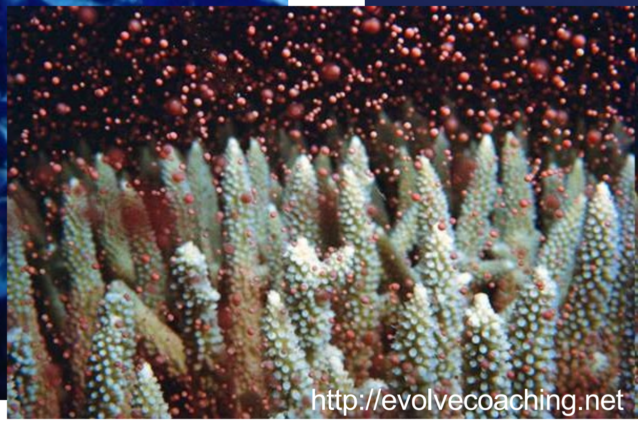
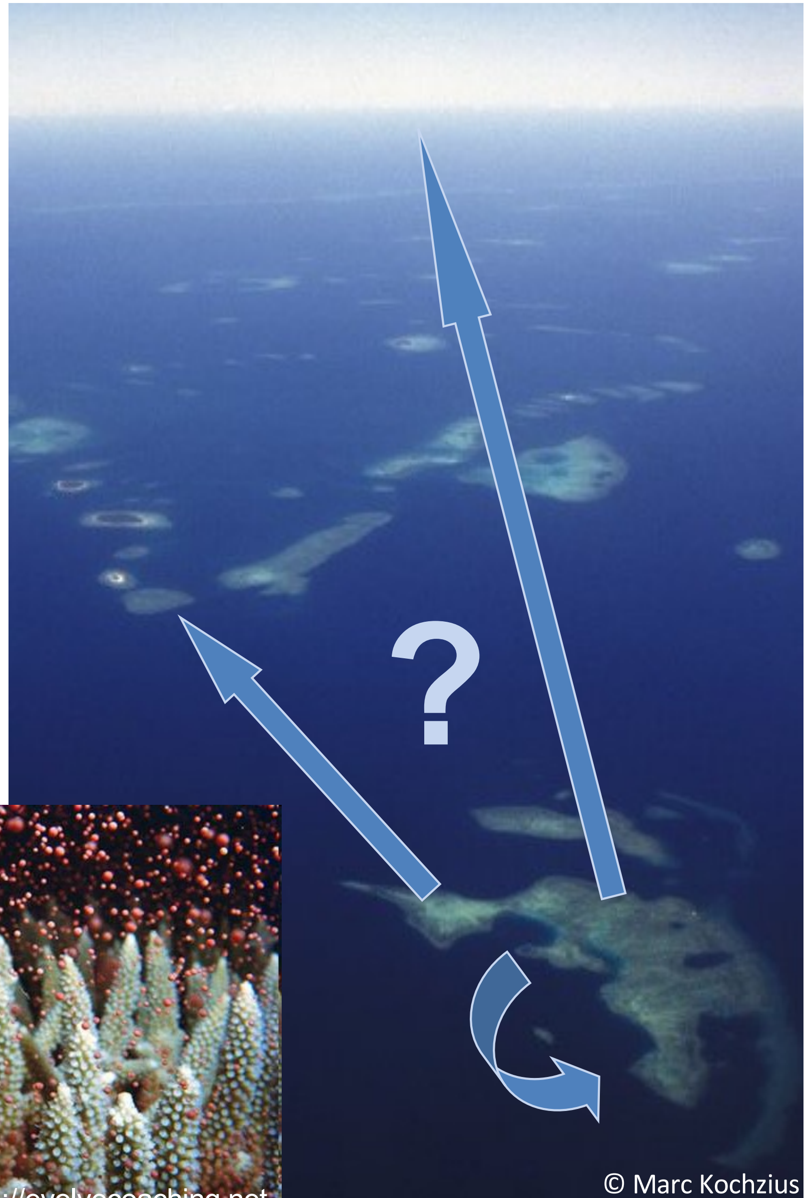
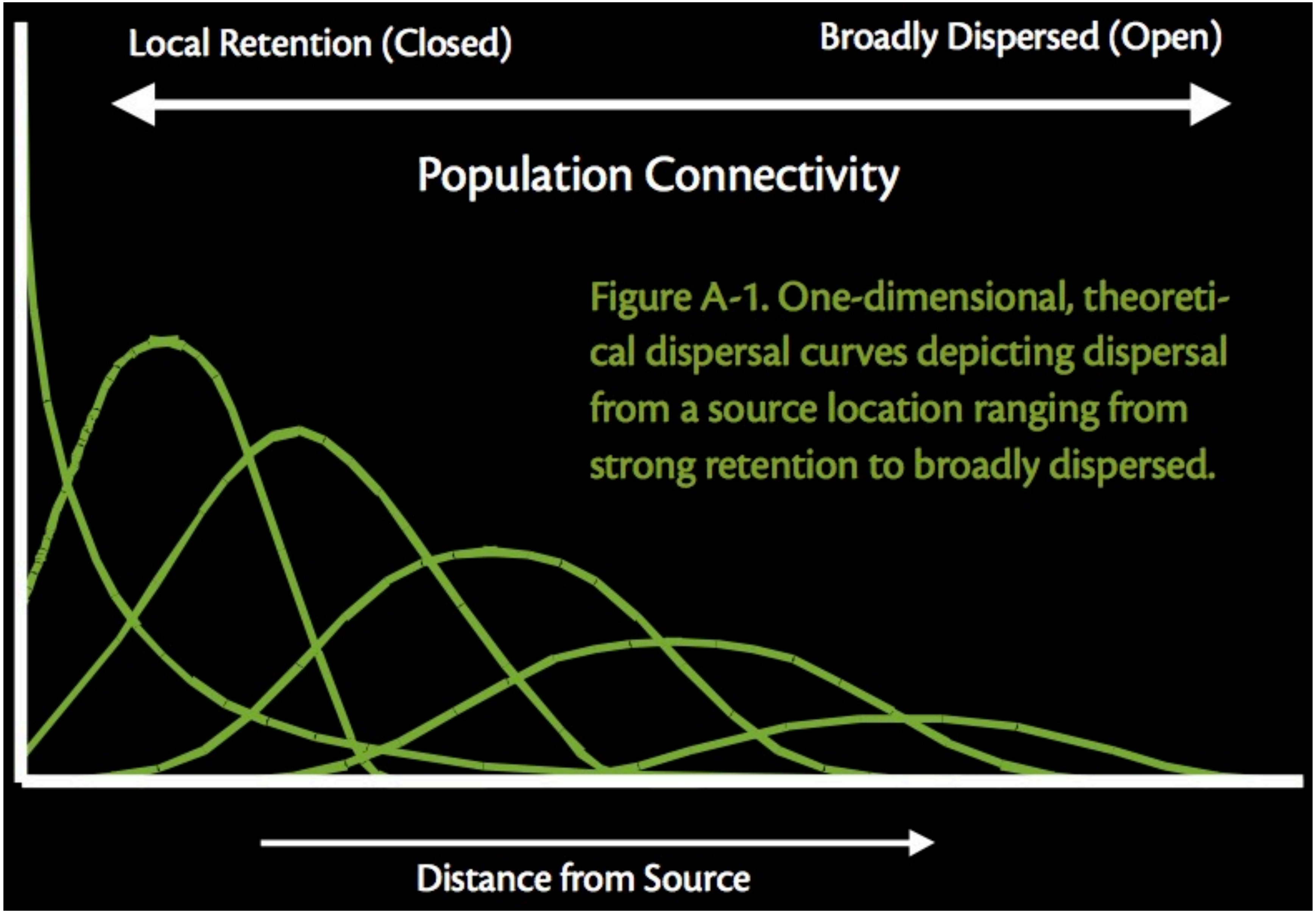
Connectivity

Connectivity: Dispersal of coral reef fauna





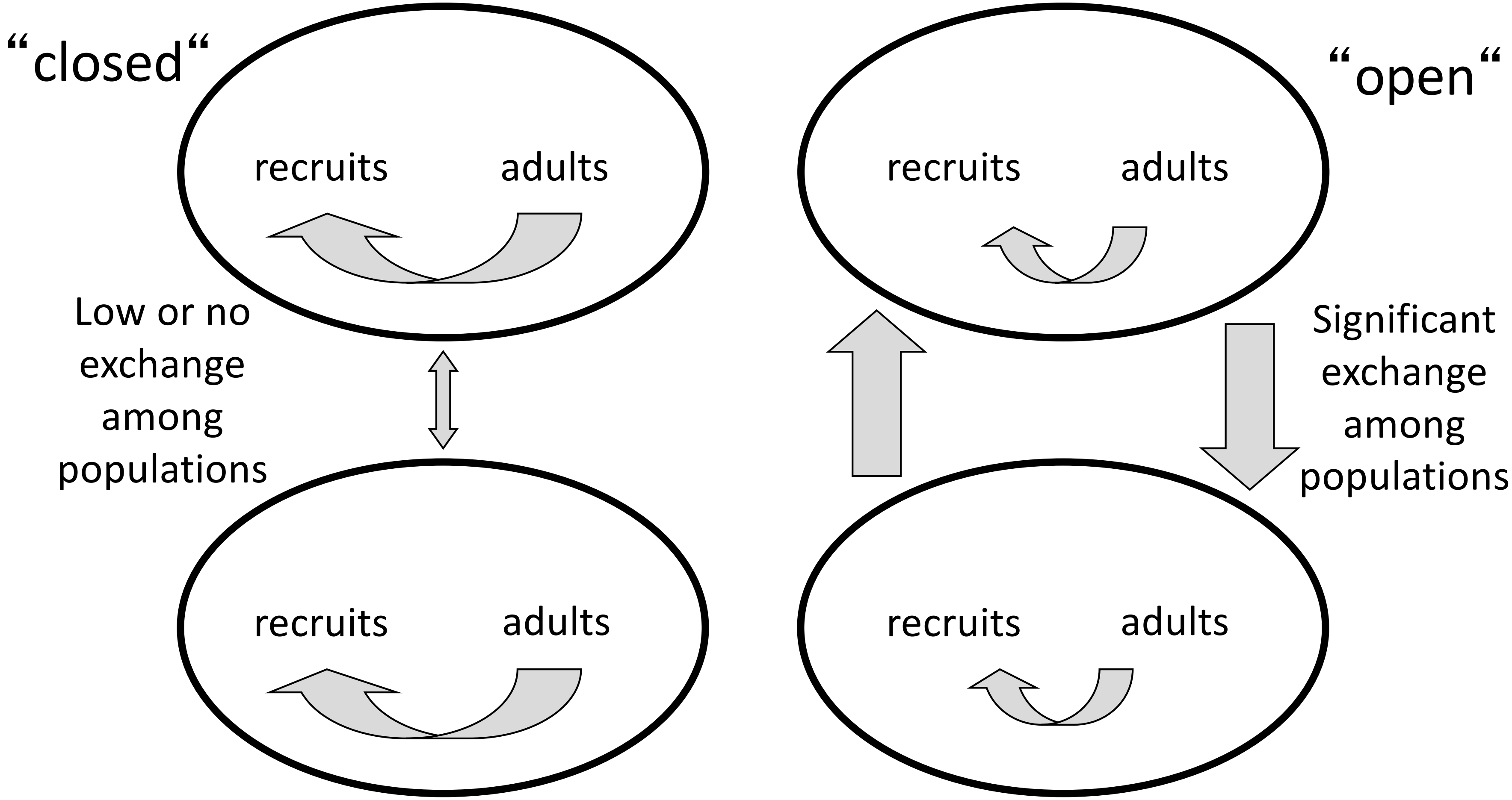
Connectivity: Dispersal



(Cowen *et al.* 2007)

Connectivity: Dispersal

Do we have "closed" or "open" populations?
… or in terms of fisheries: one or several stocks?
… or in terms of genetics: restricted gene flow or panmixia?



Connectivity: Dispersal

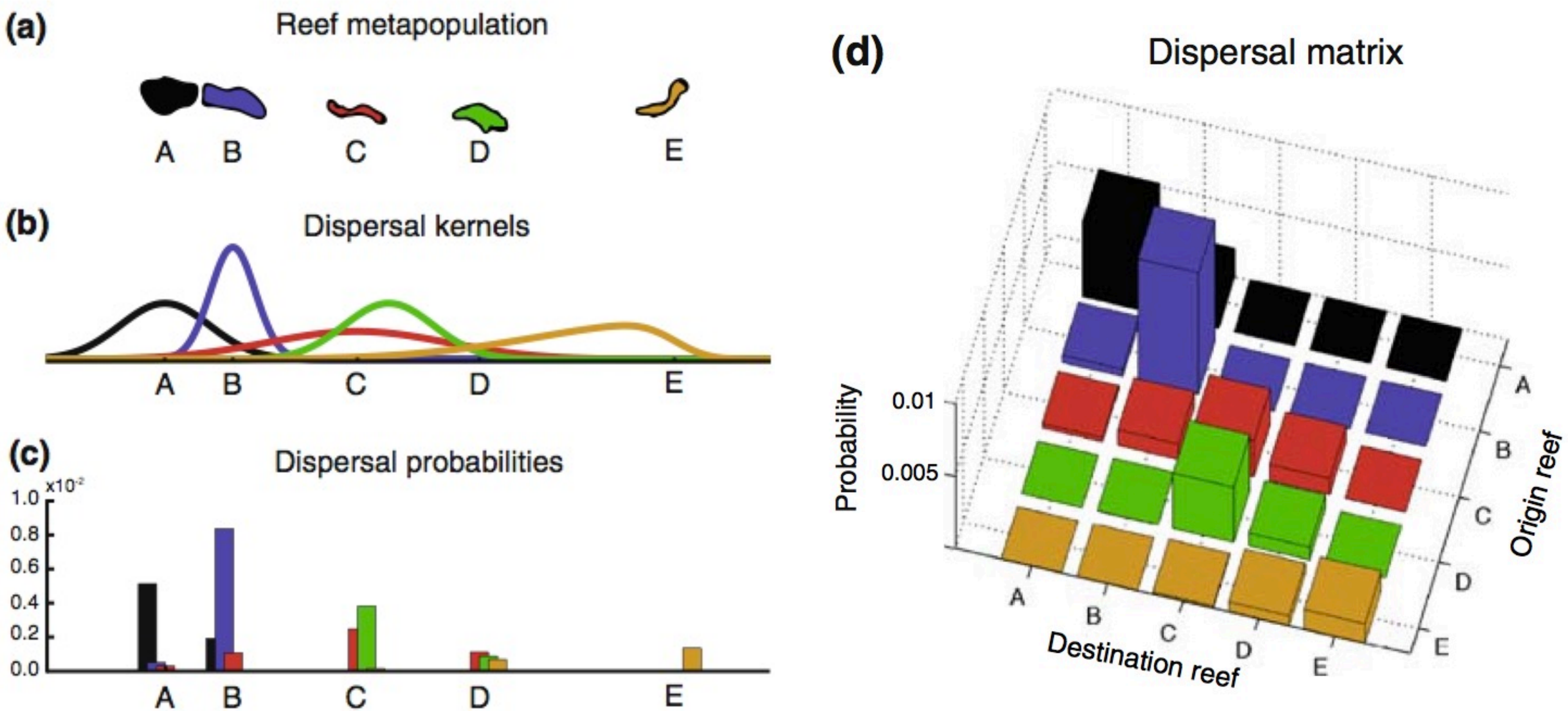


Fig. 1 A hypothetical one-dimensional example of a coral reef configuration that demonstrates the elements of the dispersal matrix. **a** The geographical configuration, **b** the dispersal kernels for each reef, with varying shape, diffusion, and advection, **c** a discrete-space version of the dispersal kernels, with each reef being a spatial unit, assuming constant larval survivorship of 0.01, **d** the corresponding dispersal matrix

(Botsford *et al.* 2009)

Connectivity: Dispersal

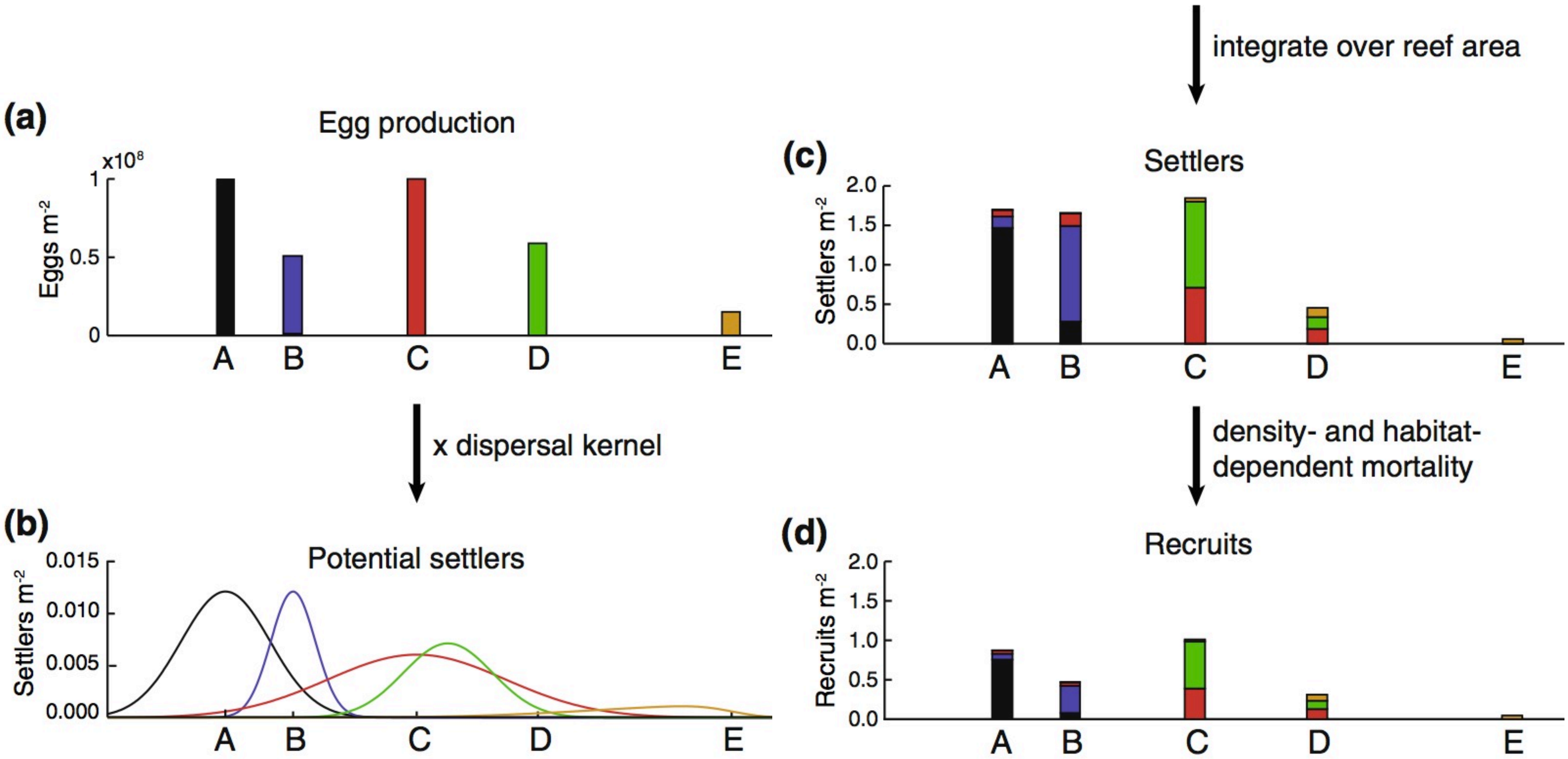


Fig. 3 An example of one step in the connectivity process for the metapopulation occupying the reefs depicted in Fig. 1. **a** The total egg production on each reef. Reef B has lower output due to low quality habitat. Reefs D and E have lower output due to low population density. **b** Egg production multiplied by the dispersal kernel gives the spatial distribution of potential settlers (assuming homogenous larval mortality). **c** Integrating the settler distribution over the area on each reef gives the total settlers in each location. **d** Settler densities are reduced due to habitat- and density-dependent mortality. Settlers at each reef experience density-dependent Beverton–Holt mortality with density-independent survivorship of 0.8 and an asymptotic maximum recruit density of 1 recruit m^{-2}. On reef B, poor habitat causes per-capita fecundity and density-independent survivorship to be 50% of that on the other reefs

(Botsford *et al.* 2009)

Connectivity: how to measure or estimate dispersal?

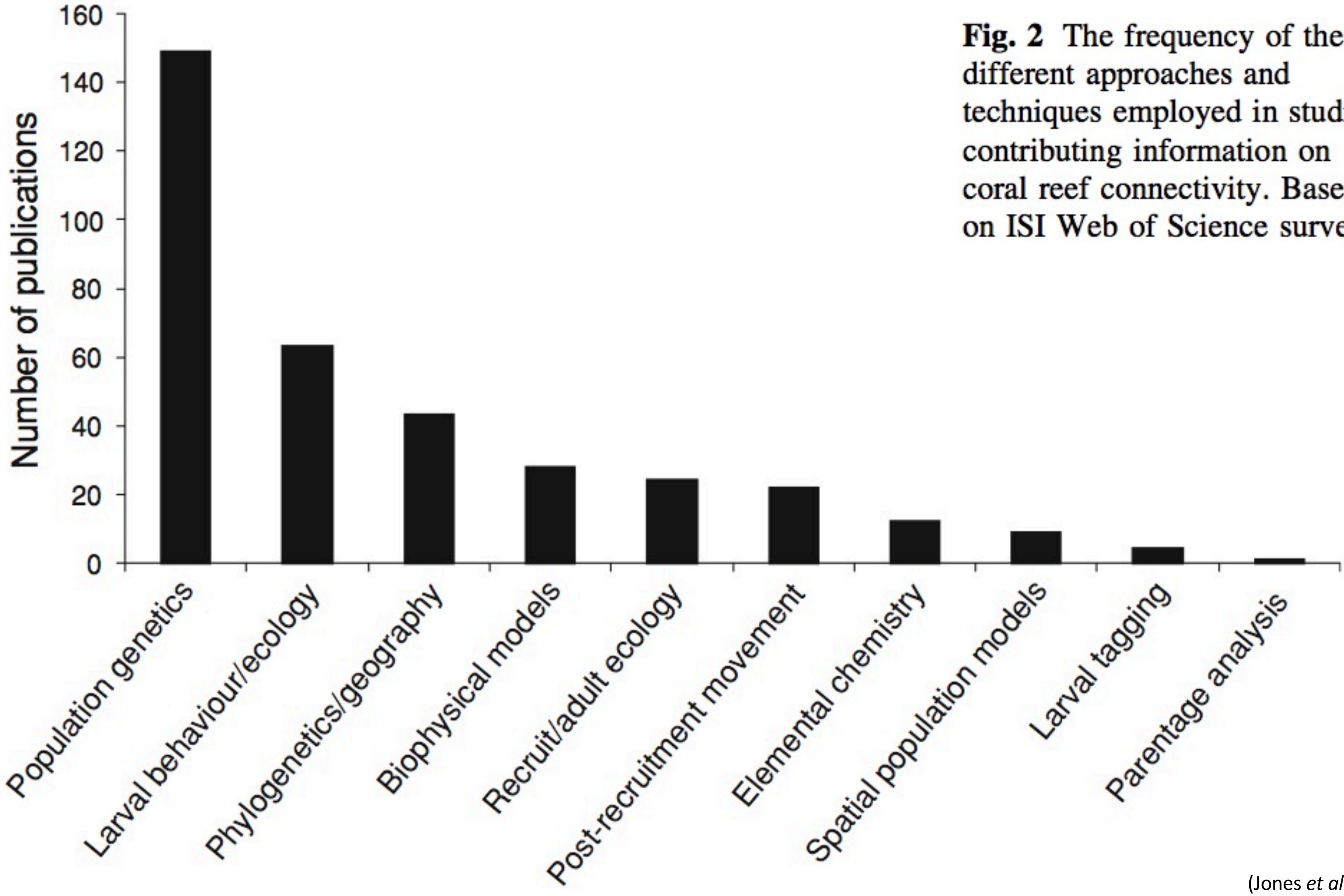


Fig. 2 The frequency of the different approaches and techniques employed in studies contributing information on coral reef connectivity. Based on ISI Web of Science survey

(Jones *et al.* 2009)

Connectivity: how to measure or estimate dispersal?

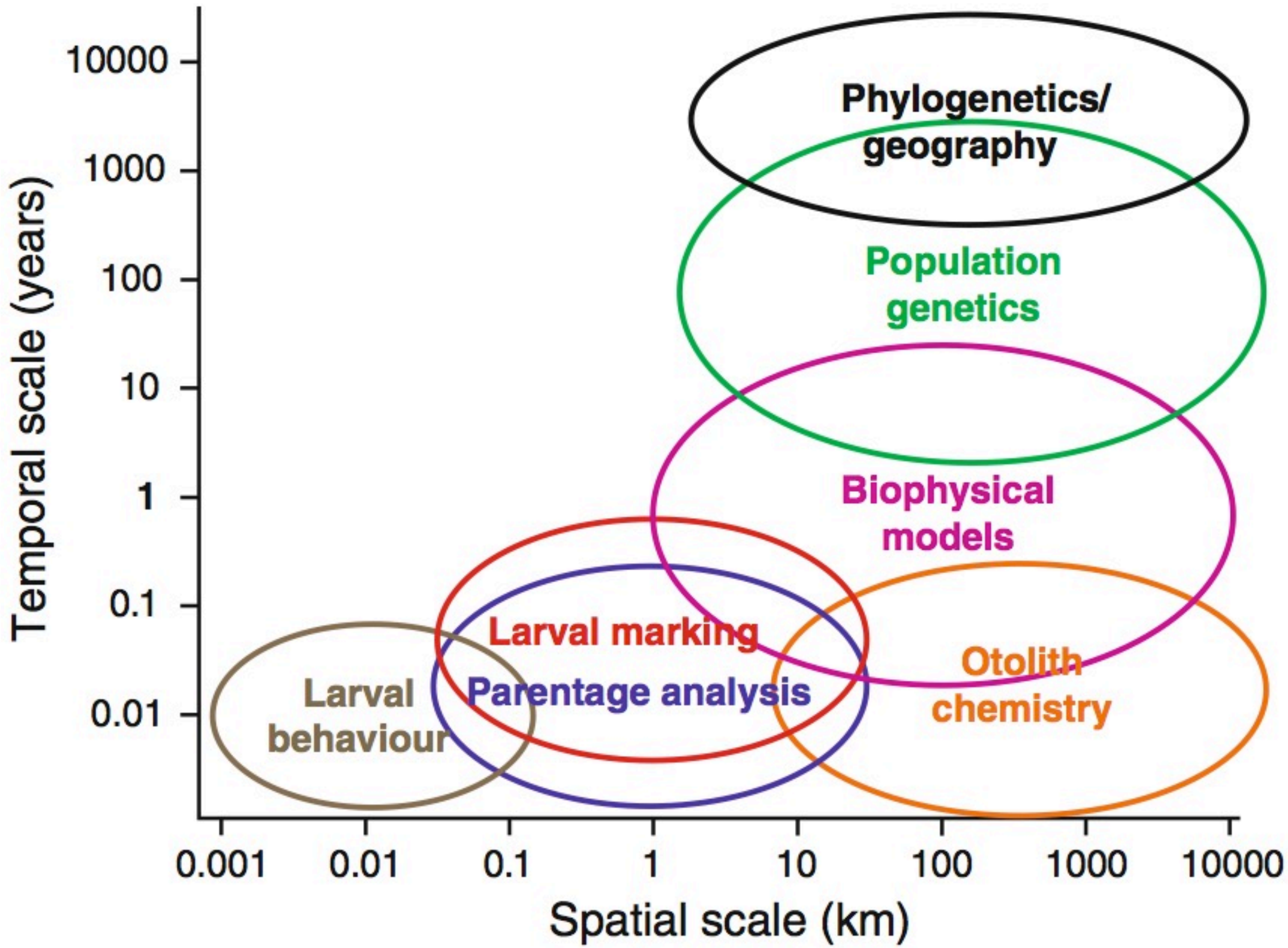


Fig. 3 Schematic view of the spatial and temporal scales over which different approaches and techniques can provide information on larval retention and dispersal in coral reef organisms with pelagic larvae

(Jones *et al.* 2009)

Connectivity: mark and recapture

Self-recruitment in a coral reef fish population

G. P. Jones, M. J. Milicich, M. J. Emslie & C. Lunow

NATURE | VOL 402 | 16 DECEMBER 1999

- Marking of otoliths (ear bones) of over 10 million developing
- embryos of the damselish *Pomacentrus amboinensis*
- examination of 5,000 juveniles settling at the same location; 15 marked individuals found
- On the basis of an estimate of the proportion of embryos marked (0.5-2 %), as many as 15-60 % of juveniles may be returning to their natal population (self-recruitment)

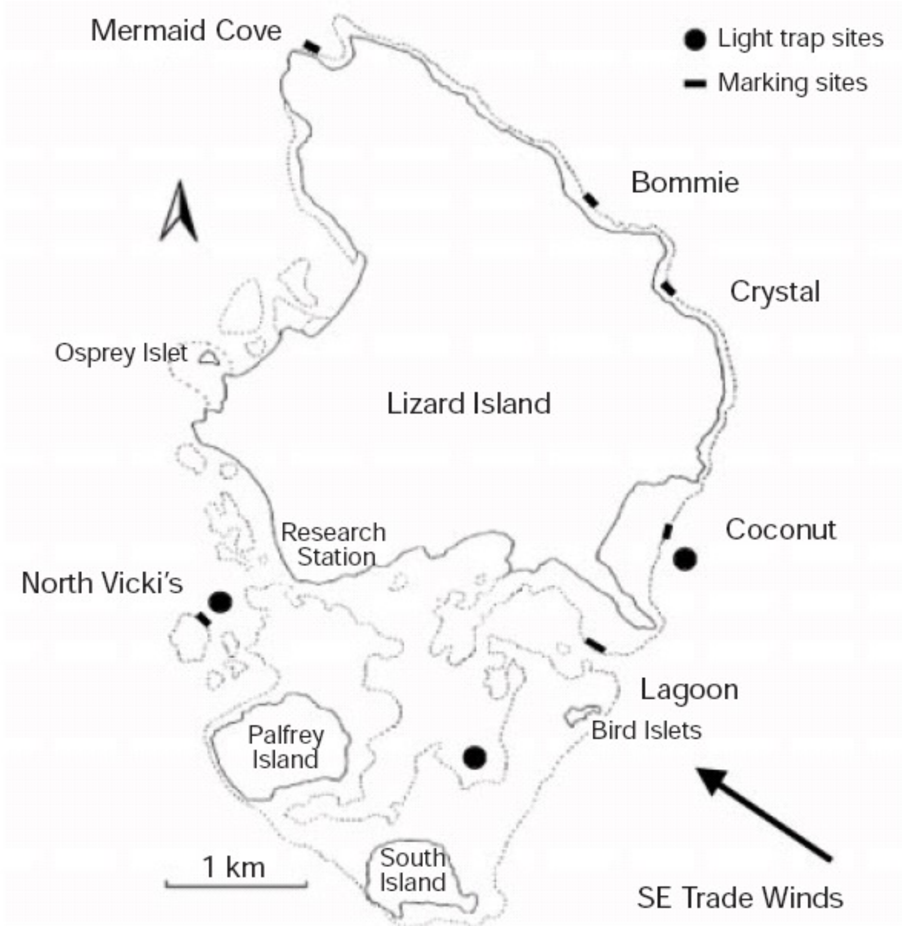


Figure 1 Map of Lizard Island on the northern Great Barrier Reef, showing the location of the six 150-m stretches of reef edge where all embryos of *Pomacentrus amboinensis* were marked over a three-month period (October–December 1994). Light traps were placed at three sites to collect incoming larvae ready to settle onto the reef, with four light traps at the windward site, two at the lagoon site and two at the back reef site. Dotted lines indicate the reef.

Connectivity: mark and recapture

Local Replenishment of Coral Reef Fish Populations in a Marine Reserve

Glenn R. Almany,[1*] Michael L. Berumen,[1,2] Simon R. Thorrold,[3]
Serge Planes,[4] Geoffrey P. Jones[1]
2007 VOL 316 **SCIENCE**

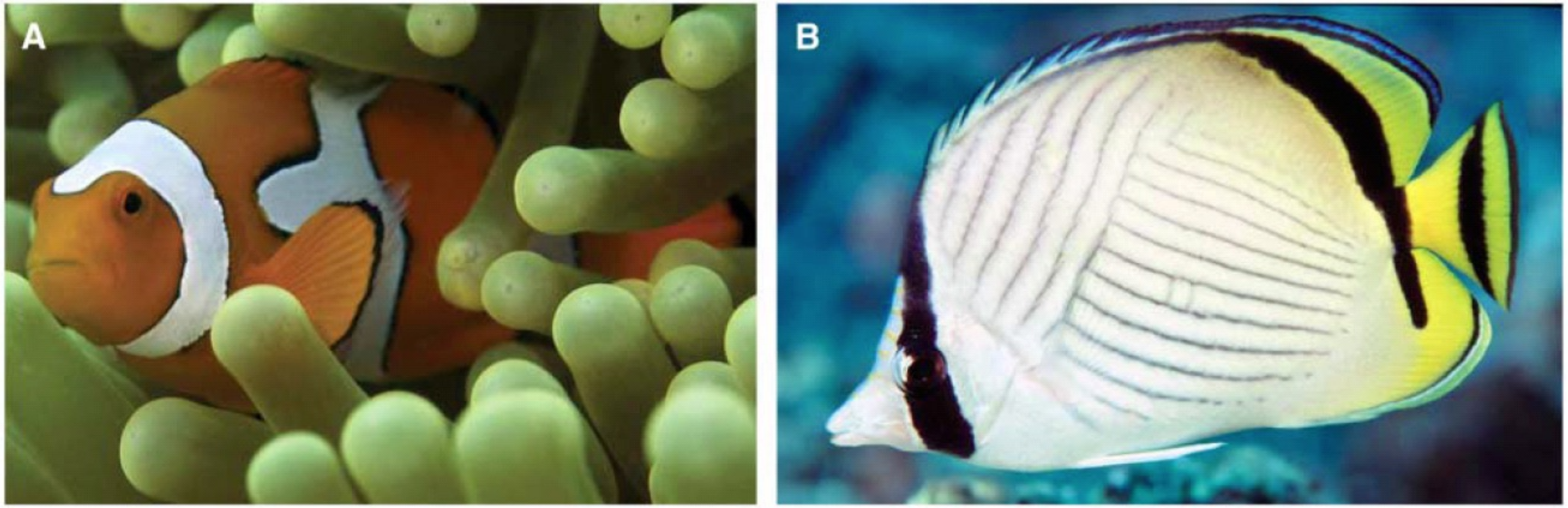
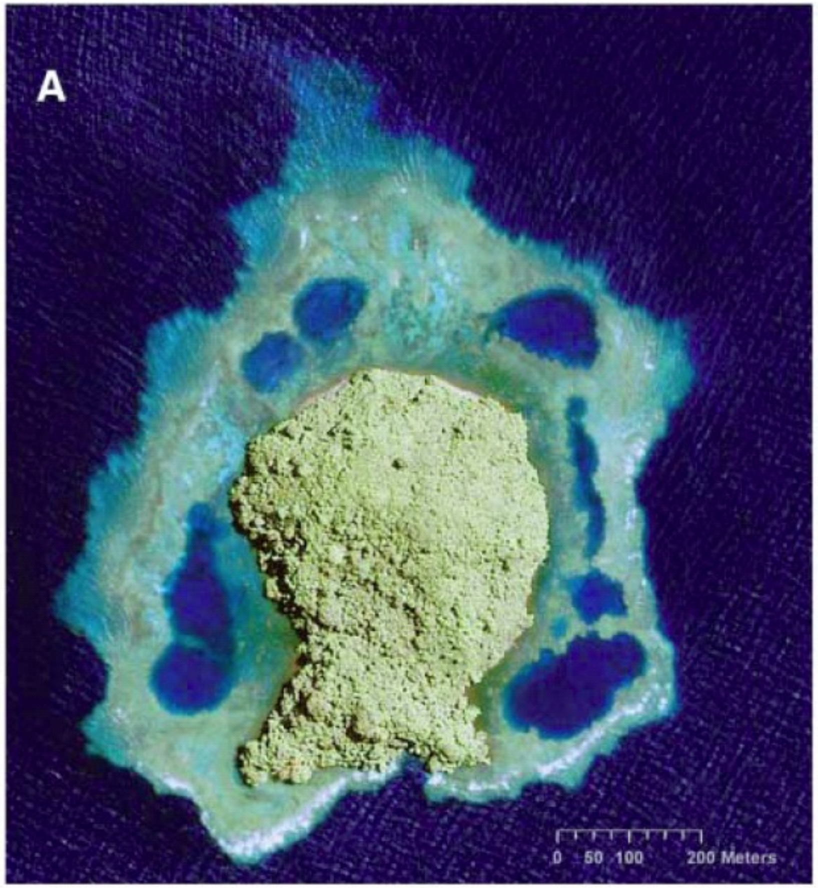


Fig. 1. Study species. An adult (**A**) *A. percula* (photo by S. R. Thorrold) and (**B**) *C. vagabundus* (photo by R. Patzner).

- Marking of embryos by injecting a $BaCl_2$ solution that was highly enriched in ^{137}Ba and depleted in ^{135}Ba as compared to natural Ba isotope values
- 176 clownfish females and 123 butterflyfish were captured and injected at Kimbe Island
- Quantification of Ba isotope ratios in the otolith cores of settlers, using laser ablation inductively coupled plasma mass spectrometry (ICP-MS)

Connectivity: mark and recapture

(Almany *et al.* 2007)



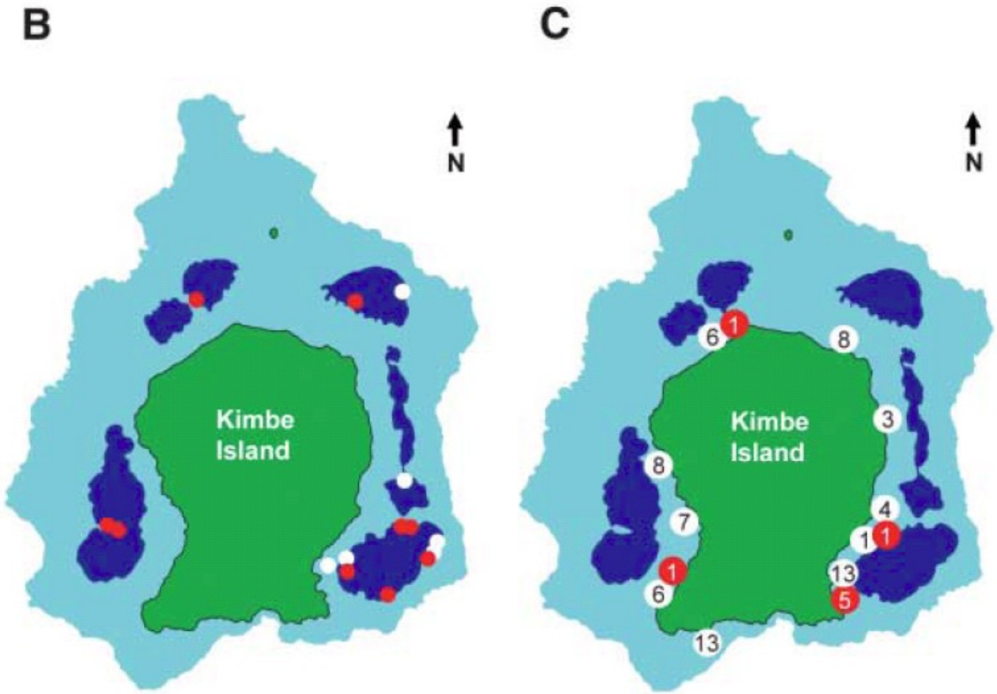


Fig. 2. (**A**) Satellite image of the Kimbe Island MPA (taken by the IKONOS-2 satellite at a resolution of 1 m). (**B** and **C**) Schematic diagrams of Kimbe Island showing the locations of tagged (red circles) and untagged (white circles) juveniles collected in February 2005. The locations of juvenile (B) *A. percula* (*n* = 15) and (C) *C. vagabundus* (*n* = 77) are shown. In (C), the number in each circle corresponds to the number of juveniles collected from that location.

- Assuming that all clownfish larvae produced were tagged, 60 % of juveniles made the return journey
- Scaling the proportion of tagged juveniles (8 of 77) to the proportion of adults injected with Ba indicated that a remarkable 60.1 % of juvenile butterflyfish returned to their reef

Connectivity: DNA parentage analysis

Larval dispersal connects fish populations in a network of marine protected areas

Serge Planes[a,b,1], Geoffrey P. Jones[c], and Simon R. Thorrold[d]

PNAS | April 7, 2009 | vol. 106 | no. 14 | 5693–5697

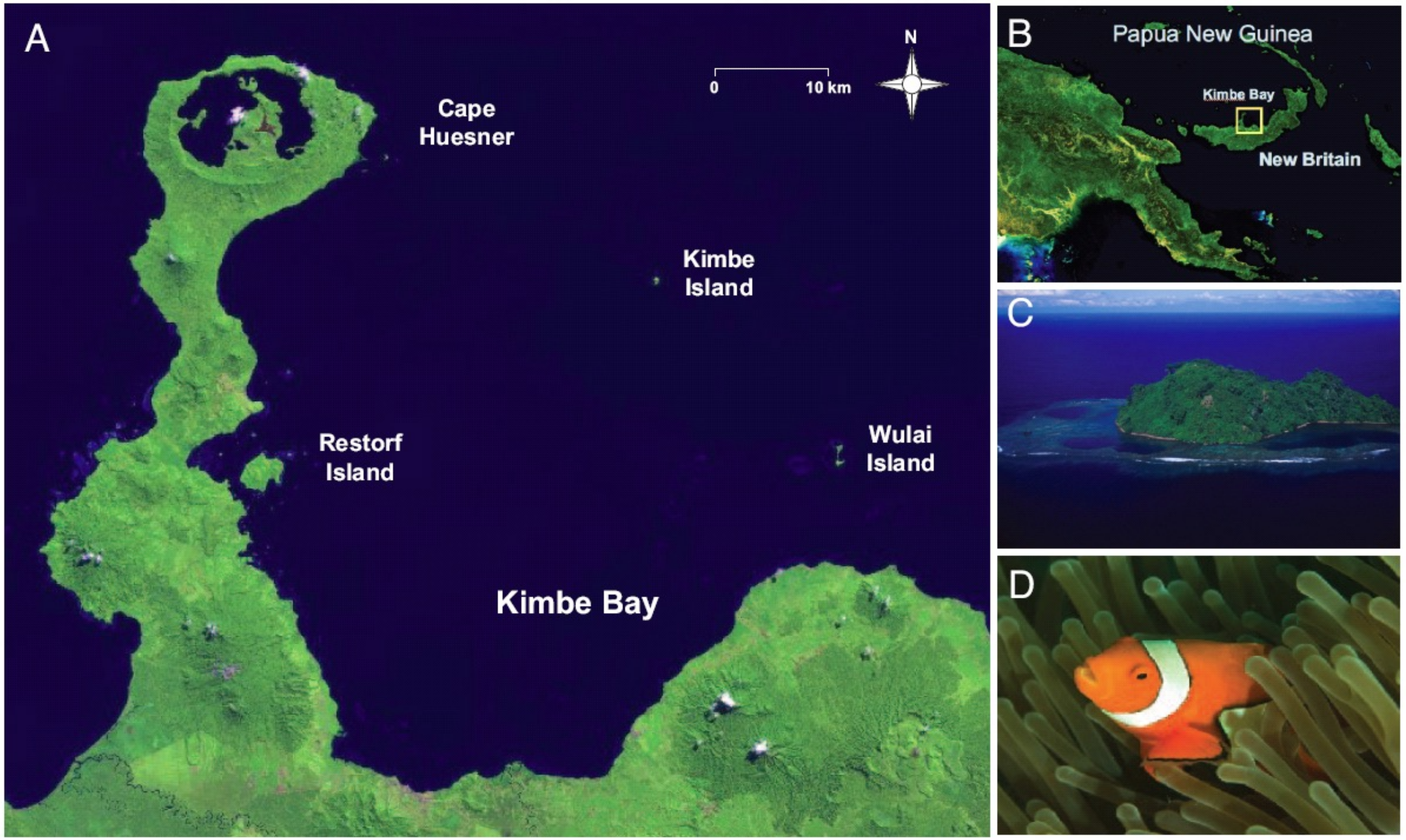


Fig. 1. Location maps and focal species. (*A*) LANDSAT satellite image of western Kimbe Bay showing the study sites. (*B*) Location of Kimbe Bay on the north side of New Britain, Papua New Guinea. (*C*) Aerial photograph of Kimbe Island showing lagoonal habitats in which *A. percula* are concentrated in the study area. (Photo courtesy of Tami Pelusi.) (*D*) *A. percula* sheltering in an anemone, Kimbe Bay. (Photo courtesy of Simon Thorrold.)

Connectivity: DNA parentage analysis

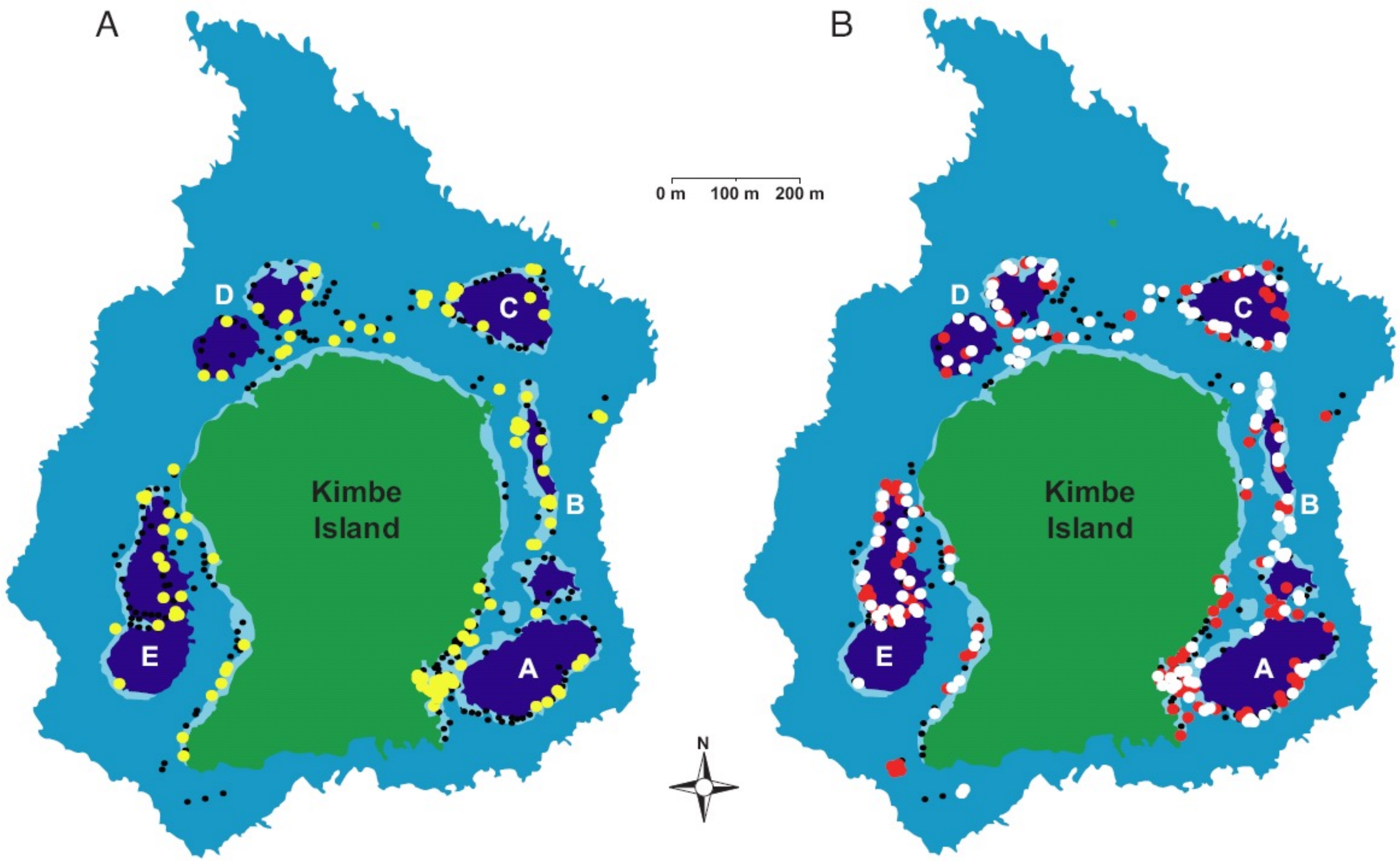


Fig. 2. Map of locations of all anemones in each of 5 lagoons (A– E) that harbored adult or juvenile *A. percula* around Kimbe Island. (*A*) Location of anemones with adult *A. percula* that either produced larvae that subsequently settled into anemones around Kimbe Island (yellow symbols) or did not produce larvae that returned to Kimbe Island (black symbols). (*B*) Location of anemones with recently settled juvenile *A. percula* that either were progeny of Kimbe Island adults (red symbols) or had dispersed from reefs at least 6 km away from Kimbe Island (white circles).

Screening of 16 polymorphic microsatellite DNA markers from a total of 506 potential *A. percula* parents at Kimbe Island and 400 newly settled juveniles (Planes *et al.* 2009)

Connectivity: DNA parentage analysis

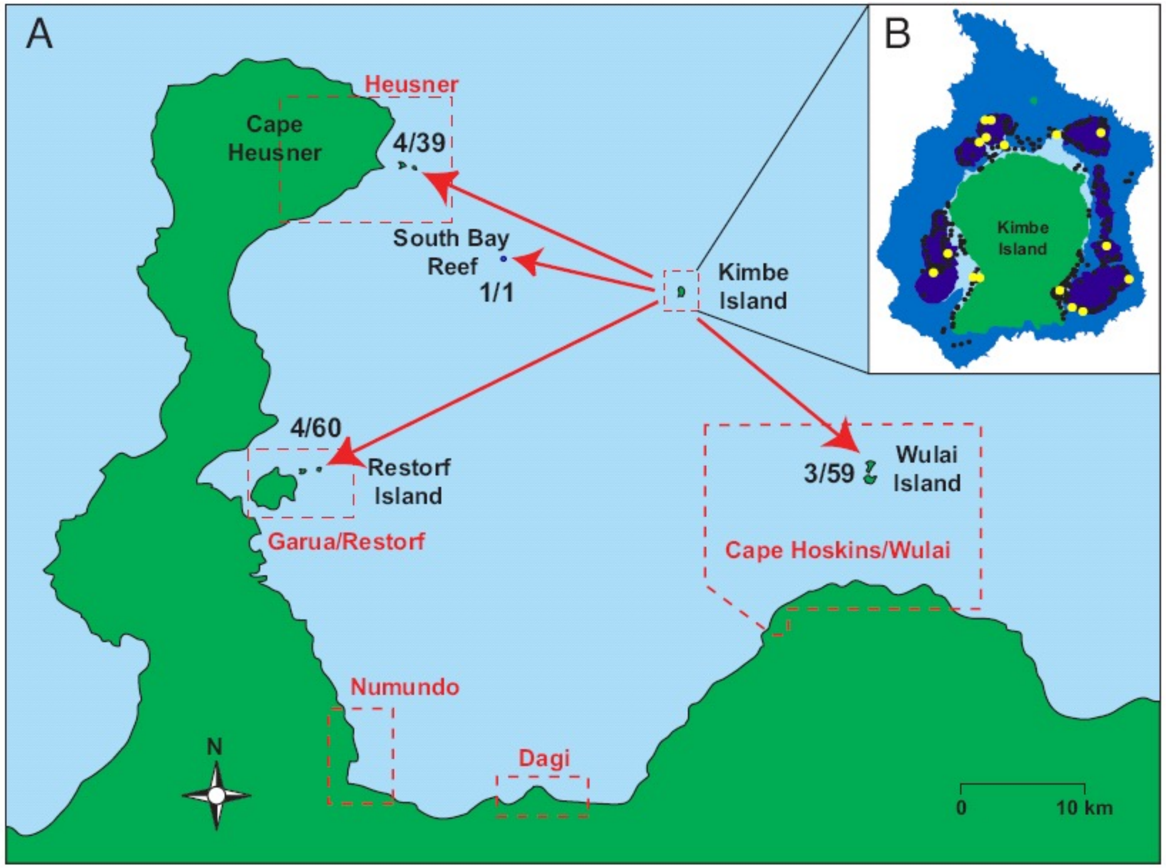


Fig. 3. Larval dispersal of *A. percula* from Kimbe Island to other designated marine reserves in western Kimbe Bay. (*A*) Proportion of recently settled juvenile *A. percula* collected at each of 4 locations that were progeny of Kimbe Island *A. percula*. The red boxes outline proposed reserve boundaries (6). (*B*) Location of adult *A. percula* that produced larvae that successfully dispersed and settled on anemones away from Kimbe Island (yellow symbols).

- Approximately 40% of larvae settling into anemones in Kimbe Island were derived from parents resident at that island
- Juveniles spawned by Kimbe Island residents had dispersed as far as 35 km
- dispersers accounted for up to 10% of the recruitment in the adjacent MPAs (Planes *et al.* 2009)

Connectivity: mark and recapture + DNA parentage analysis

Current Biology, Vol. 15, 1314–1318, July 26, 2005

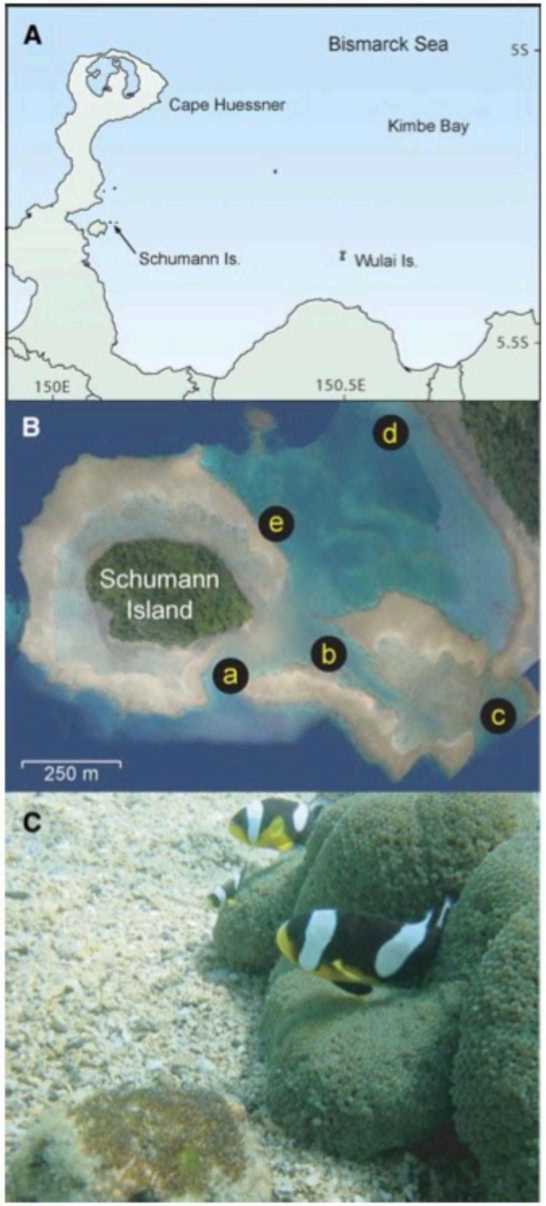
Coral Reef Fish Larvae Settle Close to Home

Geoffrey P. Jones,[1,*] Serge Planes,[2] and Simon R. Thorrold[3]

Table 1. Estimates of Self-Recruitment from Tetracycline Marking and Paternity Analysis

	2002	2003	
Total number of pairs marked	22	33	
Total area marking (km^2)	0.2	0.5	
Number of embryos marked	69,250	125,900	
Total number of recruits collected	63	73	
Number of recruits marked	10 tet	23 tet	23 pat
% Self recruitment	15.9%	31.5%	31.5%

Shown are the summary statistics for tetracycline marking of *Amphiprion polymnus* embryos at Schumann island in 2002 and 2003, and paternity analysis in 2003, including the number of pairs for which embryos were marked, the area over which marking took place, the total number of embryos marked, the total number of recruits collected, and the total number of marked recruits collected. tet denotes the number of tetracycline-marked juveniles collected, and pat denotes the number of juveniles collected that were classified to resident parents by paternity analysis.



Connectivity: mark and recapture + DNA parentage analysis

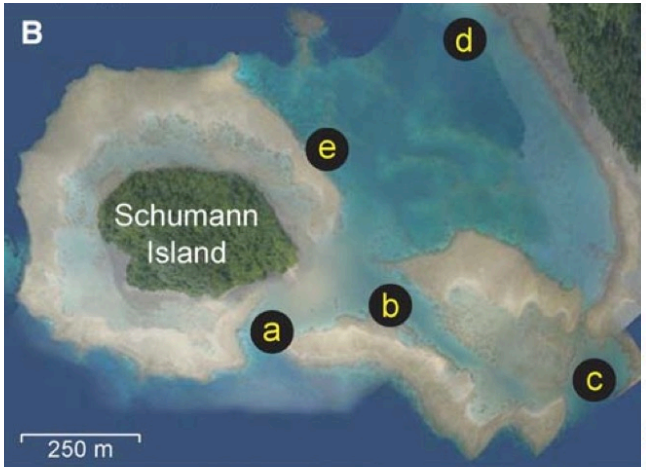


Table 2. Spatial Distribution of Self-Recruitment

Subarea	2002 Total Recruits	2002 Marked Recruits (tet)	2003 Total Recruits	2003 Marked Recruits (tet)	2003 Marked Recruits (pat)
a	28	4	15	4	5
b	17	3	13	4	5
c	18	3	34	12	11
d	X	X	8	3	2
e	X	X	3	0	0

Recruitment and self-recruitment estimates to subareas a–e in 2002 and 2003.

(Jones *et al.* 2005)

Connectivity: mark and recapture + DNA parentage analysis

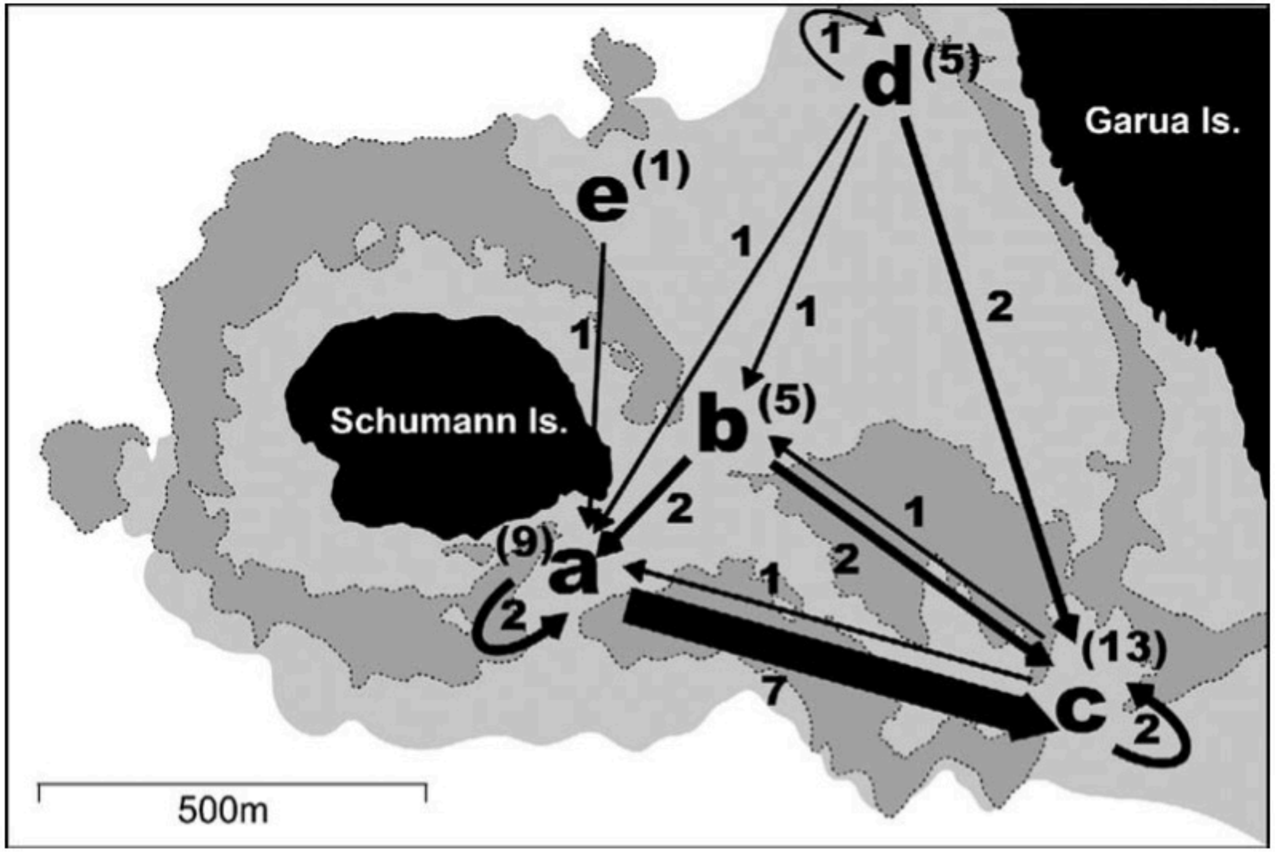
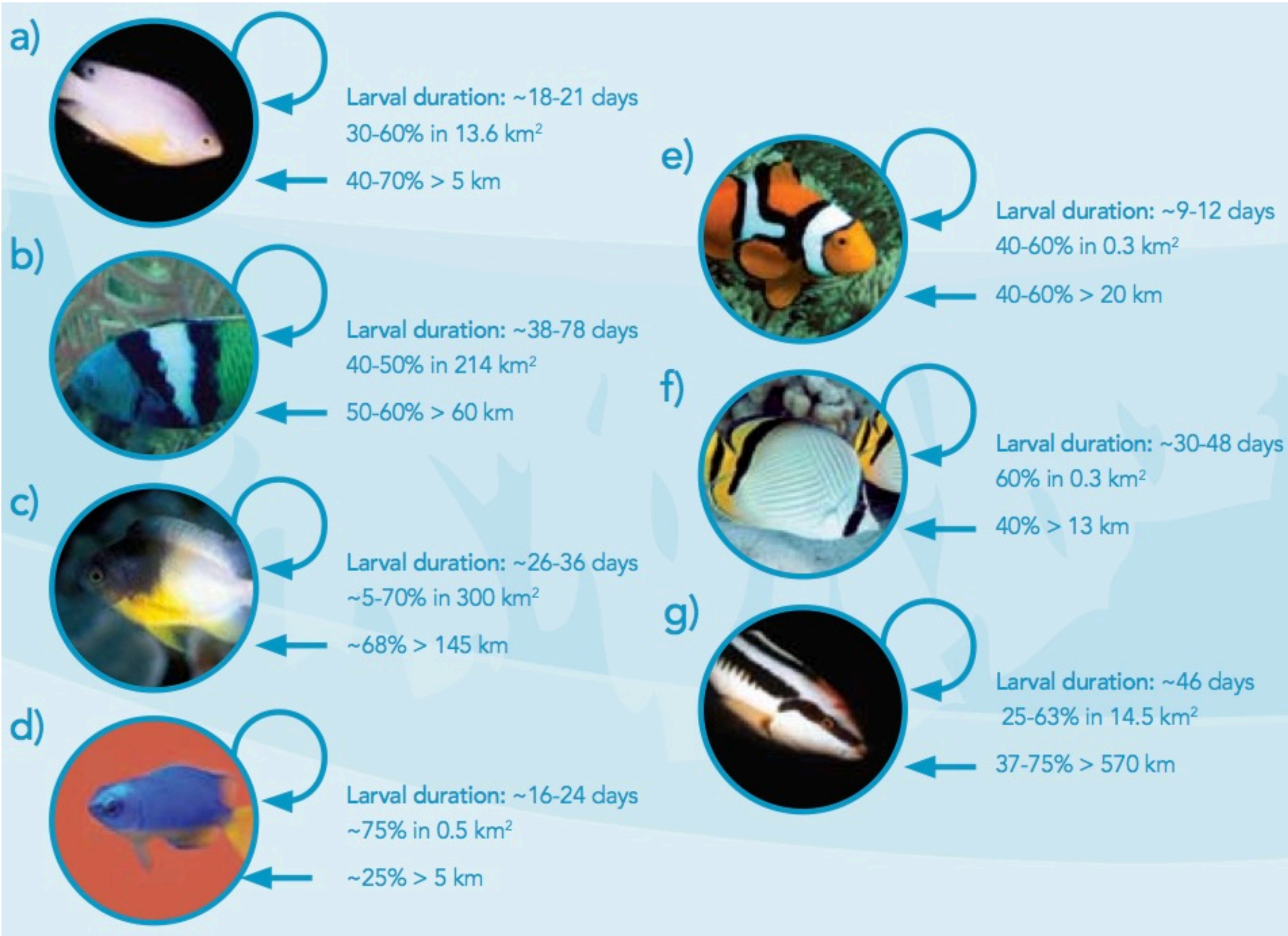


Figure 3. Local-Scale Connectivity Network

Map showing distance and direction of fine-scale dispersal of all juvenile panda clownfish settling within their natal population at Schumann Island, as determined from parentage analysis. The thickness of the arrows reflects numbers of juveniles either moving between subareas a–e or returning to the subarea of their birth. The number of adult pairs at each subarea is indicated in brackets. Total reproductive output in each subarea is proportional to the number of adult pairs.

(Jones *et al.* 2005)

Connectivity: Estimates of self-recruitment and connectivity



a) ***Pomacentrus amboinensis***, Lizard Island, Great Barrier Reef. Jones et al. (1999); James et al. (2002). Methods: Tetracycline tagging; Biophysical modelling. **b)** ***Thalassoma bifasciatum***, St. Croix, Caribbean. Swearer et al. (1999); Hamilton et al. (2008). Method: Otolith microchemistry. Photo: Istock **c)** ***Stegastes partitus***, Barbados, Caribbean. Paris et al. (2002); Paris & Cowen (2004). Method: Biophysical modelling. Photo: John E. Randall **d)** ***Pomacentrus coelestis***, Lizard Island, Great Barrier Reef. Patterson et al. (2005). Method: Otolith microchemistry. **e)** ***Amphiprion percula***, Kimbe Island, PNG. Almany et al. (2007); Planes et al. (2009). Methods: Barium tagging; Parentage analysis. Photo: Brian Donahue **f)** ***Chaetodon vagabundus***, Kimbe Island, PNG. Almany et al. (2007). Method: Barium tagging. Photo: Paul Asman **g)** ***Coris picta***, Lord Howe Island, Australia. Patterson & Swearer (2007). Method: Otolith microchemistry. Credit for figure: Geoffrey P. Jones

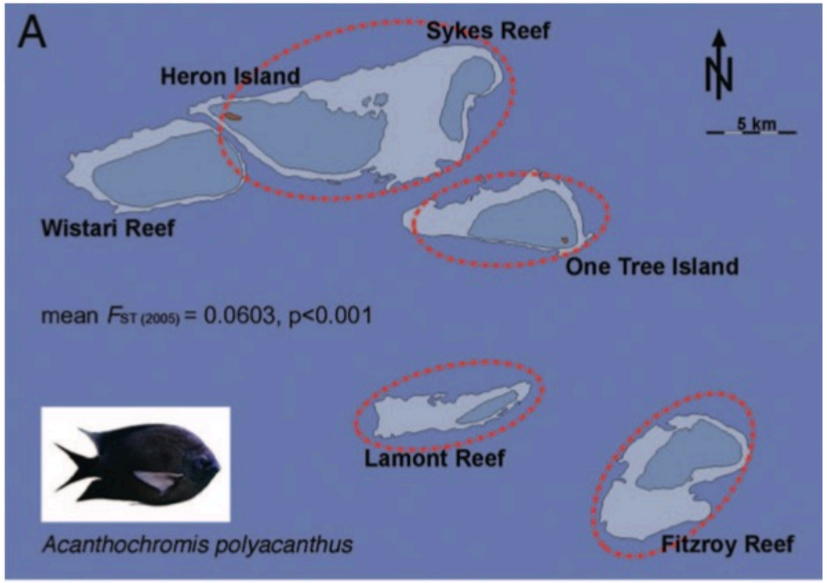
(Sale *et al.* 2010)

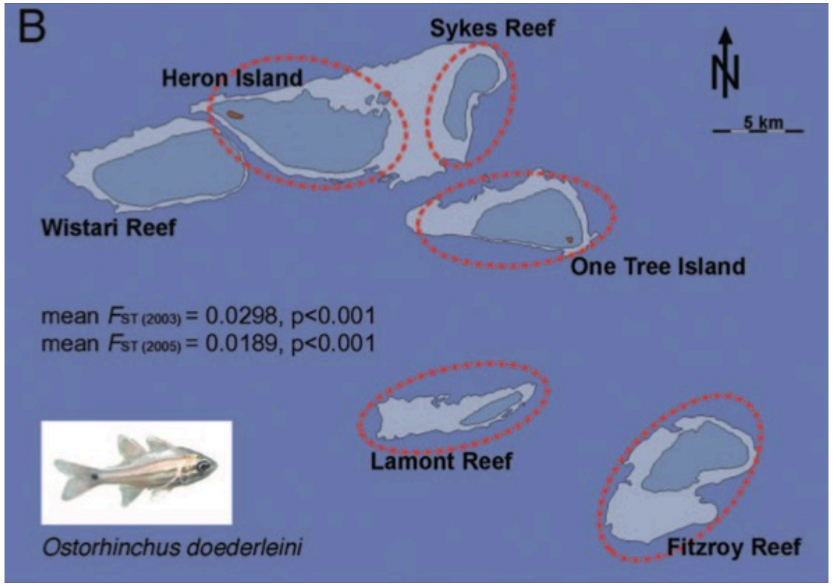
Connectivity: Olfactory sensing of coral reefs by fish larvae

858–863 | PNAS | January 16, 2007 | vol. 104 | no. 3

Smelling home can prevent dispersal of reef fish larvae

Gabriele Gerlach*†, Jelle Atema‡, Michael J. Kingsford§, Kerry P. Black¶, and Vanessa Miller-Sims‡





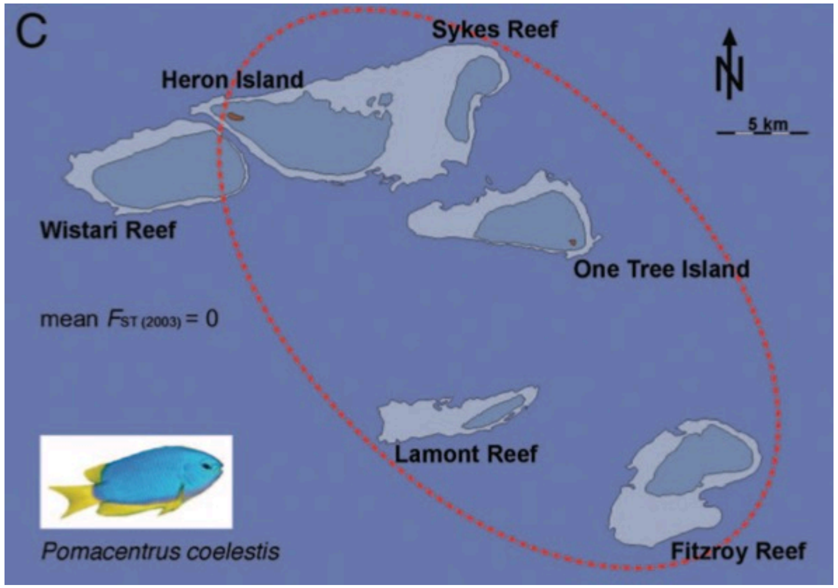


Fig. 2. Genetic substructure of three fish populations across five test reefs. (*A*) *A. polyacanthus* without pelagic larval dispersal stage. (*B*) *O. doederleini* with 3-week larval dispersal. (*C*) *P. coelestis* with 3-week larval dispersal. Red dotted circles enclose genetically different populations. Mean F_{ST} values among reefs are provided on the graph.

Connectivity: Olfactory sensing of coral reefs by fish larvae

Table 2. Olfactory preference of larval reef fish for water from home versus foreign reefs

Species	Home reef preference ± SE, %	*n*	*P*
O. doederleini	7.0 ± 2.3	66	0.023
O. doederleini OTI	12.4 ± 5.7	22	0.05
Apogon sp. 1	17.1 ± 3.7	55	0.000
Apogonid sp. 2–9	9.0 ± 2.6	114	0.000
P. coelestis	8.5 ± 3.3	66	0.002
Pomacentrus sp. 1–4	15.3 ± 6.2	21	0.016
A. polyacanthus	−16.7 ± 7.3	6	0.094

Preference is expressed as mean difference in time spent in home versus foreign water during odor-choice test in a two-channel flume. Positive values indicate preference for home reef odor, and negative values indicate preference for foreign reef odor. Animals were caught at two different home reefs (OTI and F) and tested against water from four other reefs. *O. doederleini* OTI refers to the larvae that were later genetically assigned to the OTI adult population. Unidentified *Apogon* sp. 1 was common in our catches and could be analyzed separately.

(Gerlach *et al.* 2007)

Connectivity: Acoustic sensing of coral reefs by fish larvae

Homeward Sound

Stephen D. Simpson,[1*] Mark Meekan,[2] John Montgomery,[3]
Rob McCauley,[4] Andrew Jeffs[5]

SCIENCE VOL 308 8 APRIL 2005

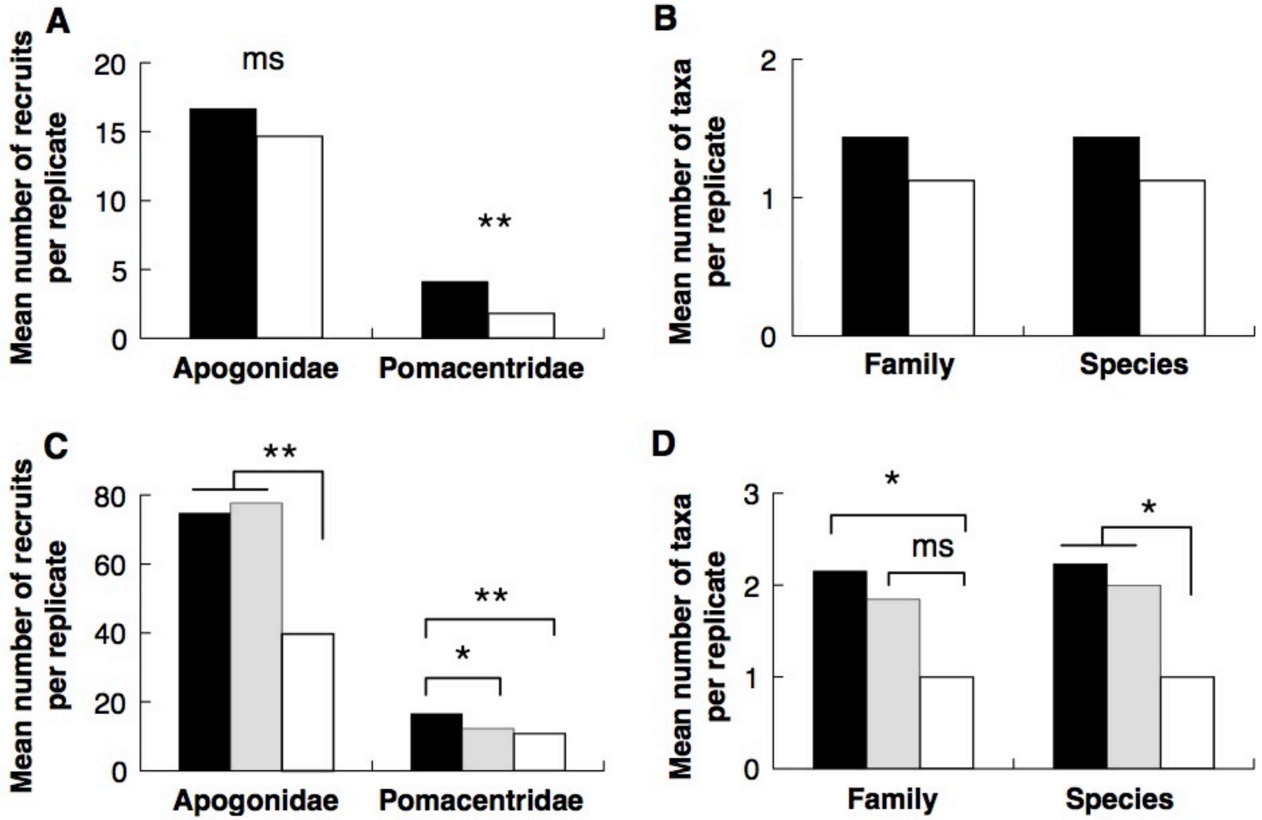
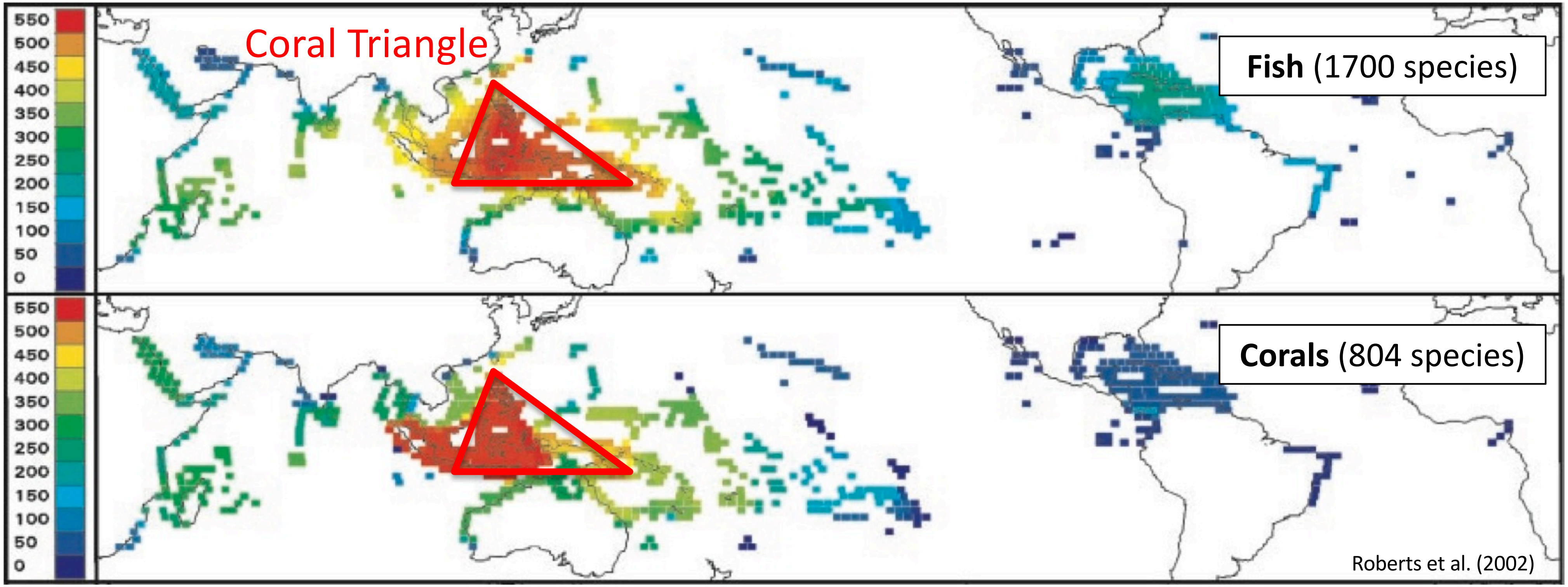
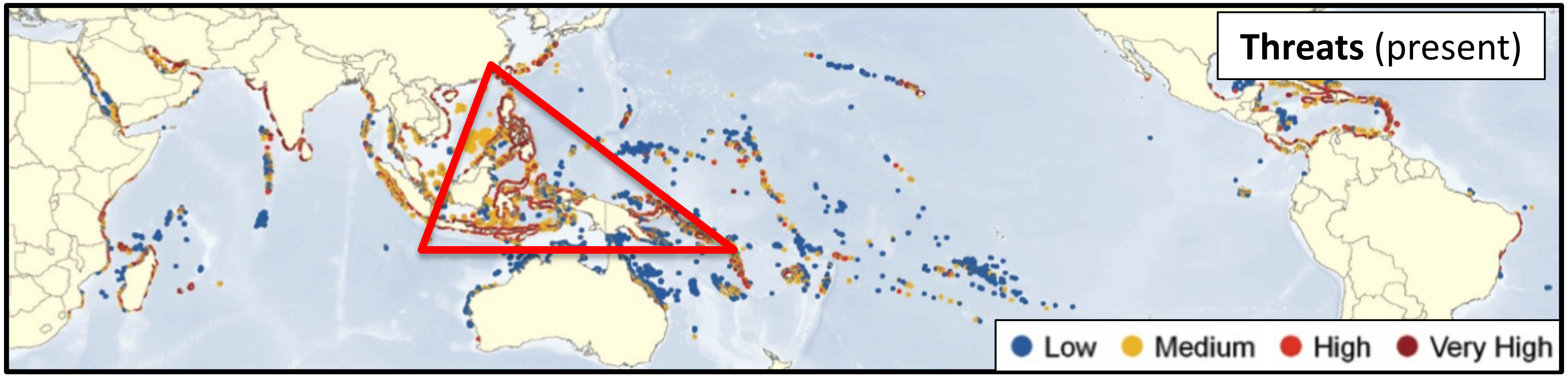


Fig. 1. Comparison of catches from patch reefs with different sound treatments (tables S1 to S3). (**A** and **B**) Reefs broadcasting reef noise (black) or silent reefs (white). (**C** and **D**) Reefs with high-frequency (black) or low-frequency (gray) reef noise or silent reefs (white). Statistical results are for (A) Chi-squared analyses, (B) Wilcoxon's matched pairs test, (C) pairwise Chi-squared analyses with Bonferroni corrections, and (D) pairwise Wilcoxon's matched pairs test with Bonferroni corrections (ms, $P < 0.1$; *, $P < 0.05$; **, $P < 0.01$). All apogonids and pomacentrids were excluded from the analyses in (B) and (D).

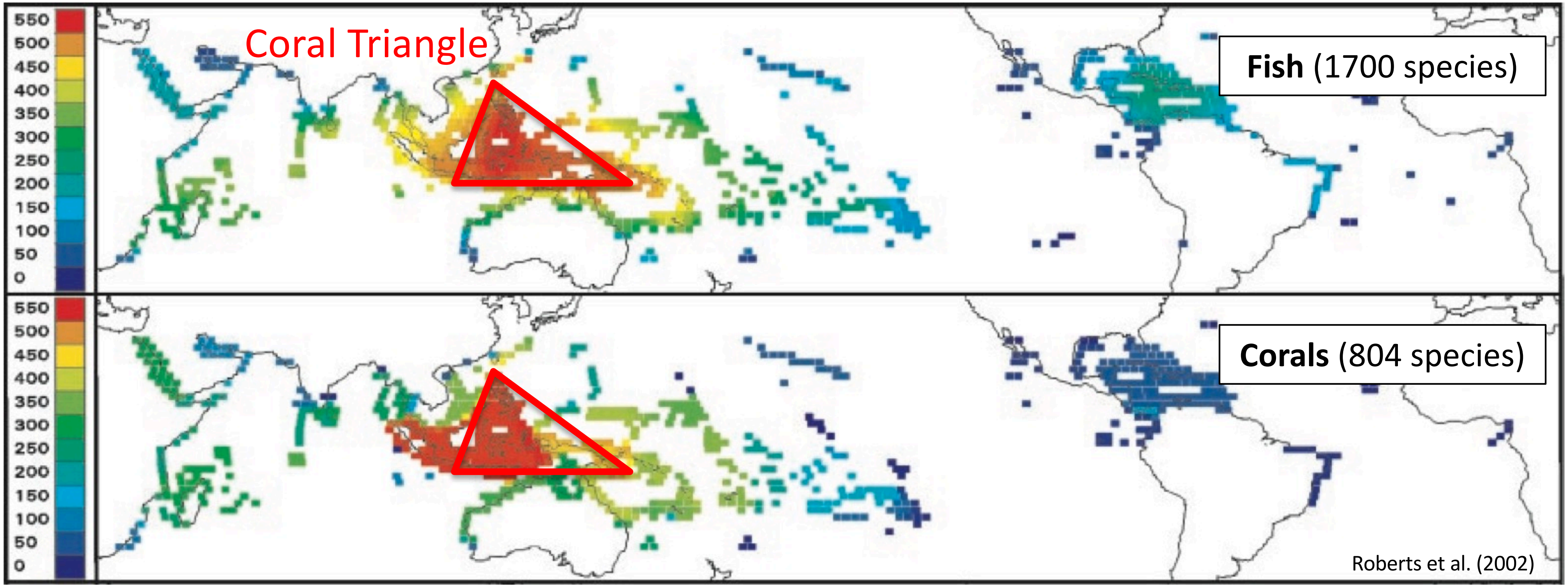
Tropical marine biodiversity in the Indo-Pacific

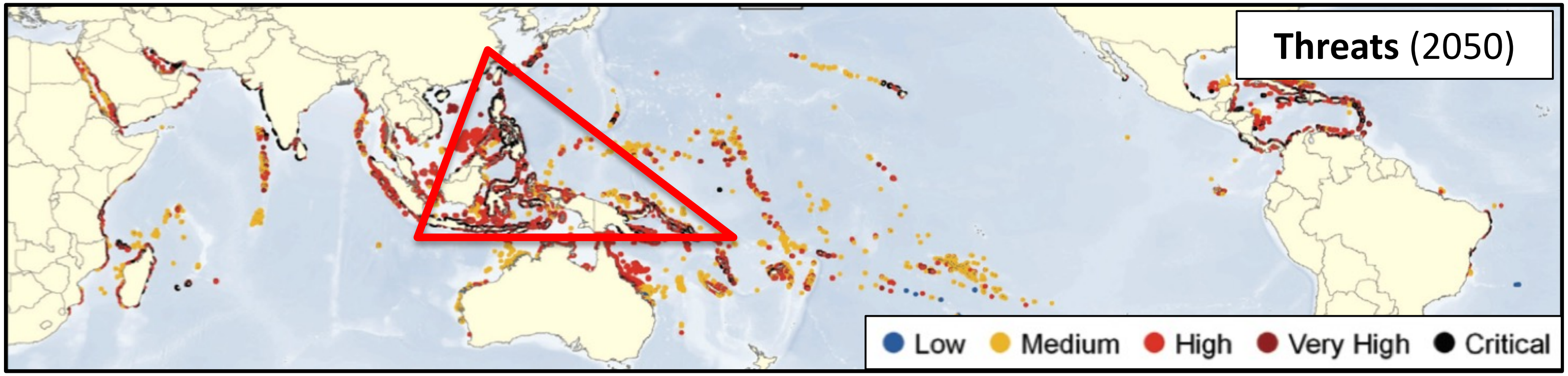




Burke et al. (2011)

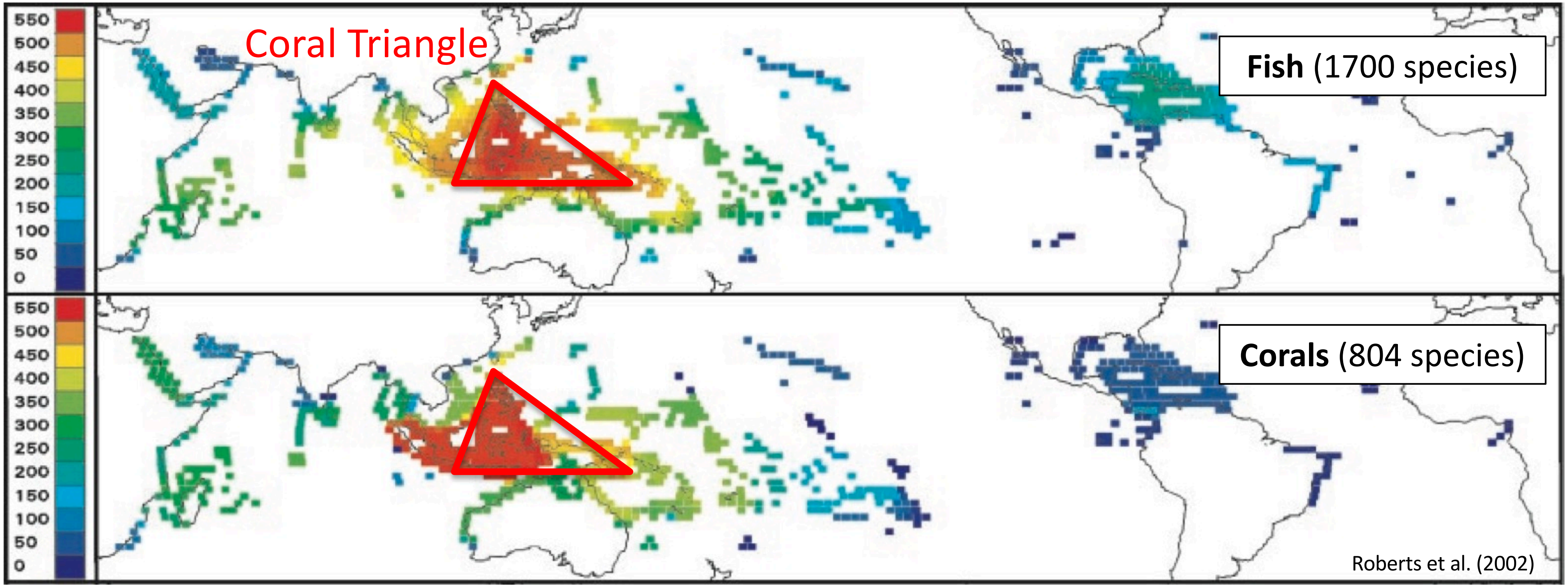
Tropical marine biodiversity in the Indo-Pacific





Burke et al. (2011)

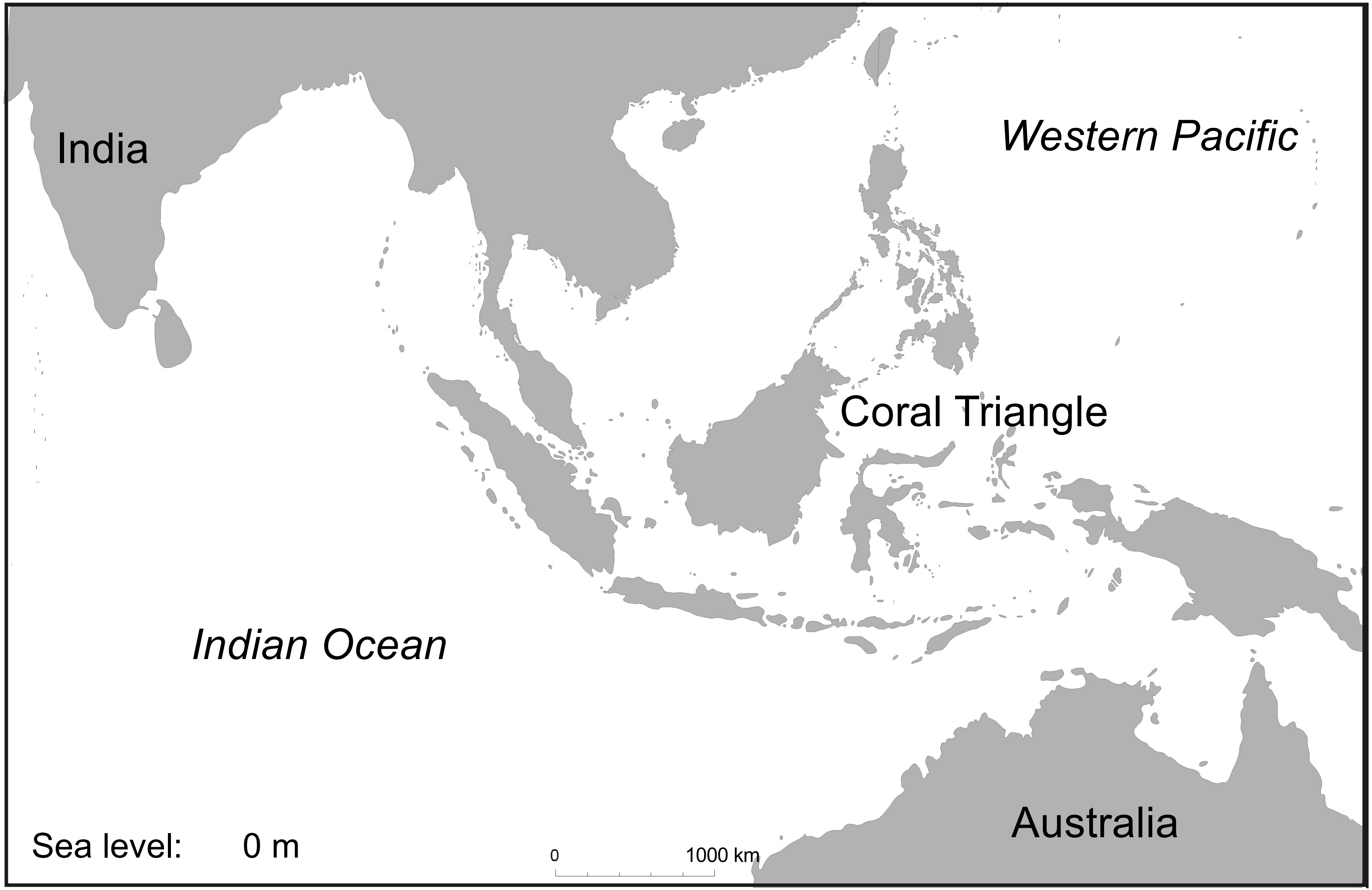
Tropical marine biodiversity in the Indo-Pacific



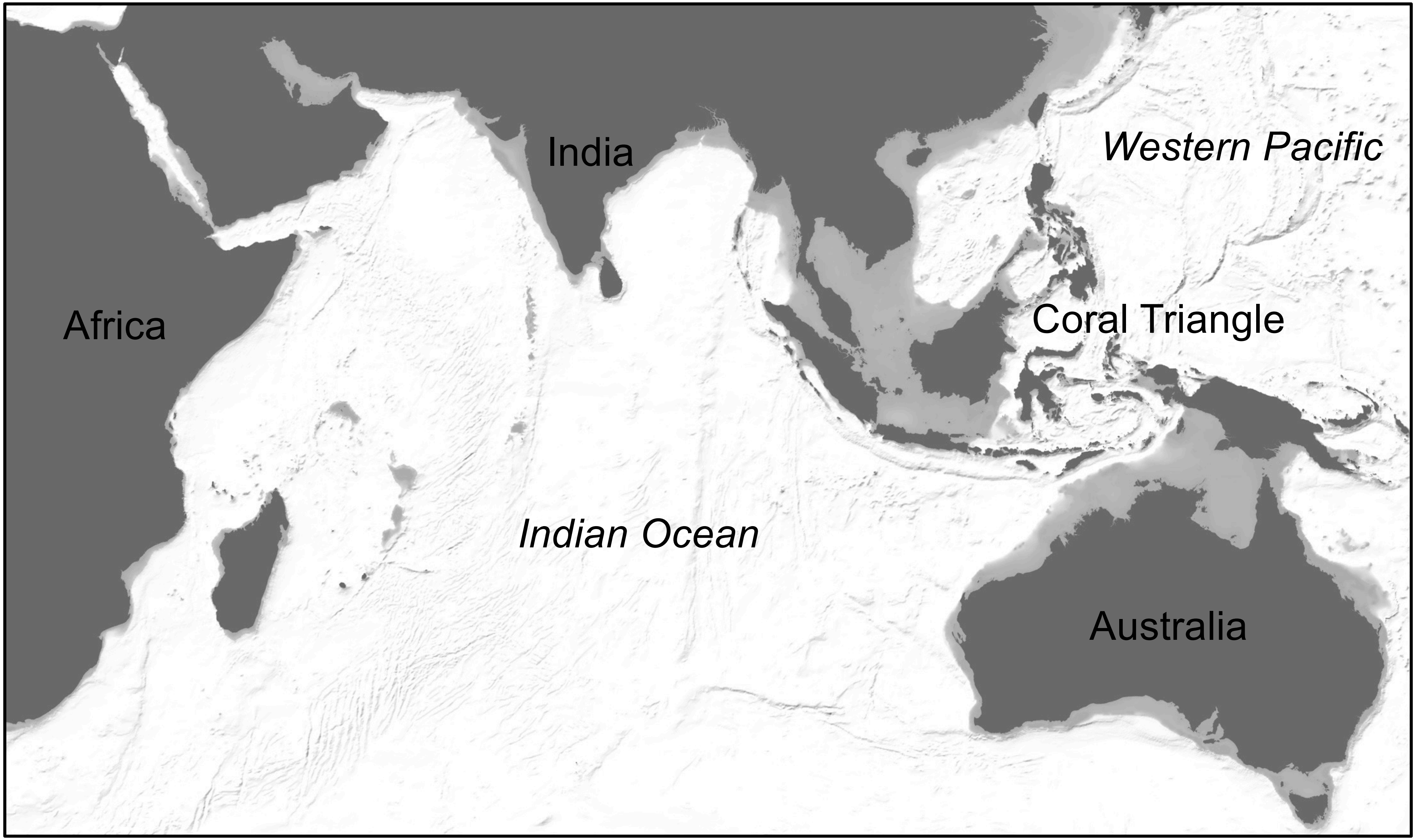
Hypothesis that try to explain the high diversity in the Coral Triangle:

- **Centre of evolutionary radiation** from where new species disperse (Briggs 1999)
- **Centre of overlap** of the Indian and Pacific Ocean biota (Woodland 1983)
- **Centre of accumulation** of species that originated in peripheral areas (Jokiel & Martinelli 1992)
- **Centre of survival** due to maintained habitat heterogeneity (Paulay 1990, Barber & Bellwood 2005)

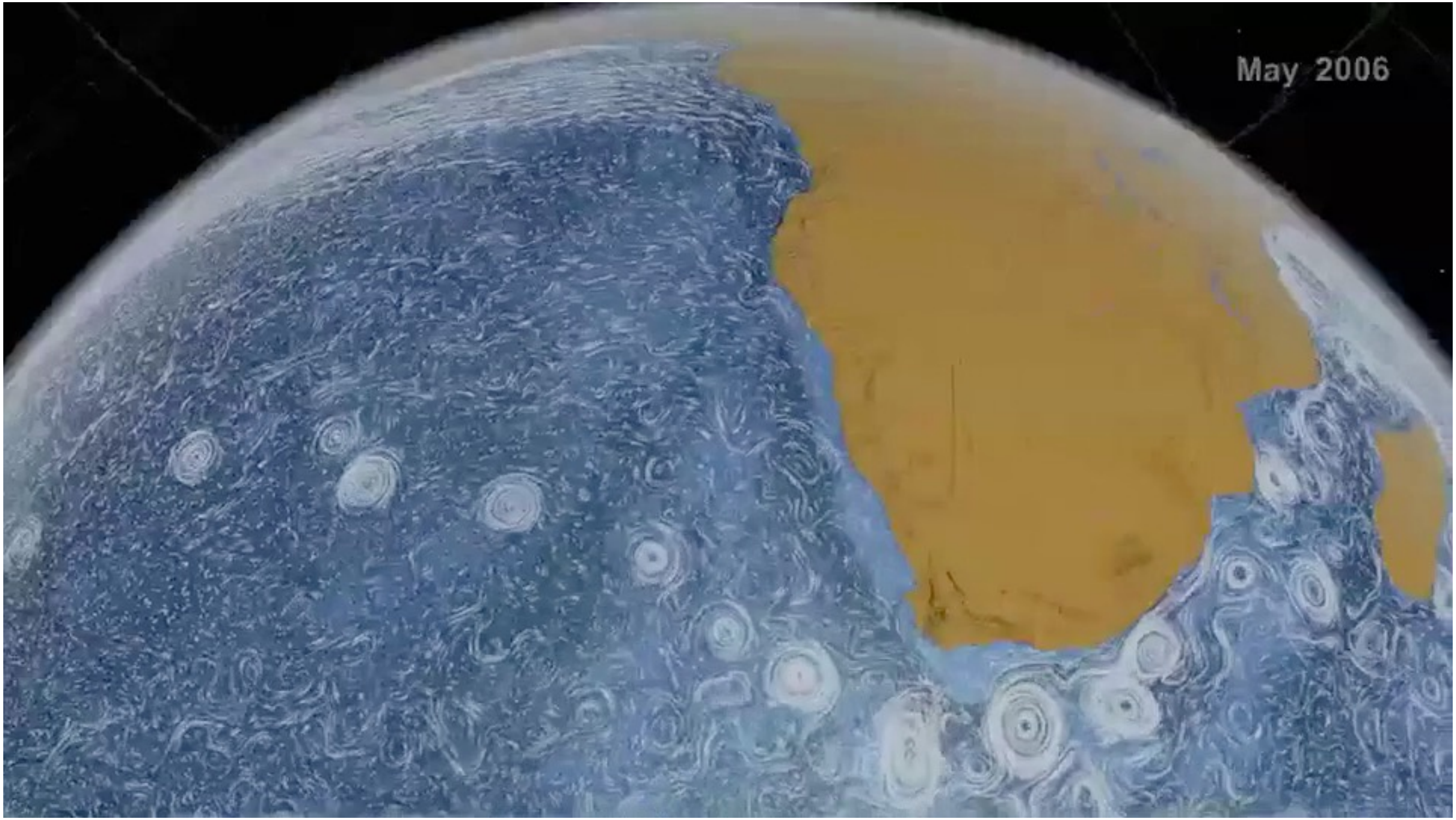
Impact of Pleistocene glaciations on the Coral Triangle



Impact of Pleistocene glaciations on the Western Indian Ocean

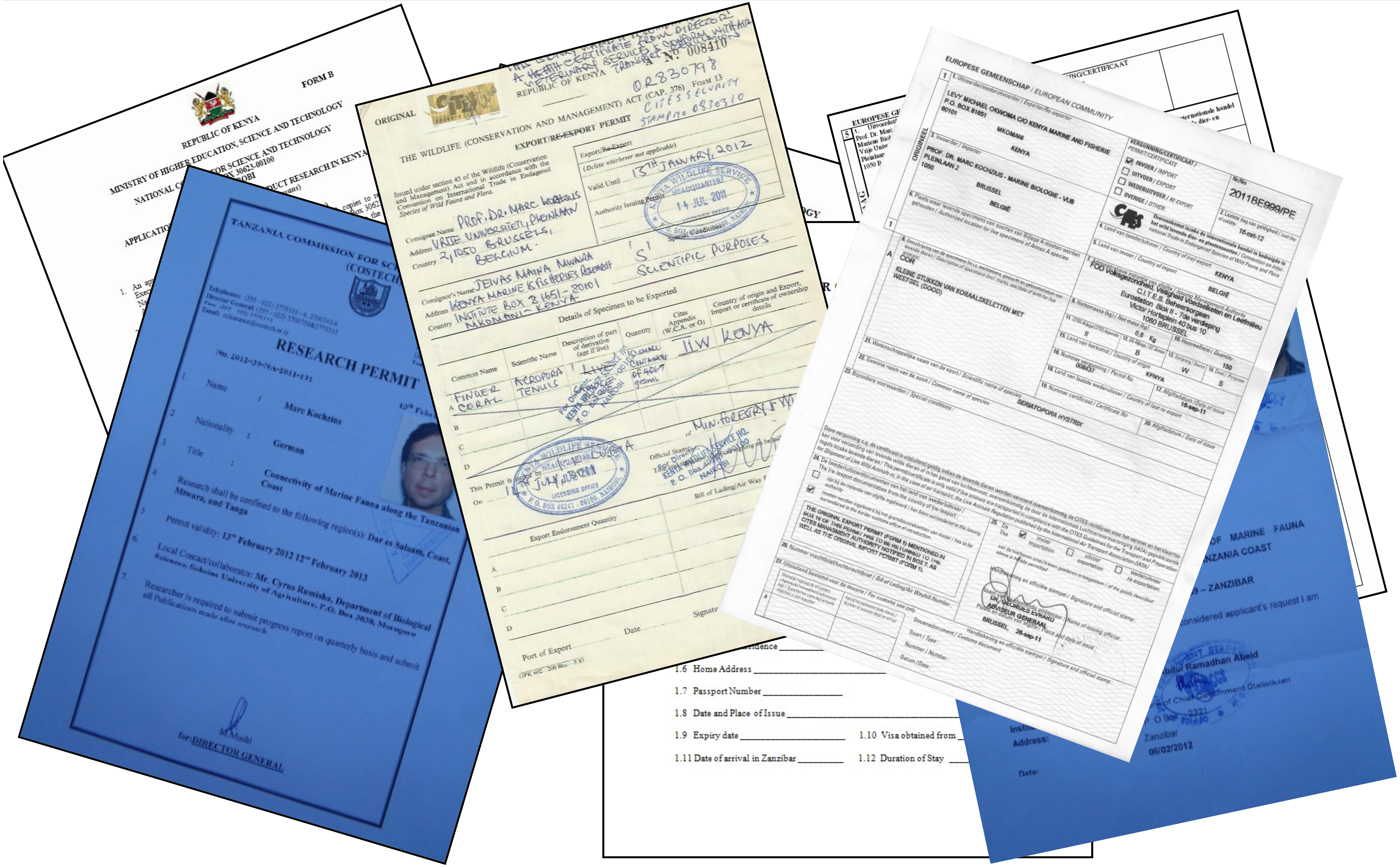


Oceanography of the Indo-West Pacific



NASA (2012)

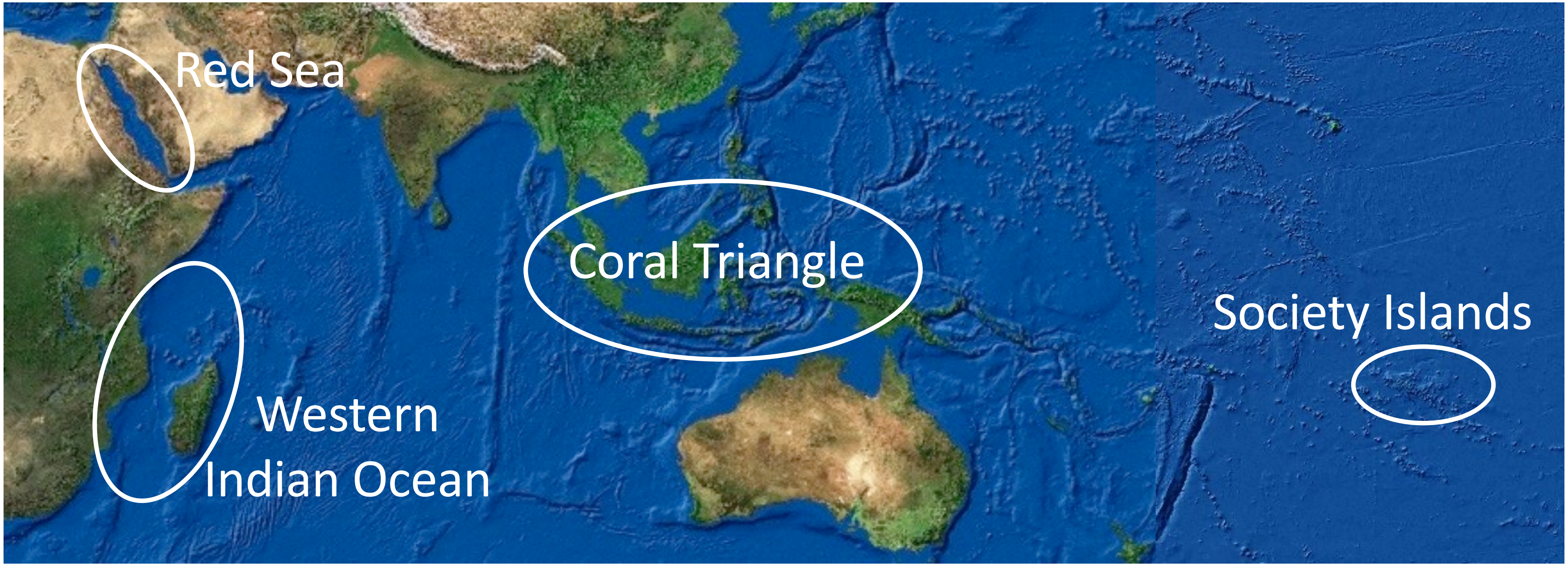
Administration: research permits, sample export permits, CITES permits…



Sampling of Indo-West Pacific marine fauna

© Lars Abromeit, GEO

Sampling of Indo-West Pacific marine fauna



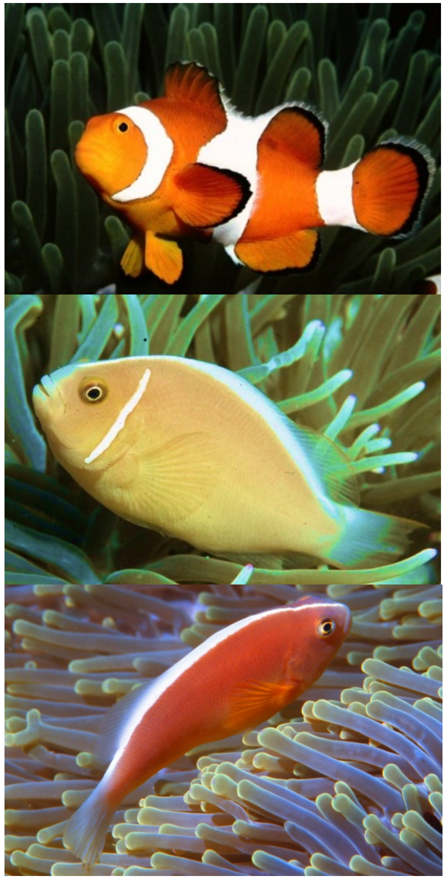
DNA extraction → PCR amplification

DNA sequencing ← | → Microsatellites

↓ Population genetic and phylogeographic data analysis

Studied coral reef taxa

Anemonefish

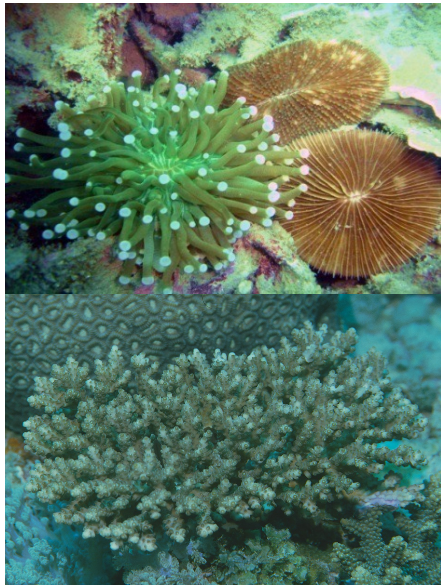


Amphiprion ocellaris: A. perideraion; A. akallopisos
- demersal eggs
- pelagic larval duration (PLD): 8-18 days

Giant clams

Tridacna crocea; T. maxima; T. squamosa
- pelagic eggs
- PLD: 9 days

Corals



Heliofungia actiniformis
- brooder, 3 days PLD

Acropora tenuis
- spawner, 69 days PLD

Invertebrates

Linckia laevigata
- pelagic eggs; PLD: 28 days

Thyca crystallina

Studied mangrove taxa

Mud whelk

Terebralia palustris

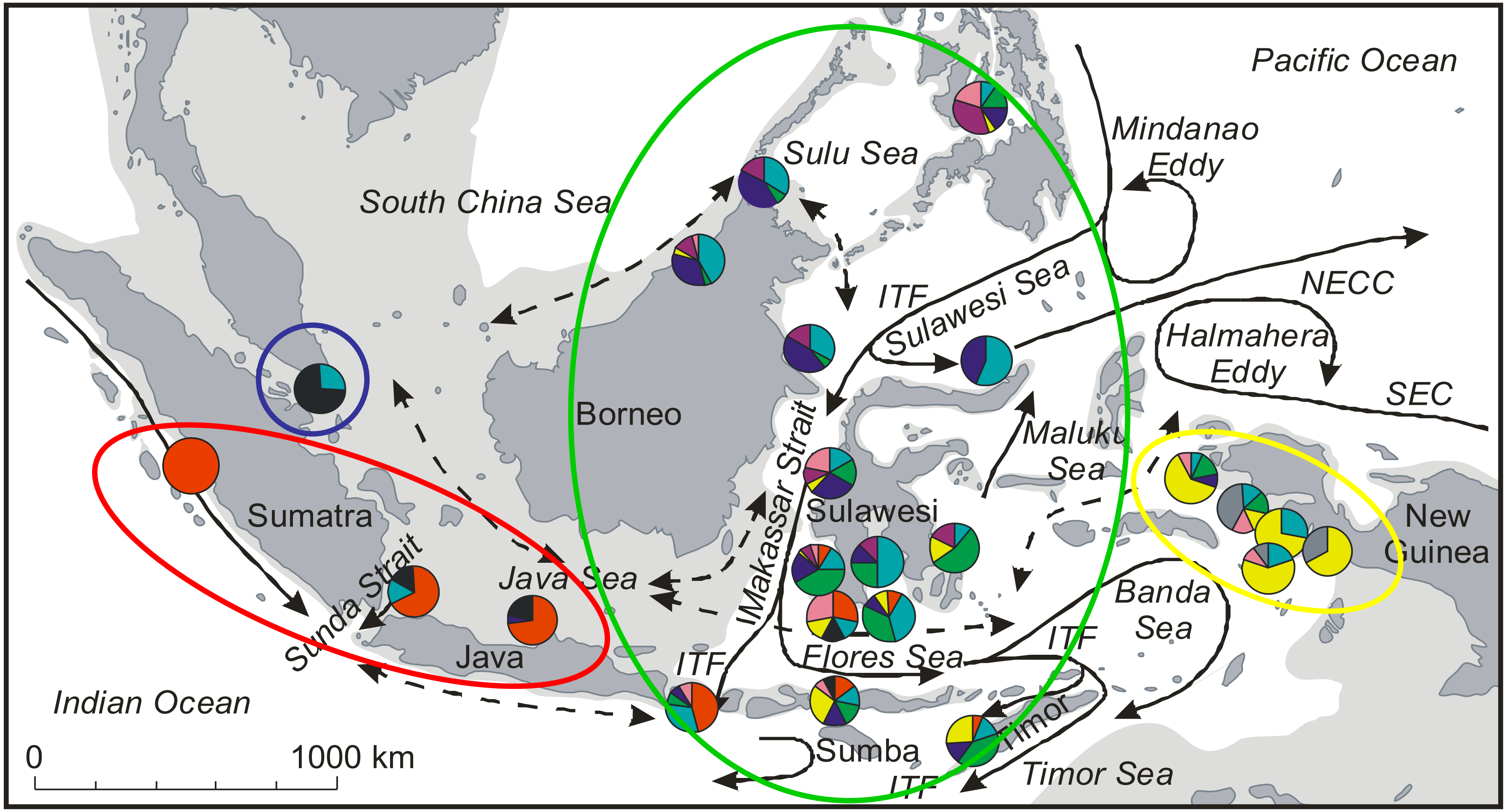
- pelagic larvae

Giant mud crab

Scylla serrata

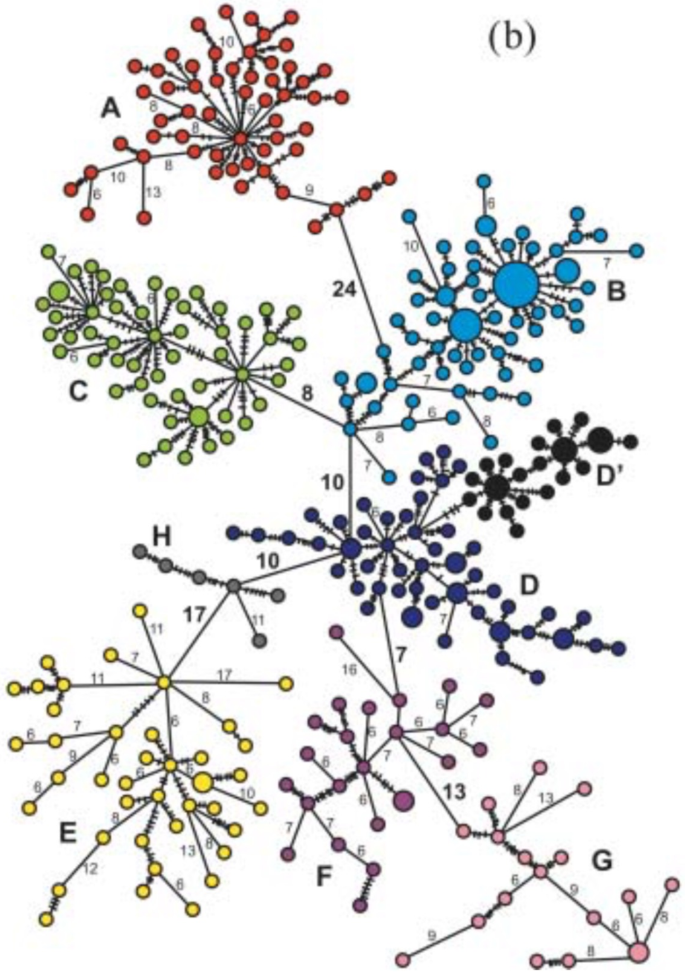
- pelagic eggs
- PLD: 21-28 days

False clownfish (*Amphiprion ocellaris*) Timm & Kochzius (2008)



- 371 control region sequences (mtDNA); 360 bp
- Hierarchical AMOVA: $\Phi_{ct} = 0.25$; $p < 0.001$

False clownfish (*Amphiprion ocellaris*) Timm & Kochzius (2008)



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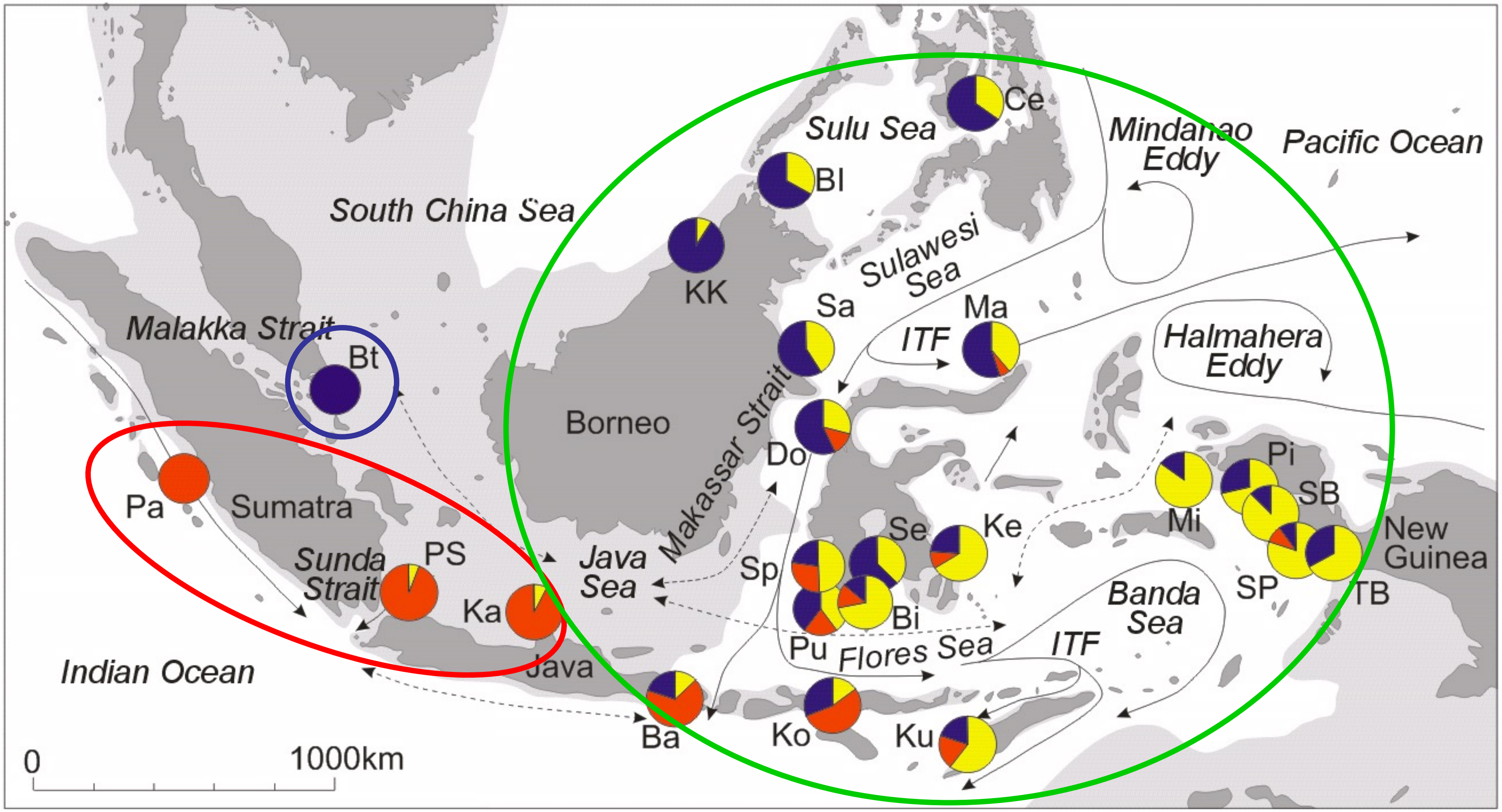
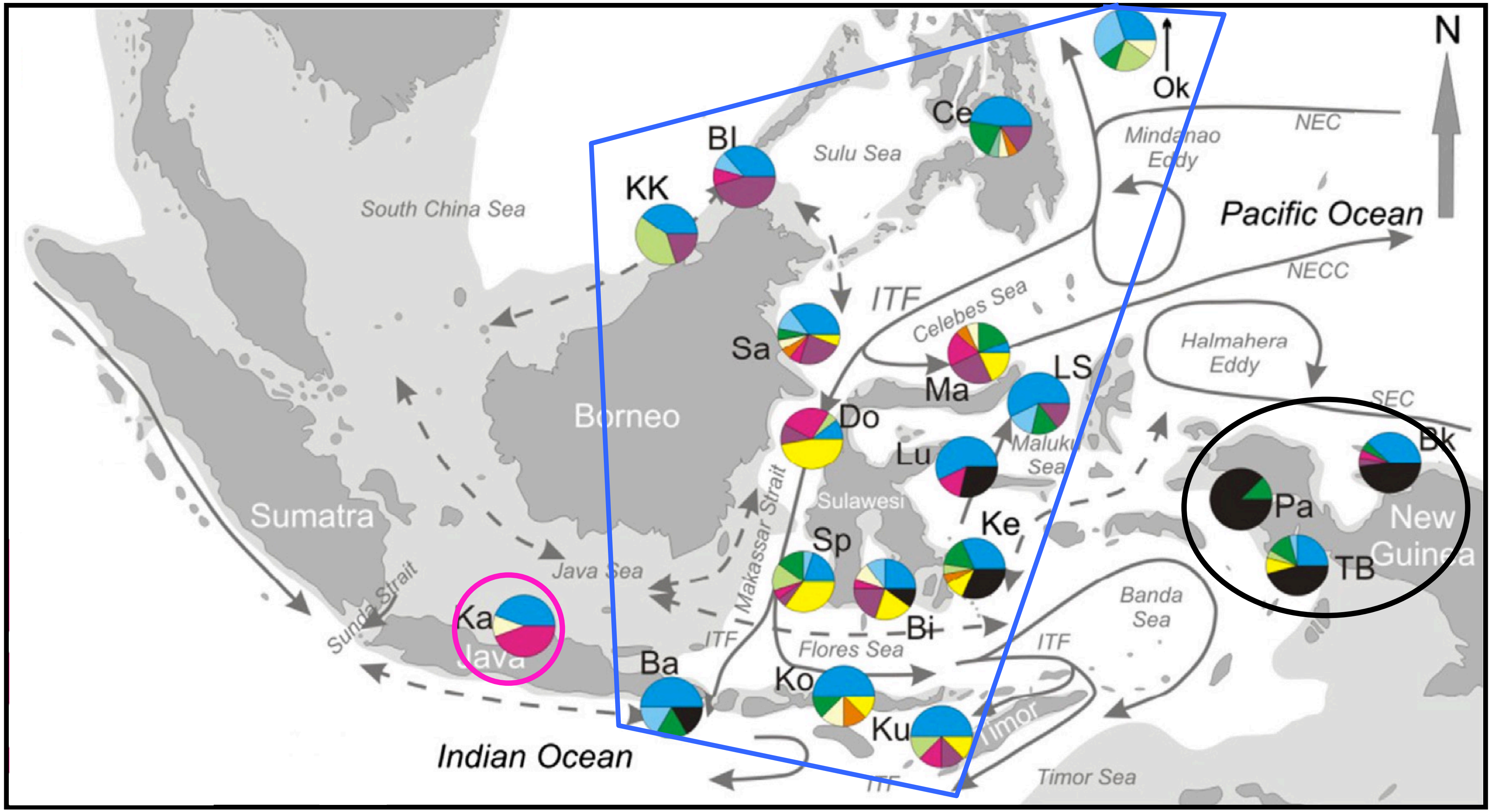
False clownfish (*Amphiprion ocellaris*) Timm, Planes & Kochzius (2012)



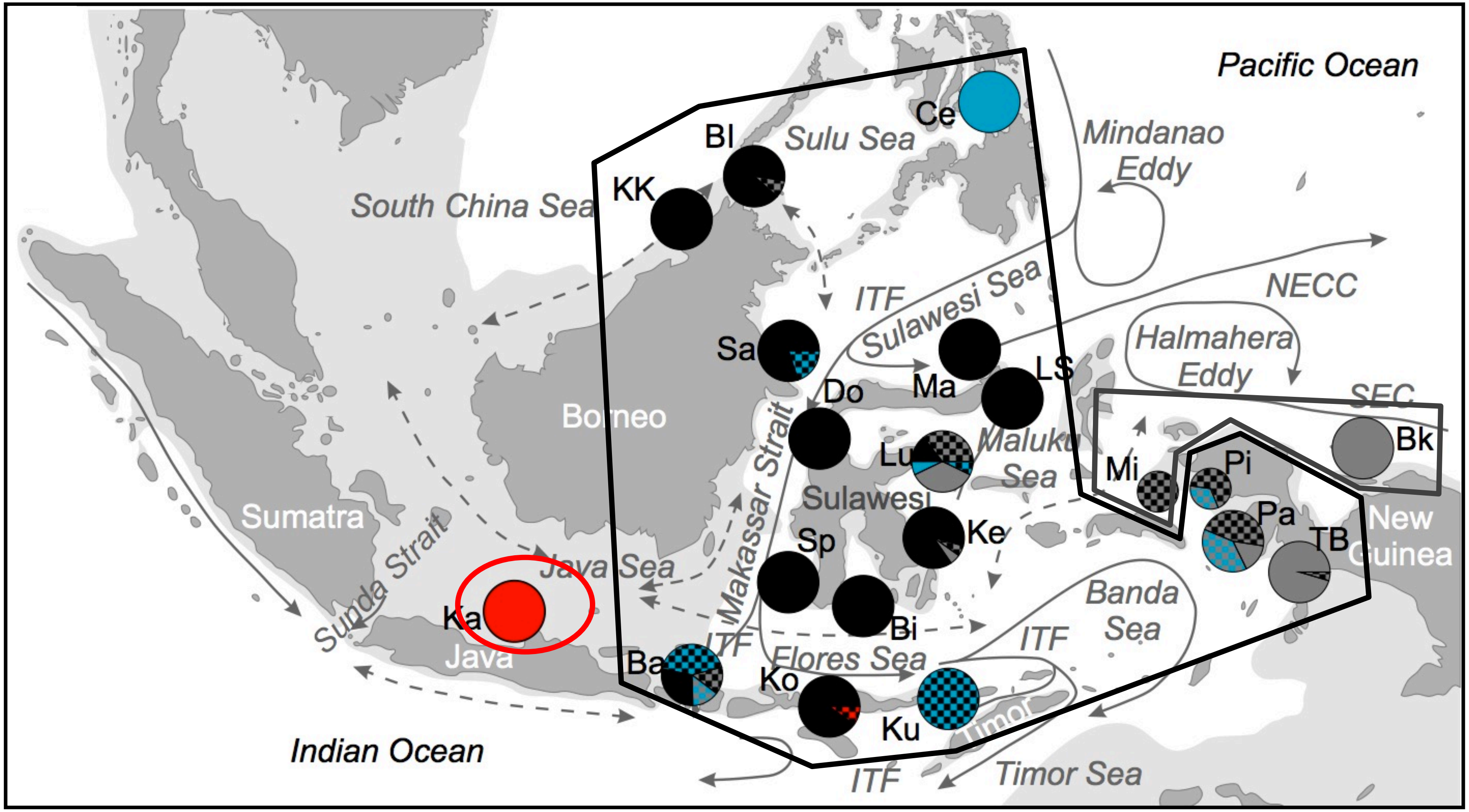
- 6 microsatellite loci (nDNA); 432 samples
- Hierarchical AMOVA: $F_{ct} = 0.24$; $p < 0.001$

Anemonefish (*Amphiprion perideraion*) Dohna, Timm, Hamid & Kochzius (2015)



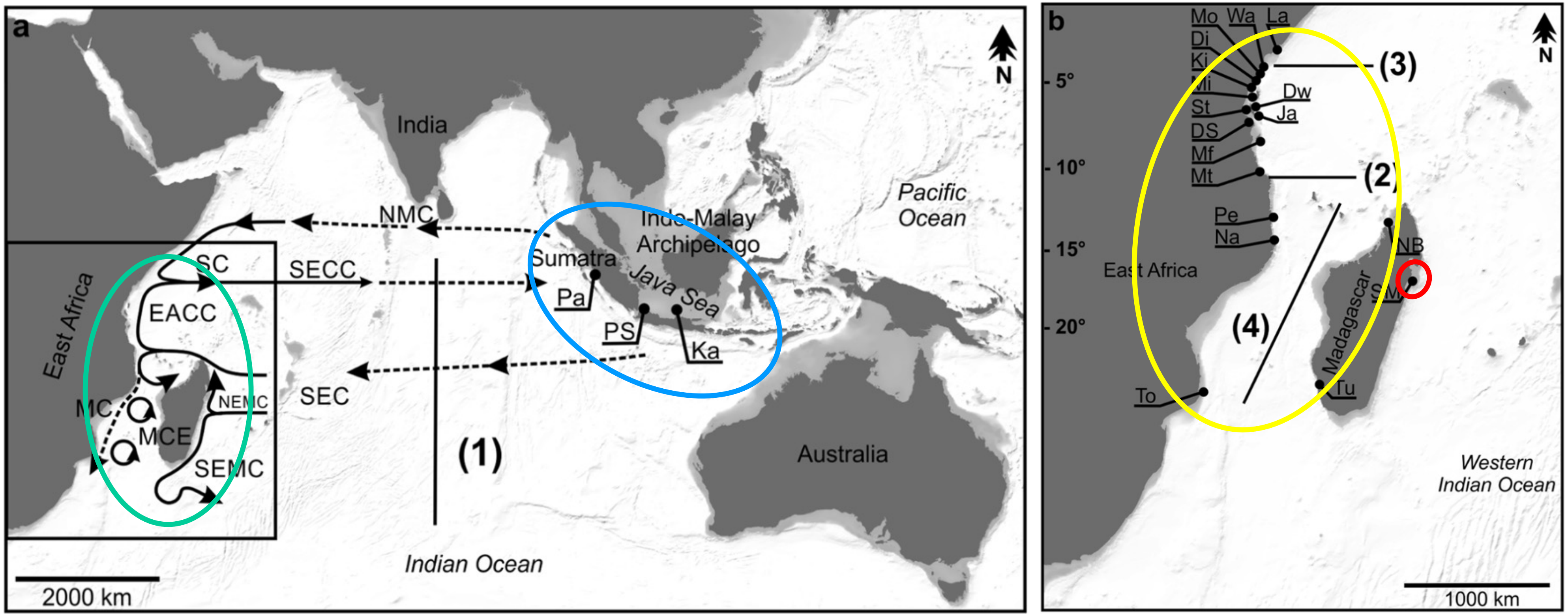
- 247 CR sequences (mtDNA); 400 bp
- Hierarchical AMOVA: $\Phi_{ct} = 0.1985$; $p < 0.001$

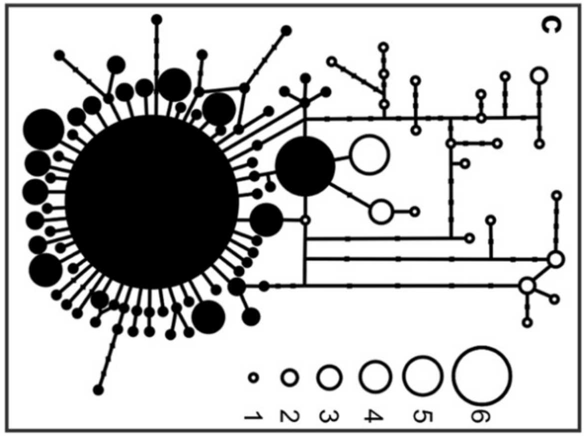
Anemonefish (*Amphiprion perideraion*) Dohna, Timm, Hamid & Kochzius (2015)



- 10 microsatellite loci (nDNA); 289 samples
- Hierarchical AMOVA: $F_{ct} = 0.0181$; $p = 0.003$

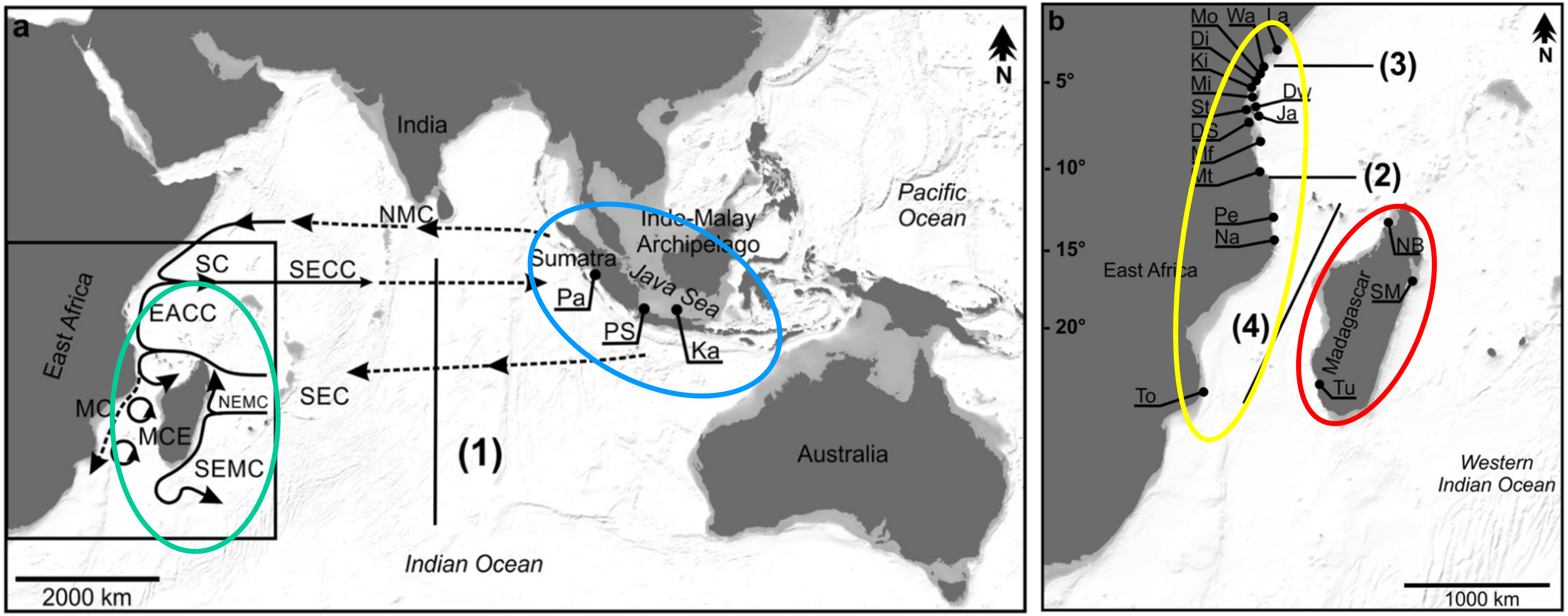
Anemonefish (*Amphiprion akallopisos*) Huyghe & Kochzius (2017, 2018)

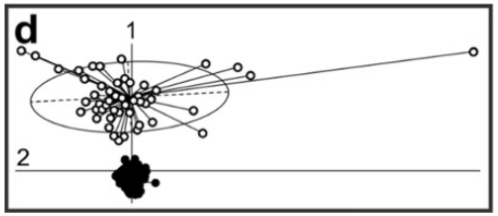




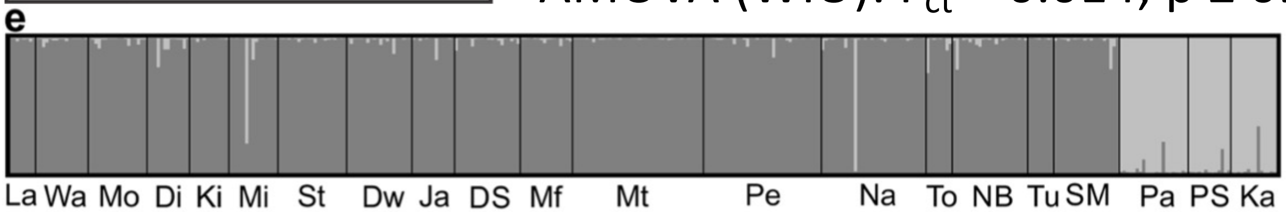
- 360 control region sequences (mtDNA); 337 bp
- Hierarchical AMOVA: $\Phi_{ct} = 0.62$; $p < 0.001$
- WIO: no hierarchical AMOVA significant, but Sainte Marie (SM)

Anemonefish (*Amphiprion akallopisos*) Huyghe & Kochzius (2017, 2018)

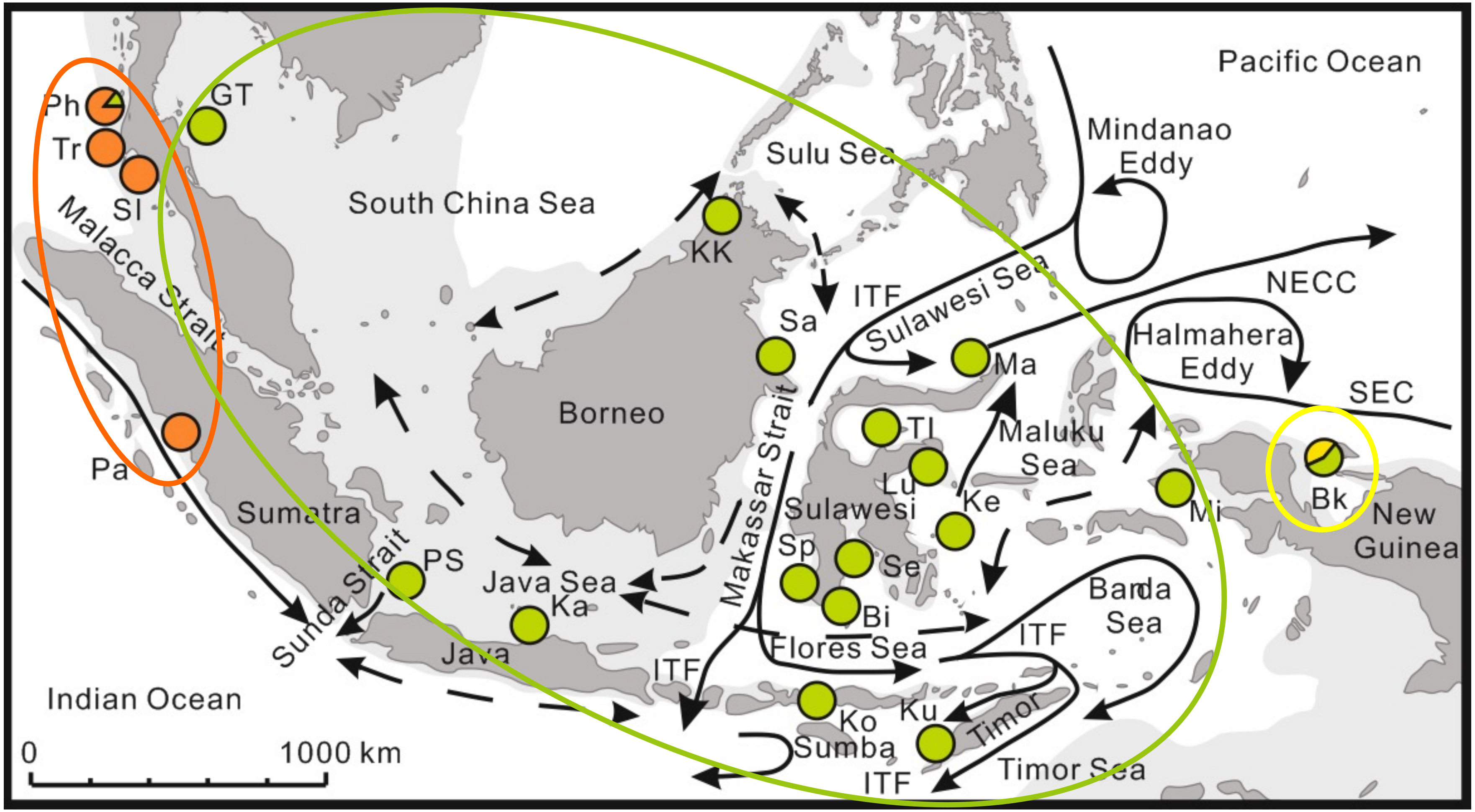




- 360 individuals genotyped with 13 microsatellite loci
- AMOVA: $F_{ct} = 0.114$; $p < 0.001$
- AMOVA (WIO): $F_{ct} = 0.014$; $p \leq 0.01$

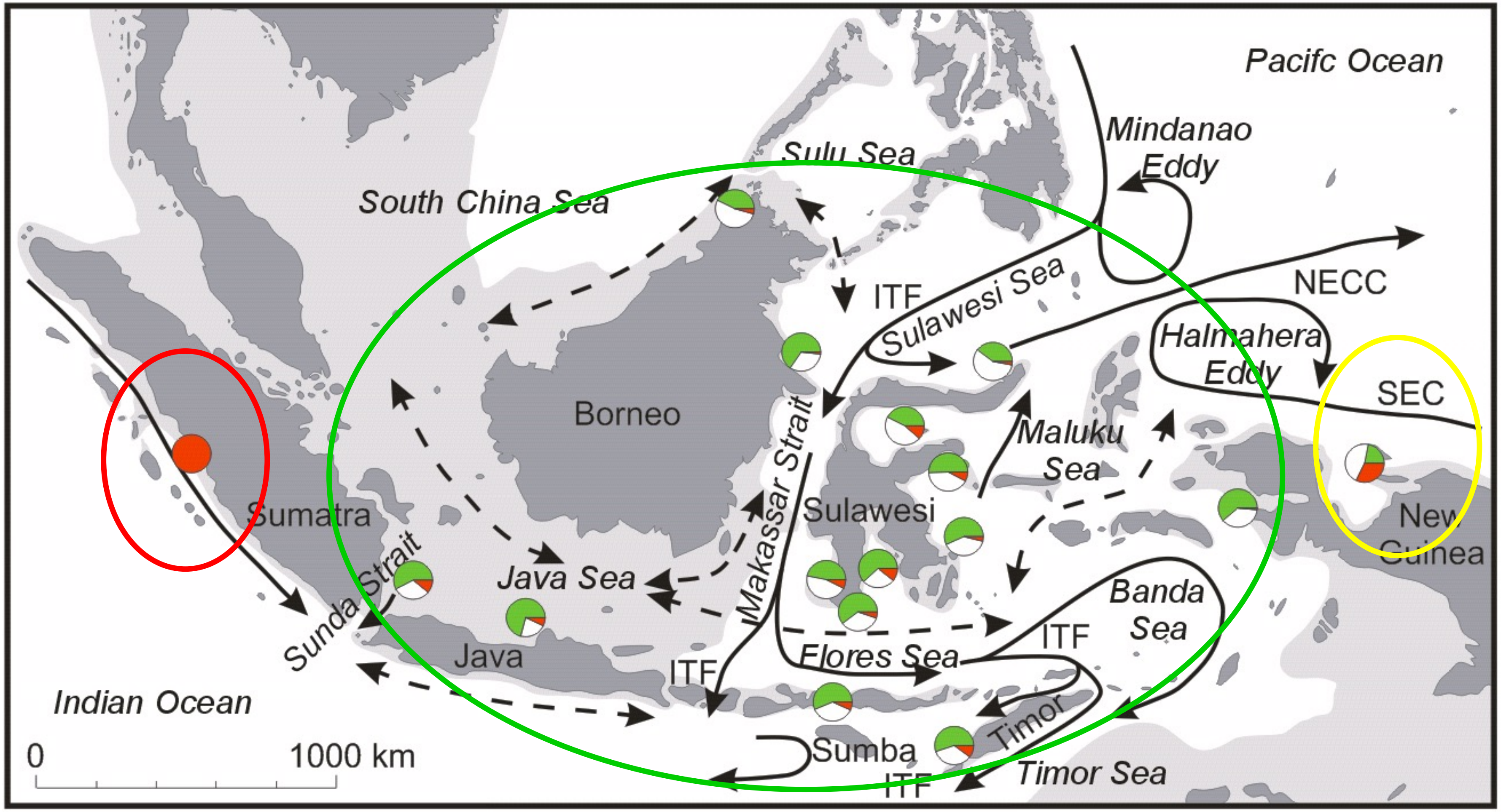


Boring giant clam (*Tridacna crocea*) Kochzius & Nuryanto (2008); Hui, Kraemer, Seidel, Joshi, Nuryanto, Kochzius (2016)



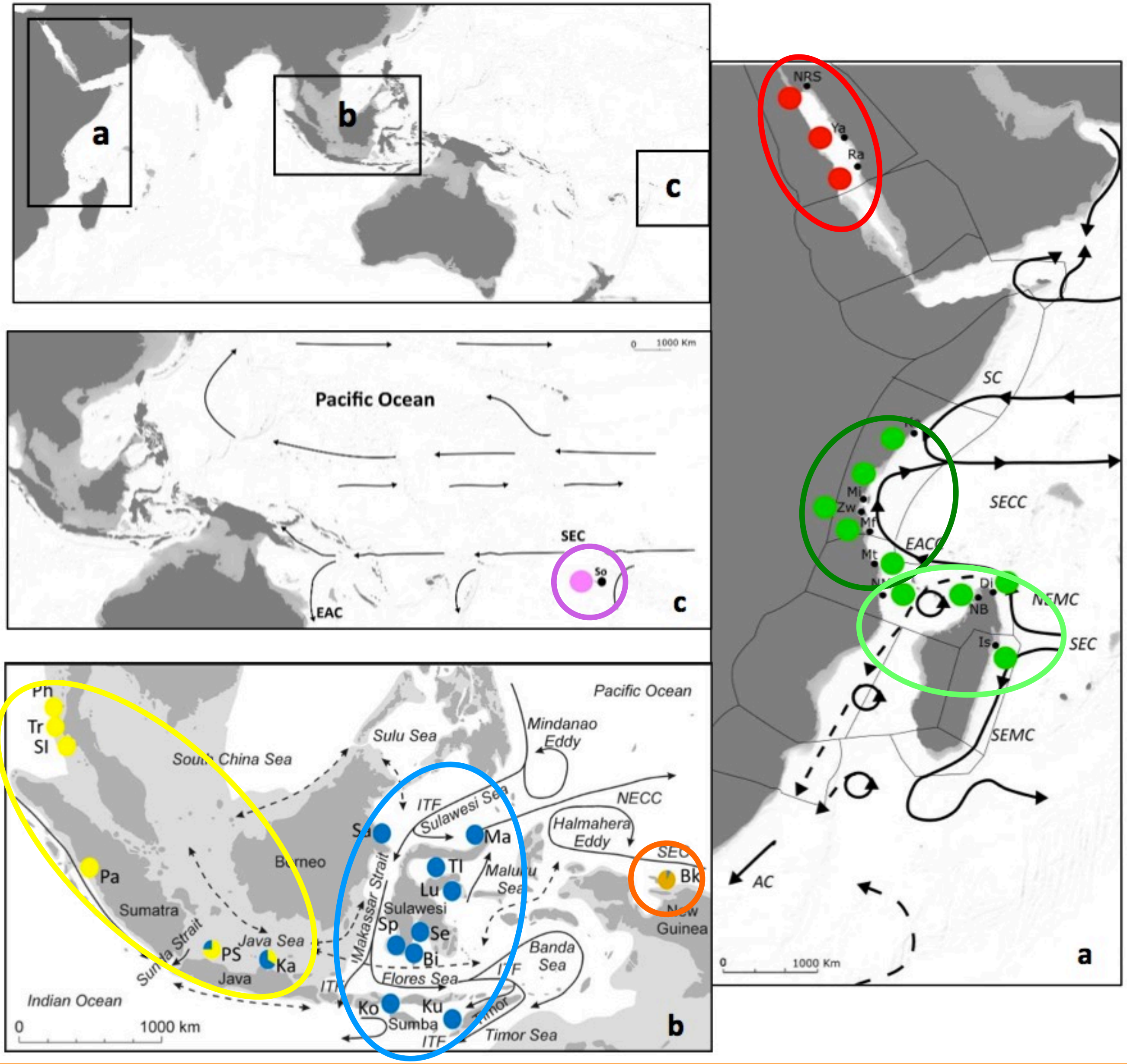
- 344 COI sequences (mtDNA); 417 bp
- Hierarchical AMOVA: $\Phi_{ct} = 0.728$; $p < 0.001$

Boring giant clam (*Tridacna crocea*) Hui, Nuryanto & Kochzius (2016)

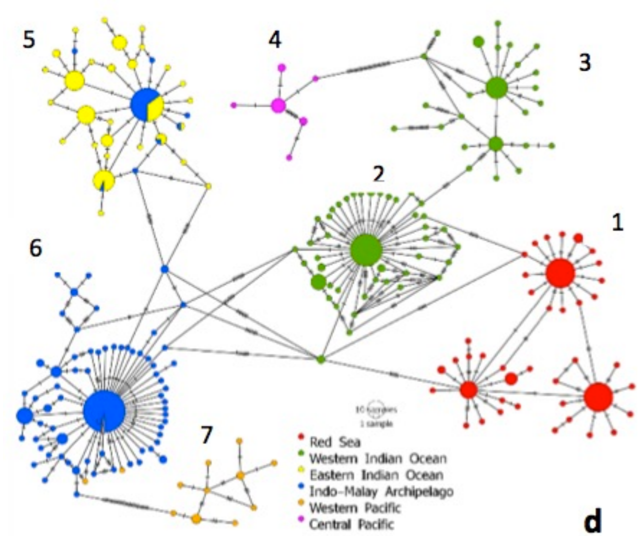


- 10 microsatellite loci (nDNA); 366 samples
- Hierarchical AMOVA: $F_{ct} = 0.063$; $0.05 \geq p \geq 0.01$

Giant clam (*Tridacna maxima*) Nuryanto & Kochzius (2009); Hui, (...), Kochzius (2016); Dissanayake & Kochzius (in prep.)

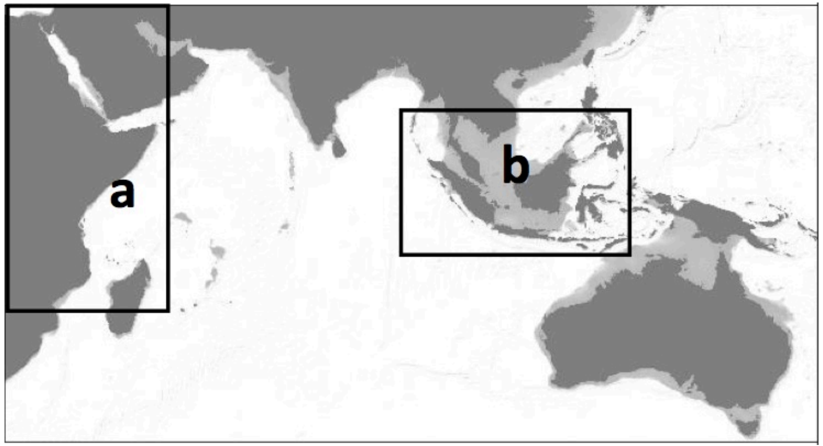


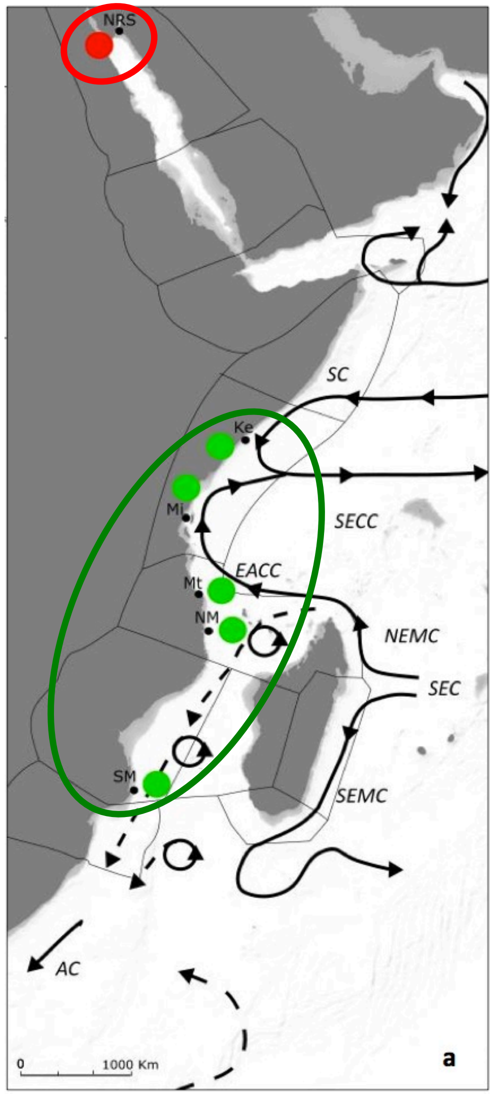
- 543 samples, 30 sites (COI)
- AMOVA: Φ_{ct} = 0.749*

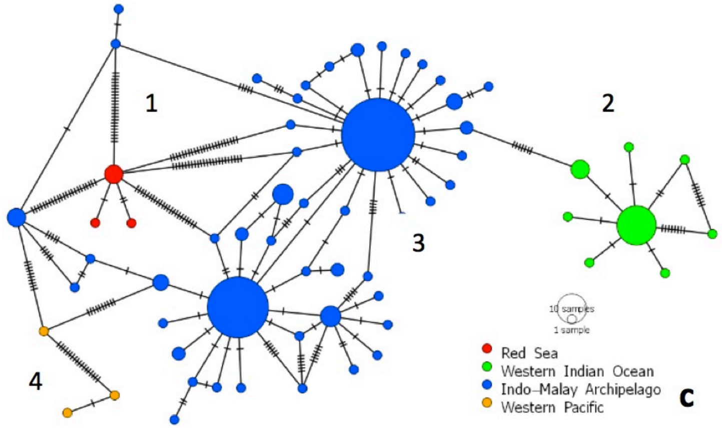


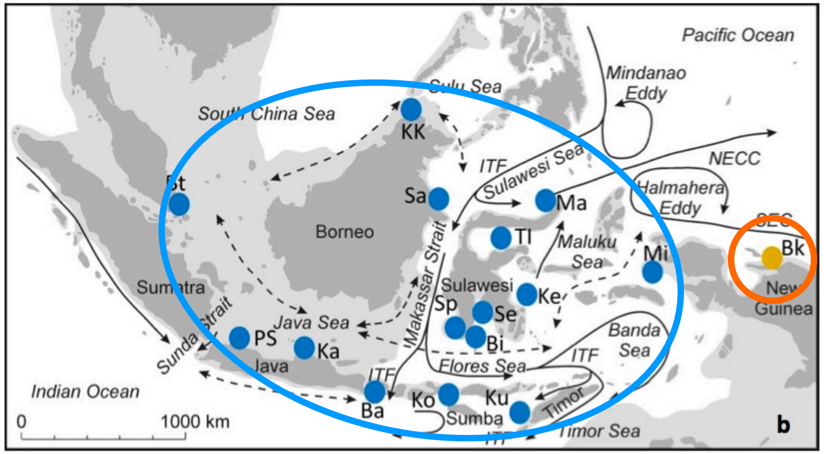
Giant clam (*Tridacna squamosa*) Hui, (...), Kochzius (2016); Dissanayake & Kochzius (in prep.)

- 208 samples, 22 sites (COI)
- AMOVA: $\Phi_{ct} = 0.857$*

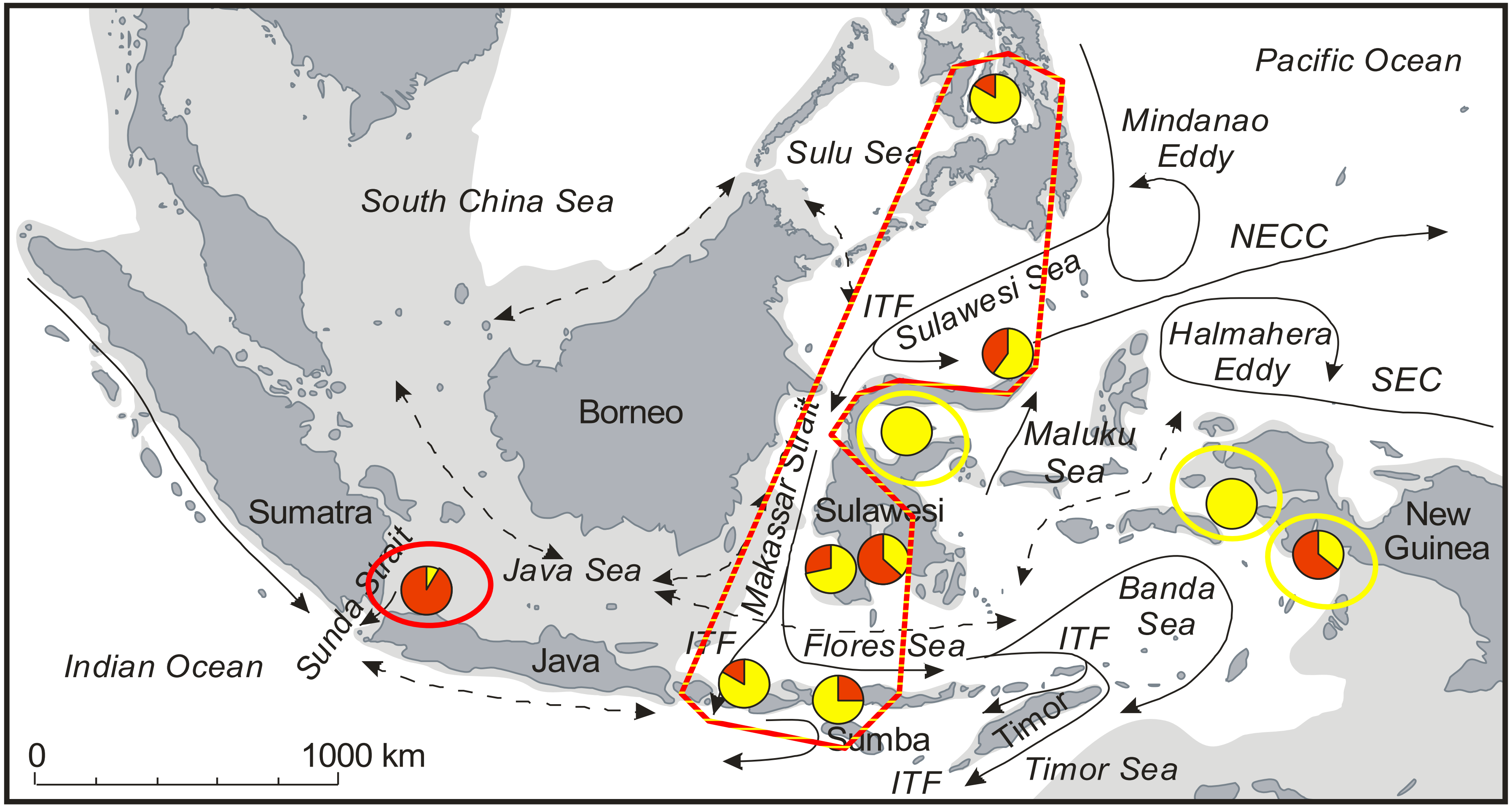






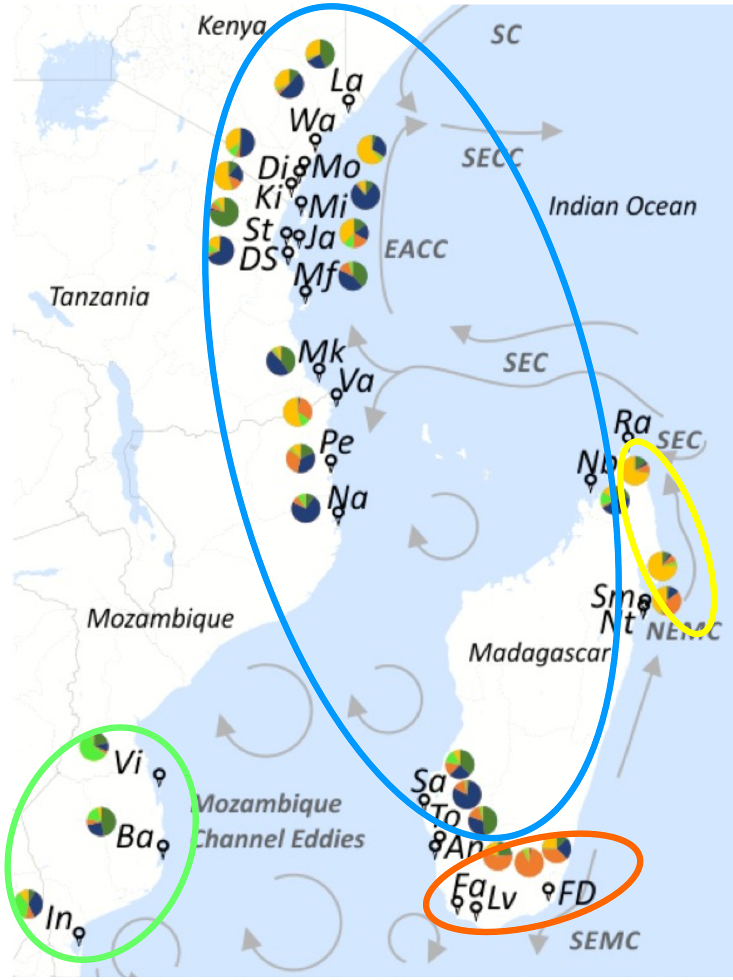


Mushroom coral (*Heliofungia actiniformes*) Knittweis, Krämer, Timm & Kochzius (2009)

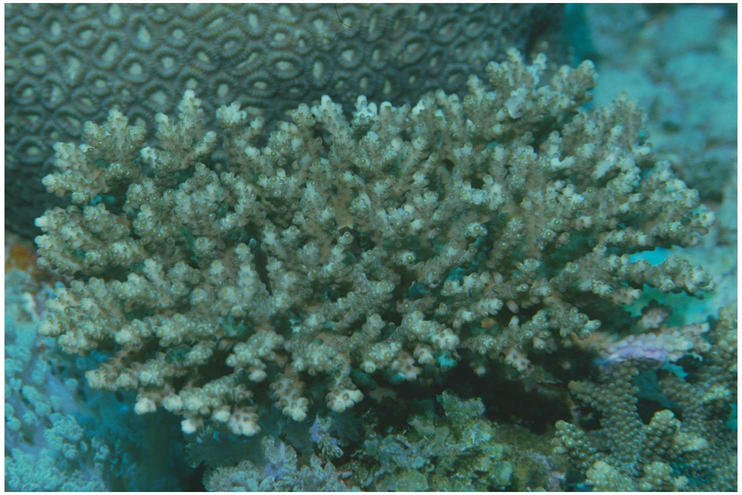


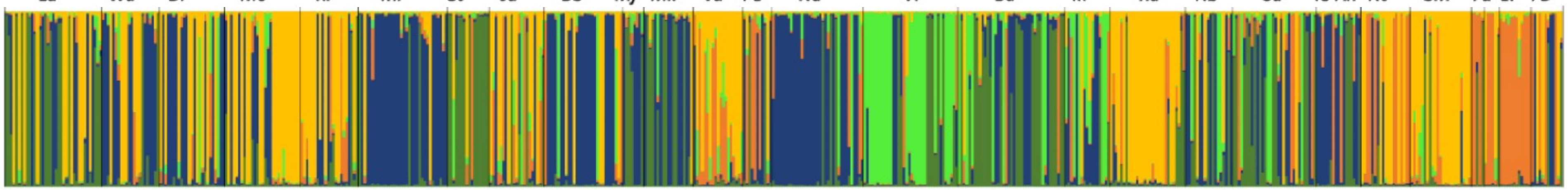
- 173 ITS sequences; 623 bp
- Hierarchical AMOVA: $\Phi_{ct} = 0.32$; $p = 0.007$

Stony coral (*Acropora tenuis*) van der Ven, Triest, De Ryck, Mwaura, Mohammed & Kochzius (2016), van der Ven (in prep.)

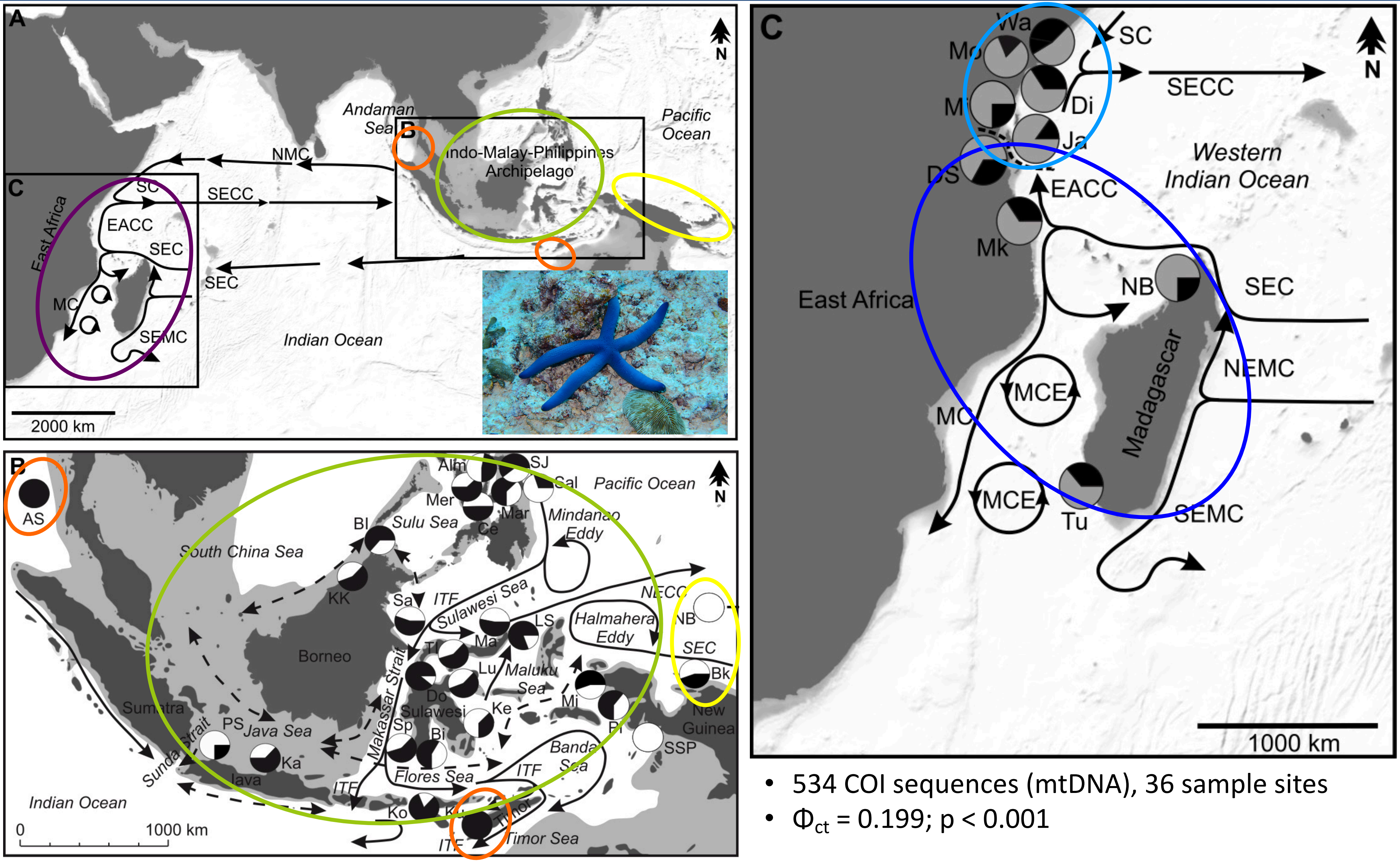


- 689 samples from 27 sites in the WIO and 1 in the Red Sea (7 microsatellites)
- Pairwise F_{st}-values ranging from 0.018 to 0.461
- 54 % of pairwise F_{st}-values significant



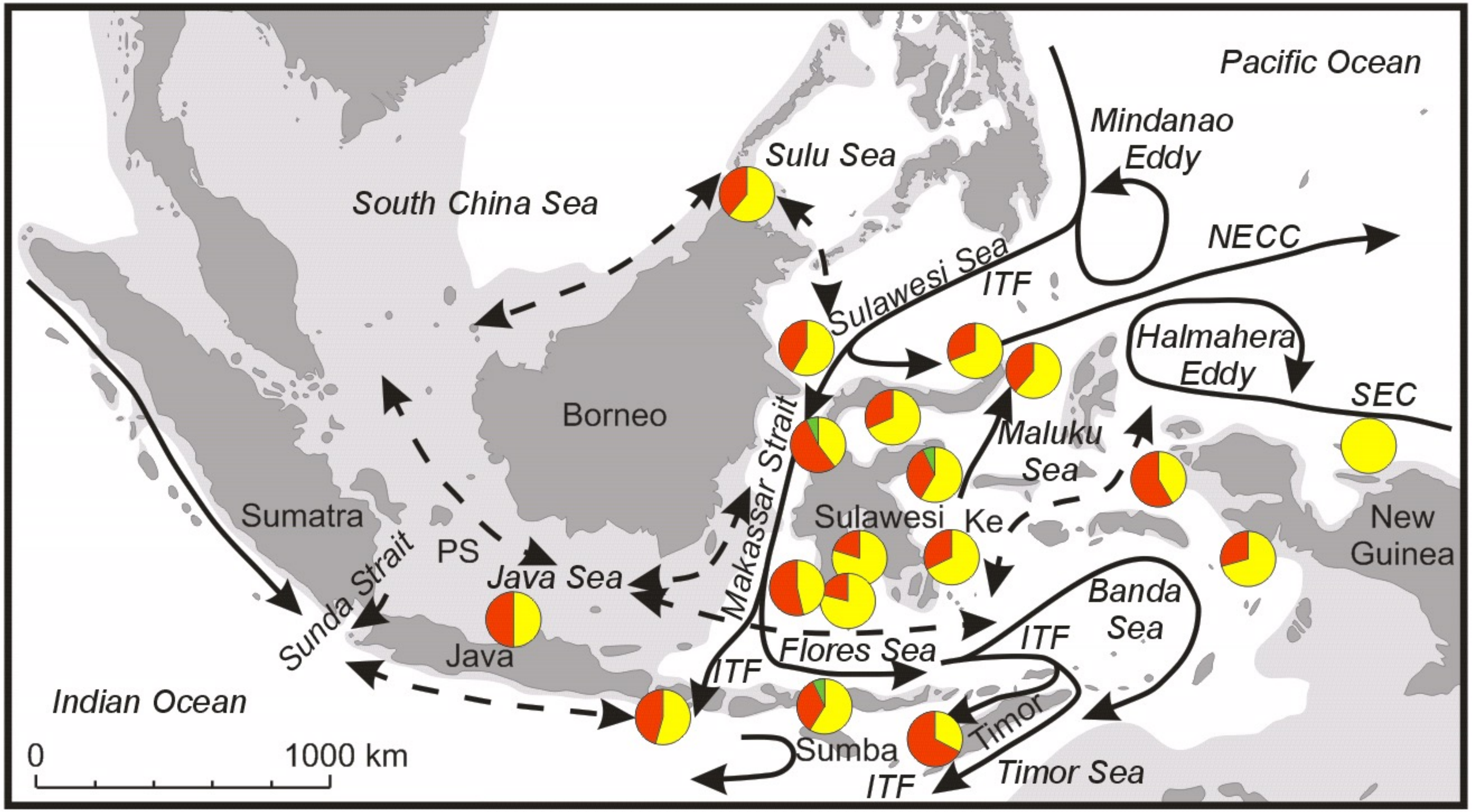


Blue sea star (*Linckia laevigata*) Kochzius et al. (2009); Alcazar & Kochzius (2016); Otwoma & Kochzius (2016)



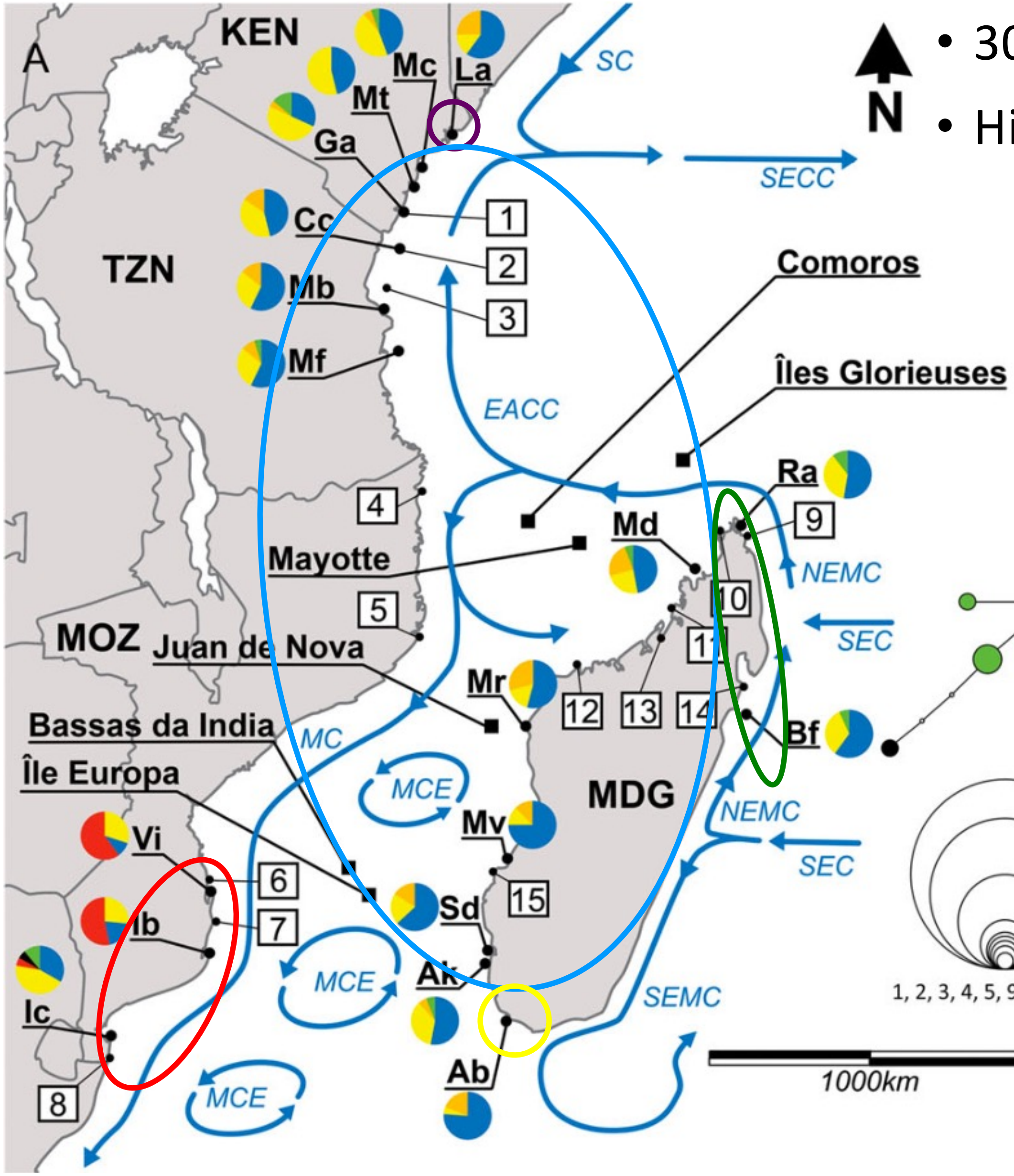
- 534 COI sequences (mtDNA), 36 sample sites
- $\Phi_{ct} = 0.199$; $p < 0.001$

Parasitic snail (*Thyca crystallina*) Kochzius et al. (2009)

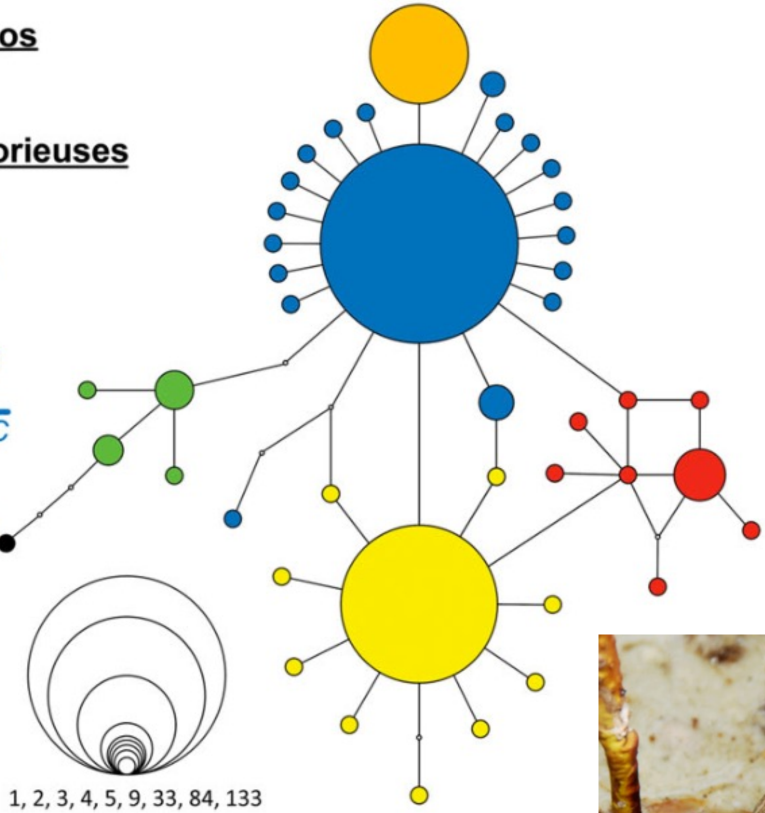


- 324 COI sequences; 401 bp
- AMOVA: $\Phi_{st} = 0.005$; $p = 0.24$

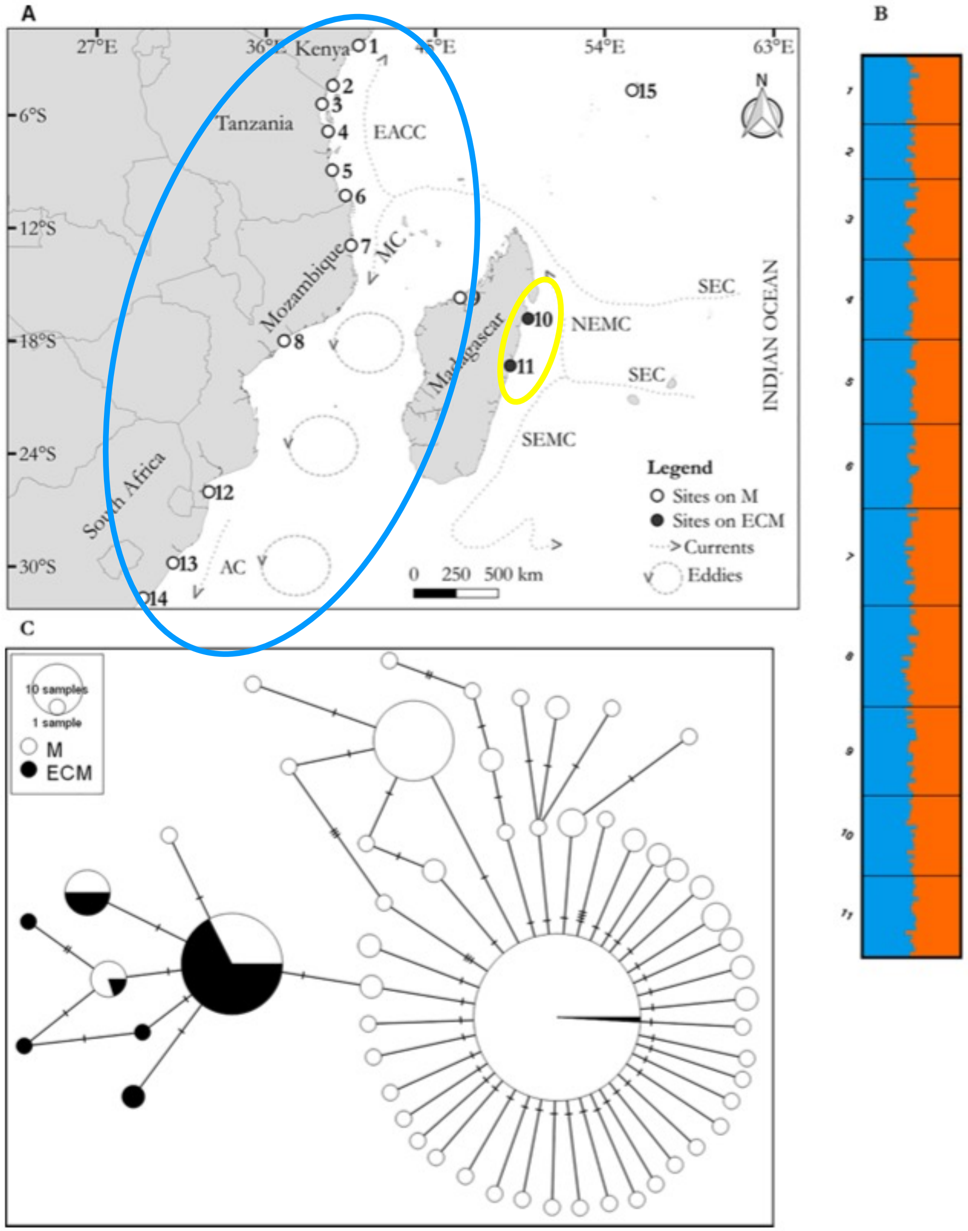
Mangrove whelk (*Terebralia palustris*) Ratsimbazafy & Kochzius (2018)



- 308 COI sequences (624 bp) from 18 sites
- Hierarchical AMOVA: $\phi_{CT} = 0.04$, P = 0.001



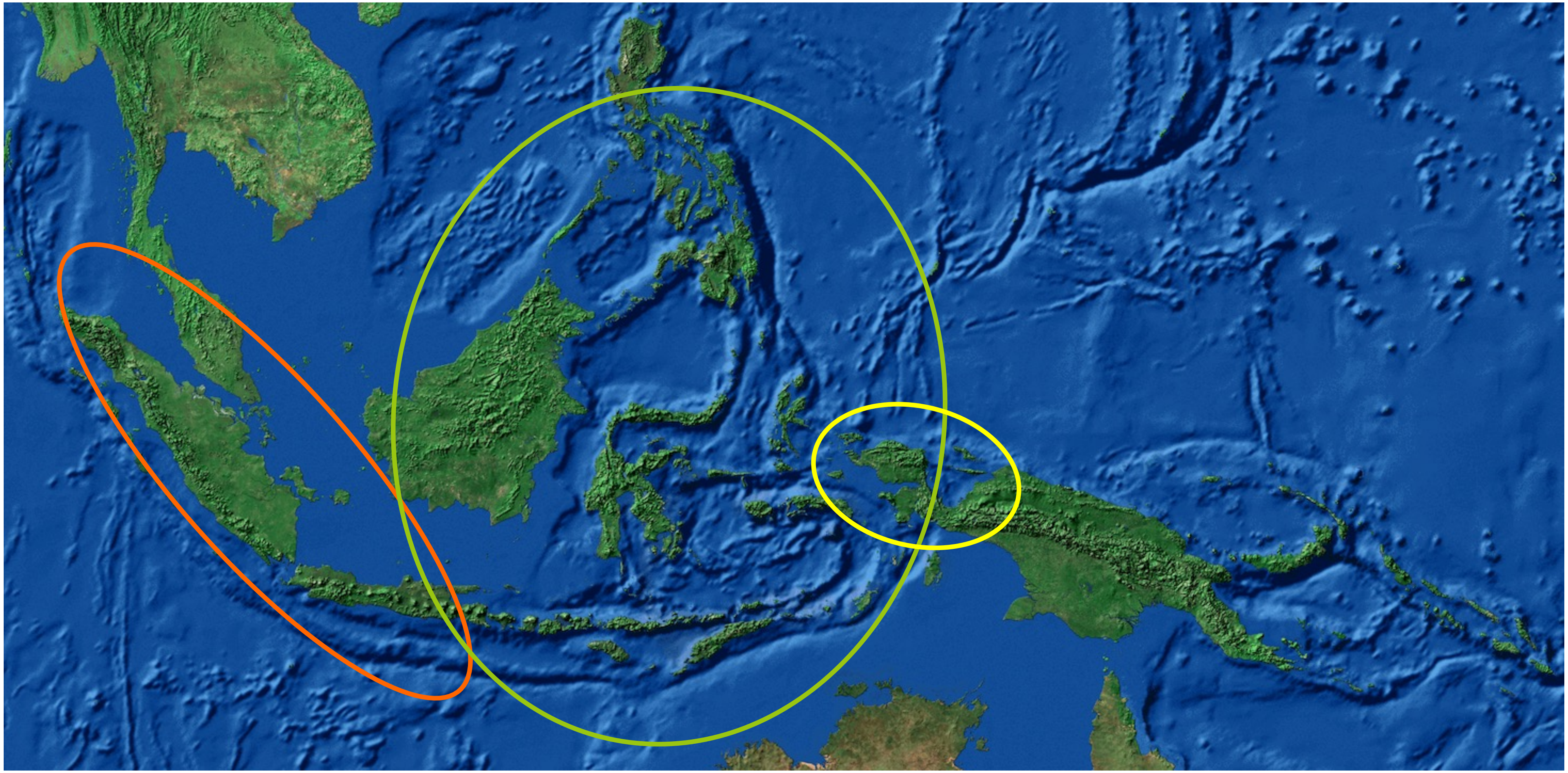
Giant mud crab (*Scylla serrata*) Rumisha, Huyghe, Rapanoel, Mascaux & Kochzius (2017)



- 355 COI sequences (535 bp) from 15 sites
- Hierarchical AMOVA: $\phi_{CT} = 0.564$, $P < 0.01$

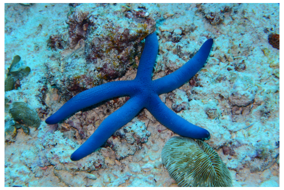
- 227 individual from 11 sample sites genotyped with 8 microsatellite loci
- $F_{st} = 0.00424$, $P > 0.05$

Phylogeography of the Coral Triangle

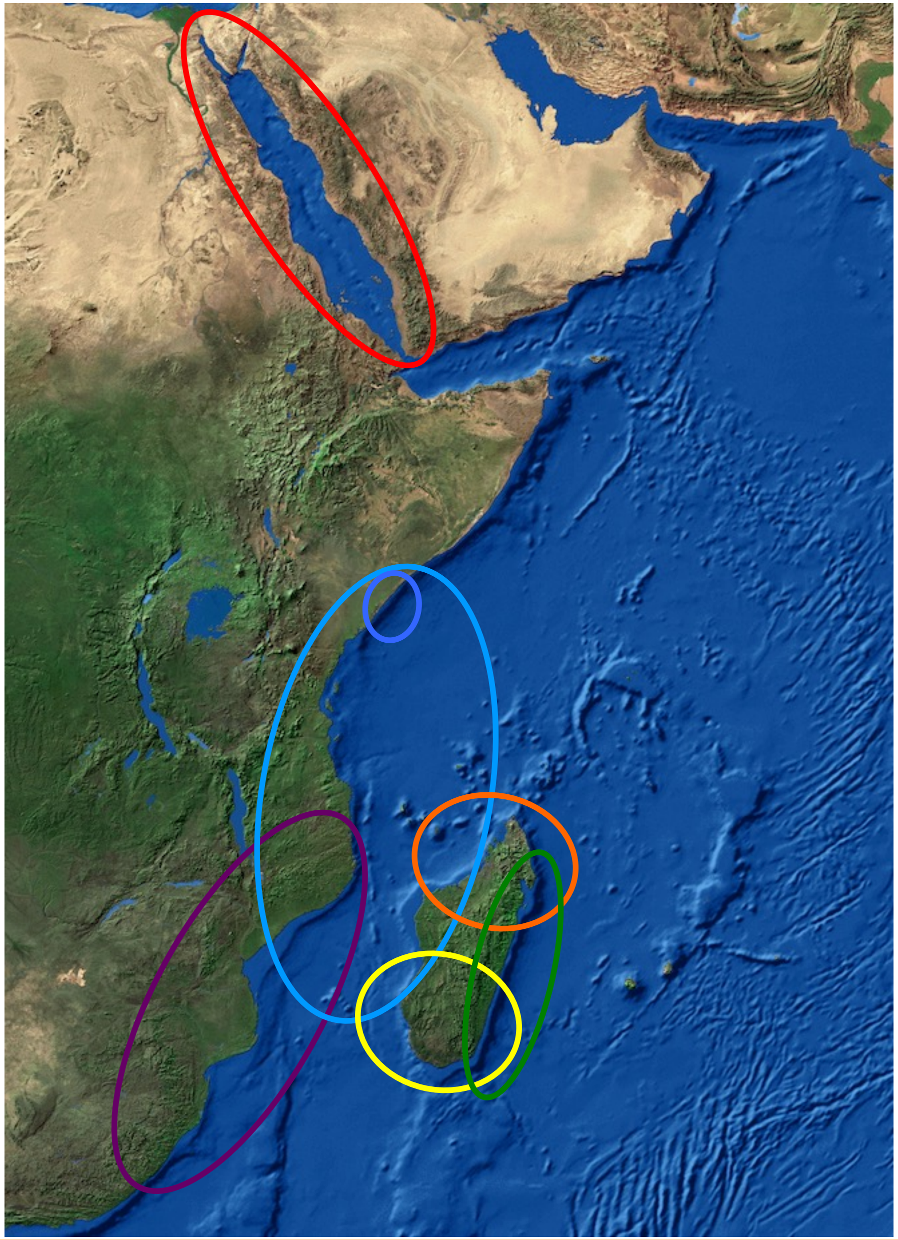


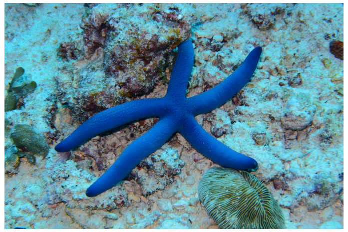


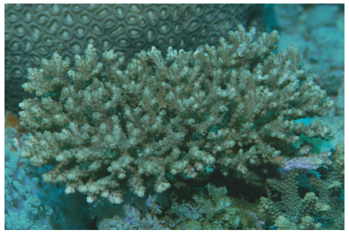


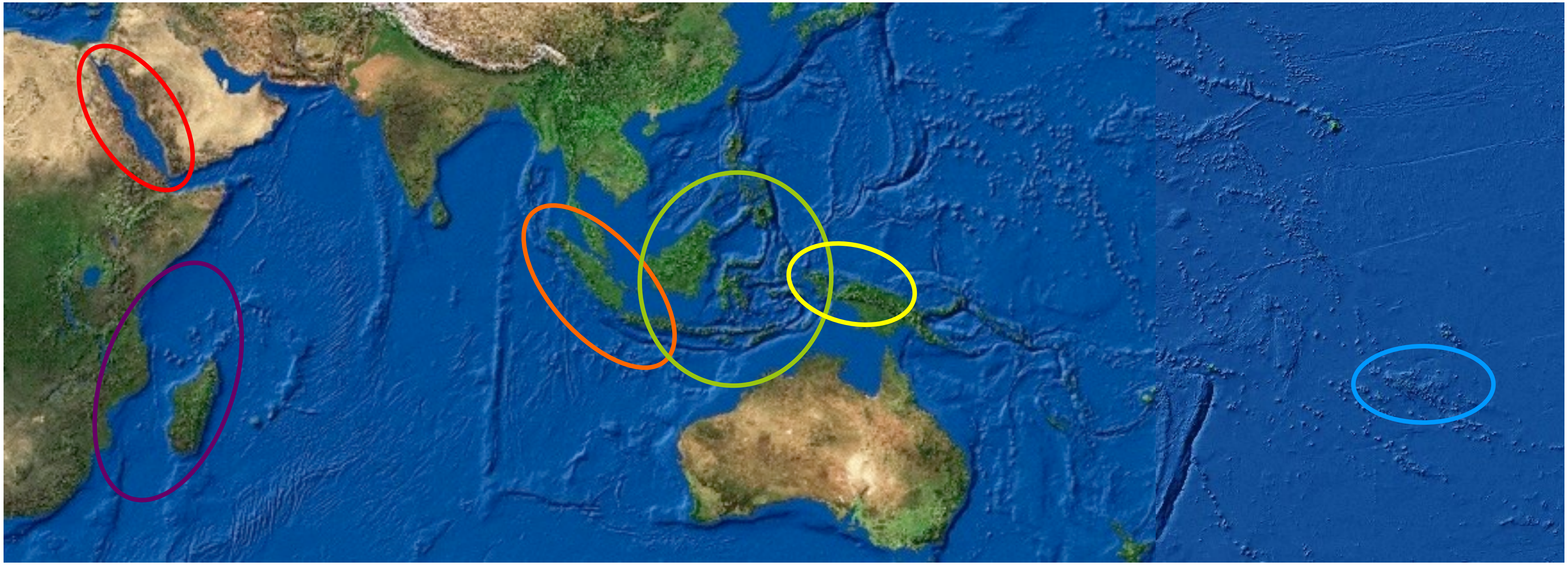

Phylogeography of the Western Indian Ocean and Red Sea

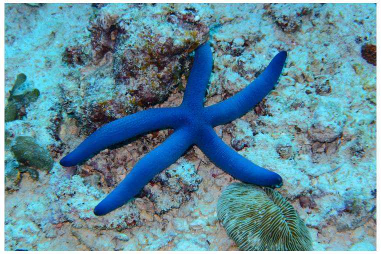


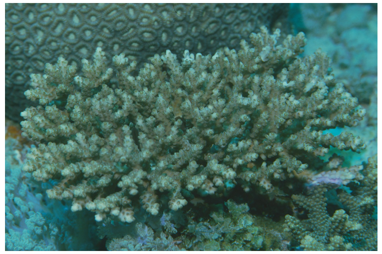




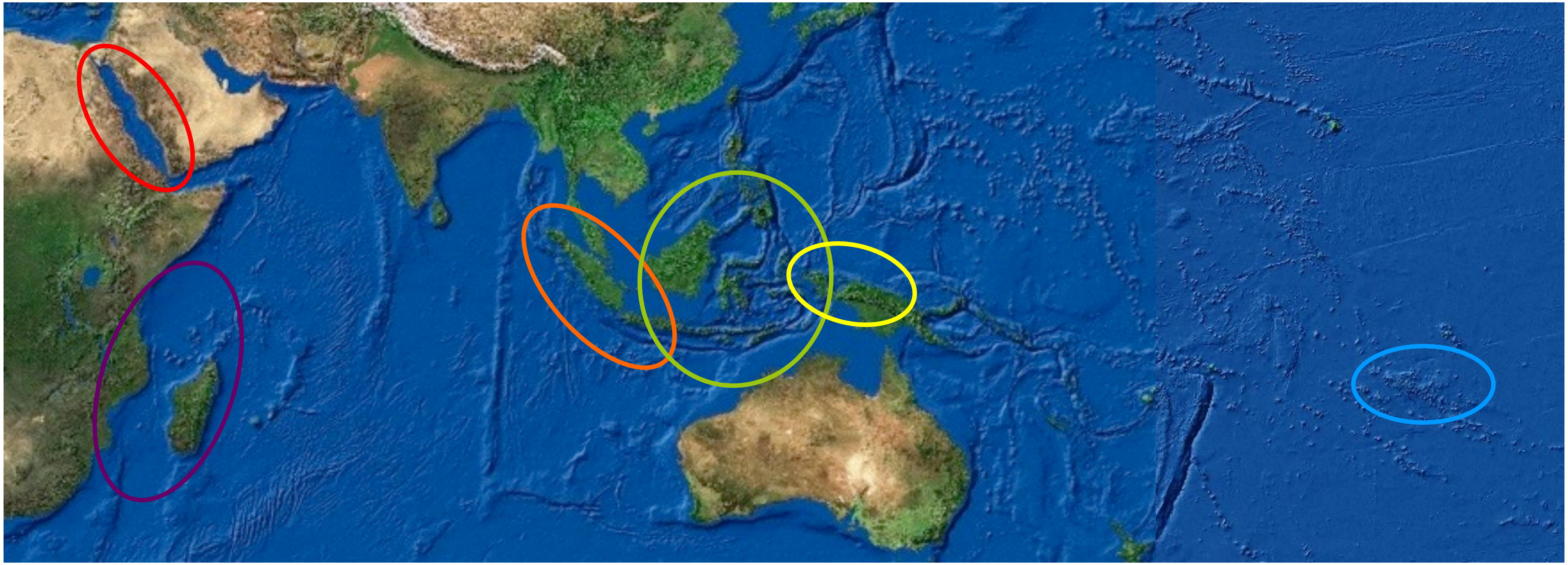
Phylogeography of the Indo-West Pacific







Phylogeography of the Indo-West Pacific



- not only one biogeographic model can explain the megadiversity in the Coral Triangle
- biodiversity feedback model (Bowen et al., 2013)
- Coral Triangle exports species to peripheral regions, where these evolve into new species
- new species are exported back to the Coral Triangle