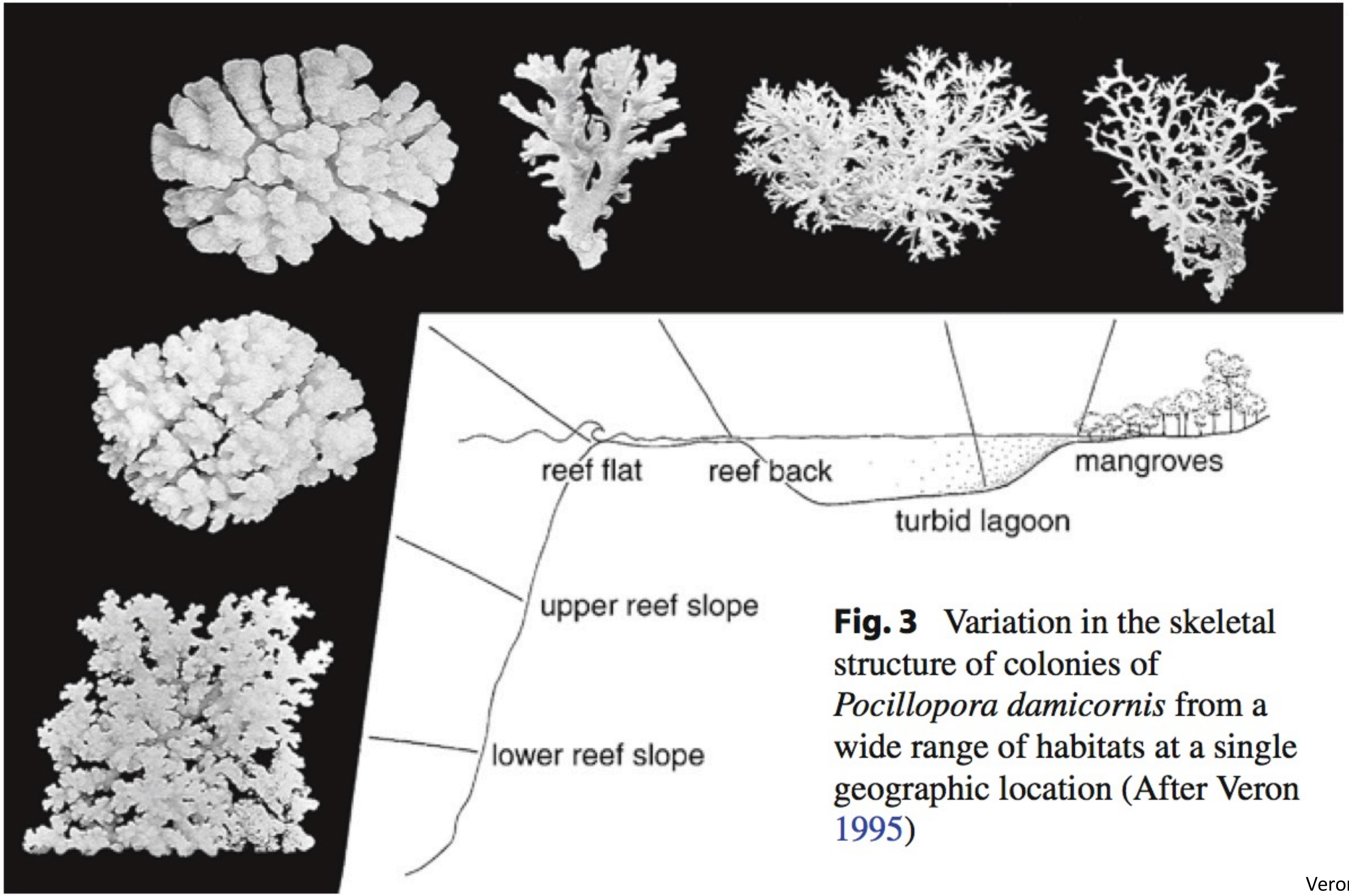
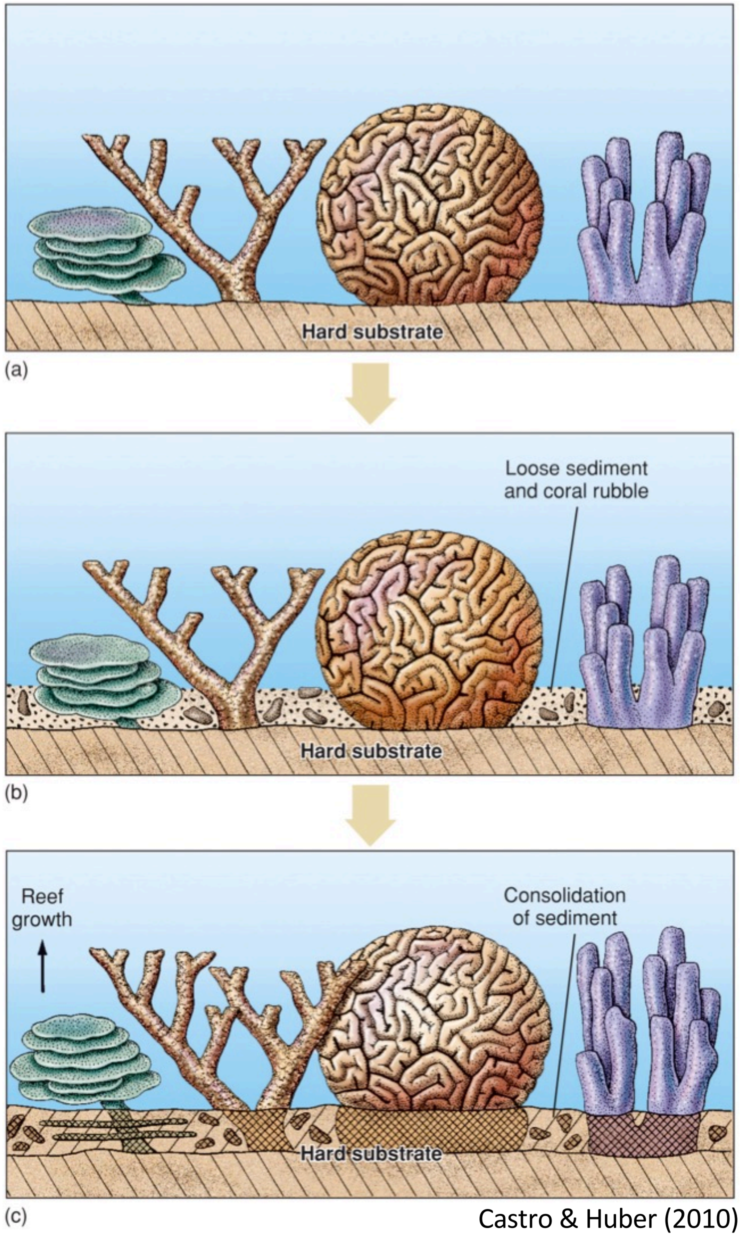


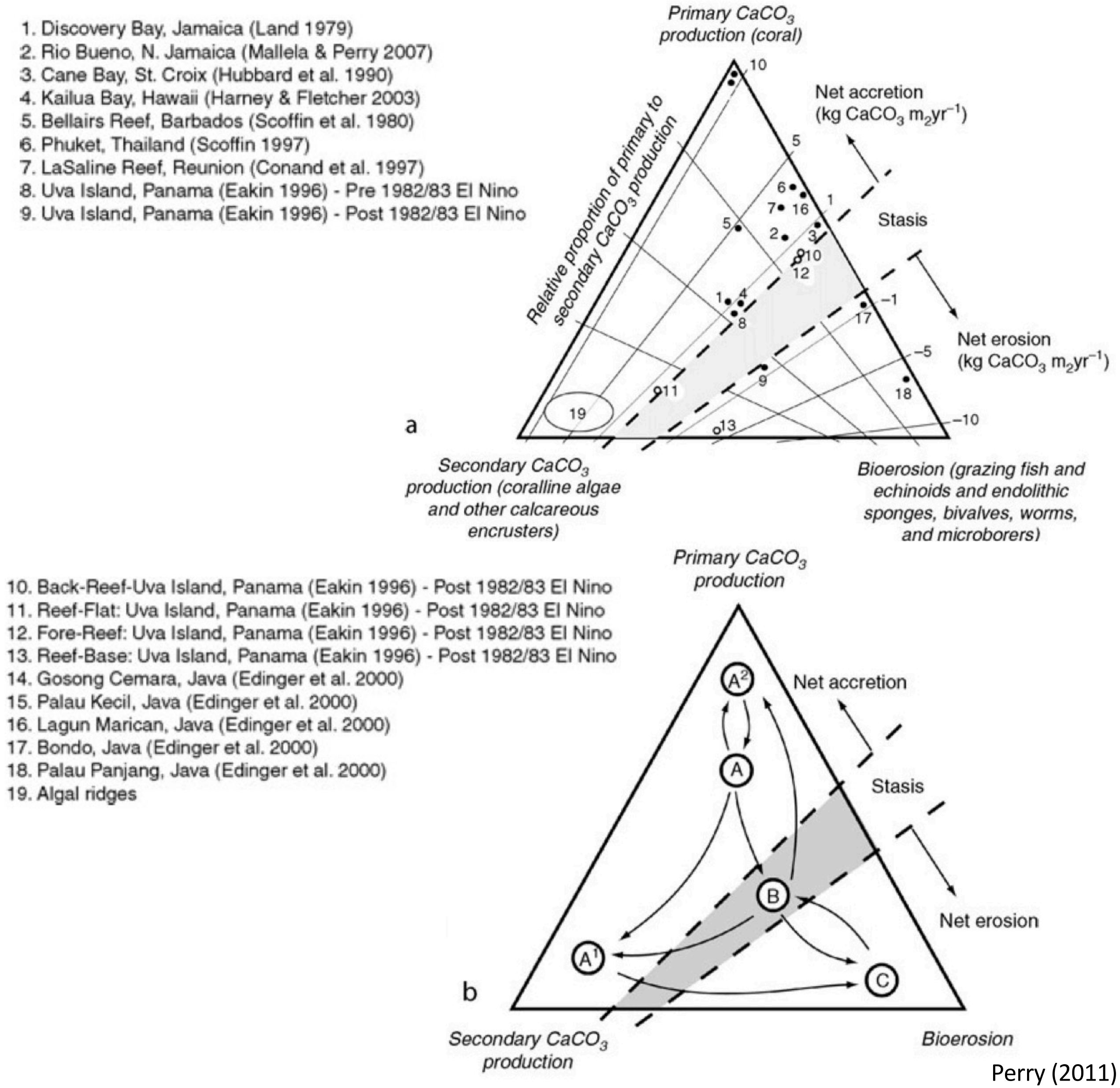
Fig. 3 Variation in the skeletal structure of colonies of *Pocillopora damicornis* from a wide range of habitats at a single geographic location (After Veron 1995)

Veron (2011)

The structure of coral reefs: reef growths

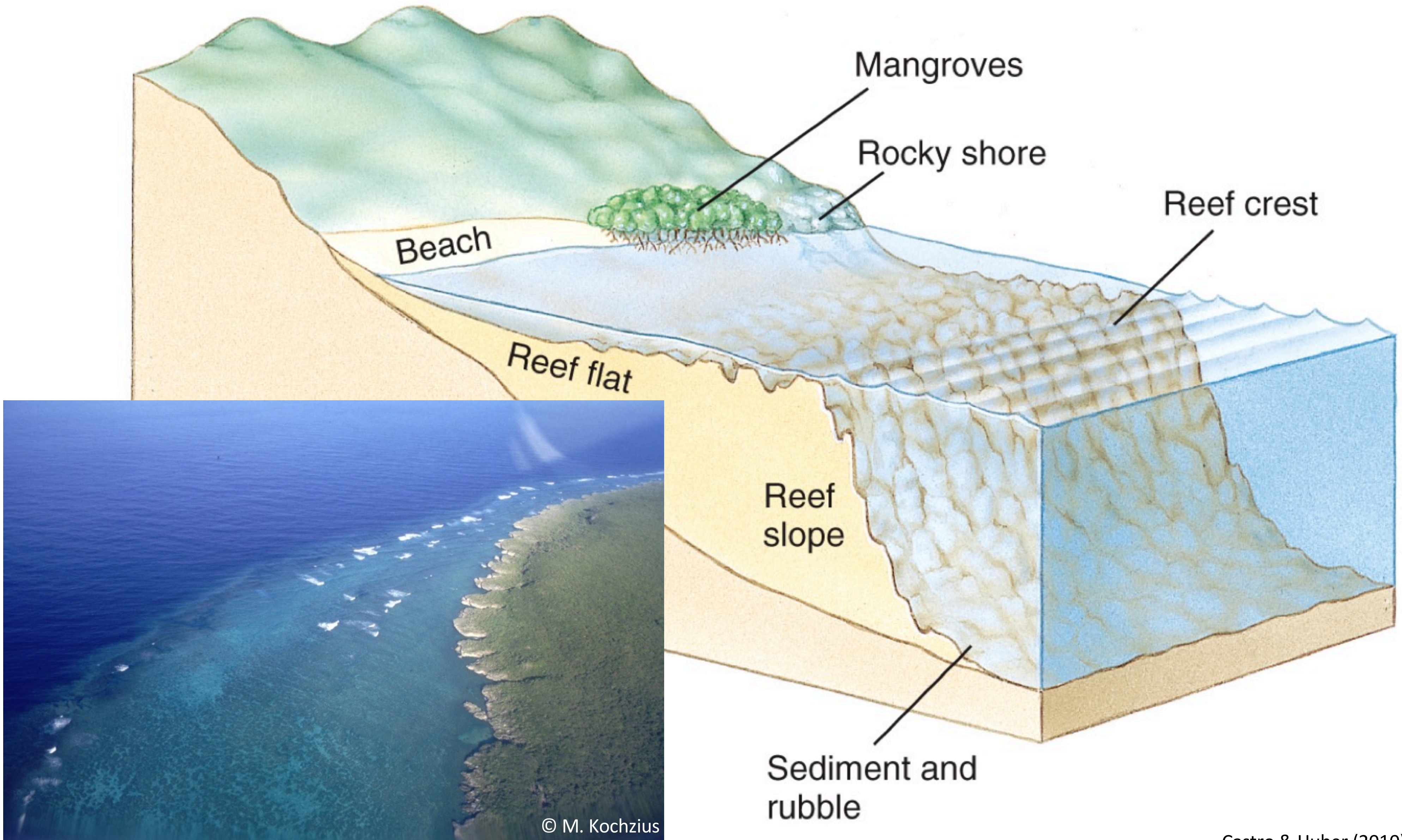


Castro & Huber (2010)



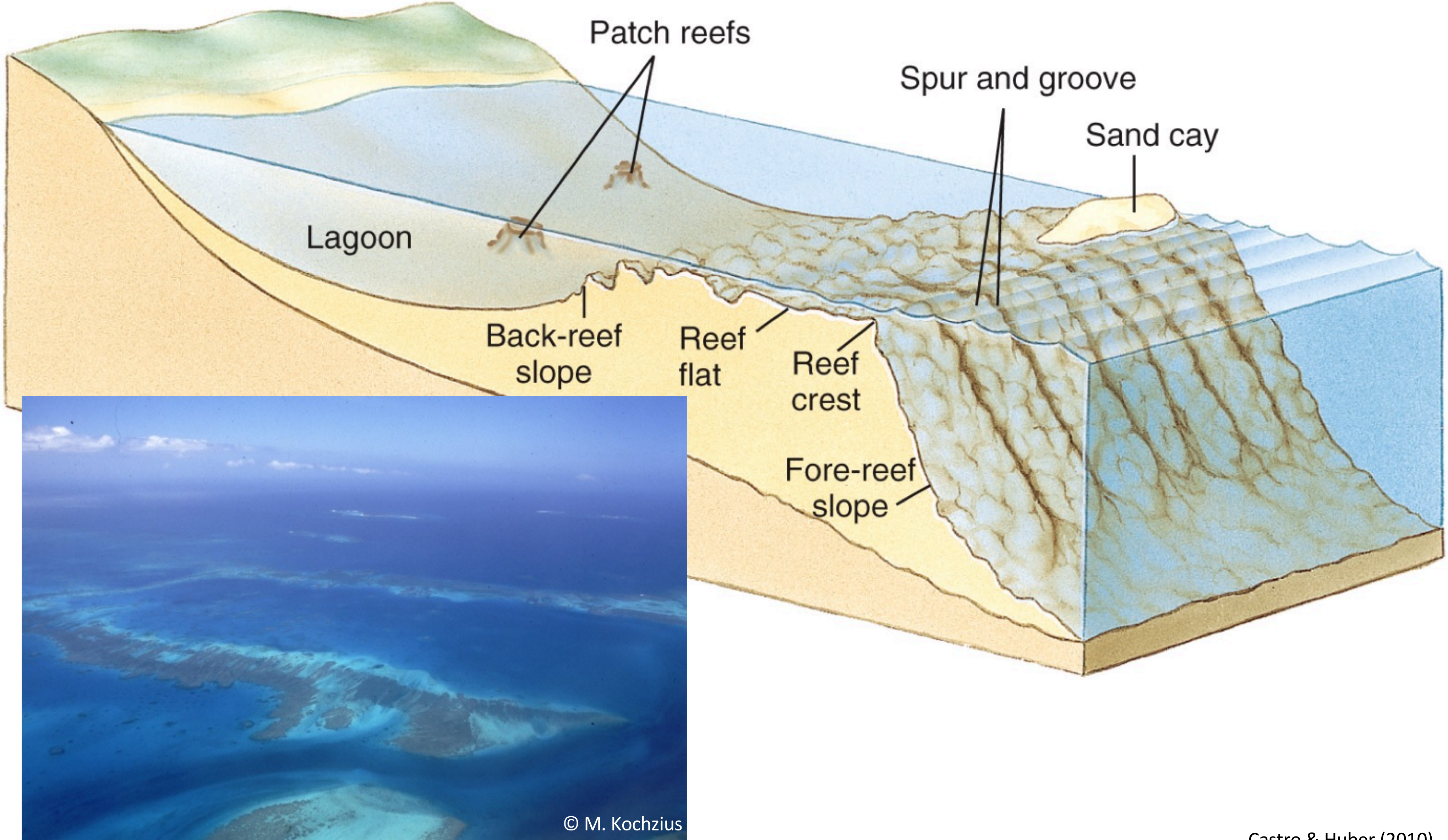
Perry (2011)

The structure of coral reefs: fringing reef



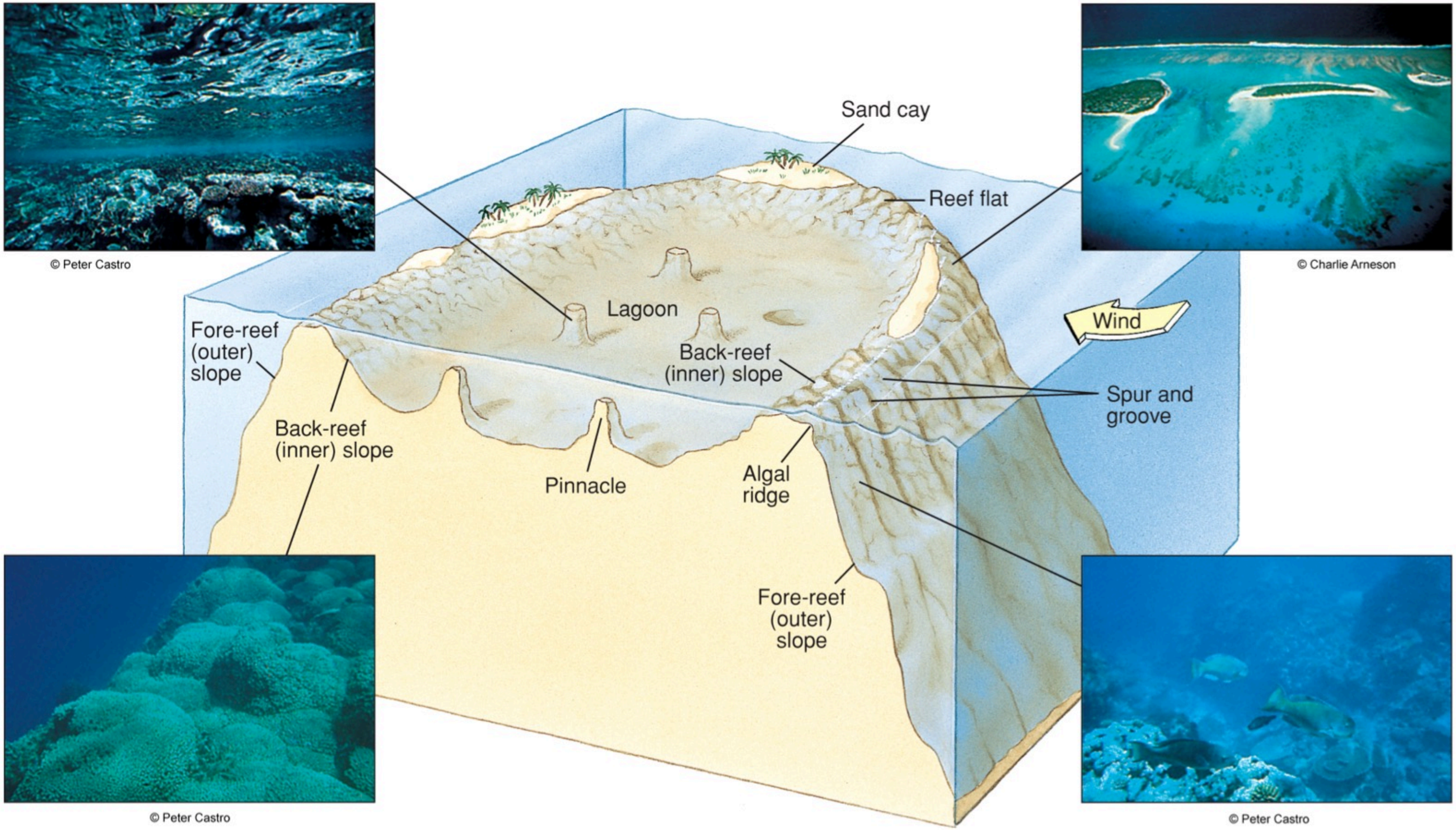
Castro & Huber (2010)

The structure of coral reefs: barrier reef



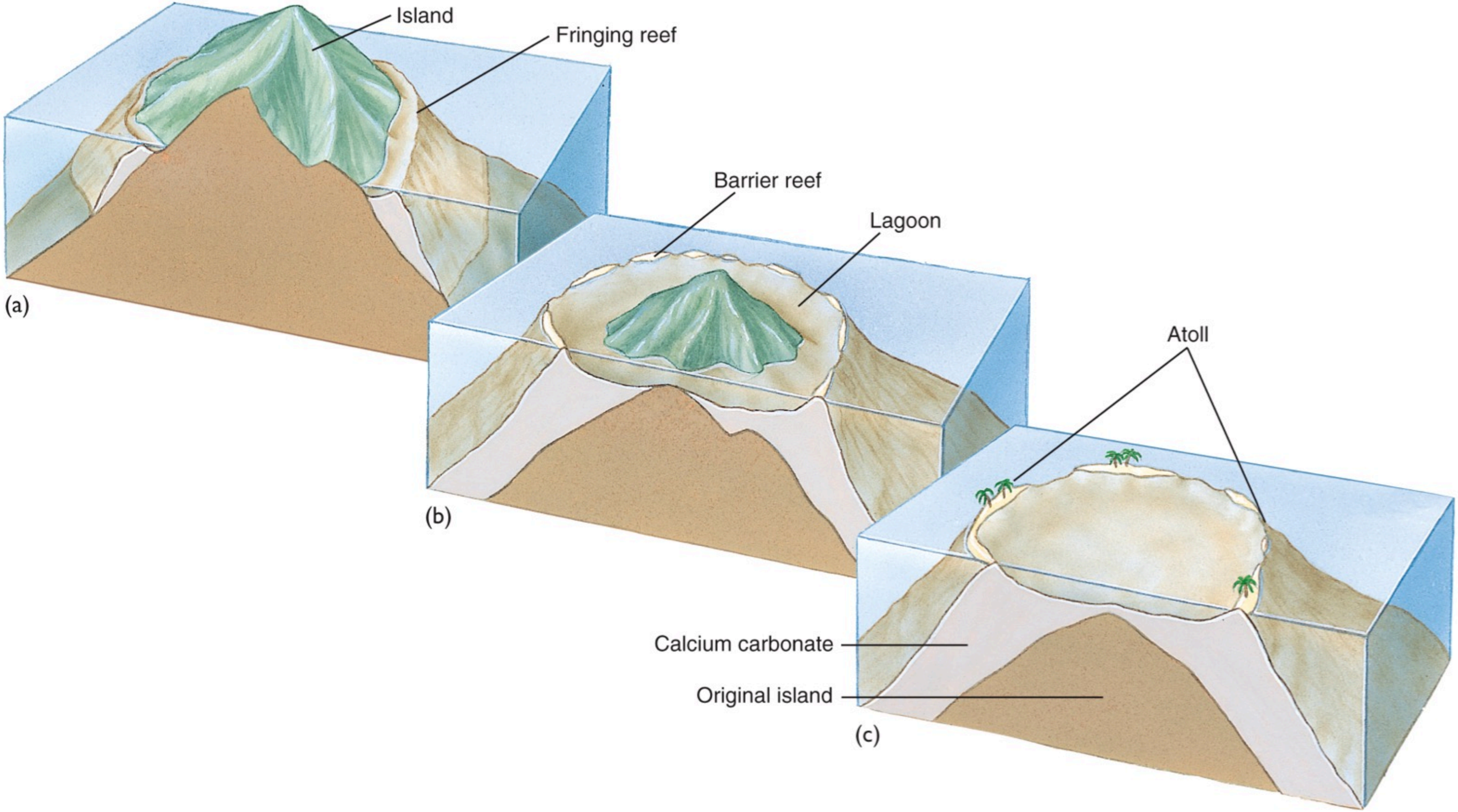
Castro & Huber (2010)

The structure of coral reefs: atoll



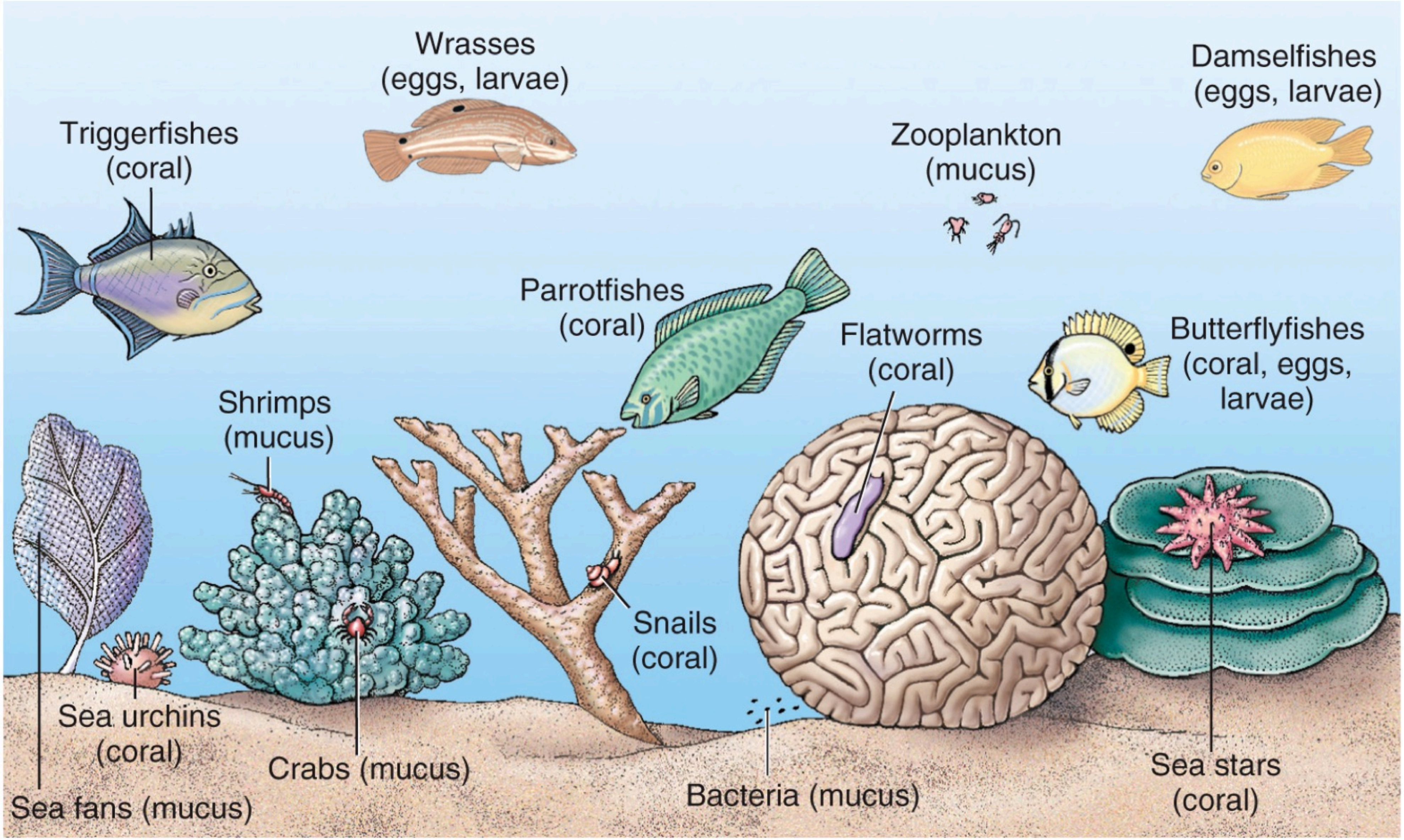
Castro & Huber (2010)

The structure of coral reefs: atoll



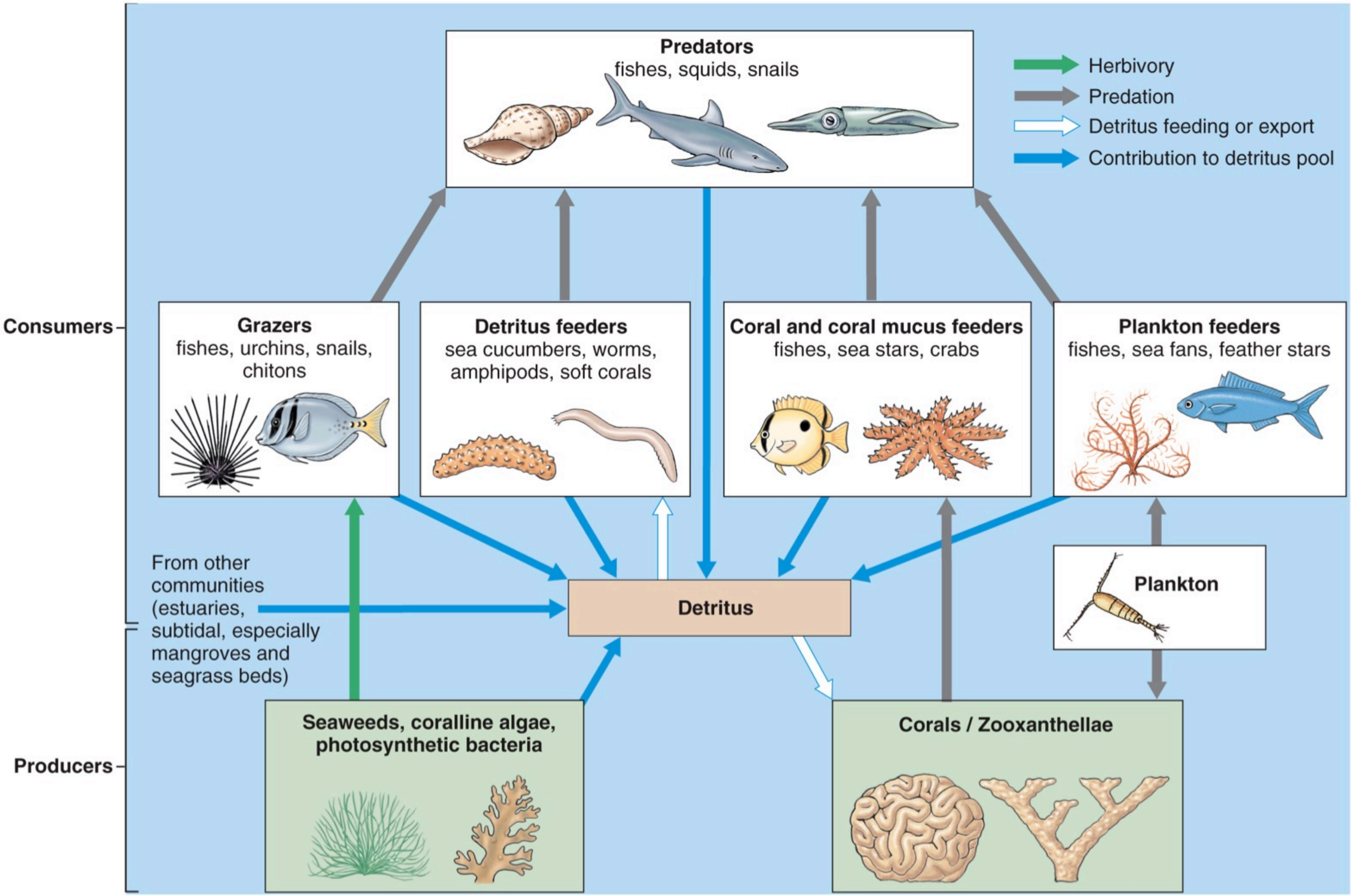
Castro & Huber (2010)

The trophic structure of coral reefs



Castro & Huber (2010)

The trophic structure of coral reefs



Castro & Huber (2010)

Phase shifts in Caribbean coral reefs

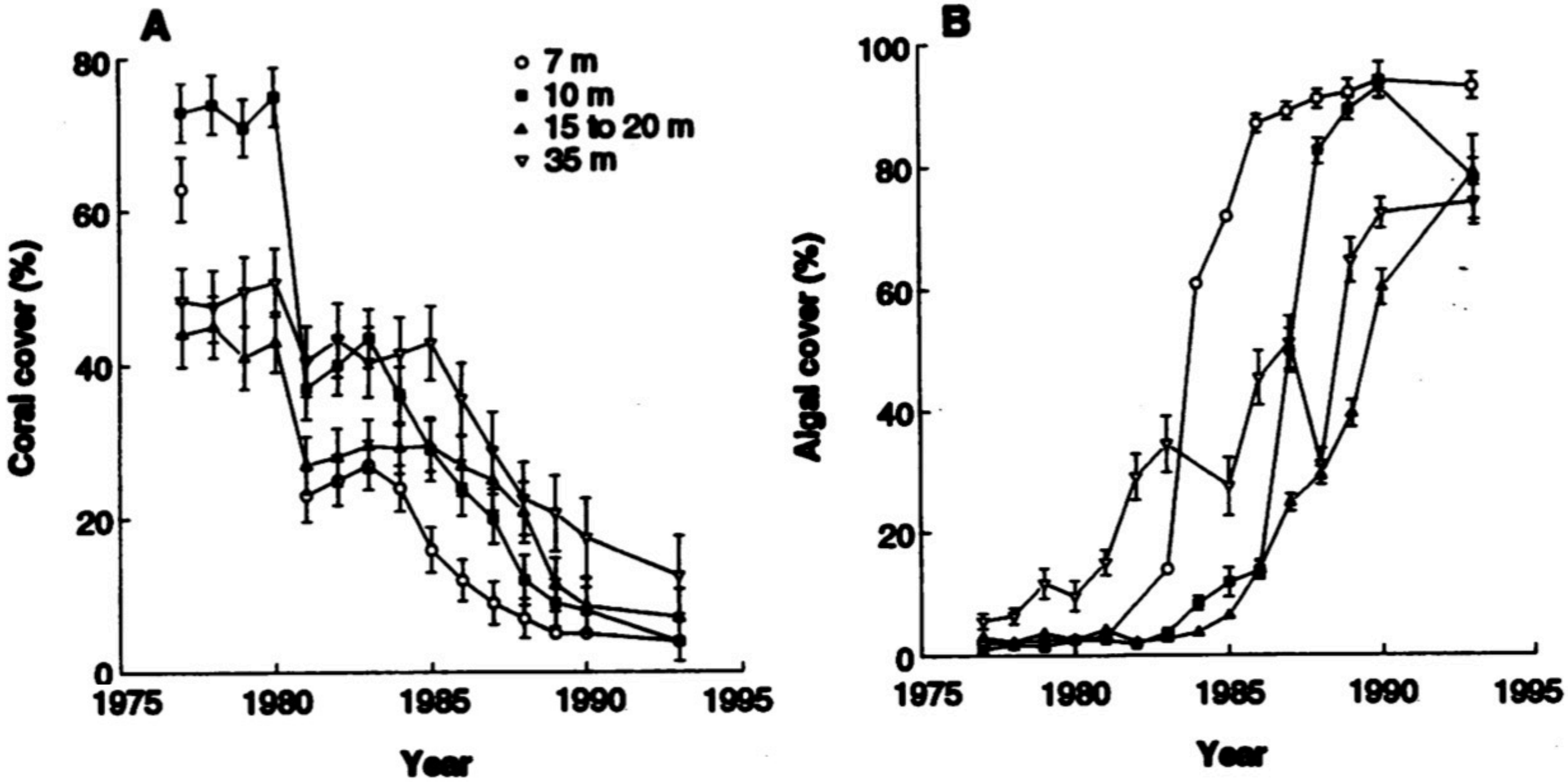


Fig. 3. Degradation of Jamaican coral reefs over the past two decades. Small-scale changes in (**A**) coral cover and in (**B**) macroalgal cover over time at four depths near Discovery Bay (*32*).

- Mass mortality of *Diadema antillarum* in 1983 due to a species-specific pathogen
- Hurricane Allen (category 5) in 1980 damaged shallow water reefs severely

Hughes (1994)

Phase shifts in Caribbean coral reefs

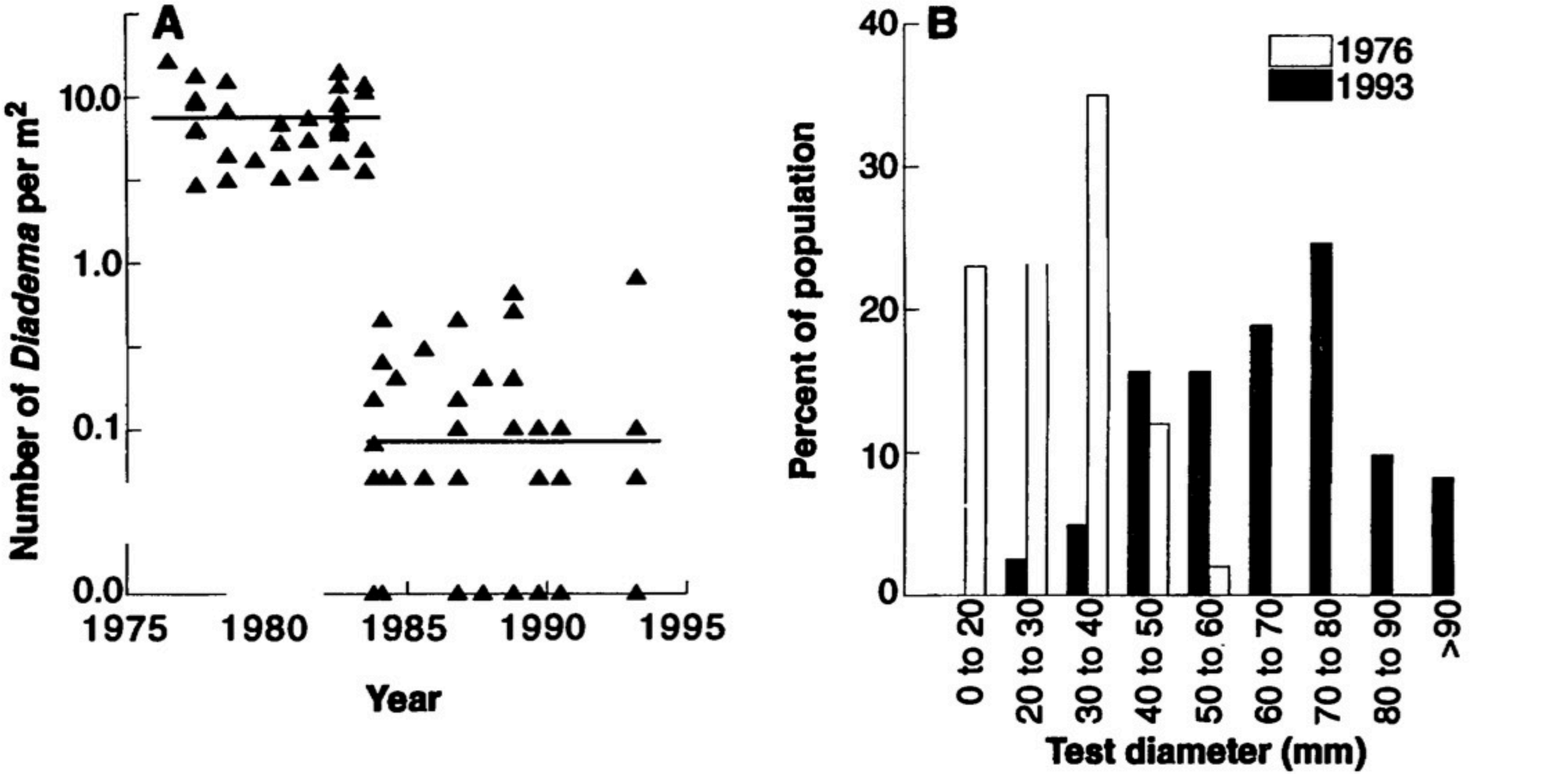


Fig. 4. Long-term dynamics of the echinoid *Diadema antillarum* on Jamaican reefs. (**A**) Abundances over time based on estimates at 14 sites along >100 km of coastline over nearly two decades. Note the 99% drop in 1983 (from a mean of 9 to 0.09 per square meter), with no recovery after 10 years. (**B**) Population structure of *Diadema* (*33*) before and after the 1983 die-off.

Hughes (1994)

Phase shifts in Caribbean coral reefs

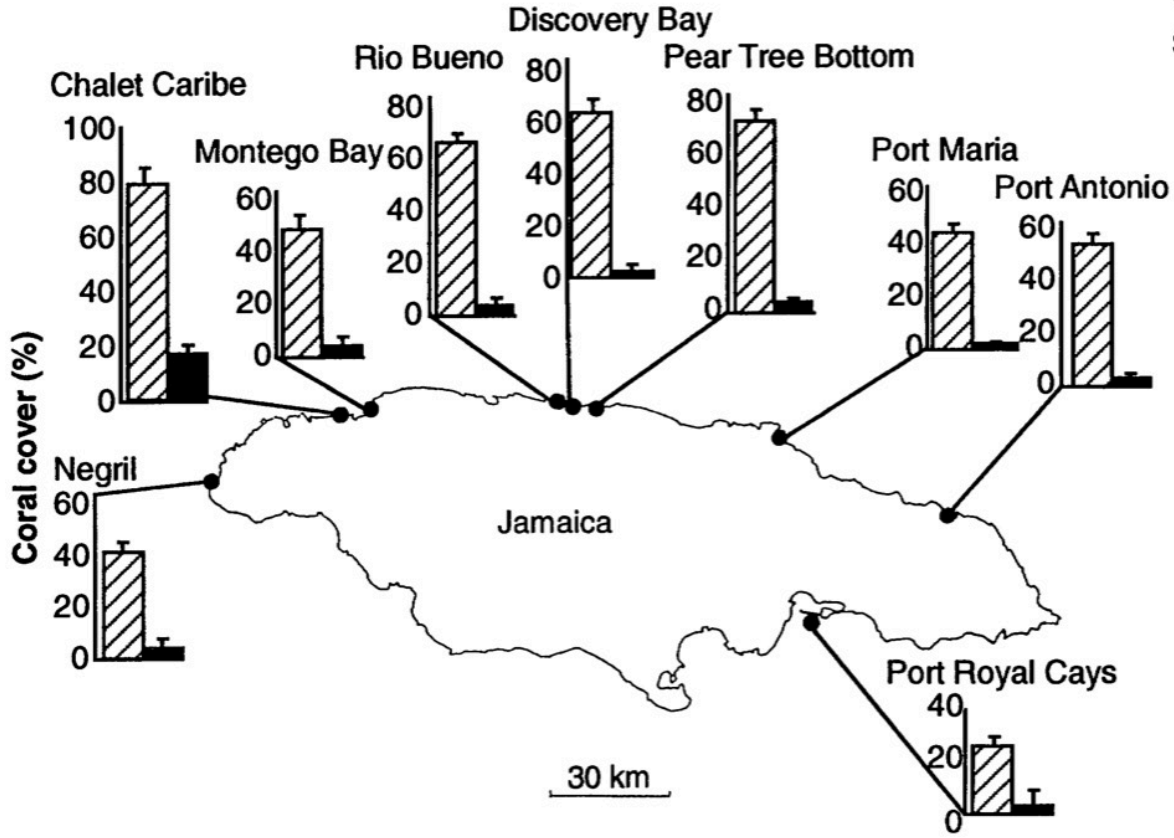
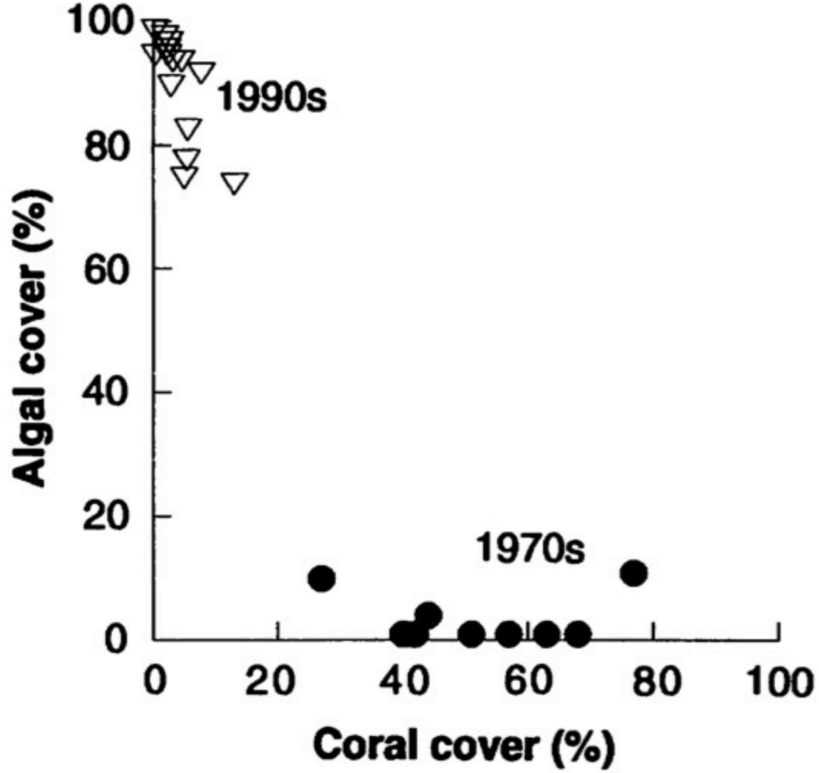


Fig. 5. Large-scale changes in community structure at fore-reef sites along >300 km of the Jamaican coastline, surveyed in the late 1970s (1977, hatched bars) and the early 1990s (1993, solid bars) (*34*).

Fig. 6. Large-scale community phase shifts on Jamaican reefs, from coral- to algal-dominated systems (*34*).

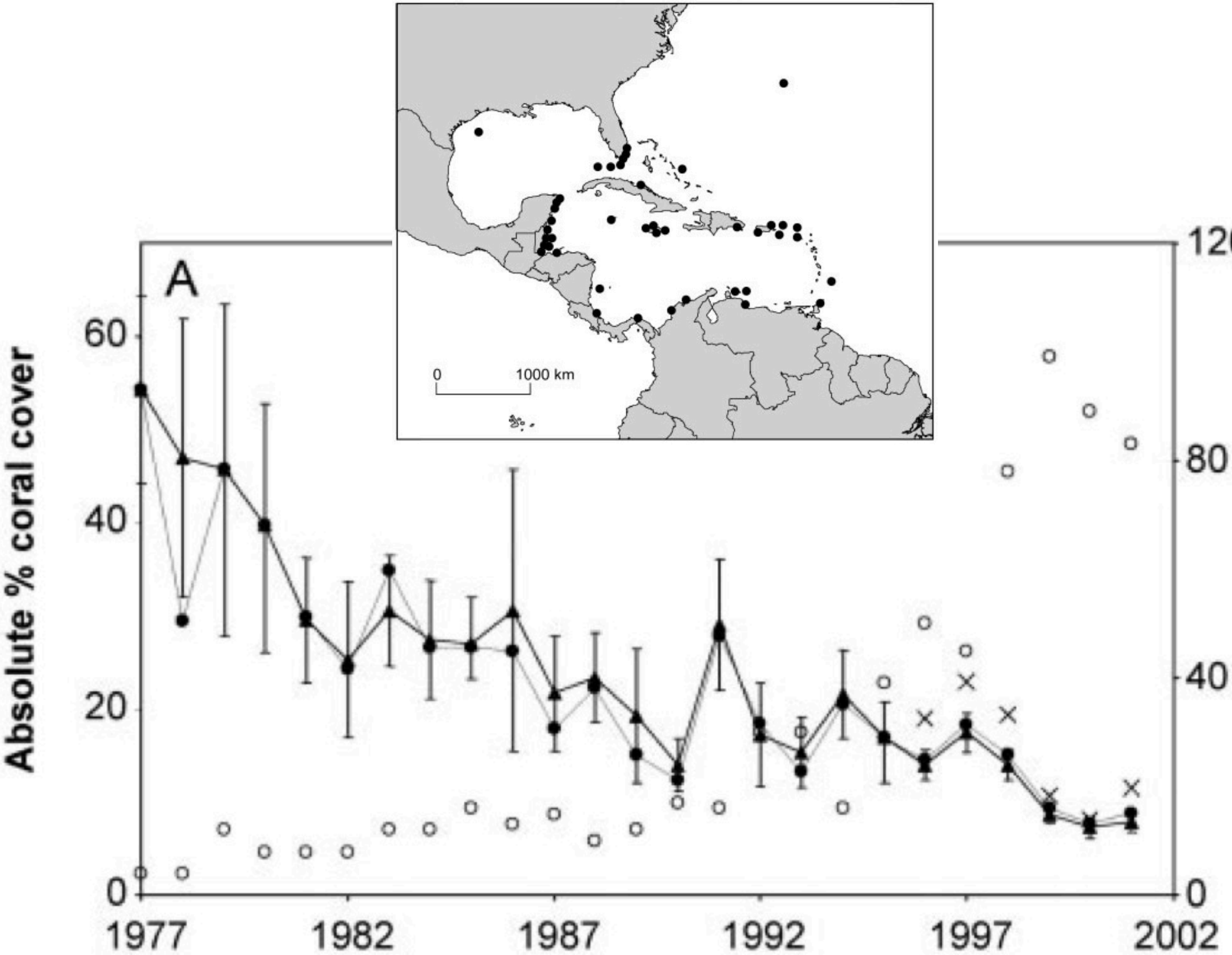


- Decline in coral cover from a mean of 52 % (1977-1980) to 3 % (1990-1993)
- Increase in cover of fleshy macroalgae from am mean of 4 % (1977-1980) to 92 % (1990-1993)

Hughes (1994)

Phase shifts in Caribbean coral reefs

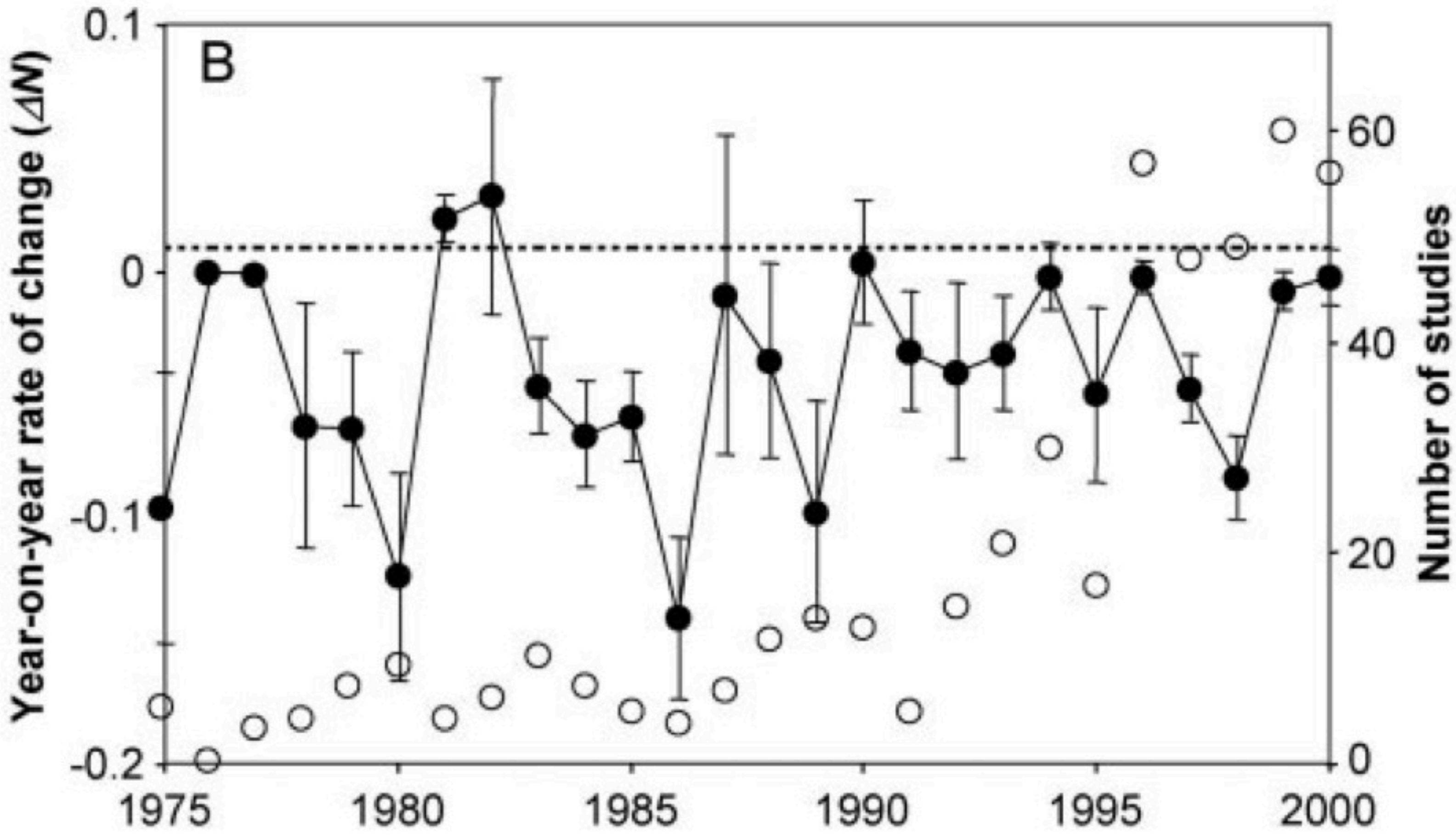
Fig. 2. Total observed change in percent coral cover across the Caribbean basin during the past three decades. (**A**) Absolute percent coral cover from 1977 to 2001. Annual coral cover estimates (▲) are weighted means with 95% bootstrap confidence intervals. Also shown are unweighted mean coral cover estimates for each year (●), the unweighted mean coral cover with the Florida Keys Coral Monitoring Project (1996–2001) omitted (×), and the sample size (number of studies) for each year (○).



Gardner et al. (2003)

Phase shifts in Caribbean coral reefs

(**B**) Year-on-year rate of change [mean $\Delta N \pm$ SE (*8*)] in percent coral cover across all sites reporting data for at least two consecutive years between 1975 and 2000 (●), and the sample size (number of studies) for each period (t, $t + 1$) (○).



Gardner et al. (2003)

Phase shifts in Caribbean coral reefs

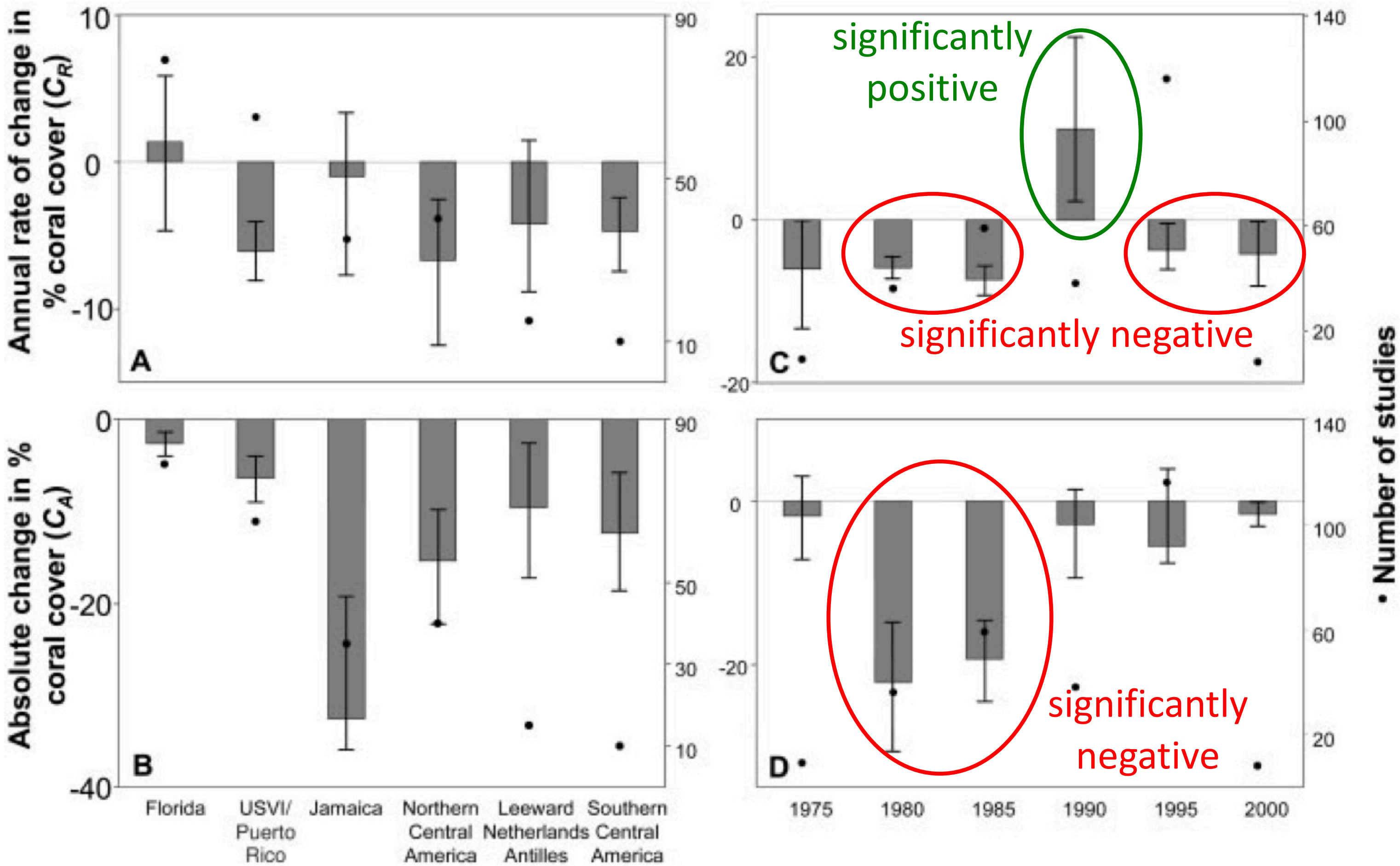


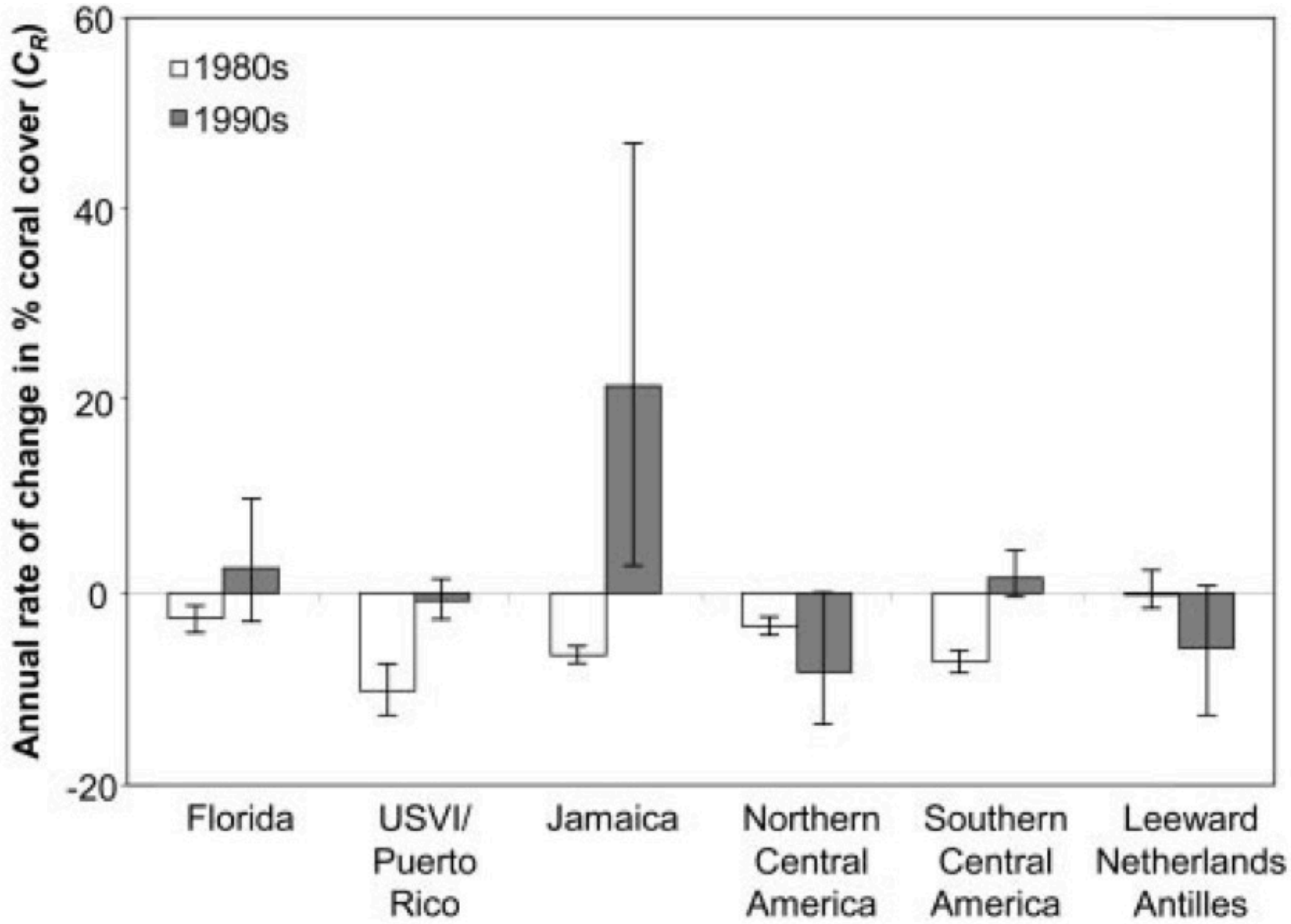
Fig. 3. Coral cover change for subregions of the Caribbean and for 5-year time periods from 1975 to 2000, expressed as annual rate of change in percent coral cover, C_R (**A** and **C**), and as change in absolute percent coral cover, C_A (**B** and **D**). The Leeward Netherlands Antilles includes Venezuela. Temporal averages were taken across all studies whose midpoint fell within each time interval; time periods are indicated by the first year of the interval. For the interval starting in 2000, only 2 years are included. Bootstrap-generated 95% confidence intervals and sample sizes are shown.

- no significant variation in annual rate of change in % coral cover (A)
- significant difference between regions in absolute loss of coral cover (B)
- significant temporal variation in coral decline for rate of change (C) and absolute change in % coral cover (D)

Gardner et al. (2003)

Phase shifts in Caribbean coral reefs

Fig. 4. Subregional variability in mean rate of change in coral cover observed during the decades starting in 1980 (open bars) and 1990 (shaded bars). Geographic regions are as in Fig. 3. Bootstrap-generated 95% confidence intervals are shown. Sample sizes for the 1980s and 1990s, respectively, are as follows: Florida, 4 and 64; U.S. Virgin Islands (USVI)/Puerto Rico, 33 and 26; Jamaica, 29 and 7; northern Central America, 12 and 29; southern Central America, 8 and 3; and Leeward Netherlands Antilles, 4 and 12.



Severe degradation of the Mesoamerican barrier reef system after bleaching caused by the 1998 El Niño and hurricane Mitch

Gardner et al. (2003)

Degradation of the Great Barrier Reef

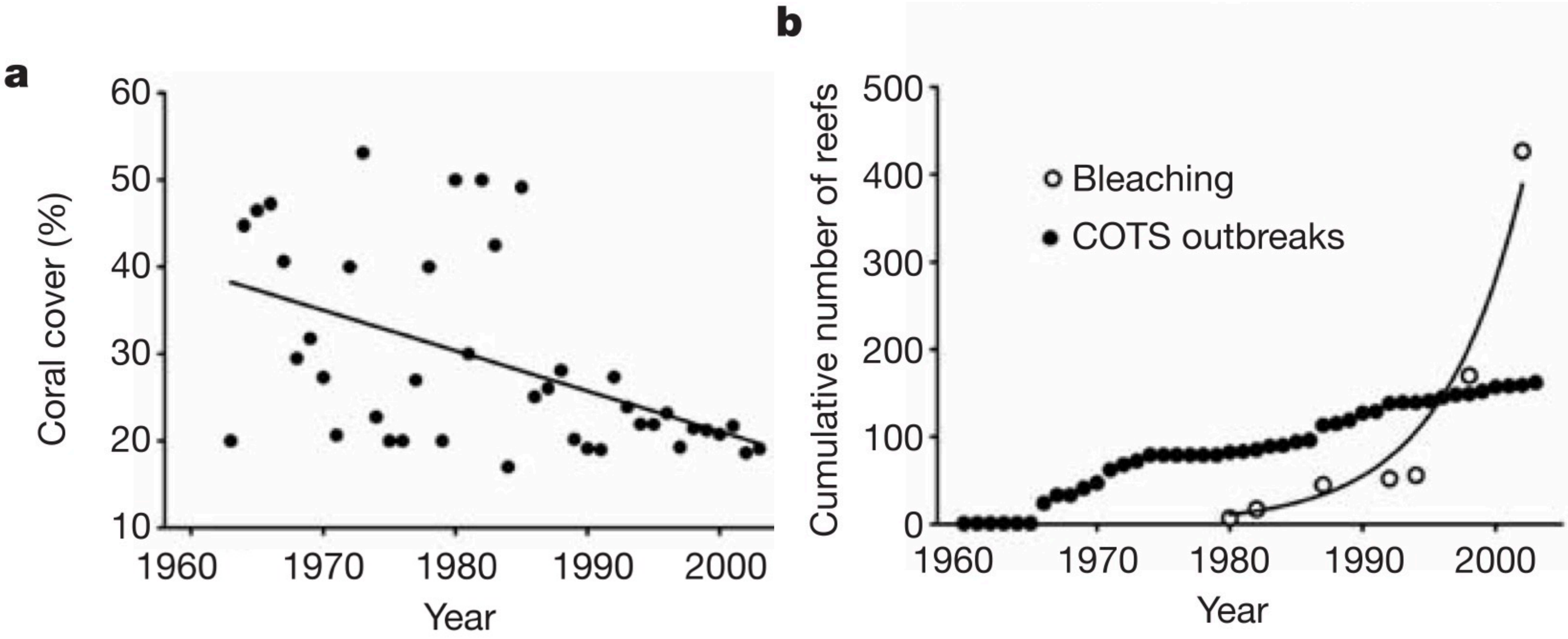


Figure 1 Degradation of coral reefs. **a**, Results of a meta-analysis of the literature, showing a decline in coral cover on the Great Barrier Reef. Each point represents the mean cover of up to 241 reefs sampled in each year. **b**, The recorded number of reefs on the Great Barrier Reef, Australia, substantially damaged over the past 40 yr by outbreaks of crown-of-thorns starfish (COTS) and episodes of coral bleaching.

Bellwood et al. (2004)

Degradation of the Great Barrier Reef

De'ath et al. (2012)

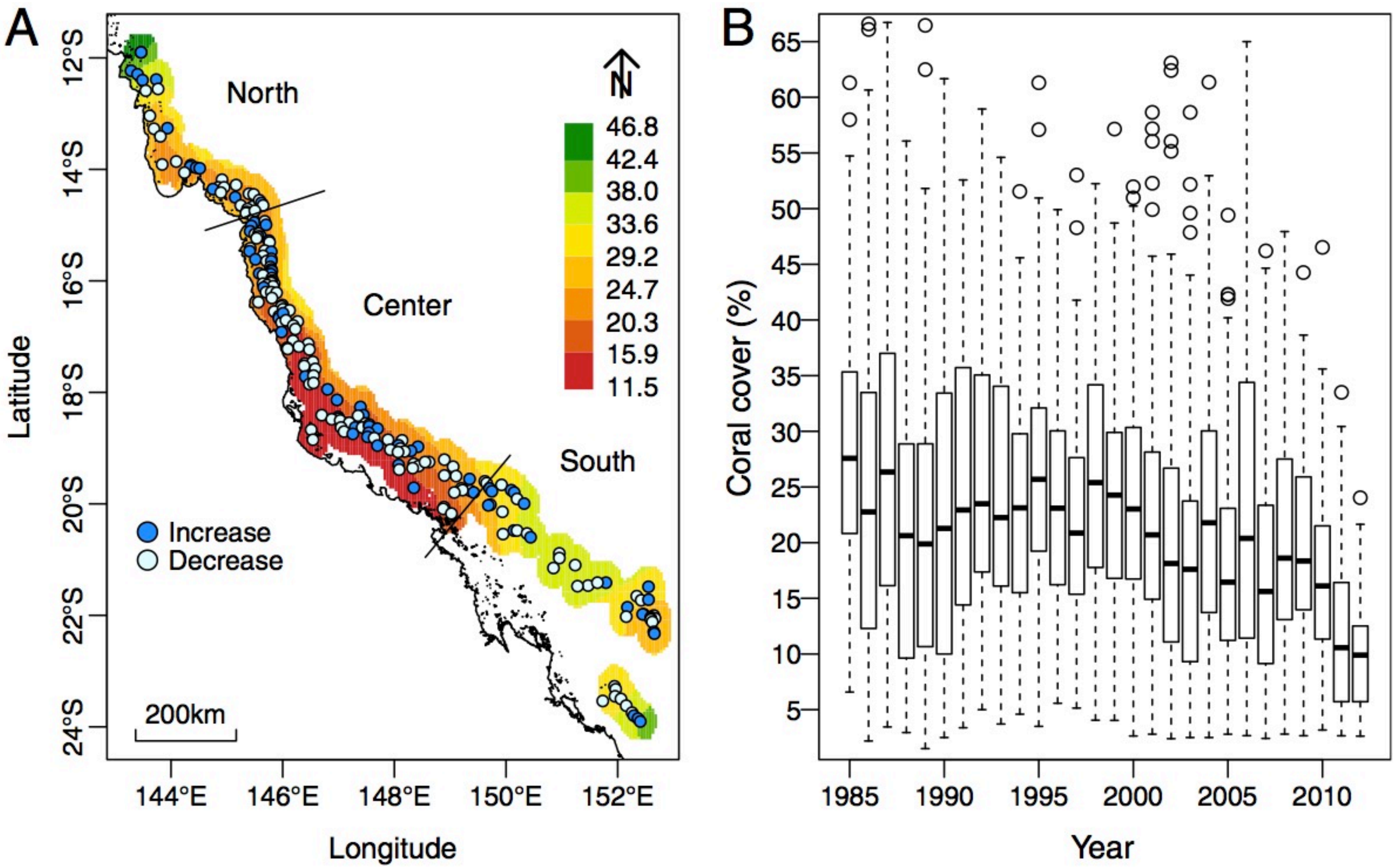


Fig. 1. Coral cover on the GBR. (*A*) Map of the GBR with color shading indicating mean coral cover averaged over 1985–2012. Points show the locations of the 214 survey reefs in the northern, central, and southern regions, and their color indicates the direction of change in cover over time. (*B*) Box plots indicate the percentiles (25%, 50%, and 75%) of the coral cover distributions within each year and suggest a substantial decline in coral cover over the 27 y.

Based on the world's most extensive time series data on reef condition (2,258 surveys of 214 reefs over 1985–2012), the authors show a major decline in coral cover from 28.0 % to 13.8 % (0.53 % y^{-1}), a loss of 50.7 % of initial coral cover

Degradation of the Great Barrier Reef

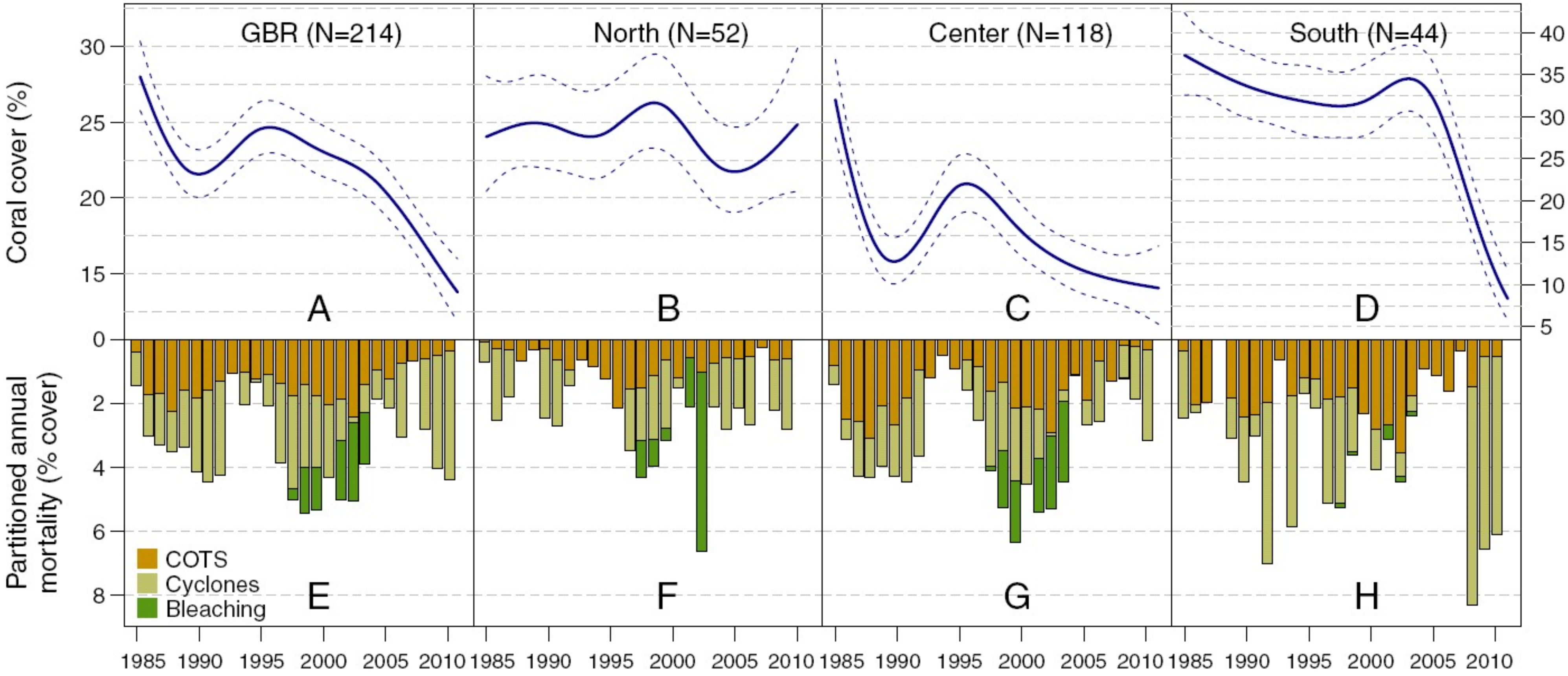
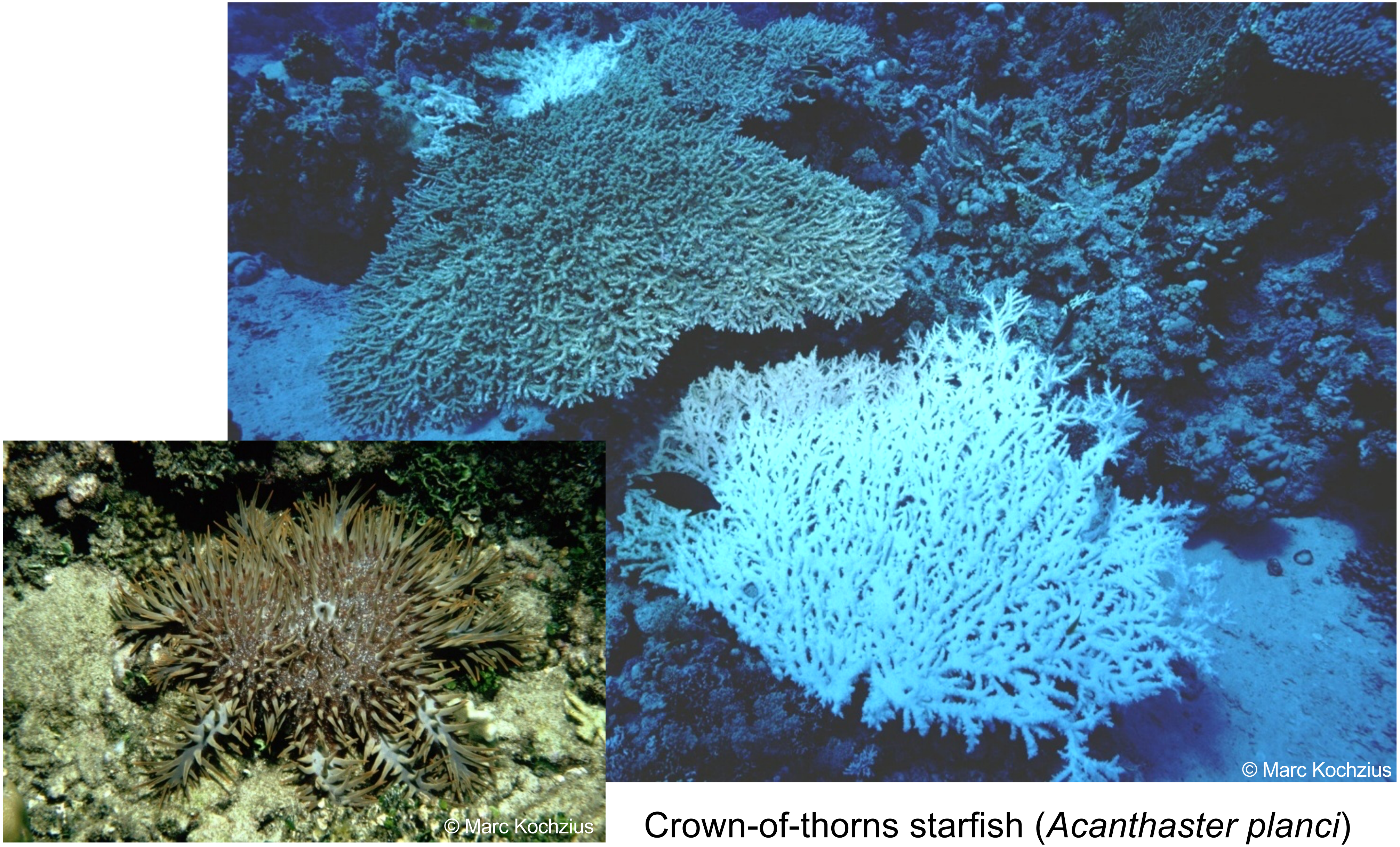


Fig. 2. Temporal trends in coral cover (*A–D*) and annual mortality due to COTS, cyclones, and bleaching (*E–H*) for the whole GBR and the northern, central, and southern regions over the period 1985–2012 (N, number of reefs). (*A–D*) Trends in coral cover, with blue lines indicating estimated means (±2 SEs) of each trend. (*E–H*) Composite bars indicate the estimated mean coral mortality for each year, and the sub-bars indicate the relative mortality due to COTS, cyclones, and bleaching. The periods of decline of coral cover in *A–D* reflect the high losses shown in *E–H*.

De'ath et al. (2012)

Crown-of-thorns starfish (COTS) outbreaks



Crown-of-thorns starfish (*Acanthaster planci*)

Crown-of-thorns starfish (COTS) outbreaks

Laboratory experiments

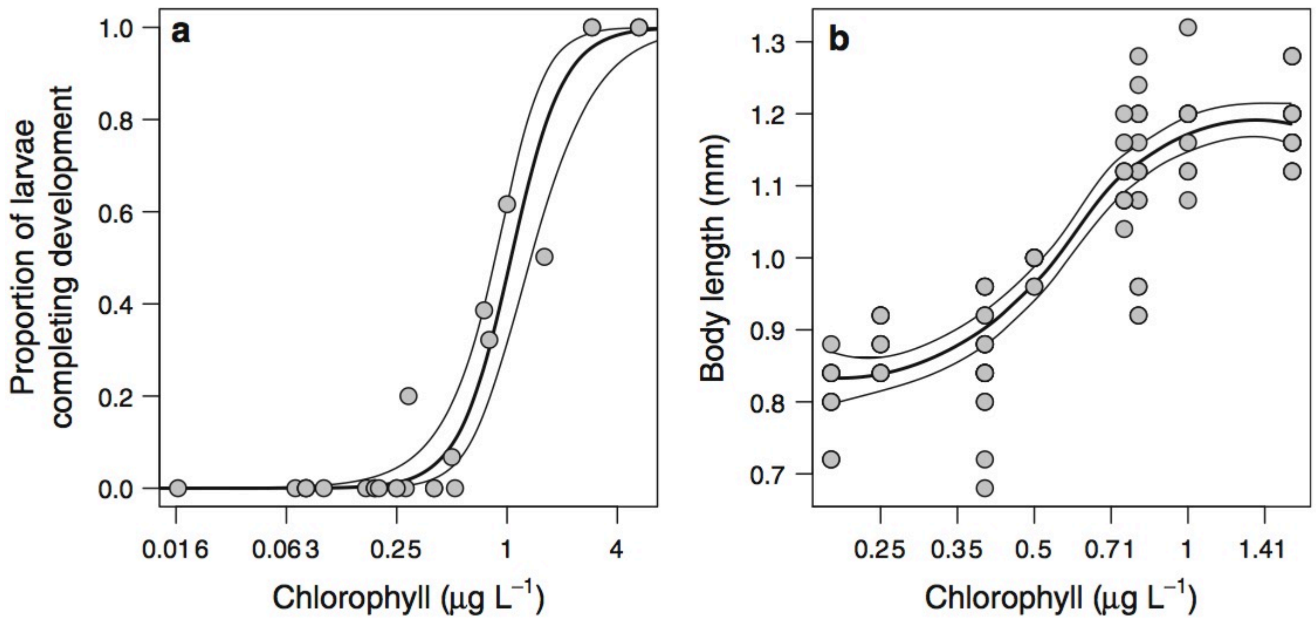
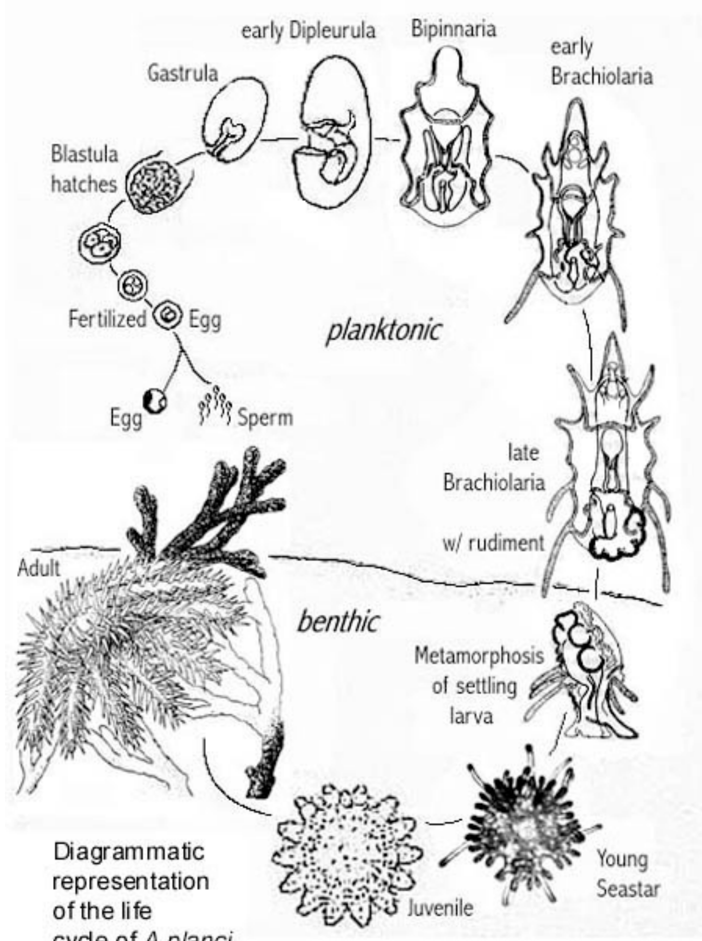


Fig. 2 **a** Relationship between chlorophyll *a* concentration and the proportion of *A. planci* larvae completing their development. **b** Body length of *A. planci* larvae at 17–20 days of age. Each point represents the mean results of duplicate or triplicate deployments per treatment. *Black lines* are model fits, the thin *black lines* are 2 SE of the mean



Diagrammatic representation of the life cycle of *A. planci*. Drawing not to scale. http://www.aims.gov.au/pages/reflib/cot-starfish/pages/cot-q27.html

Fabricius et al. (2010)

Crown-of-thorns starfish (COTS) outbreaks

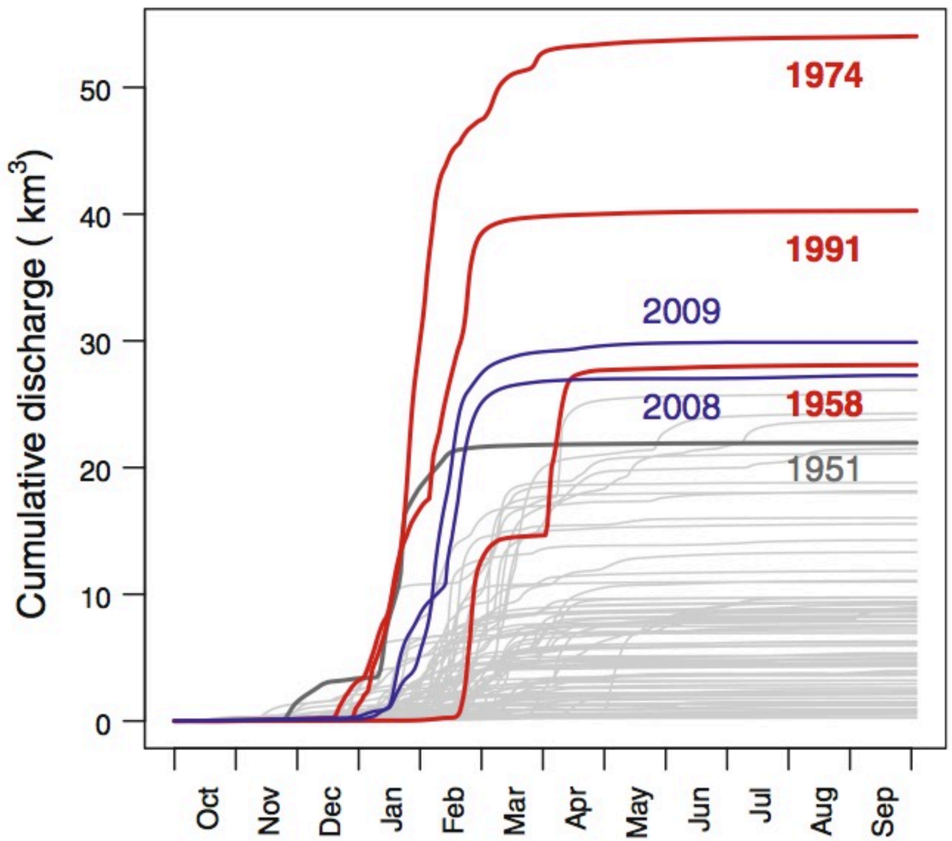


Fig. 4 Cumulative discharge volumes of the Burdekin River into the GBR for each year since 1922. *Red lines* indicate the three large floods that preceded the three recorded primary outbreaks of *A. planci* in 1966, 1979 and 1994. The *dark gray line* shows an early large flood in 1951, but no data exist from that period. The *blue lines* show the large 2008 and 2009 Burdekin floods, potentially predicting the onset of a fourth primary outbreak

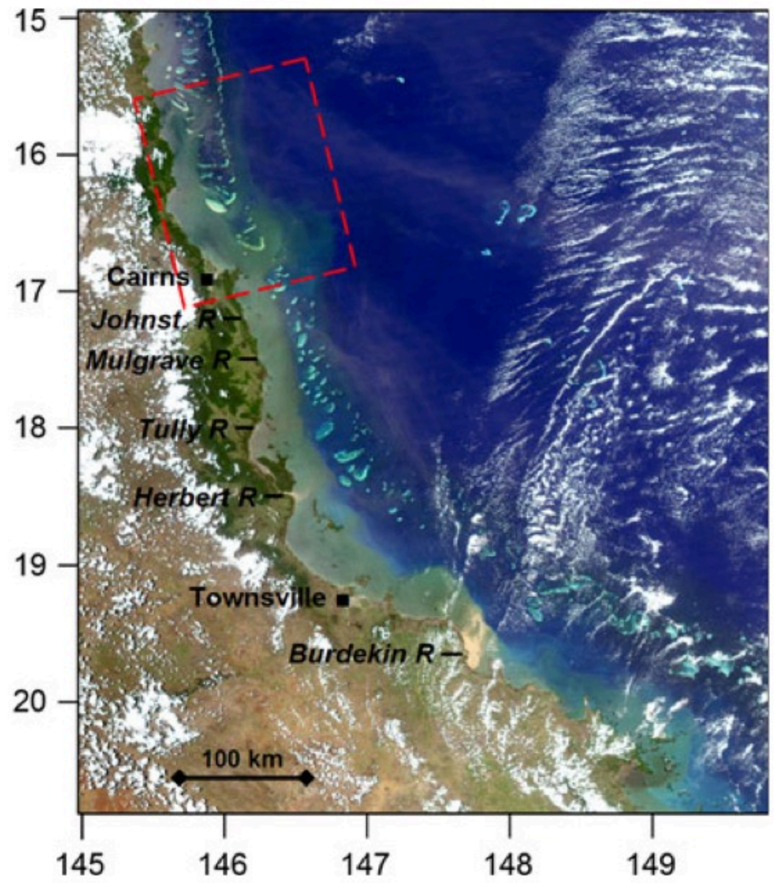
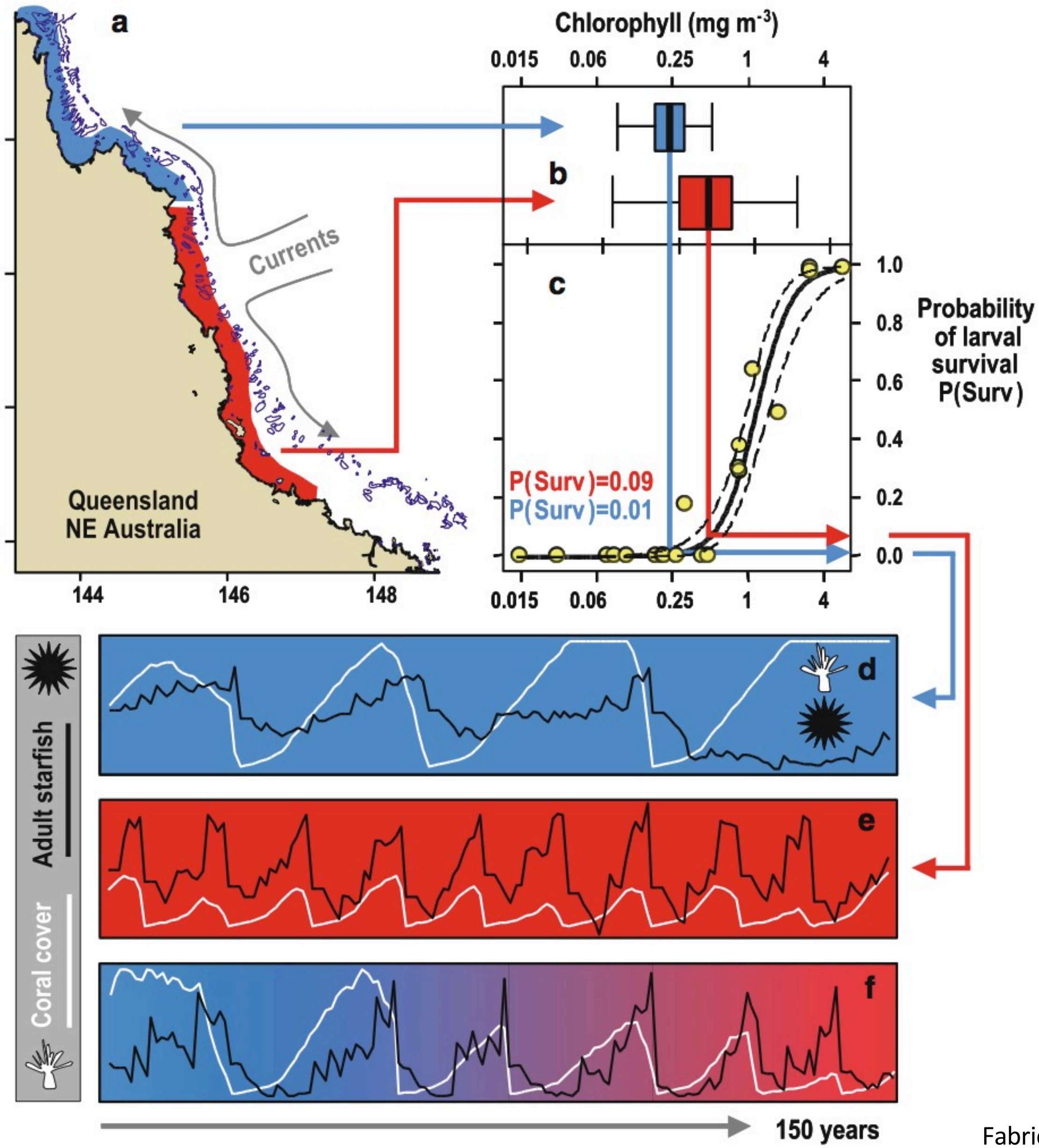


Fig. 5 Satellite image of the central GBR (Modis, 10th February 2007), also showing the locations of the mouths of the main rivers, and towns (*filled square*). All inshore reefs, and the mid- and outer-shelf reefs north of latitude 17°S (the presumed location of source reefs for primary *A. planci* outbreaks on the GBR, *red box*) are inundated by flood waters from the merged plumes of several rivers, while the remaining mid- and outer-shelf reefs are not intercepted by the flood plumes during this moderate flood event

Fabricius et al. (2010)

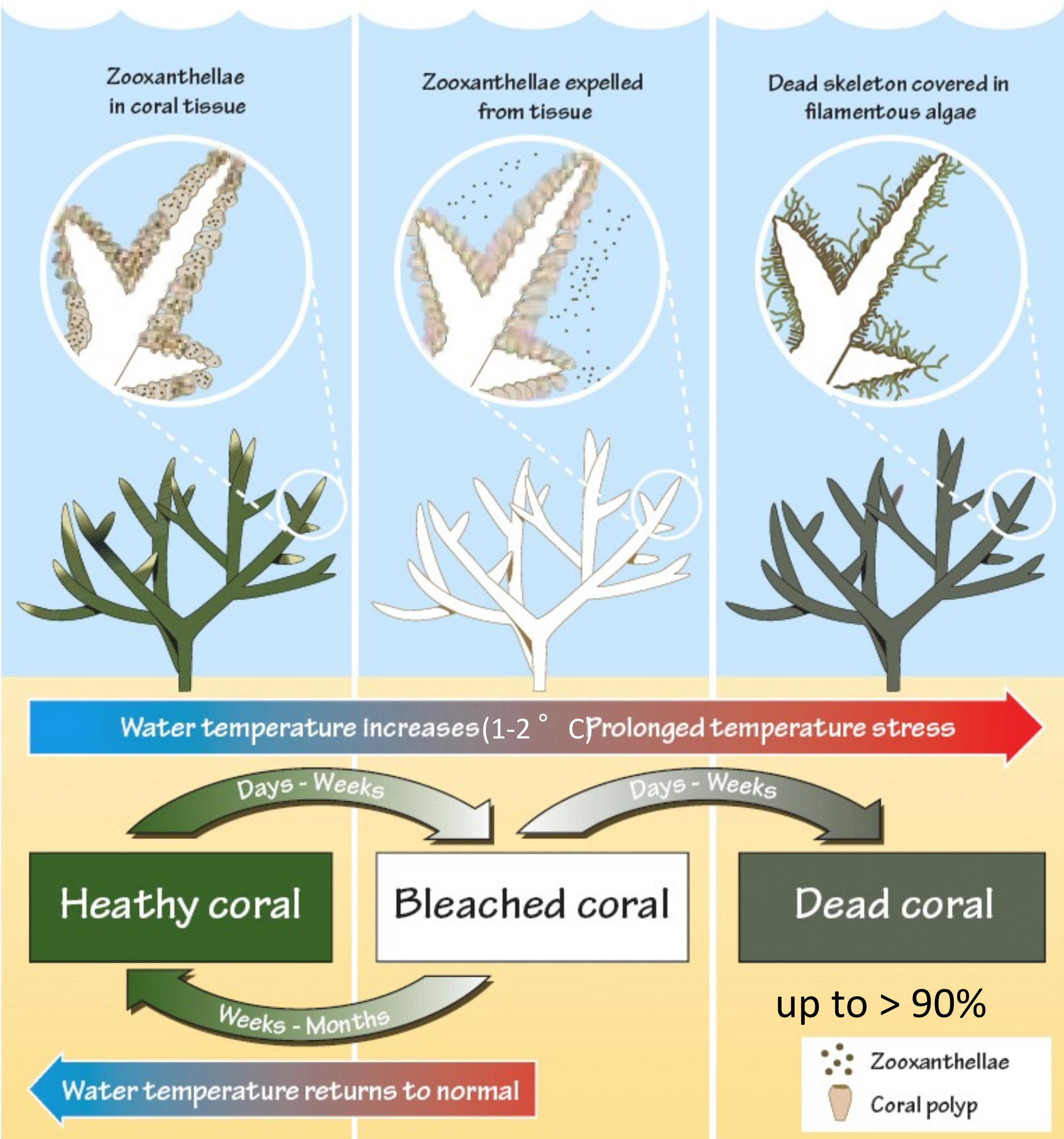
Crown-of-thorns starfish (COTS) outbreaks

Fig. 6 Relationship of *Acanthaster planci* population dynamics and chlorophyll in the Great Barrier Reef (GBR) off the NE of Australia. **a** Map of the GBR. **b** Long-term average chlorophyll concentrations in the GBR in the far northern (FN, *blue*) and central/northern (CN, *red*) region, monitored near-monthly since 1992. Applying the results from the laboratory experiments **c** showed that the odds for survival of *A. planci* larvae was ~ 8-fold higher at chlorophyll levels found in CN compared with FN. Simulations of *A. planci* and coral population dynamics show that in FN (**d**), outbreaks occur at 50–80-year intervals and coral cover recovers between outbreaks (Table 4). In CN (**e**), outbreaks occur at 15-year intervals and corals only recover to 30–40% of potentially obtainable values. These data form the basis to model the transition (**f**) in chlorophyll, *A. planci* and coral cover in CN from pre-European (*blue*) to contemporary levels (*red*)



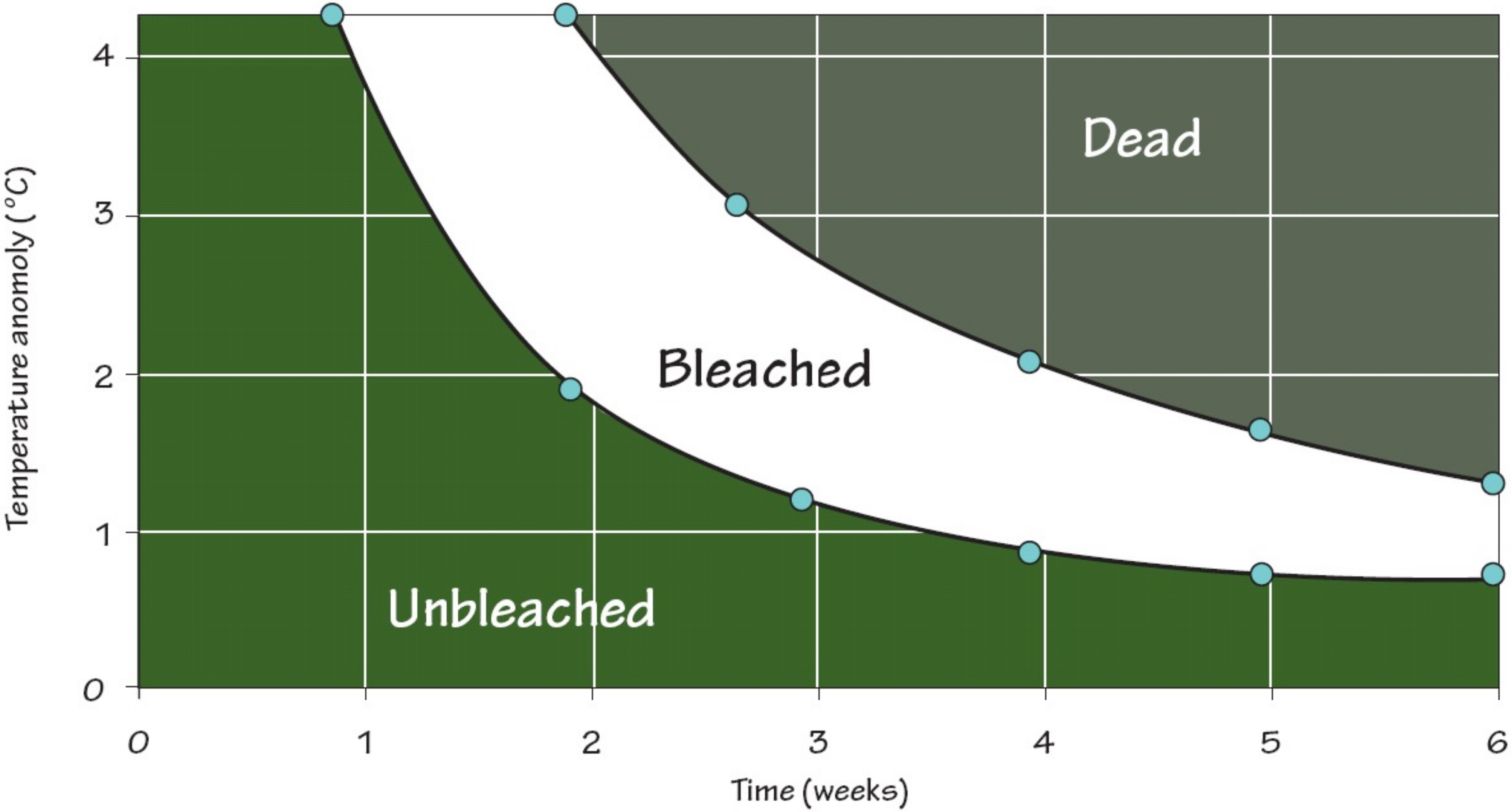
Fabricius et al. (2010)

Coral bleaching



Marshall & Schuttenberg (2006)

Coral bleaching



Marshall & Schuttenberg (2006)

Coral bleaching

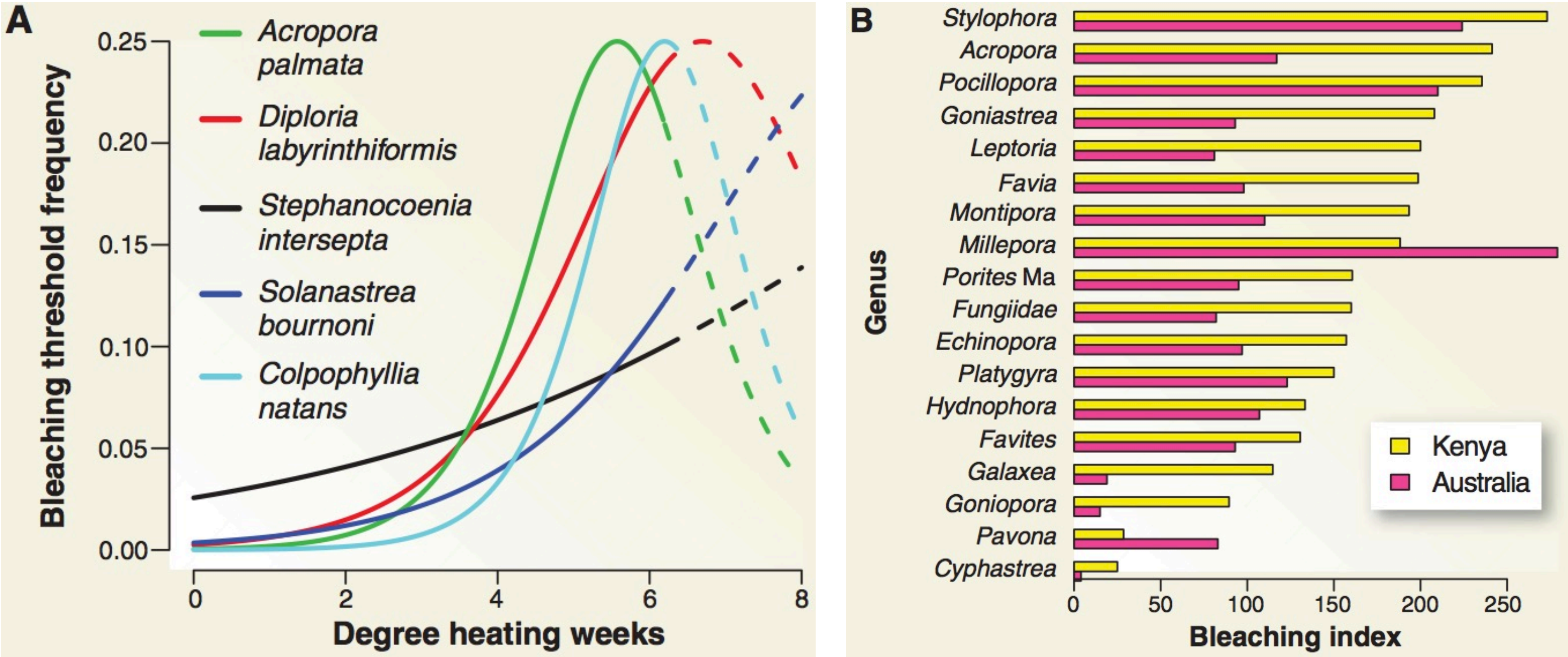
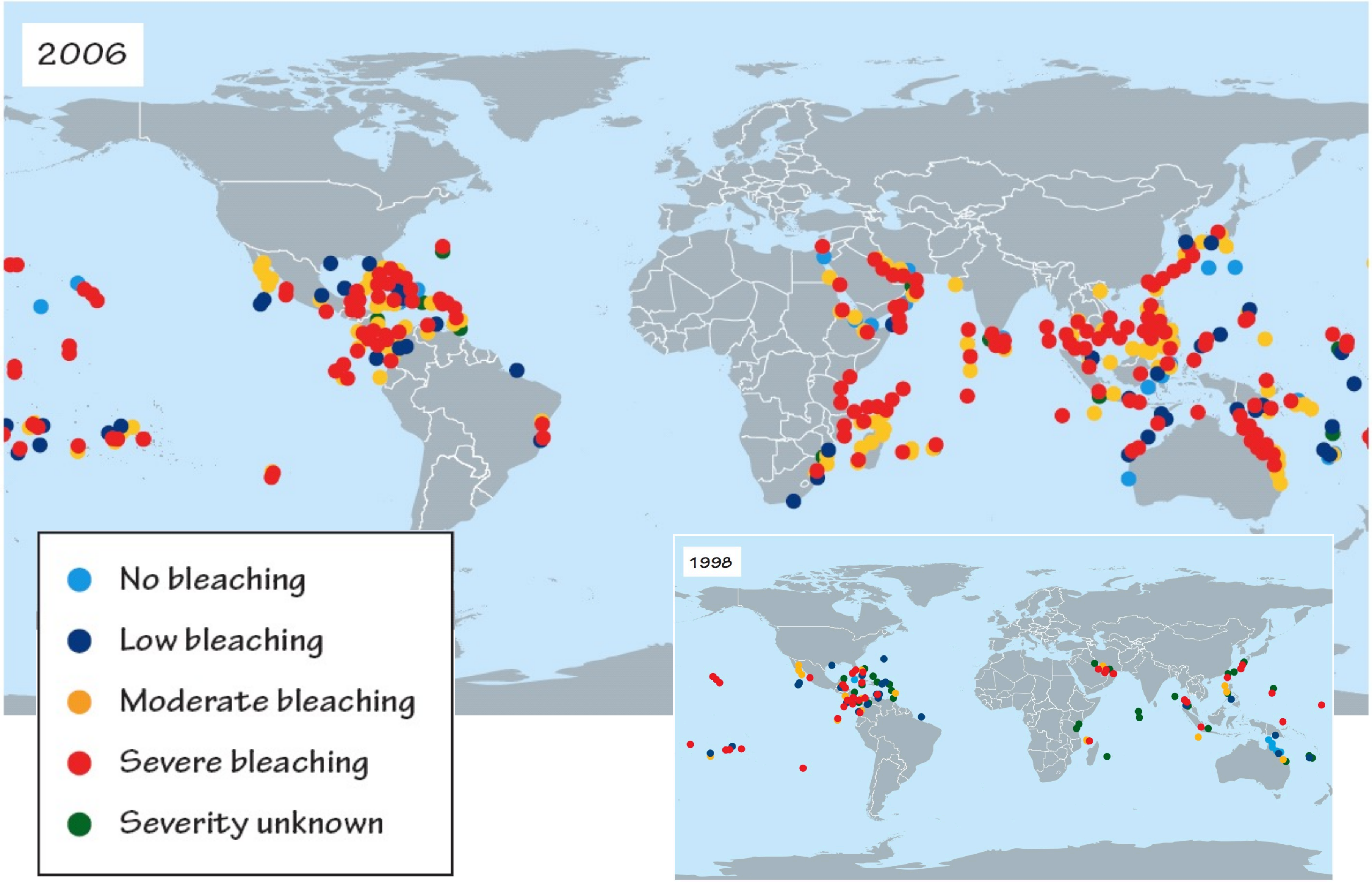


Fig. 2. Bleaching severity differs within and between species, but these differences vary among bleaching events. (**A**) Estimated probability distribution of bleaching thresholds for five species of Caribbean corals, based on logistic regression models fitted to bleaching data from the Florida Keys and Dry Tortugas, under environmental conditions corresponding to the average observed for each species (*29*). The width of the distribution indicates the within-population variation in the temperature at which bleaching is expected to occur. (**B**) Variation in bleaching intensity between Kenya and Australia, during the 1998 mass bleaching event [compare with figure 2 in (*28*)]. Bleaching intensity is a weighted average of the proportion of colonies in different bleaching categories (*28*). Taxa are displayed in rank order of bleaching severity in Kenya. Data provided by A. H. Baird and T. R. McClanahan.

Pandolfi et al. (2011)

Coral bleaching

Marshall & Schuttenberg (2006)



Coral bleaching

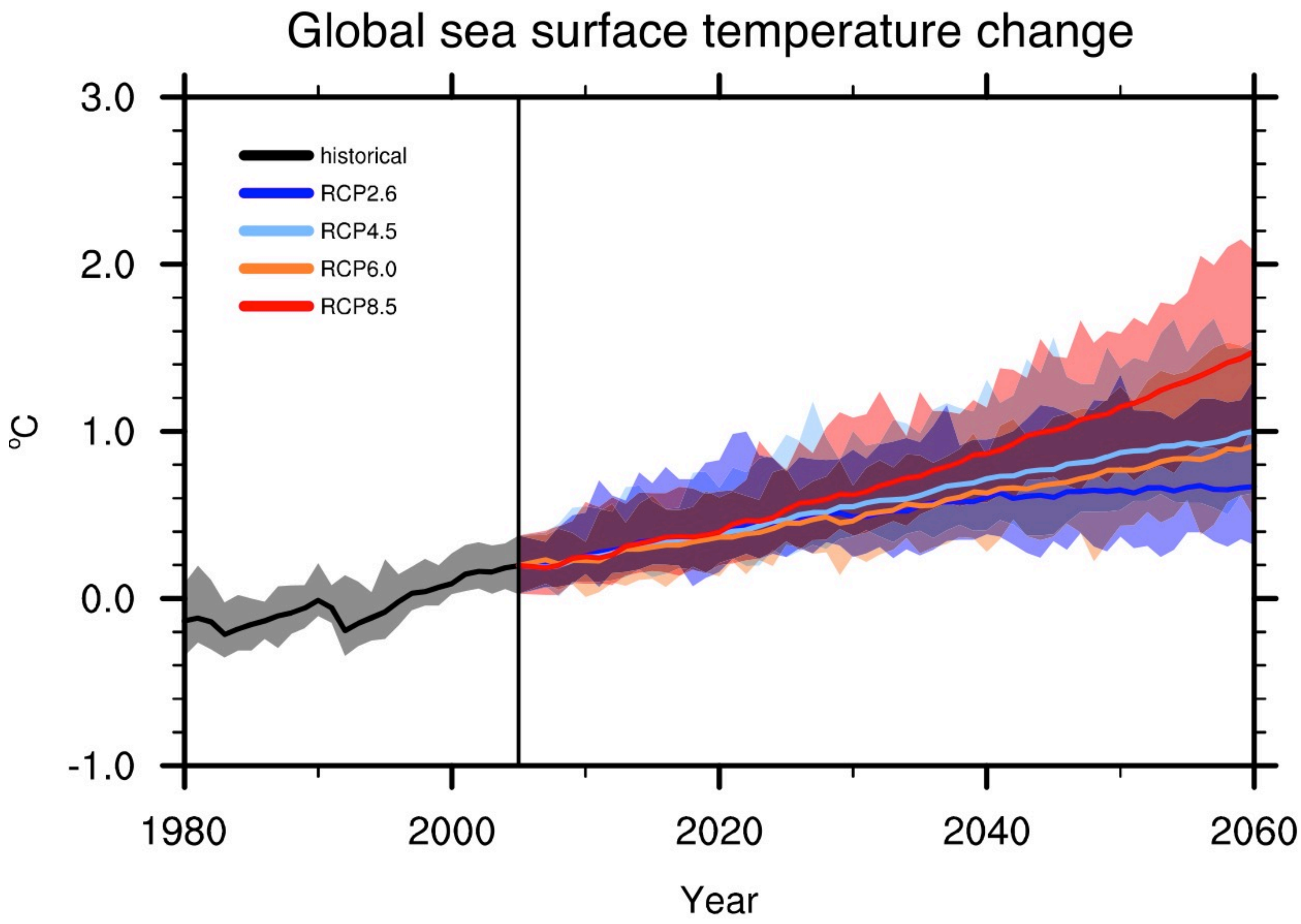
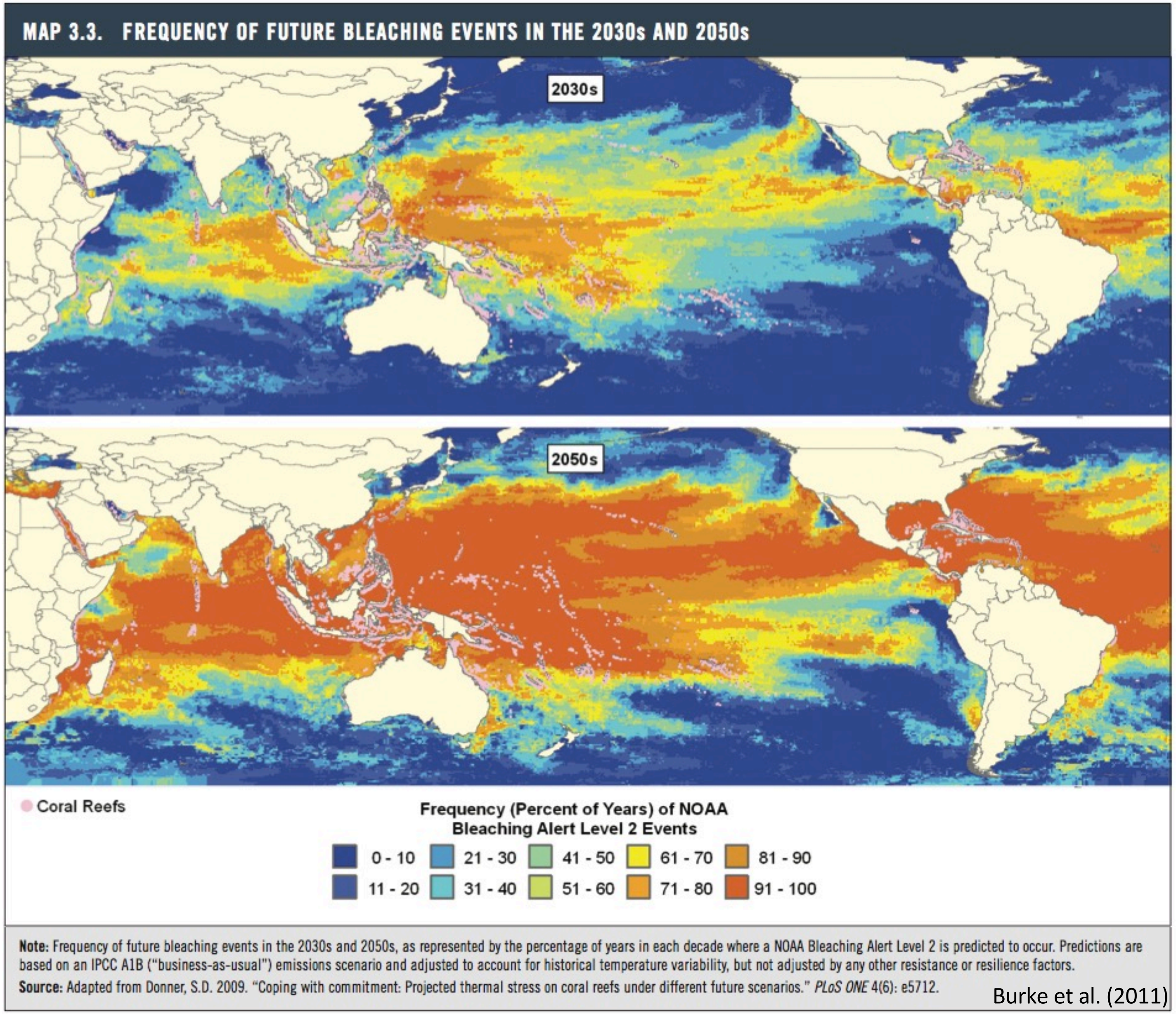


Figure 11.19: Projected changes in annual-averaged, globally-averaged, surface ocean temperature based on twelve AOGCMs from the CMIP5 (Meehl et al., 2007b) multi-model ensemble, under 21st century Scenarios RCP2.6, RCP4.5, RCP6.0 and RCP8.5. Shading indicates the 90% range of projected annual global-mean surface temperature anomalies. Anomalies computed against the 1986–2005 average from the historical simulations of each model.

IPCC (2013)

Coral bleaching: remote sensing (NOAA)



Burke et al. (2011)

Table 1. Stress levels based on current algorithms for producing the CRW coral bleaching HotSpot and Degree Heating Weeks (DHW) products derived from nighttime satellite SST data.

Stress Level	Definition	Effect
No Stress	HotSpot ≤ 0	--
Bleaching Watch	$0 <$ HotSpot < 1	--
Bleaching Warning	$1 \leq$ HotSpot and $0 <$ DHW < 4	Possible Bleaching
Bleaching Alert Level 1	$1 \leq$ HotSpot and $4 \leq$ DHW < 8	Bleaching Likely
Bleaching Alert Level 2	$1 \leq$ HotSpot and $8 \leq$ DHW	Mortality Likely

Liu et al. (2012)

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Coral bleaching: adaptive bleaching hypothesis

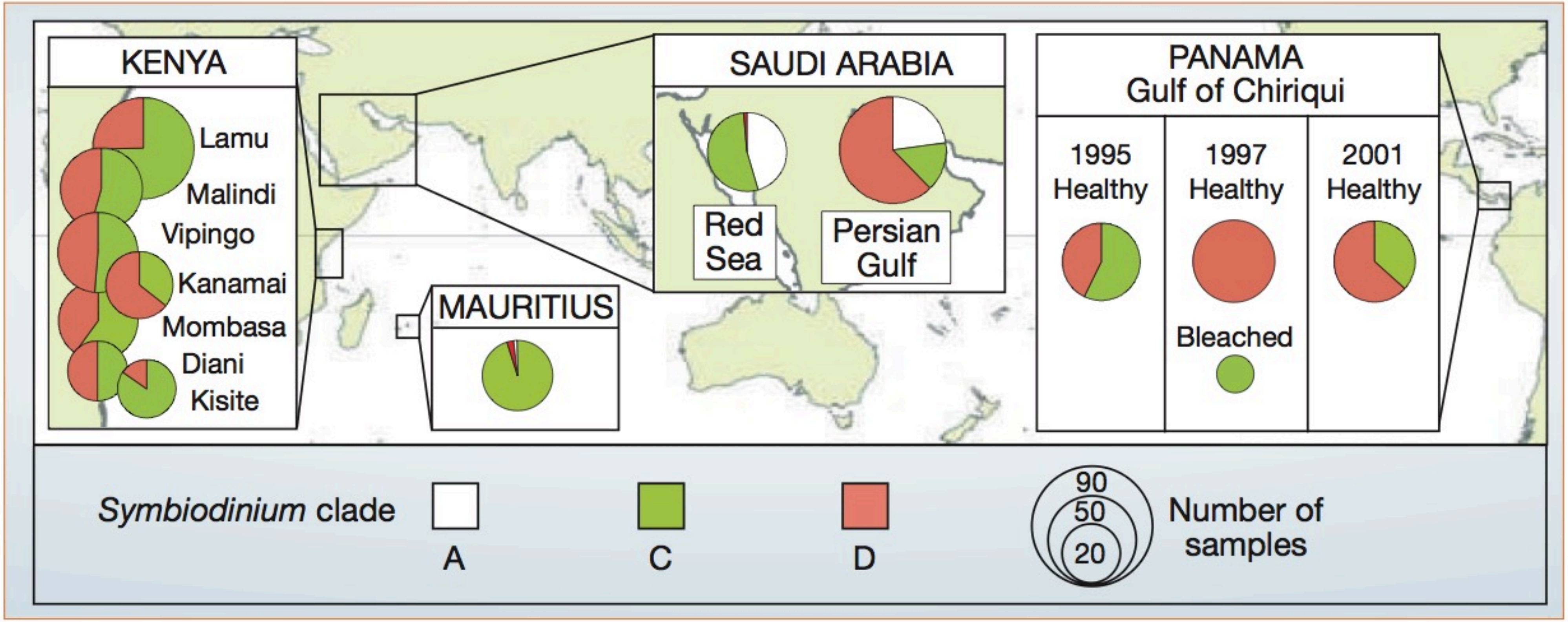


Figure 1 Distribution of *Symbiodinium* algae in shallow-water (less than 7 m depth) scleractinian corals from Kenya, Mauritius, Saudi Arabia and Pacific Panama. Pie charts show distribution of symbionts by site, except those for Panama, which show the distribution of symbionts at a single site before (1995: all colonies healthy), during (1997: some colonies healthy, others severely bleached) and after (2001: all colonies healthy) the 1997–98 El Niño. Size of pie charts is scaled to the square-root of sample size to reflect an equal area for each sample, as indicated by the inset scale. See supplementary information for sampling details for each country.

Baker et al. (2004)

Resilience of coral reefs: coral bleaching and herbivory

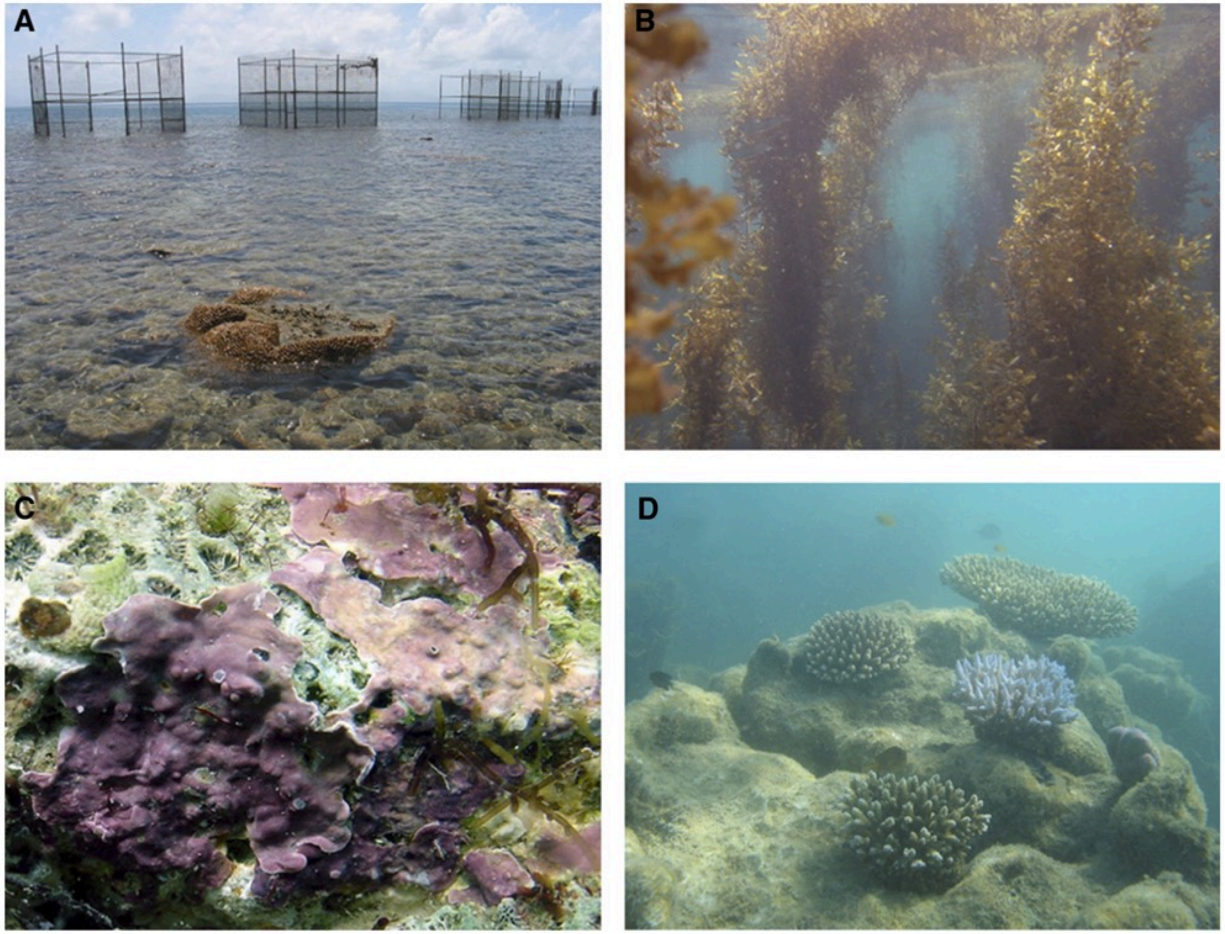


Figure 1. Experimental Phase Shifts on the Great Barrier Reef

(A) Roofless cages and partial cages constructed on the seaward edge of reef crest. Each structure is 5 × 5 m in area and 4 m tall. Note the 2 m high door in the cage in the center of the photograph, for access at low tide.
(B) Growths of *Sargassum* up to 3 m tall dwarf understory corals inside a fish-exclusion cage.
(C) When fishes were experimentally excluded, a foliose coralline alga, *Mesophyllum purpurescens*, replaced shallow-water grazer-resistant species.
(D) Coral recruits settled on dead corals killed 5 years earlier by thermally induced bleaching in 1998. Grazing of the dead substrate by herbivores is crucial for settlement and early survival of corals and coralline algae.

Hughes et al. (2007)

Resilience of coral reefs: coral bleaching and herbivory

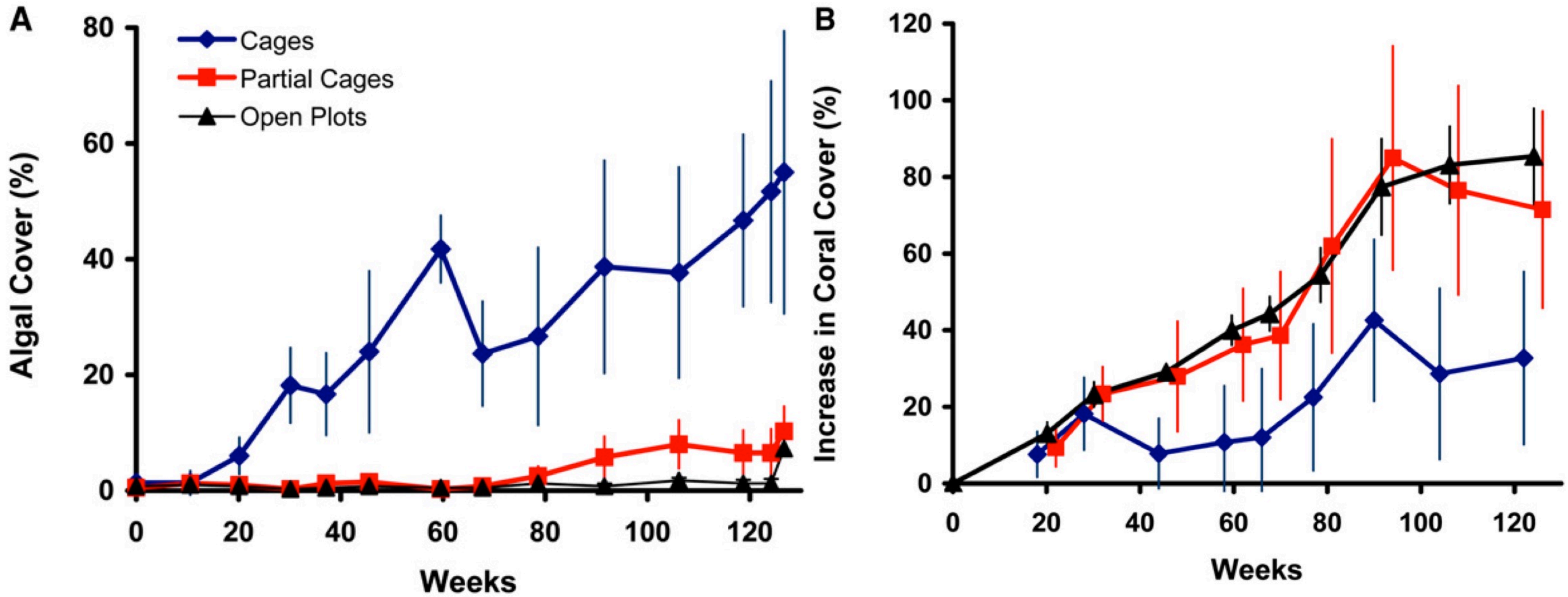


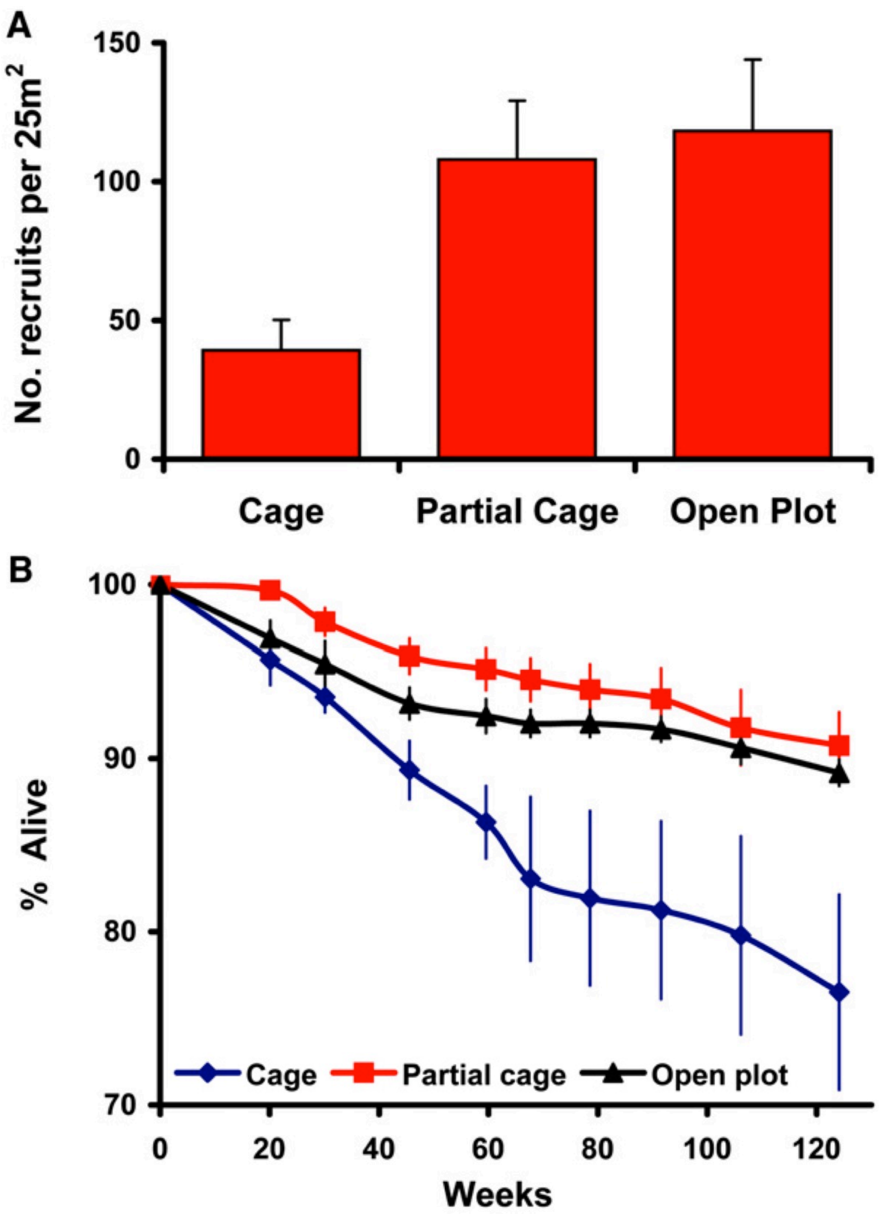
Figure 2. Contrasting Trajectories of Macroalgae and Corals after Exclusion of Fishes

(A) Macroalgal cover. Error bars are SE.

(B) Relative coral cover over time among three experimental treatments. Absolute coral cover after 130 weeks was 7.7% ± 1.0% (S.E.), 19.2% ± 2.3%, and 20.2% ± 2.2% in the three treatments (see text for analysis). Census dates were the same for all treatments and are slightly staggered in the plots for clarity. Error bars are SE.

Hughes et al. (2007)

Resilience of coral reefs: coral bleaching and herbivory



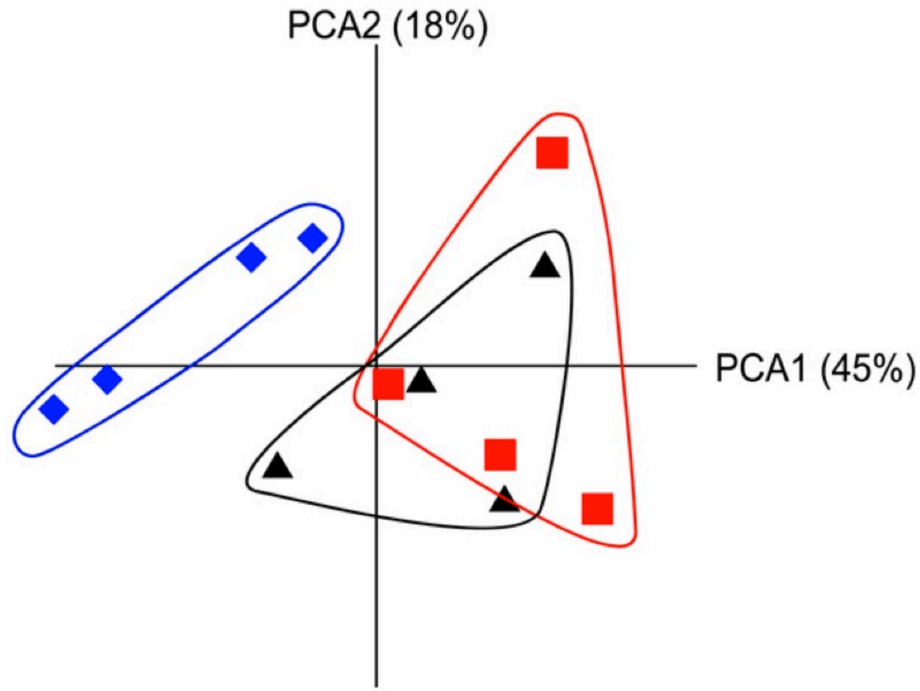


Figure 4. A Principal Component Analysis Showing the Divergent Coral Assemblages in Cages versus Other Experimental Treatments

Cages are colored blue, partial cages are colored red, and open plots are colored black. Each symbol represents one of the 4 × 25 m^2 replicates in each experimental treatment. The first two axes explain 63% of the variation among the 12 experimental replicates.

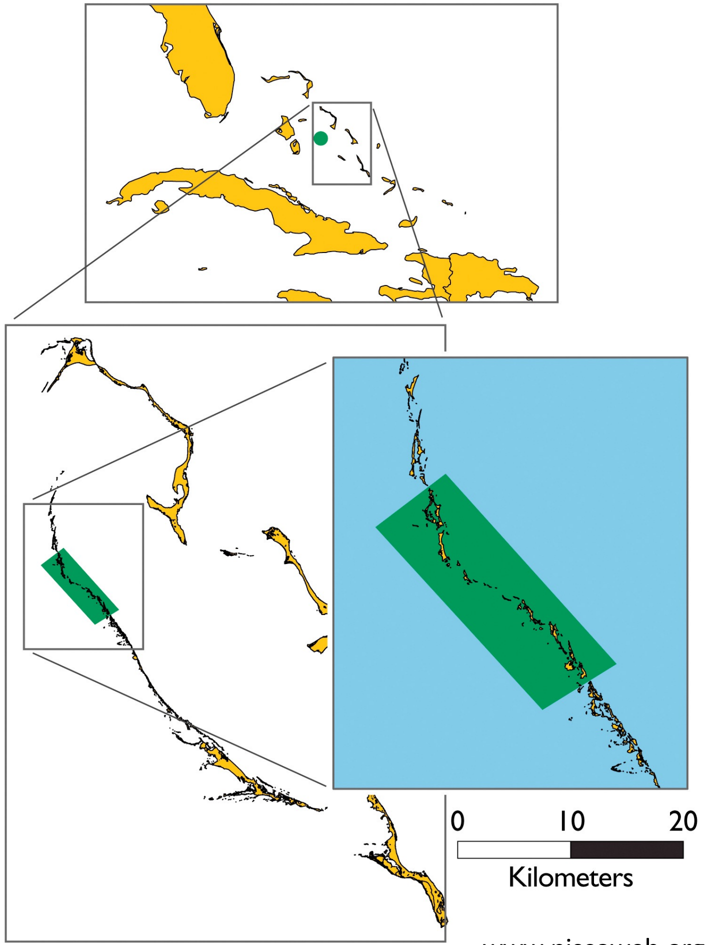
Figure 3. Demographic Responses of Corals

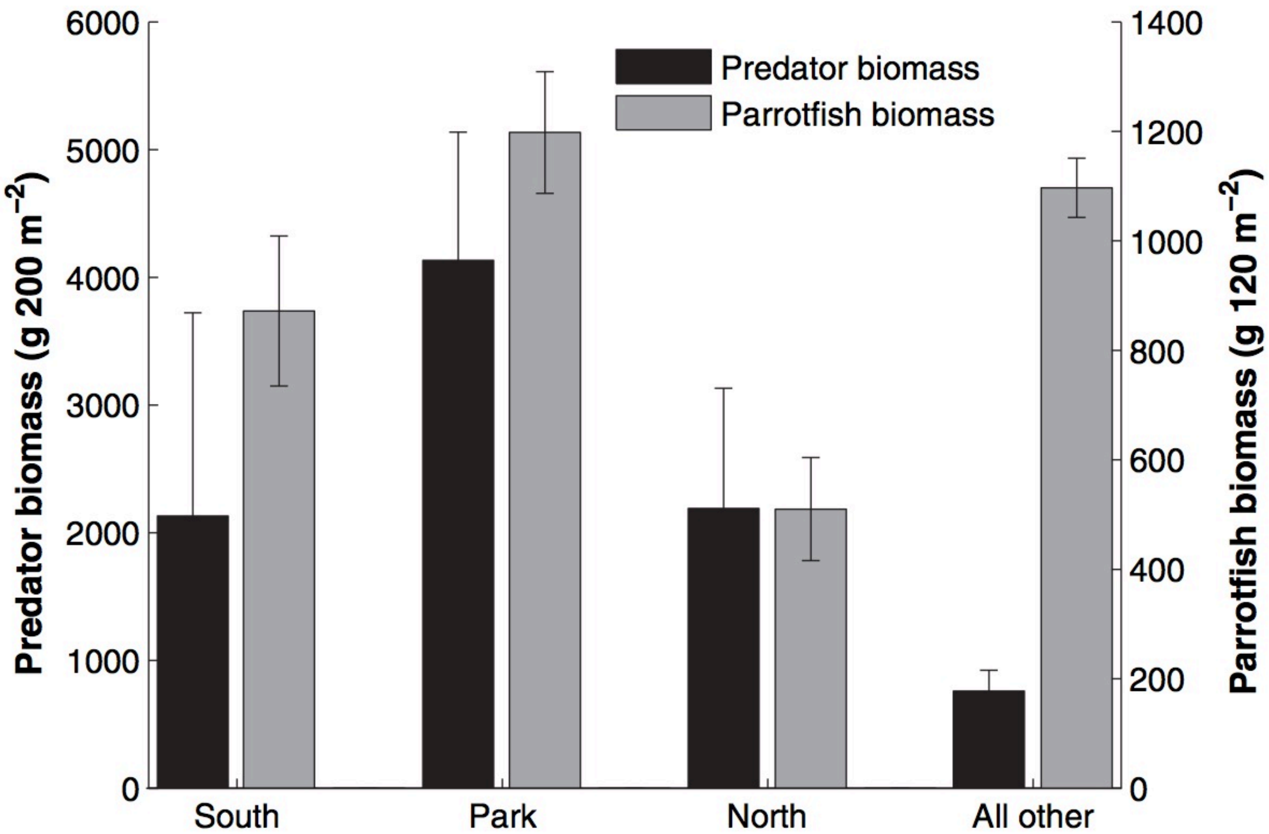
(A) Recruitment of corals into the three experimental treatments. Error bars are SE.

(B) Mortality of coral colonies originally present in cages, partial cages, and open plots. Error bars are SE.

Hughes et al. (2007)

Resilience of coral reefs: overfishing, herbivory and MPAs





Marine Reserve

Exuma Cays Land and Sea Park, Bahamas

Fig. 1. Patterns of parrotfish biomass and their predators (±SE) within the Exuma Cays and for all other surveyed areas combined. "Park" denotes the ECLSP.

Mumby et al. (2006)

Resilience of coral reefs: overfishing, herbivory and MPAs

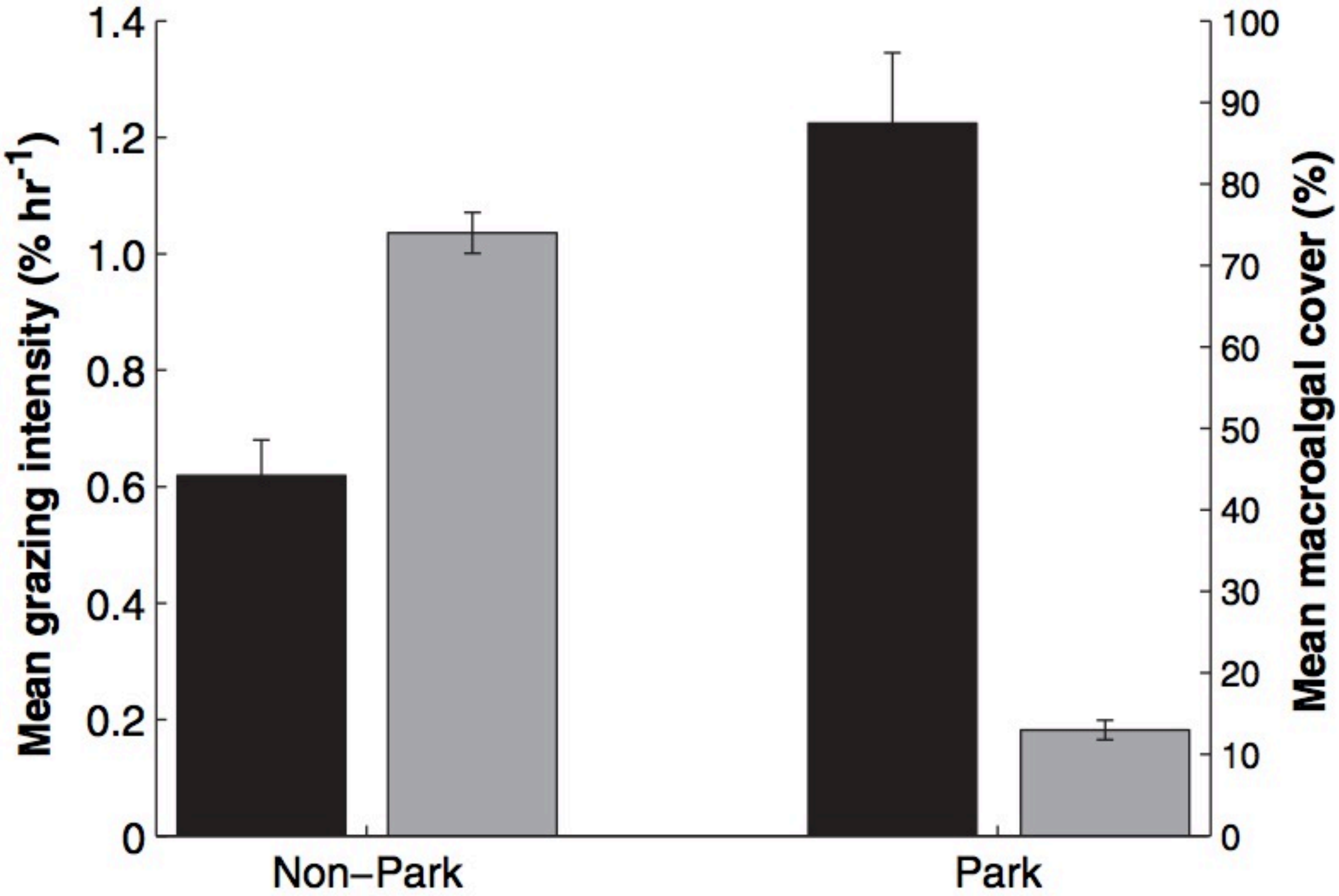
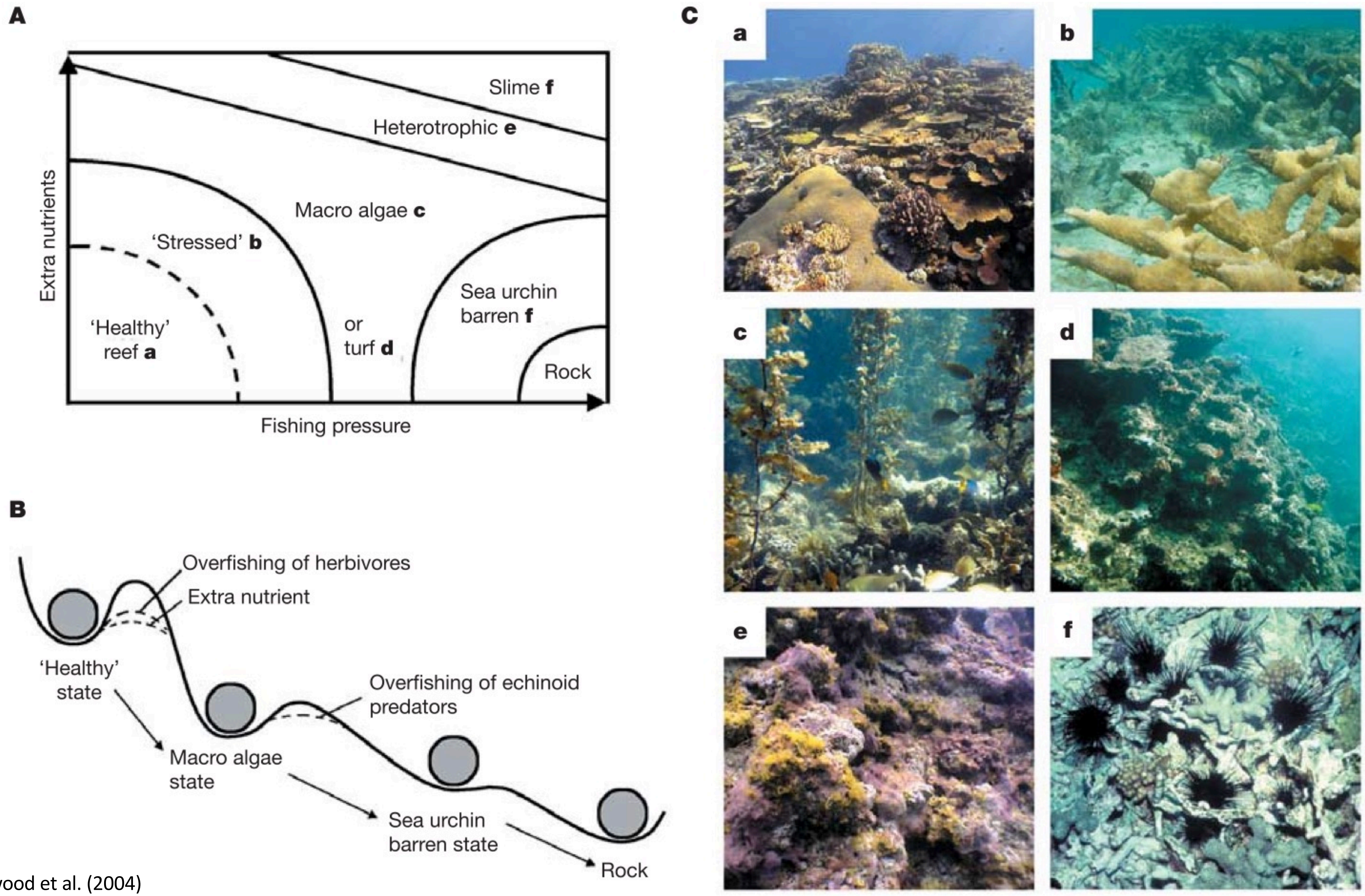


Fig. 4. Mean grazing intensity of parrotfishes (black bars) and macroalgal cover (gray bars) (±SE) inside and outside the ECLSP. Reserve impacts are significant ($P < 0.01$) for each variable.

Mumby et al. (2006)

Resilience of coral reefs



Bellwood et al. (2004)

Resilience of coral reefs

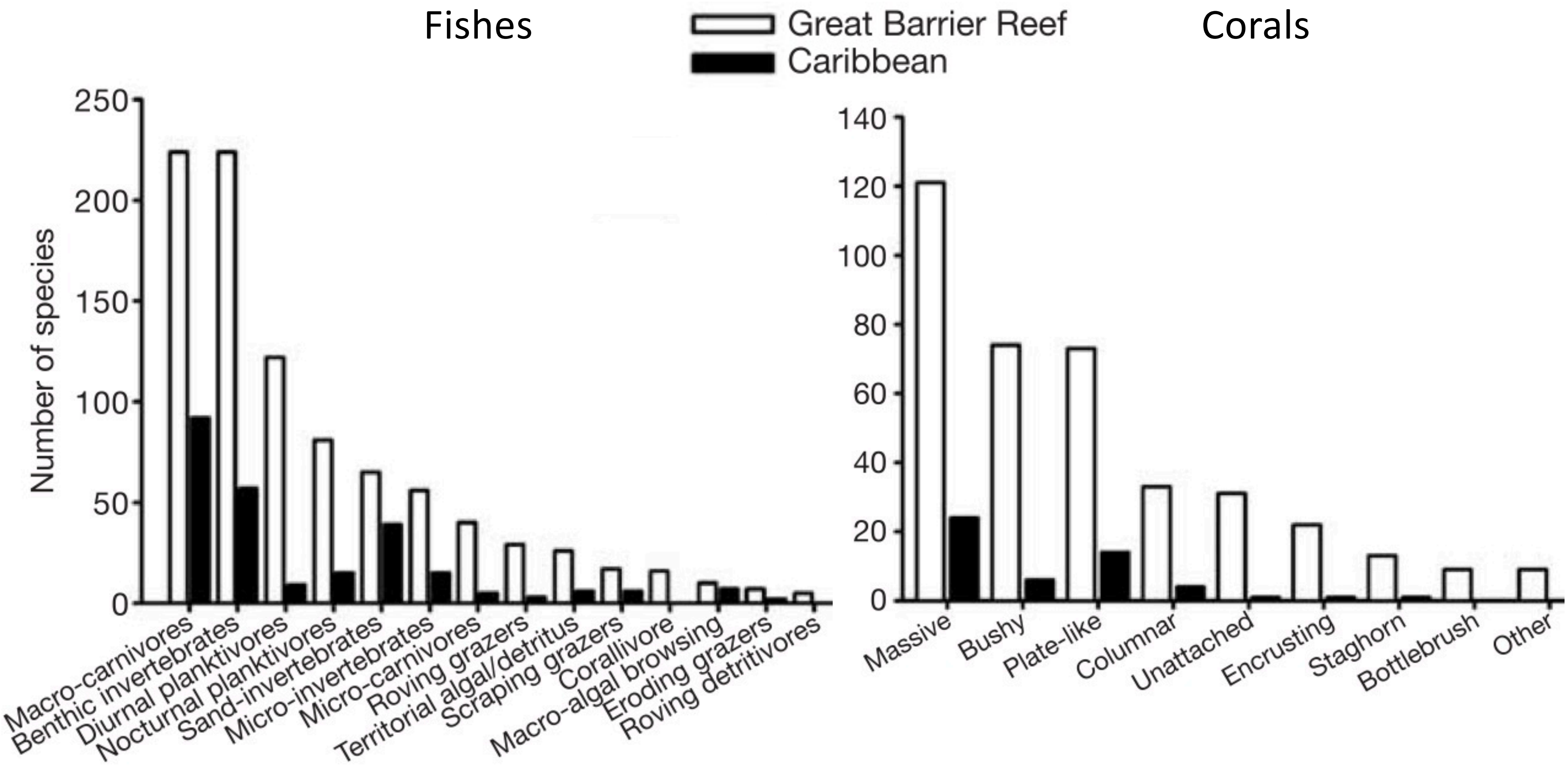
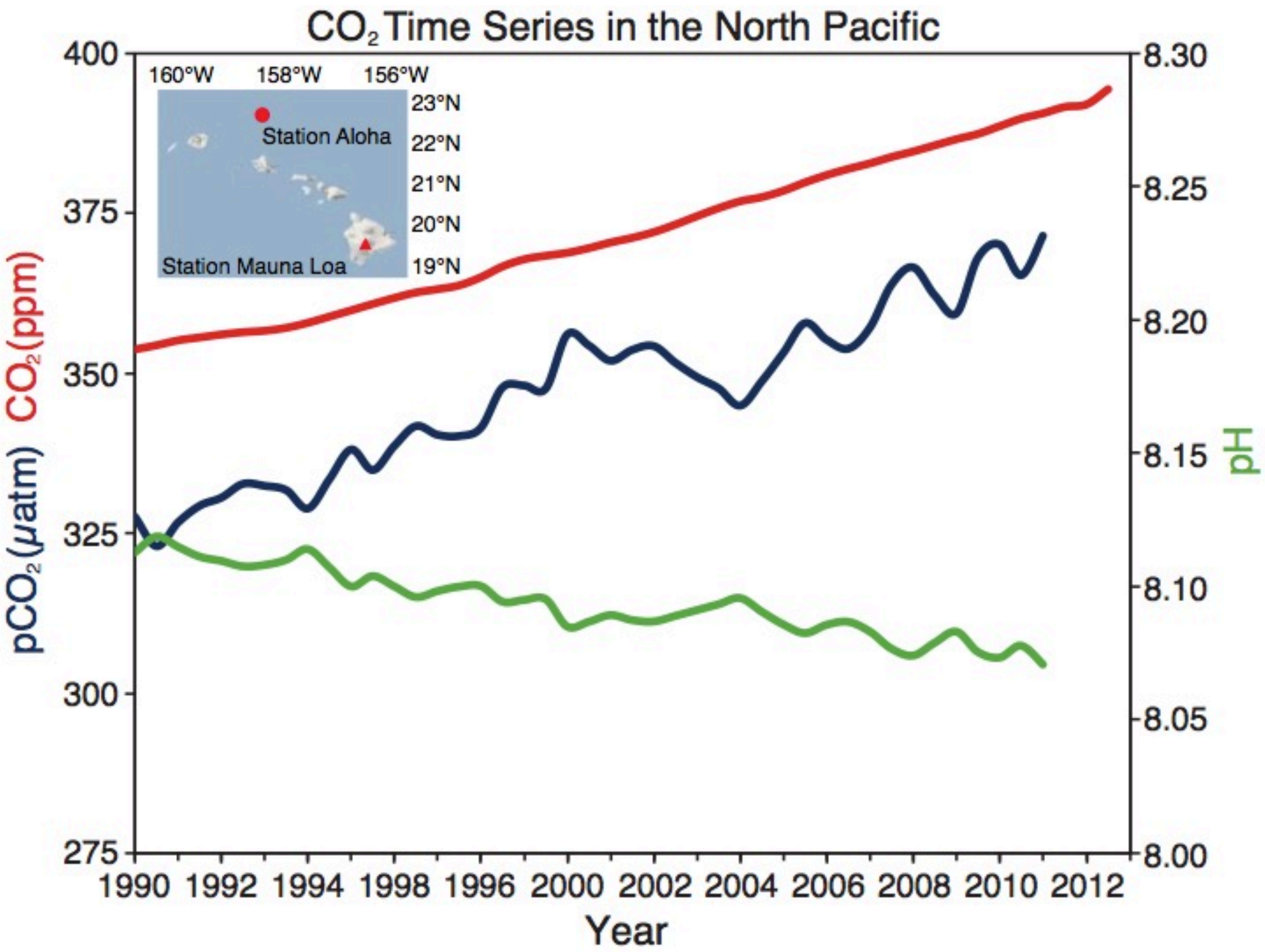


Figure 3 Functional composition of Caribbean and Great Barrier Reef assemblages of fishes and corals. The fourteen fish and eleven coral functional groups are identified by their roles in ecosystem processes.

Bellwood et al. (2004)

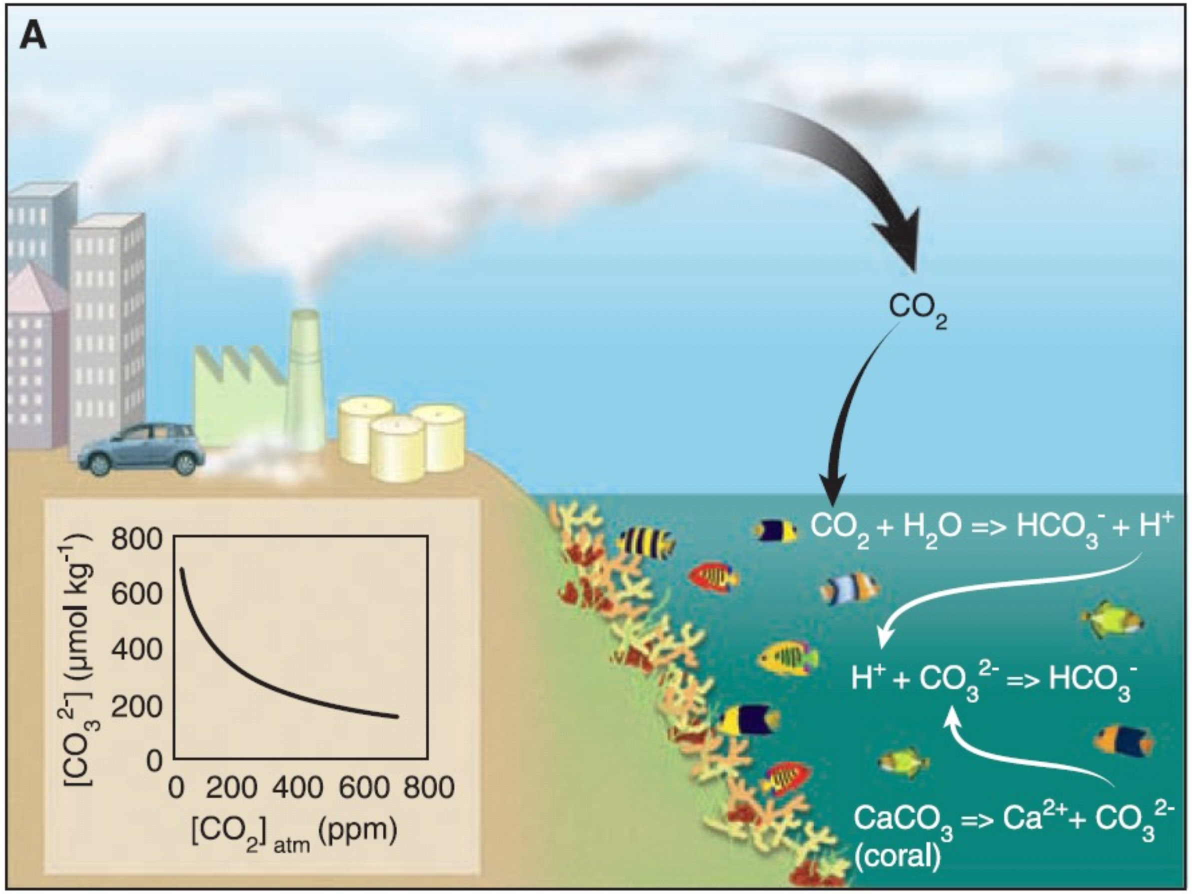
Climate change



FAQ 3.2, Figure 1: A smoothed time series of atmospheric CO_2 mole fraction (in ppm) at the atmospheric Mauna Loa Observatory (top red line), surface ocean partial pressure of CO_2 (pCO_2; middle blue line), and surface ocean pH (bottom green line) at Station ALOHA in the subtropical North Pacific north of Hawaii for the period from1990–2011 (after Doney et al., 2009; data from Dore et al., 2009). The results indicate that the surface ocean pCO_2 trend is generally consistent with the atmospheric increase but is more variable due to large-scale interannual variability of oceanic processes.

IPCC (2013)

Climate change: ocean acidification



Period	$[CO_2]_{atm}$ (ppm century^{-1})	Ratio (relative to past 420,000 years)	Temperature (°C century^{-1})	Ratio (relative to past 420,000 years)
Past 420,000 years (99% confidence interval; n = 282)	0.07 + 0.223	1	0.01 + 0.017	1
Past 136 years (1870–2006)	73.53	1050	0.7	70
IPCC B1 scenario: 550 ppm at 2100	170	2429	1.8	180
IPCC A2 scenario: 800 ppm at 2100	420	6000	3.4	420

Carbonate buffering system

- H_2CO_3: carbonic acid
- HCO_3^-: bicorbonate
- CO_3^{2-}: carbonate
- $CaCO_3$: calcium carbonate

Impact of CO_2 increase

- Current CO_2 in atmosphere: >380 ppm
- 80 ppm higher than maximum in the past 420,000 years (if not 20 million years)
- Increase of ocean temperature 0.74 ° C
- Decrease of pH by 0.1 units
- Depletion of CO_3^{2-} by 30 µmol/kg seawater
- Decrease in calcification rate and erosion at 270 µmol CO_3^{2-}/kg seawater

(Hoegh-Guldberg *et al.* 2007)

Climate change: ocean acidification

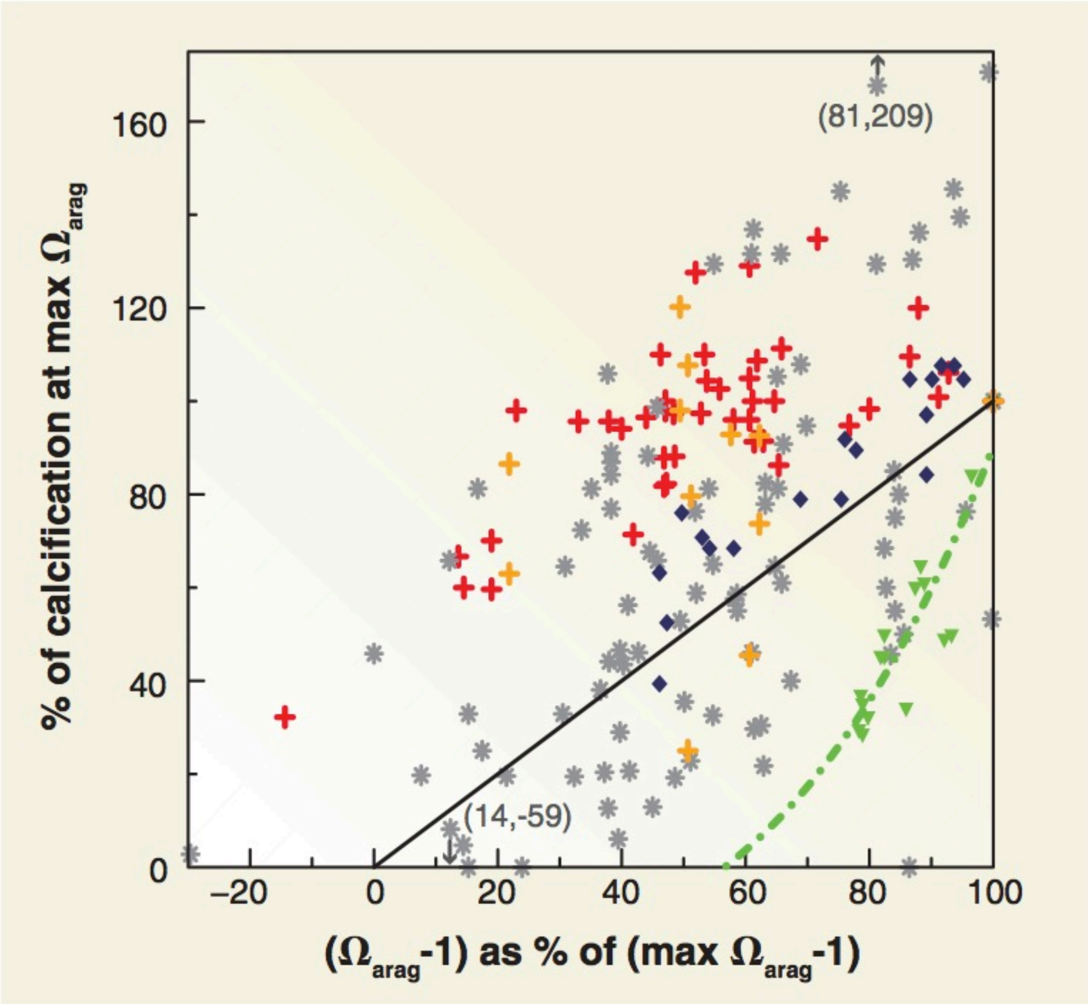


Fig. 3. Calcification response to changes in Ω_{arag} observed in experiments and in nature. Experiments using Ca to manipulate Ω_{arag} and those reporting >80% mortality under elevated CO_2 are excluded. Data are grouped as follows: (i) CO_2 invasion experiments at ambient temperature [seven studies (*45–49*, *52*, *53*), red crosses], and CO_2 invasion experiments at elevated temperature [three studies (*46*, *47*, *53*), orange crosses]. In all CO_2 invasion experiments, corals and coral reef organisms were exposed to treatment conditions for longer than 1 week. (ii) Non-CO_2 invasion experiments using different combinations of acid and base to manipulate Ω_{arag}, DIC, and p_{CO_2} [seven studies (*44*, *50*, *51*, *54*, *82*, *93*, *94*), gray asterisks]. Periods of exposure vary from hours to years. (iii) Field data from Gulf of Eilat (*58*) (green triangles) and Great Bahamas Bank (*43*) (blue diamonds). The horizontal axis is scaled to ($\Omega_{arag} - 1$) rather than Ω_{arag} because the first-order saturation-state model of (*44*) predicts that calcification is proportional to ($\Omega_{arag} - 1$), and this scaling facilitates comparing the model prediction (solid line) with the empirical data (points). The range of Ω_{arag} conditions for each experiment varied significantly, and, in several instances, corals were exposed to saturation states significantly higher (and lower) than those under which they grow naturally. Here, we set (maximum $\Omega_{arag} - 1$) in each experimental and field study at 100% and the calcification response is represented as percent of calcification recorded under the maximum Ω condition. The dash-dot green line is the fitted calcification model from (*58*).

Pandolfi et al. (2011)

Climate change: ocean acidification

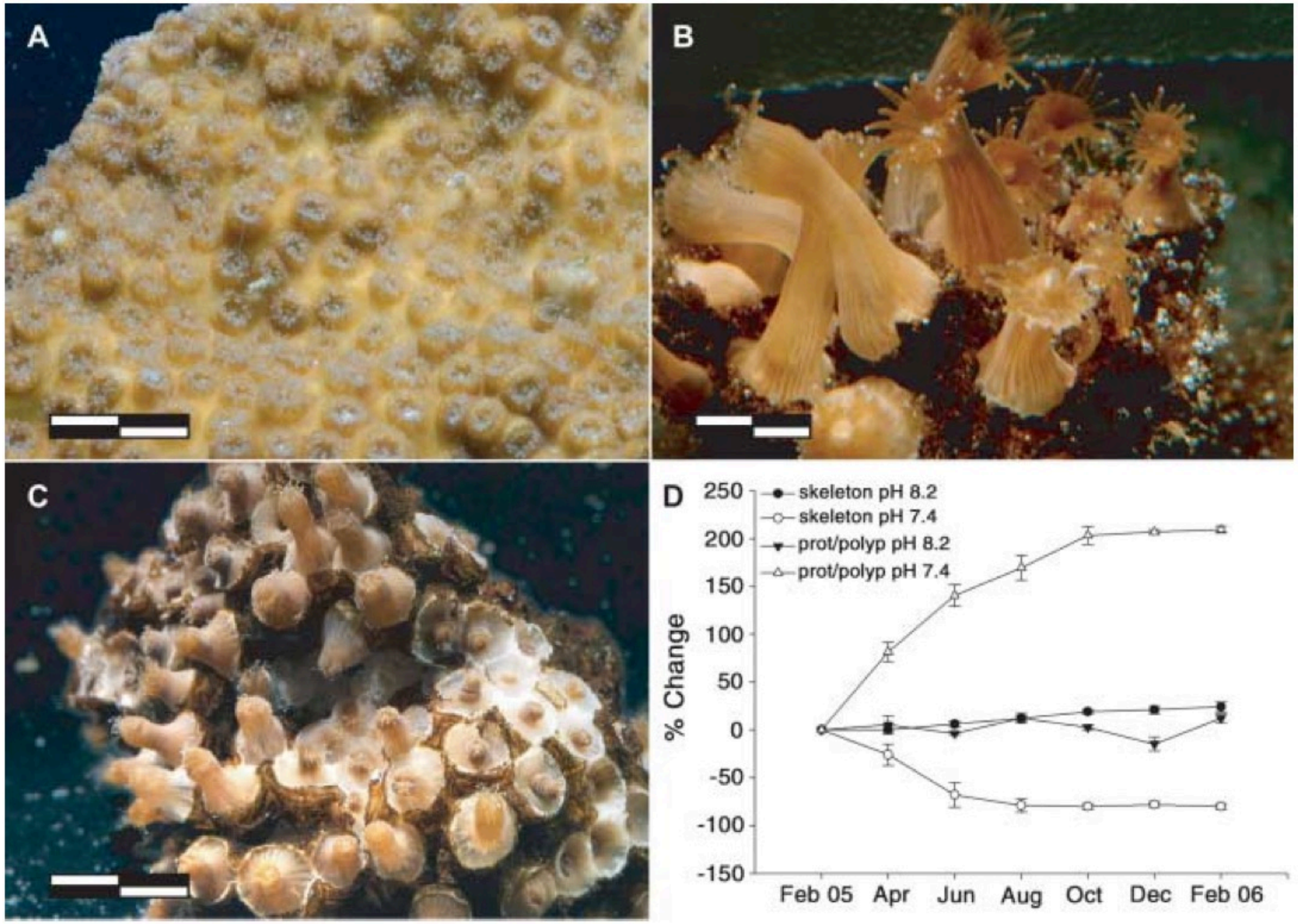
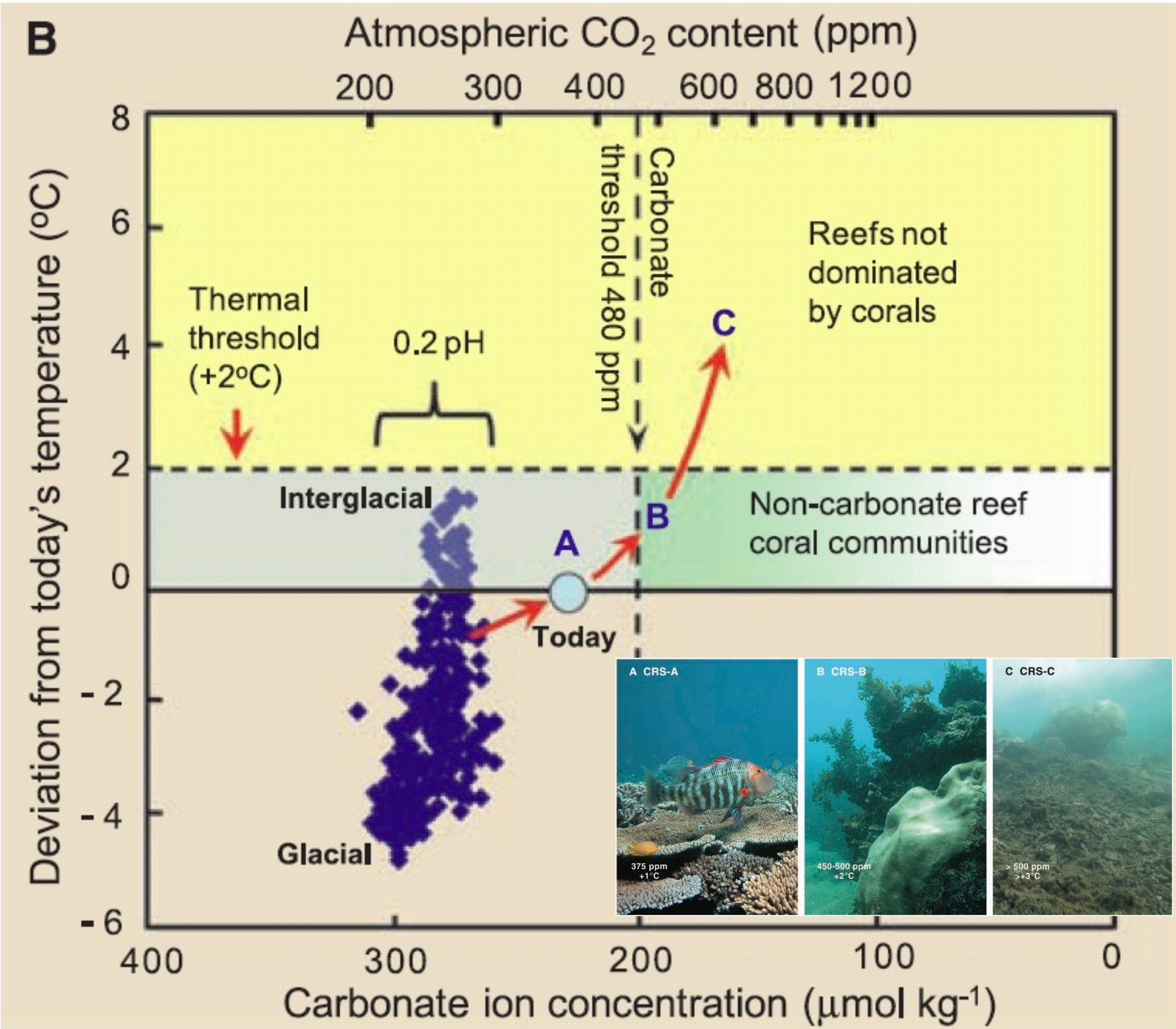


Fig. 1. Photographs of *O. patagonica*. Scale bars indicate 2 mm. (**A**) Control colony. (**B**) Sea anemone–like coral polyps following skeleton dissolution in low-pH conditions. (**C**) Solitary polyps reforming a colony and calcifying after being transferred back to normal seawater following 12 months as soft-bodied polyps in low-pH conditions. (**D**) Time series illustrating percent change (average ± SE) in protein per polyp (biomass) and total buoyant weight over 12 months in experimental (pH = 7.4) and control (pH = 8.2) seawater ($N = 20$). A two-way analysis of variance (time × pH) revealed significant changes ($P < 0.001$) between treatments over time.

Fine & Tchernov (2007)

Climate change: impact on coral reefs

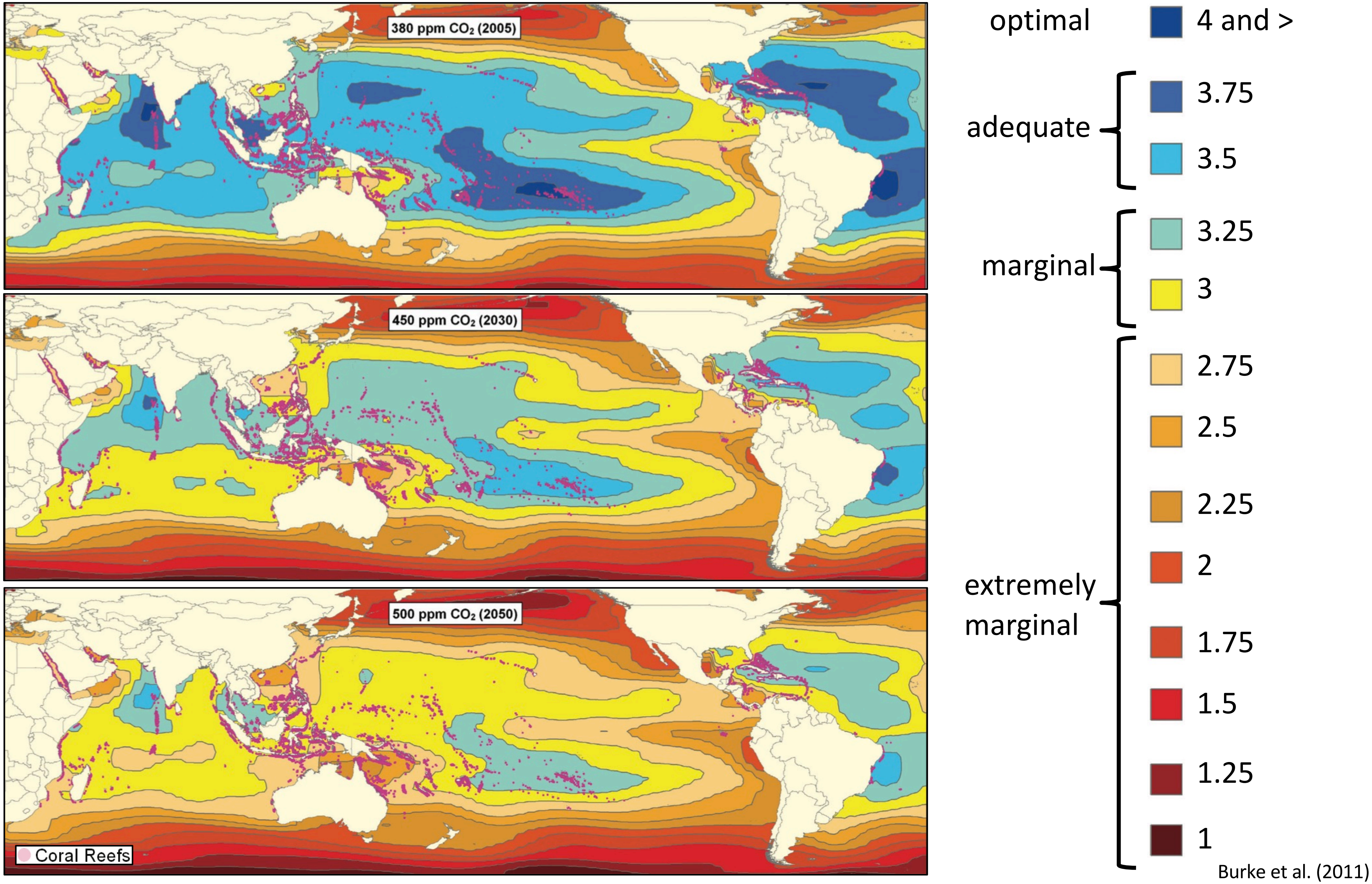


Impact of CO_2 increase

- Doubling of pre-industrial $[CO_2]_{atm}$ to 560 ppm decreased calcification + growth by up to 40 %
- Zero or negative carbonate accretion on coral reefs at aragonite saturation level of 3.3; reached at 480 ppm $[CO_2]_{atm}$ and < 200 µmol CO_3^{2-}/kg
- Increased (bio)erosion due to skeletons with less density
- Thermal stress
- Decreased reproduction
- Decrease of biodiversity
- Worst case: loss of coral reefs

(Hoegh-Guldberg *et al.* 2007)

Climate change: aragonite saturation state



Burke et al. (2011)

Climate change: impact on resilience

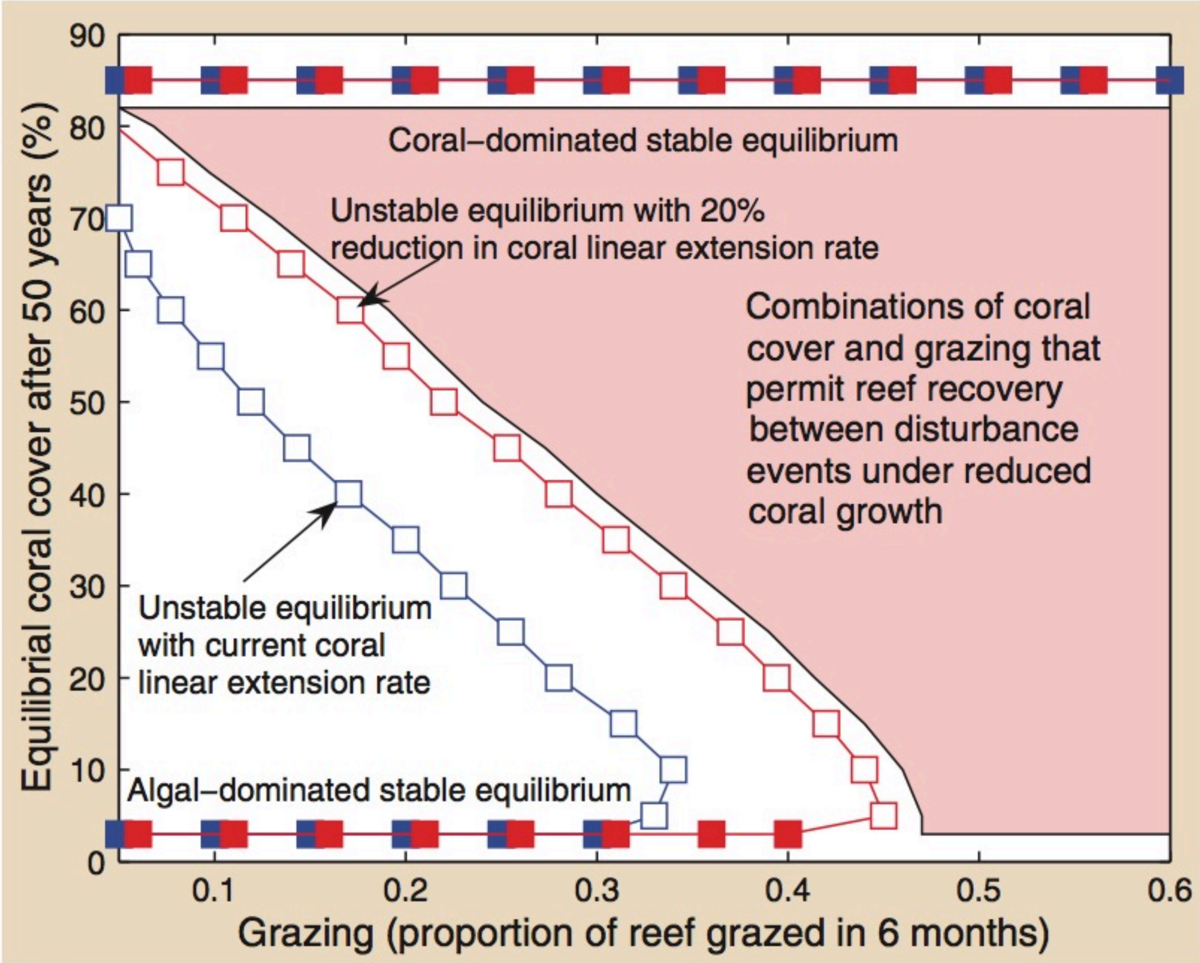


Fig. 2. Reduction in the resilience of Caribbean forereefs as coral growth rate declines by 20%. Reef recovery is only feasible above or to the right of the unstable equilibria (open squares). The "zone of reef recovery" (pink) is therefore more restricted under reduced coral growth rate and reefs require higher levels of grazing to exhibit recovery trajectories.

(Hoegh-Guldberg *et al.* 2007)

Climate change: impact on resilience

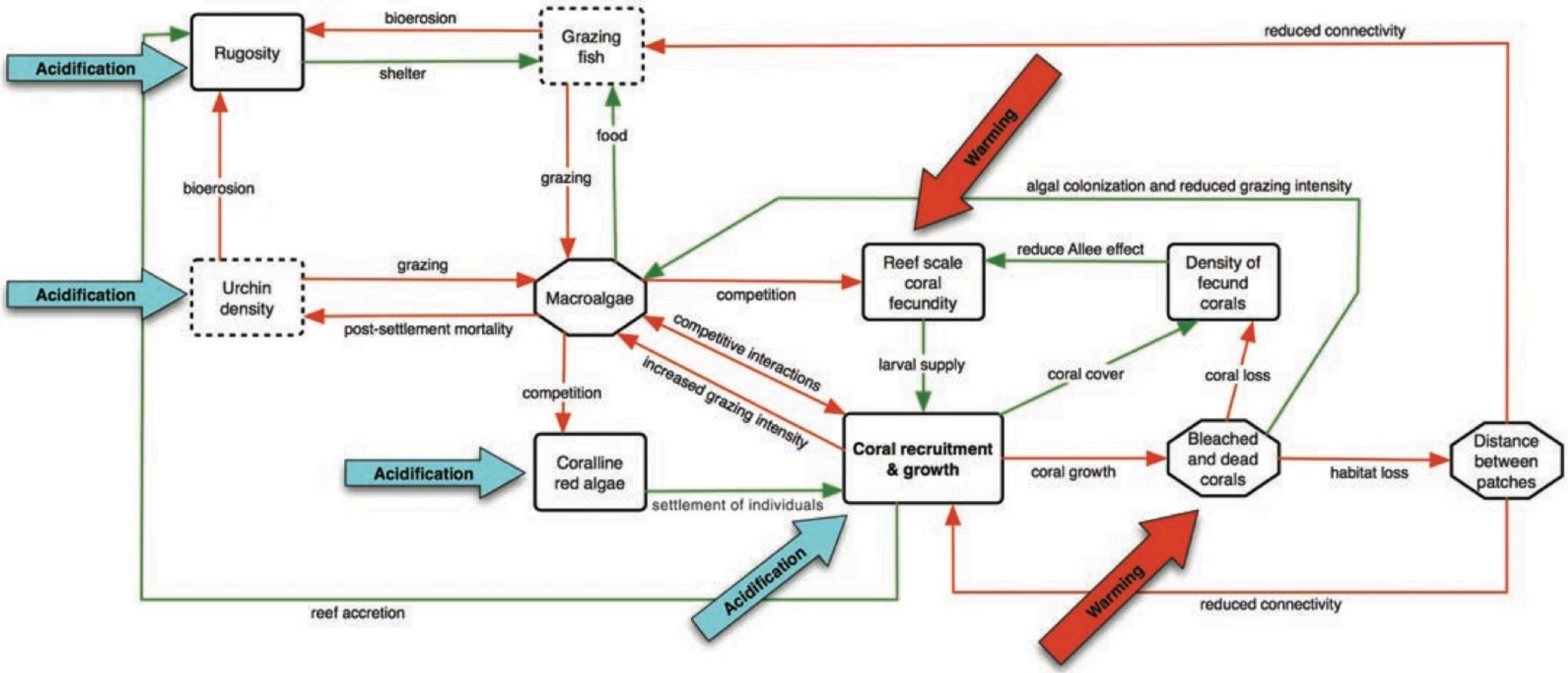
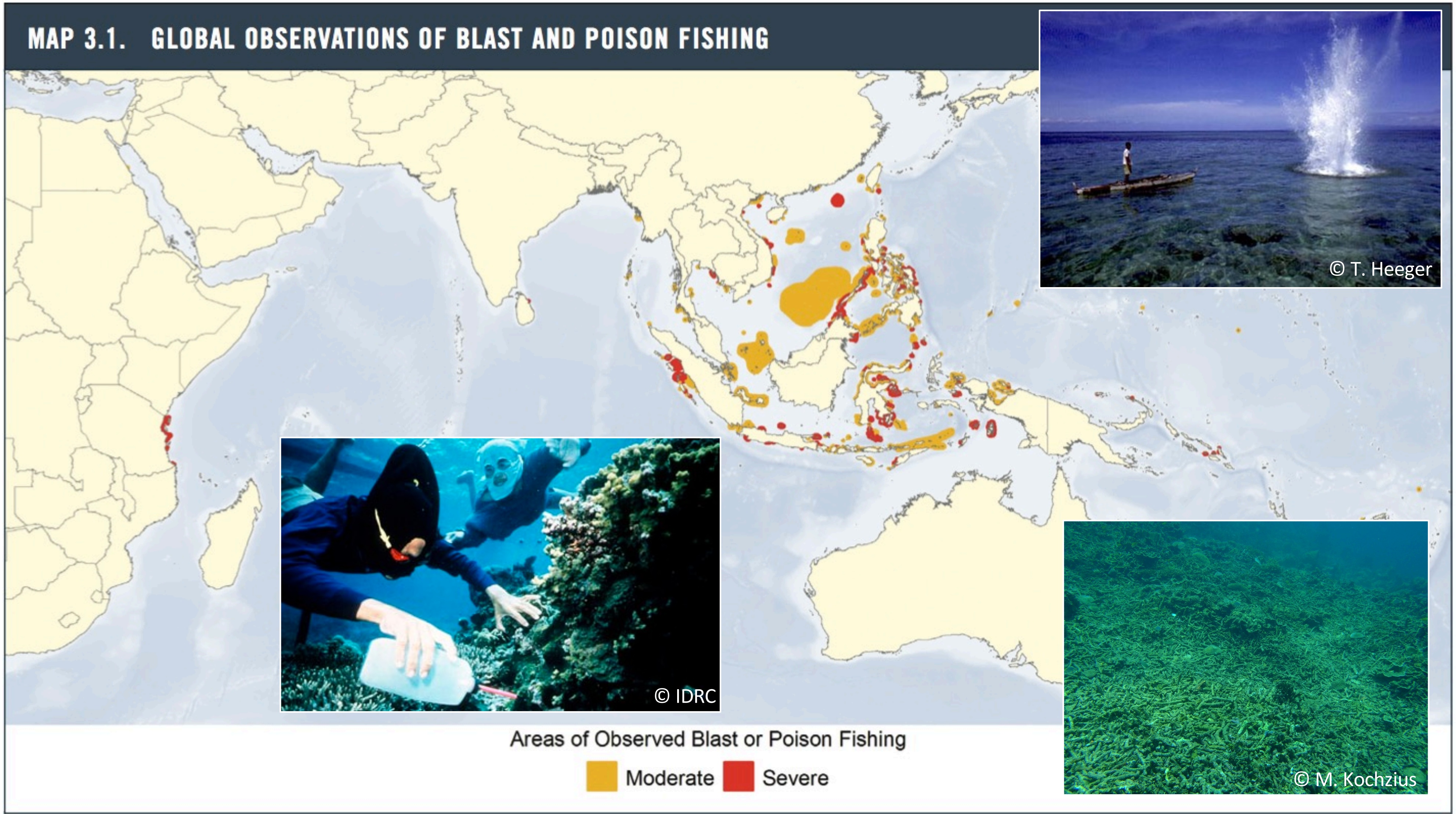


Fig. 3. Ecological feedback processes on a coral reef showing pathways of disturbance caused by climate change. Impact points associated with ocean acidification (e.g., reduced reef rugosity, coralline algae) are indicated by the blue arrows, and impact points from global warming (e.g., bleached and dead corals) by the red arrows. Boxes joined by red arrows denote that the first factor has a negative (decreasing) influence on the box indicated. Green arrows denote positive (increasing) relationships. Over time, the levels of factors in hexagonal boxes will increase, whereas those in rectangular boxes will decline. Boxes with dashed lines are amenable to local management intervention.

(Hoegh-Guldberg *et al.* 2007)

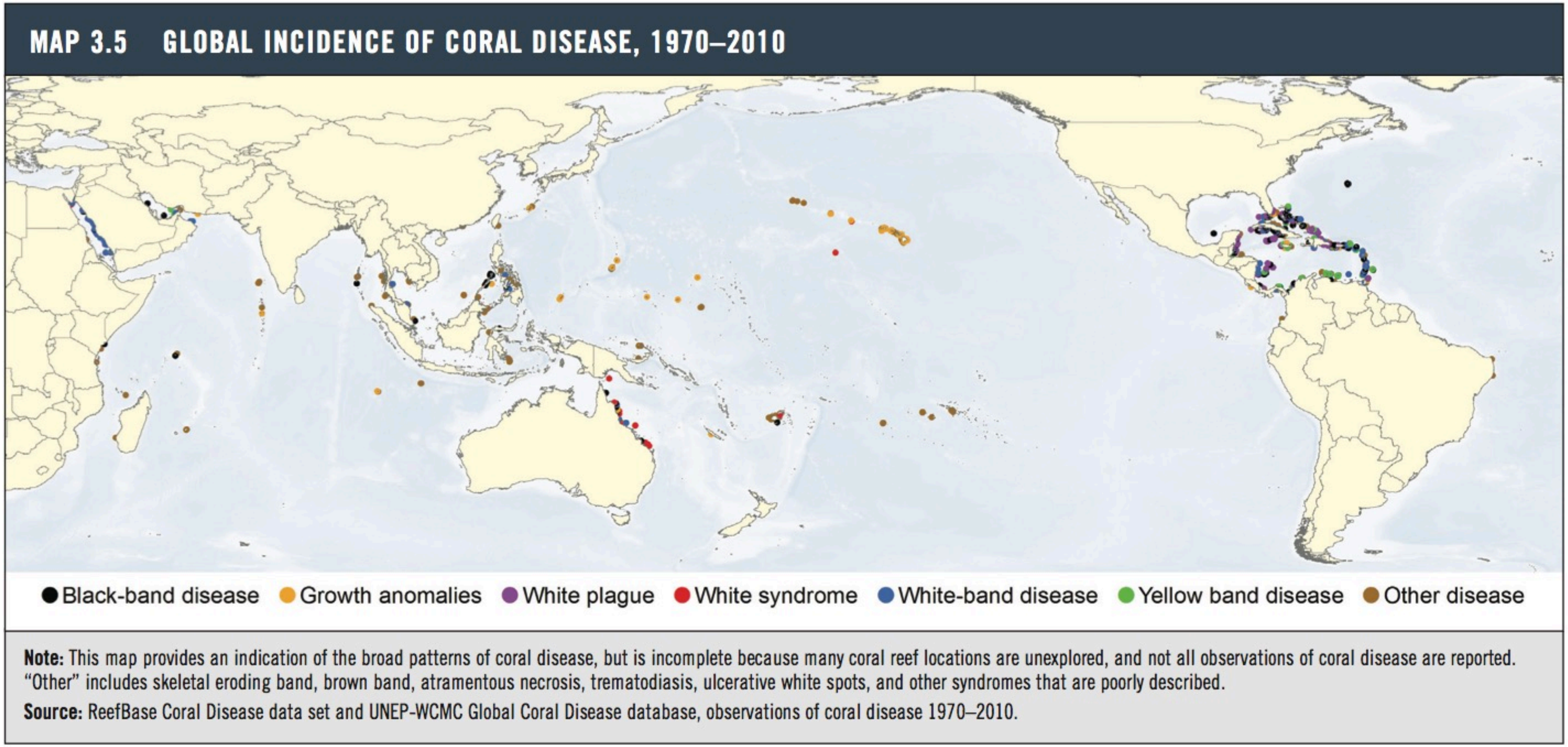
Reefs at risk: blast and poison fishing



Note: Blast and poison fishing is largely undertaken in Southeast Asia, the western Pacific, and eastern Africa. Areas of threat shown here are based on survey observations and expert opinion.
Source: WRI, 2011.

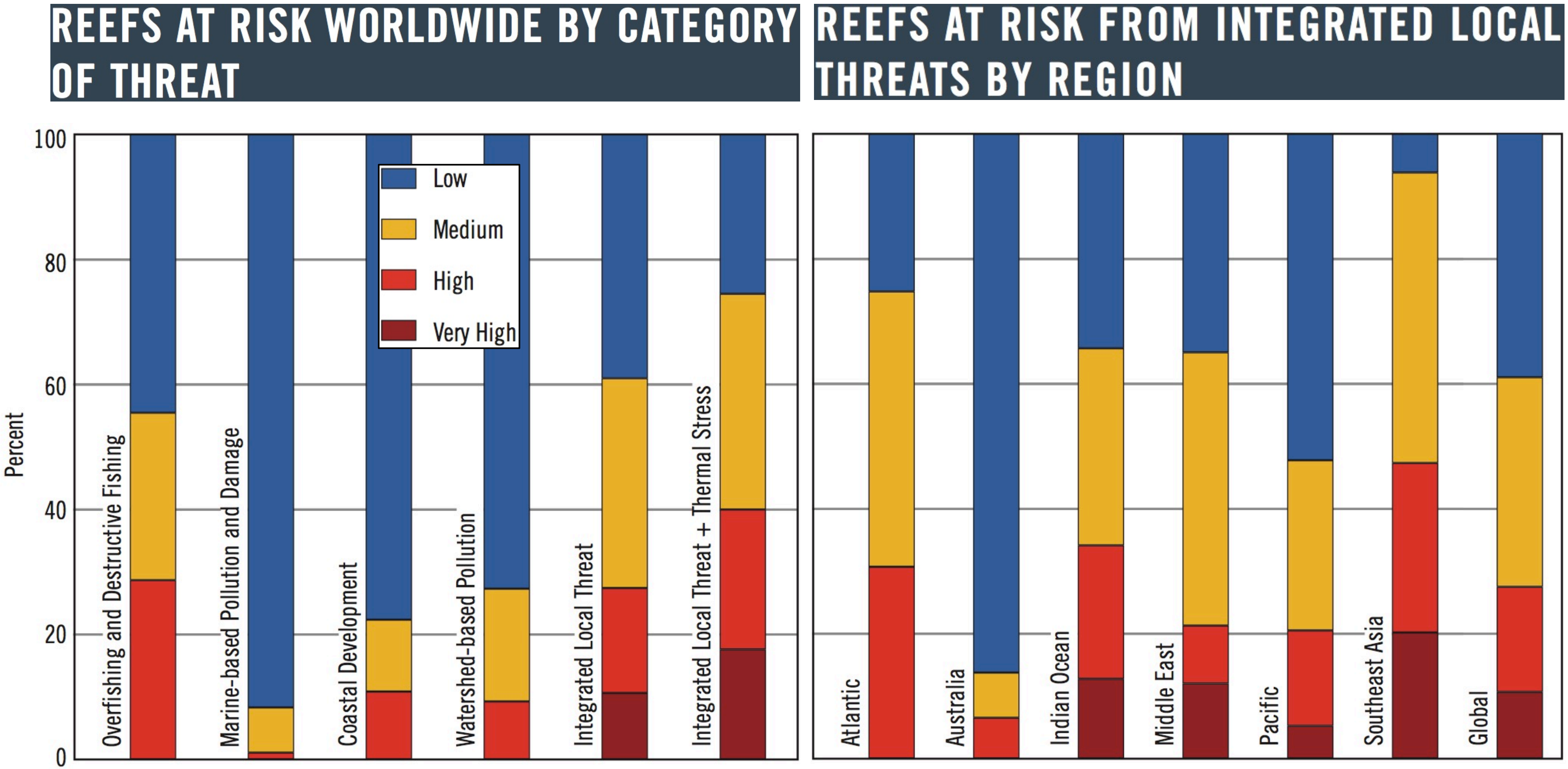
Burke et al. (2011)

Reefs at risk: coral disease



Burke et al. (2011)

Reefs at risk: current status

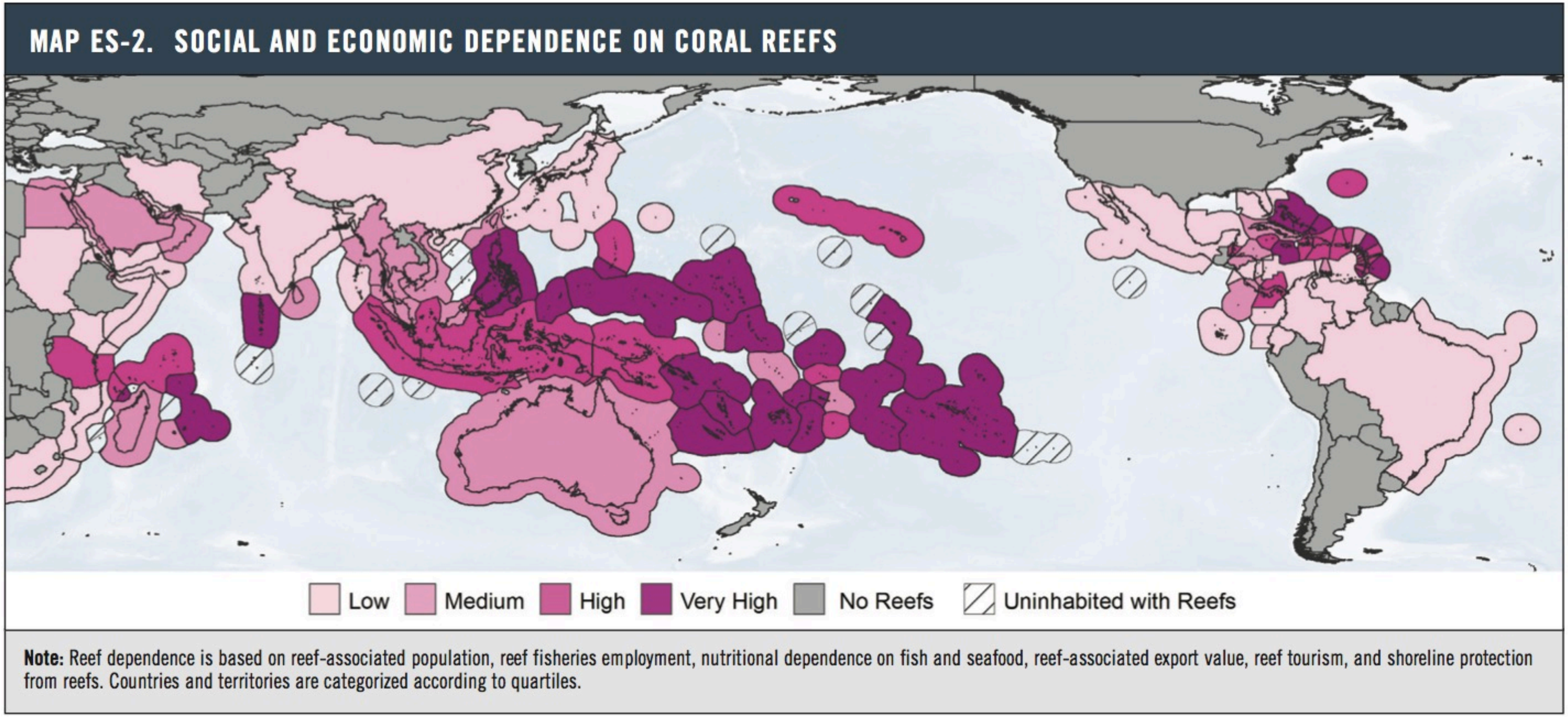


Notes: Individual local threats are categorized as low, medium, and high. These threats are integrated to reflect cumulative stress on reefs. Reefs with multiple high individual threat scores can reach the very high threat category, which only exists for integrated threats. The fifth column, integrated local threats, reflects the four local threats combined. The right-most column also includes thermal stress during the past ten years. This figure summarizes current threats; future warming and acidification are not included.

Note: Integrated local threats consist of the four local threats—overfishing and destructive fishing, marine pollution and damage, coastal development, and watershed-based pollution.

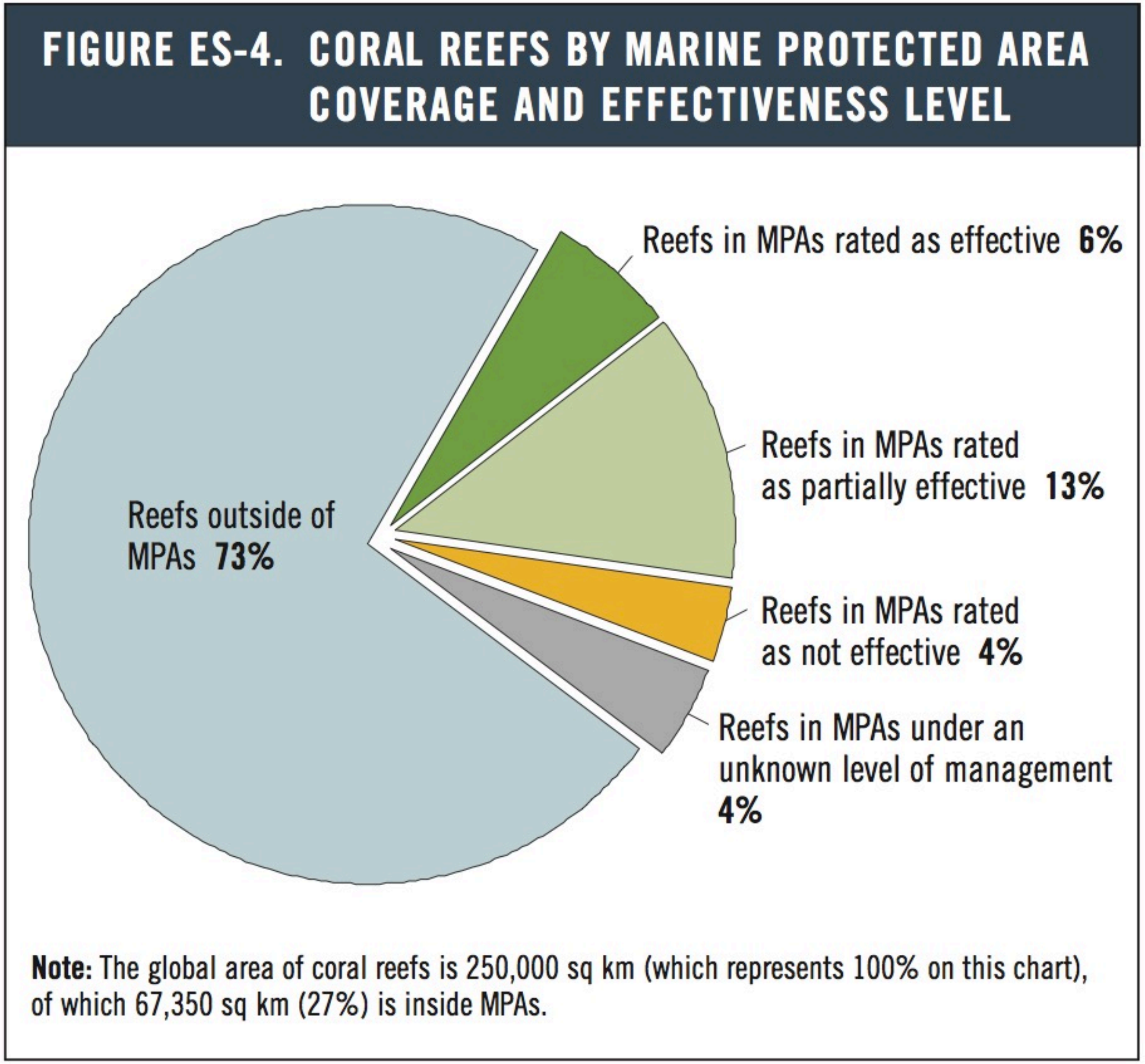
Burke et al. (2011)

Reefs at risk: socioeconomic dependence



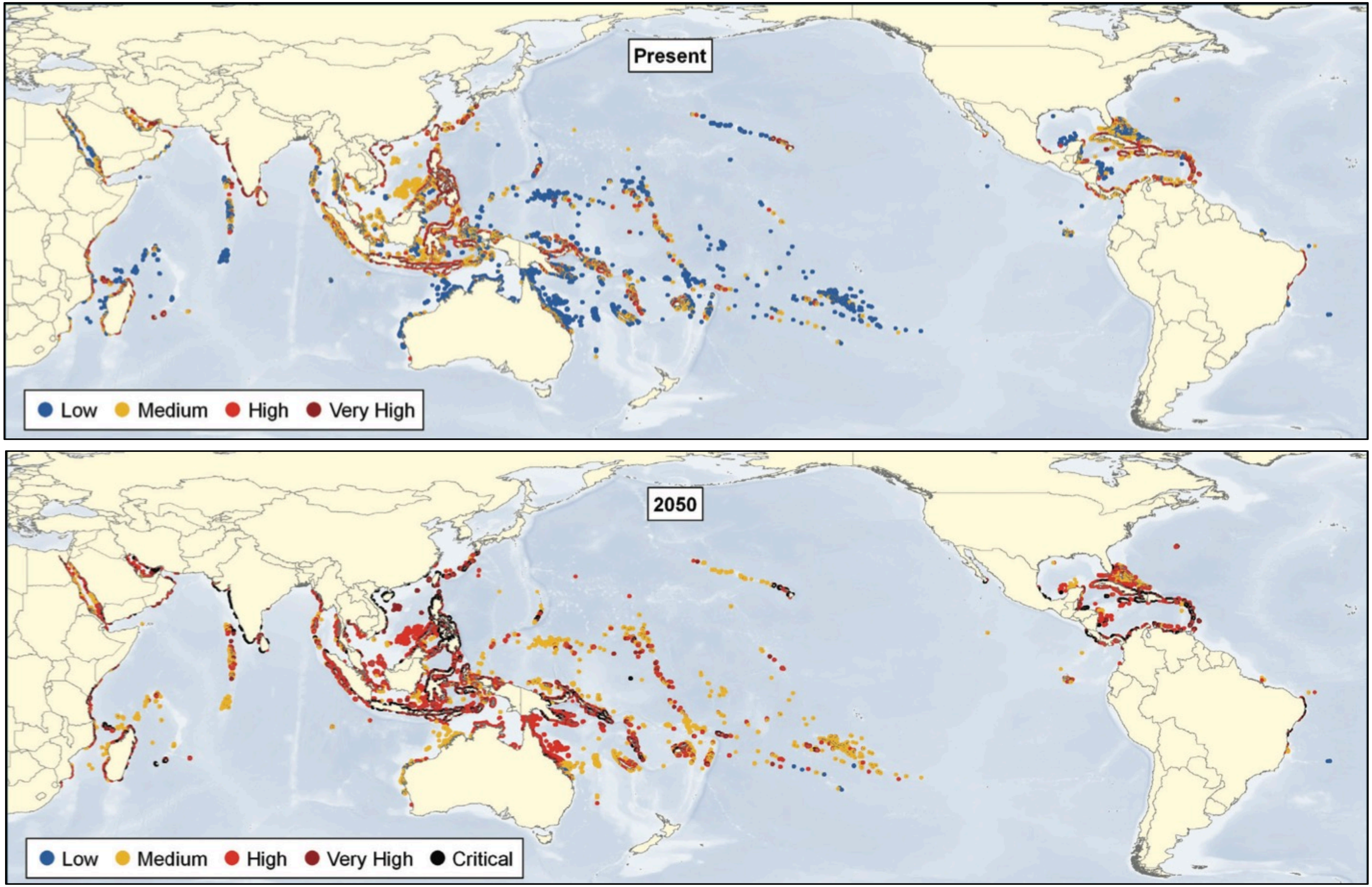
Burke et al. (2011)

Reefs at risk: marine protected areas (MPAs)



Burke et al. (2011)

Reefs at risk: future projections



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