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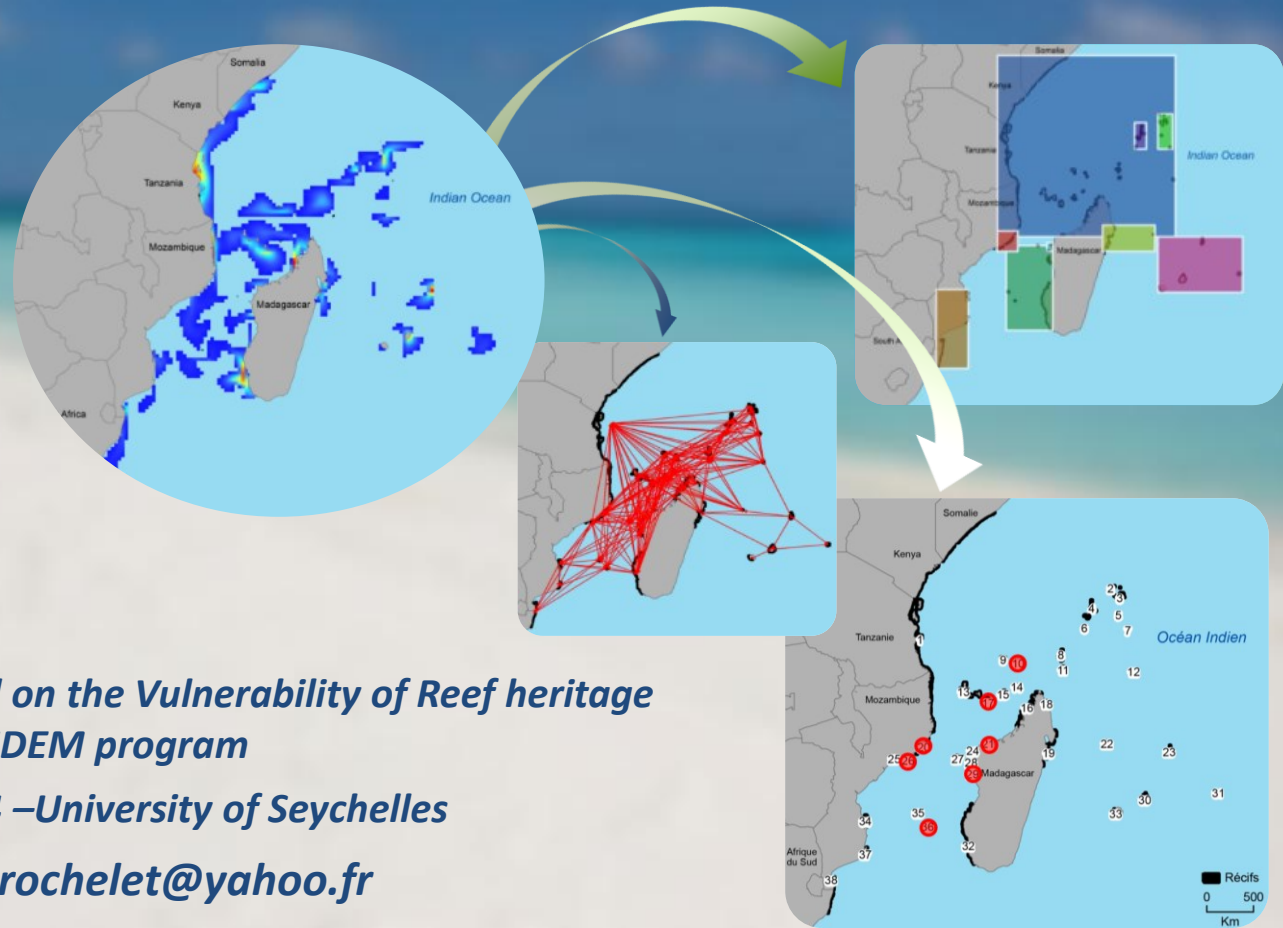
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A MODEL-BASED EVALUATION OF REEFS CONNECTIVITY AND HABITAT DEGRADATION SCENARIOS - IMPLICATIONS FOR FUTURE MARINE SPATIAL PLANNING AND MARINE CONSERVATION POLICIES IN THE WIO

*Estelle Crochelet
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*Regional thematic school on the Vulnerability of Reef heritage
DIDEM program*

June 10, 2024 – University of Seychelles

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INTRODUCTION

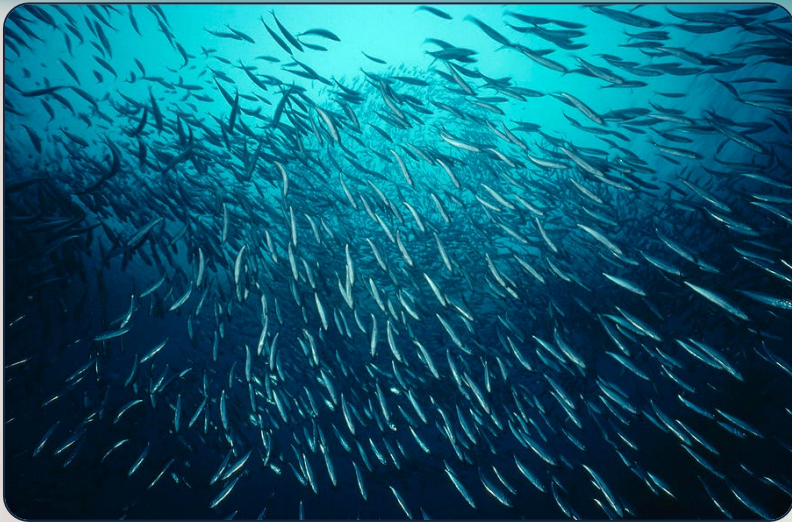


Context

- **Marine resources are under increasing pressure due to the combined impacts of human activities and climate change : ↘ or extinction of species**
- **Environmental tools such as MPAs have been proposed to protect biodiversity, restore damaged ecosystems, sustain fisheries, and rebuild overexploited stocks.**
- **Effectiveness of MPAs depends in part on the maintenance of connectivity through processes such as the dispersal of larvae, to support population replenishment, persistence, and gene flow within protected areas, between protected areas, and in adjacent habitats**

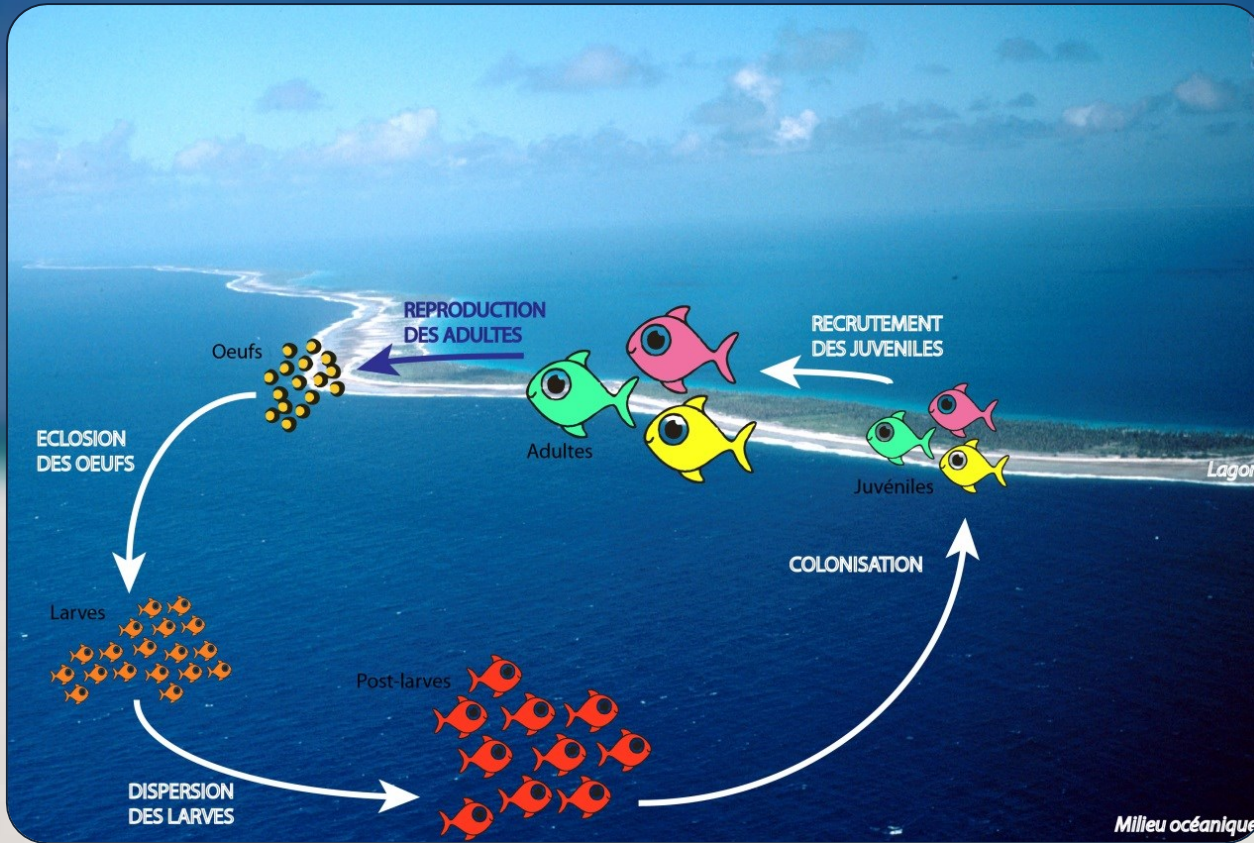
Context

- **CONNECTIVITY = exchanges of individuals between distinct populations (larvae, juveniles, adults)**



- Larval transport is the main process underlying connectivity.
→ Difficult to study because of physical processes (hydrodynamic transport : advection / diffusion); biological characteristics (PLD, swimming abilities , behavior, survival)

Reef fish life cycle

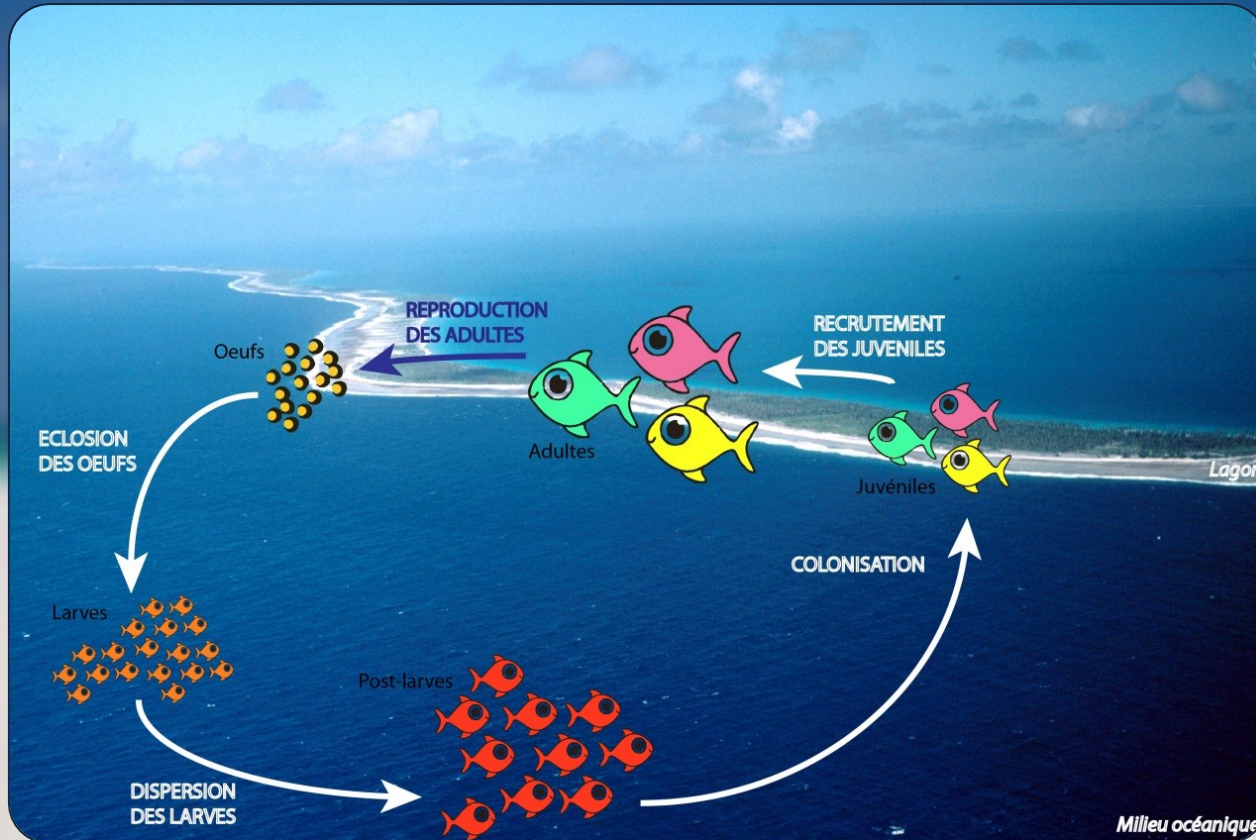


Bipartite life cycle:

→ pelagic early life stage

→ benthic reef associated stage

Reef fish life cycle

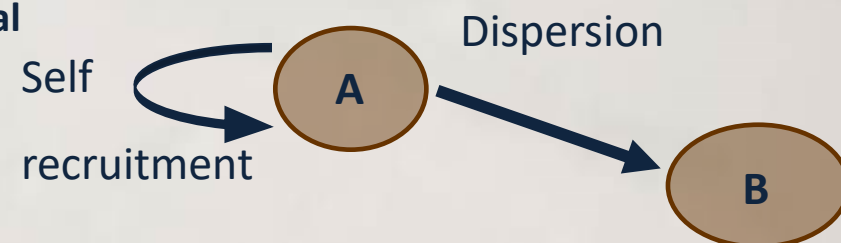


Bipartite life cycle:

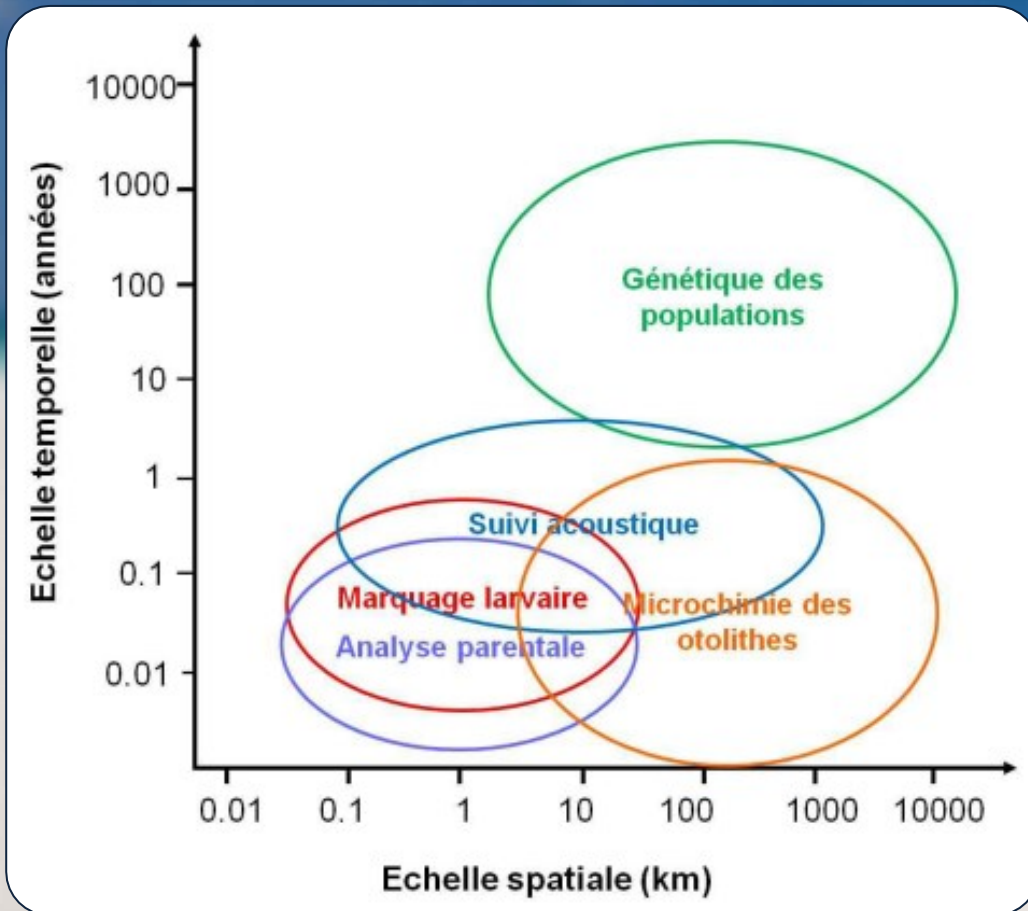
→ pelagic early life stage

→ benthic reef associated stage

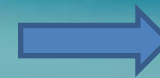
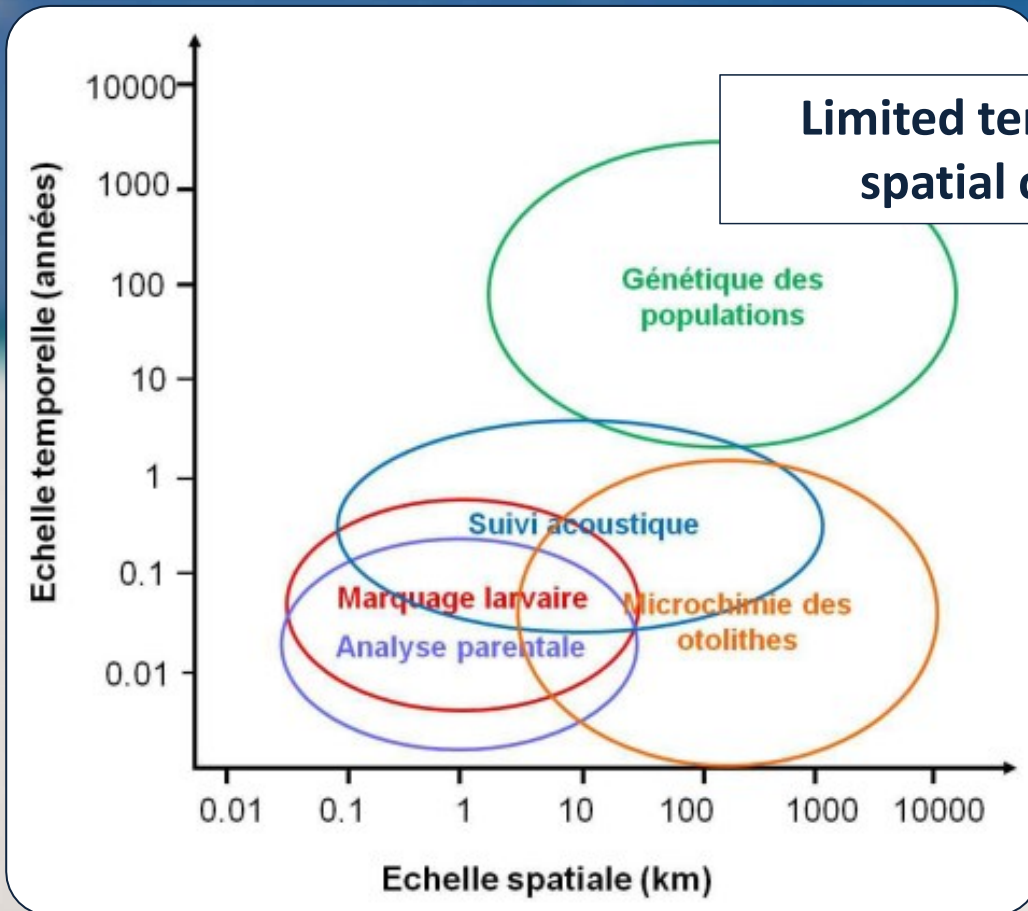
Dispersion is hard to study due to larvae size, long dispersal distance, and depend on species → knowledge of connectivity patterns is crucial for effective management



Several techniques to study connectivity



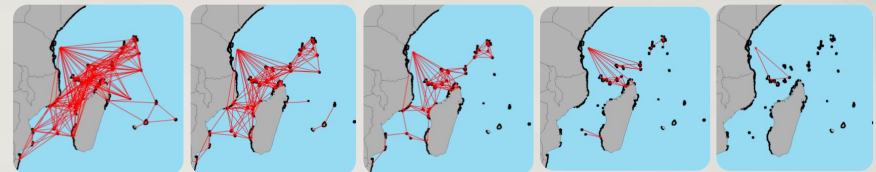
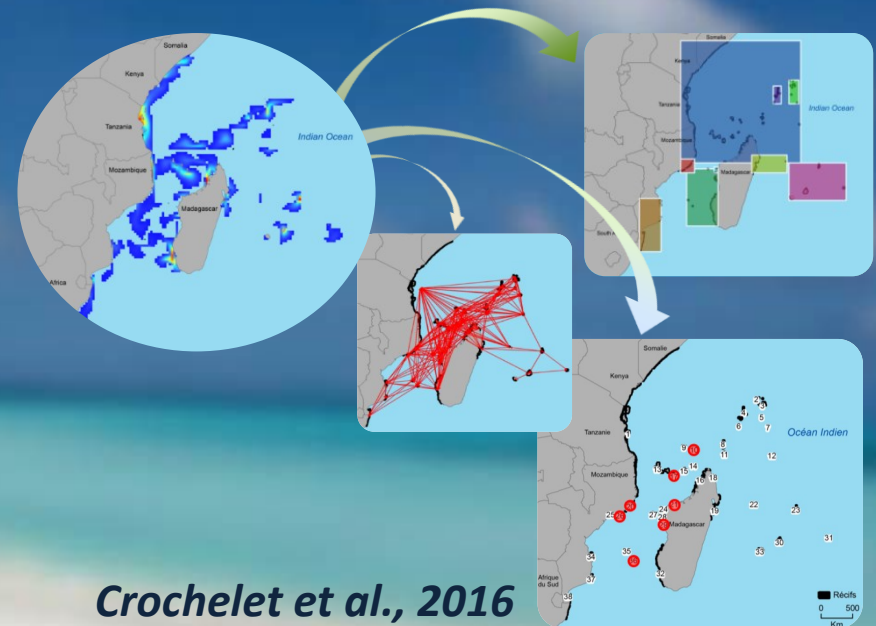
Several techniques to study connectivity



Hydrodynamic connectivity models
Follow virtual individuals across large scales

Objectives

- To evaluate coral reefs ecosystems connectivity patterns in the Western Indian Ocean, using a dispersal model
- To produce different scenarios concerning habitat degradation consequences on coral reef ecosystems connectivity patterns, to better inform anticipatory planning and management of coastal and marine resources



Habitat degradation



MATERIALS & METHODS

STUDY AREA

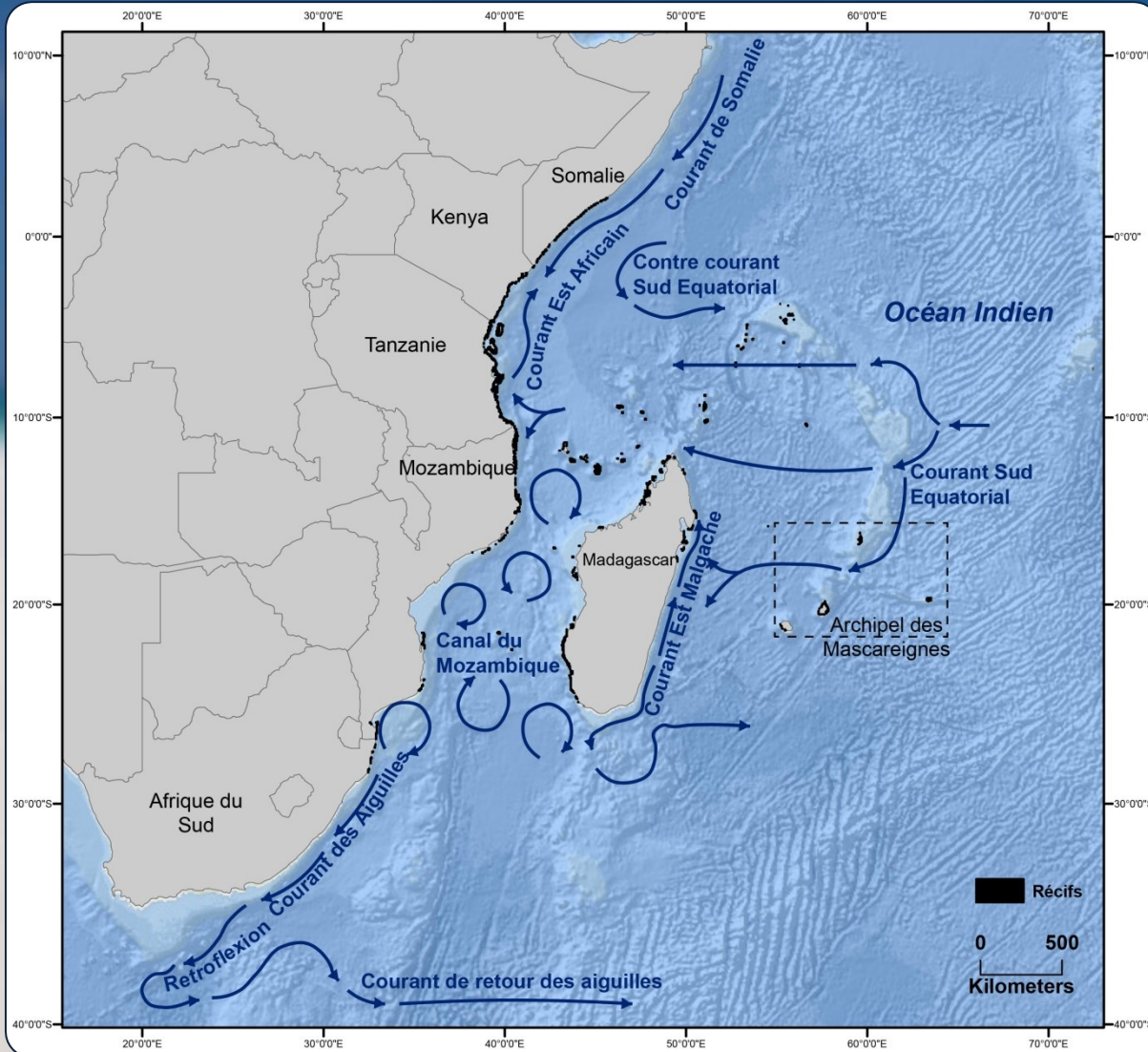


Western Indian Ocean

Tropical area

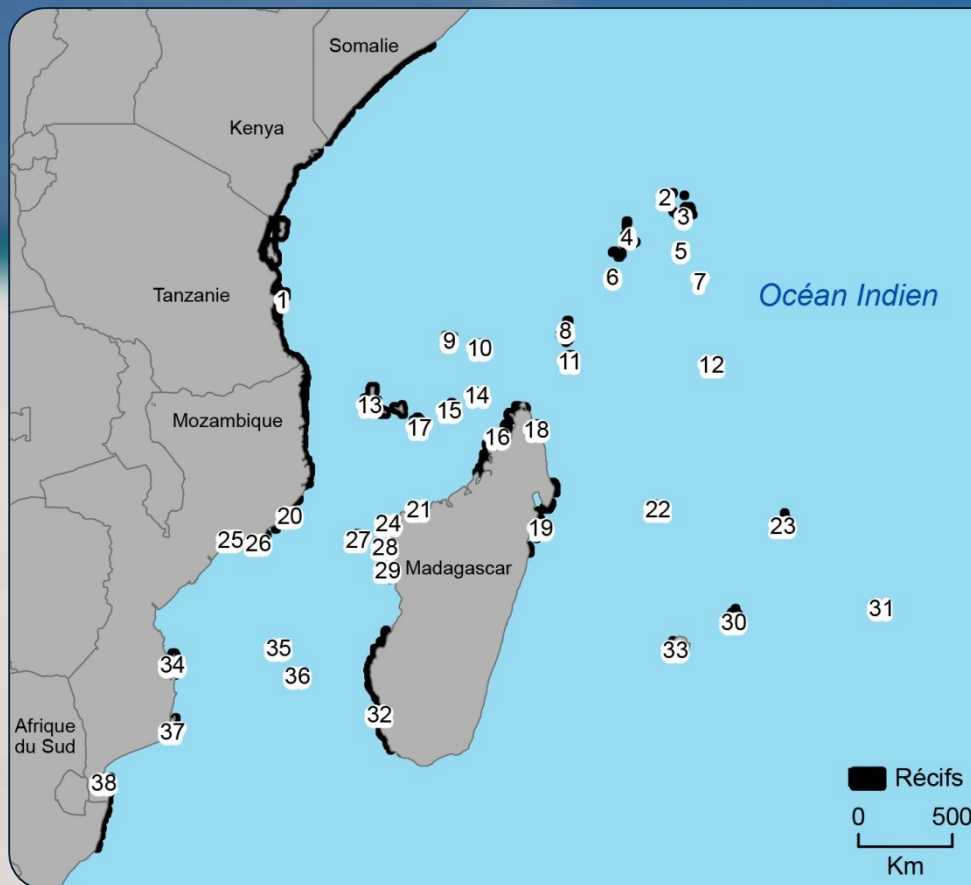
Part of a larger ocean basin = open system

Indian Ocean hydrodynamics



- South Equatorial Current
- Mozambique Channel Eddies
- East Madagascar Current
- East African Coastal Current
- Somali Current
- Agulhas Current

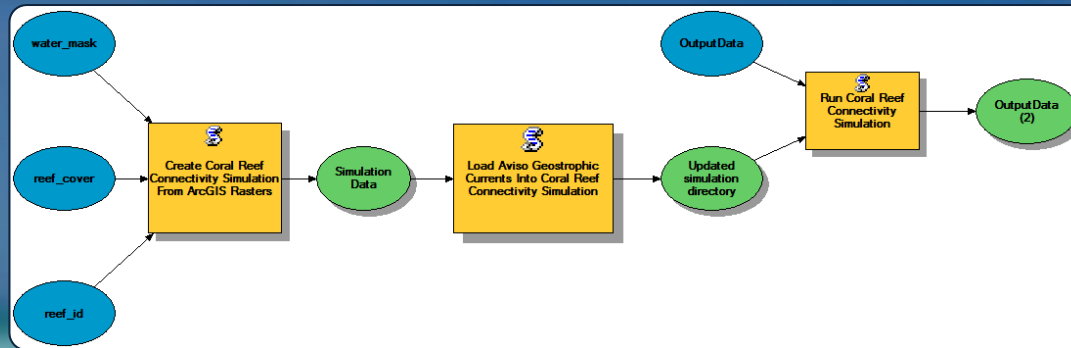
Study Sites



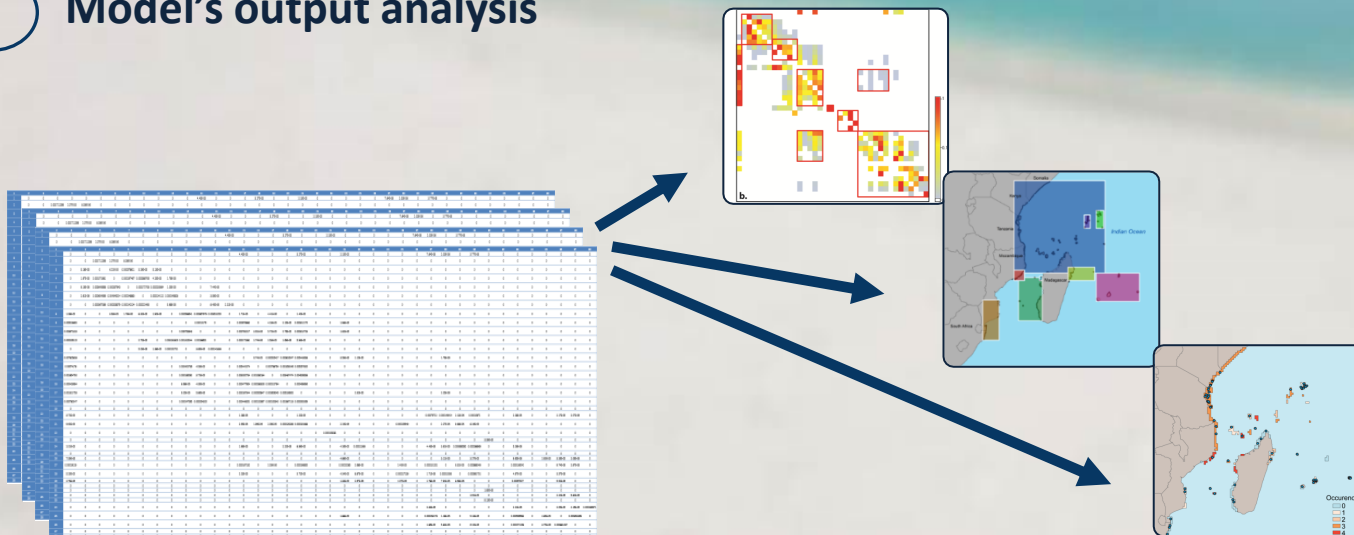
1	Mozambique/Tanzanie Kenya/Somalie	20	Angoche
2	Bird	21	Majunga
3	Seychelles	22	Tromelin
4	Poivre	23	Saint Brandon
5	Platte	24	Besalampy
6	Alphonse	25	Pebane
7	Coëtivy	26	Moma
8	Providence	27	Juan de Nova
9	Aldabra	28	Maintirano
10	Cosmoledo	29	Masoarivo
11	Farqhar	30	Maurice
12	Agalega	31	Rodrigues
13	Comores	32	Morondava - Anakao
14	Glorieuses	33	La Réunion
15	Geyser bank	34	Bazaruto arch.
16	NW tip of Madagascar	35	Bassas da India
17	Mayotte	36	Europa
18	Nosy Ankomba / Anko	37	Maxixe
19	Masoala peninsula Ste Marie	38	Maputo bay to Santa Lucia

ANALYSIS METHODS

1 Hydrodynamic connectivity model → Marine Geospatial Ecology Tools

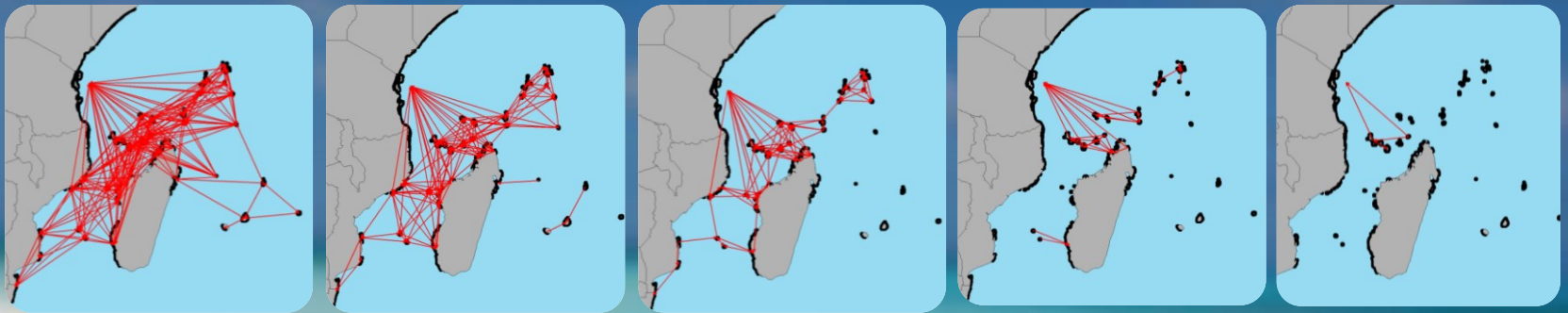


2 Model's output analysis



ANALYSIS METHODS

3 Habitat degradation scenarios



Habitat degradation

20%

50%

70%

90%

1- Hydrodynamic connectivity model

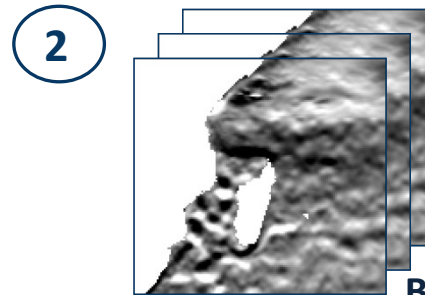
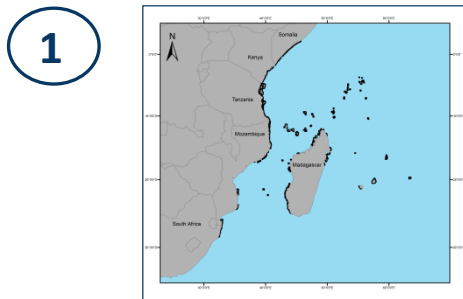
2D eulerian advection-diffusion algorithm

Larvae = passive particles

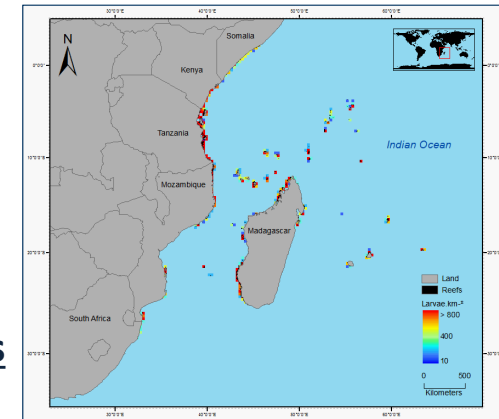
Coral reef ID and % cover maps
habitat, shoreline

Ocean currents data
(1/3° resolution, daily,
2006-2010)

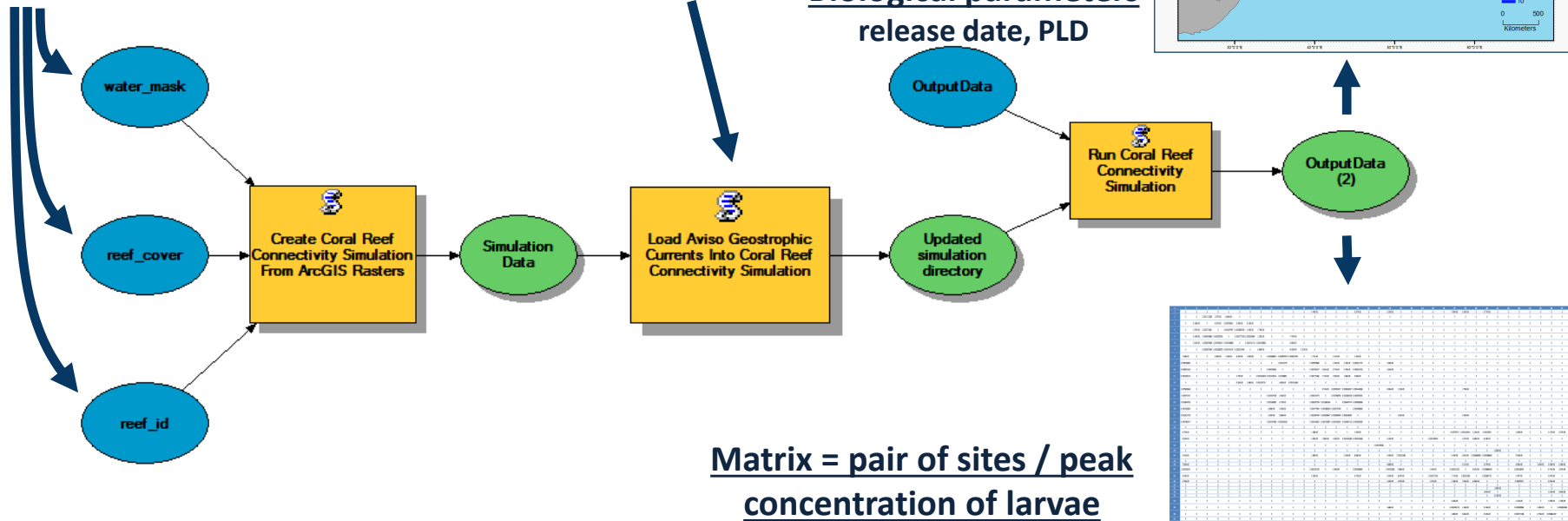
Larval density time
series rasters



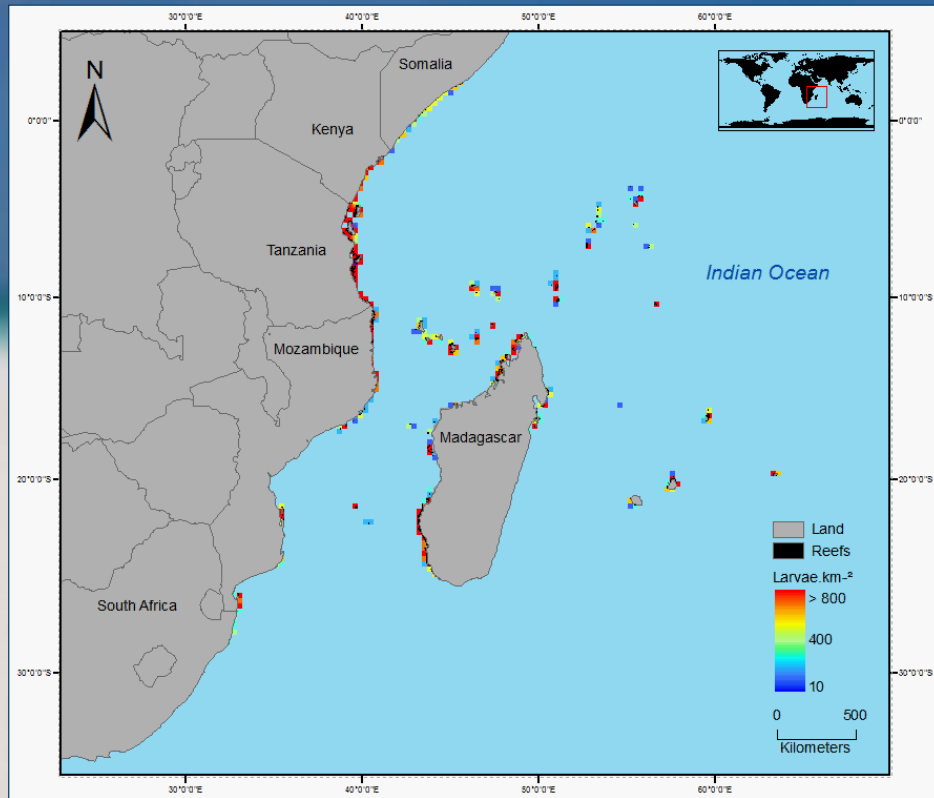
4



3
Biological parameters
release date, PLD



2- Larval density time series rasters



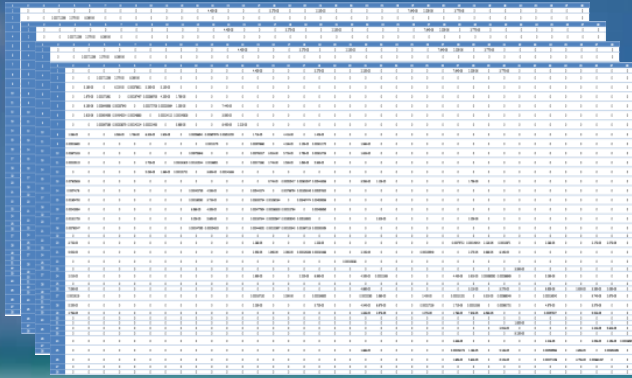
Images of larval density → larvae/km²

Pool of larvae dispersion

Time step: 1 min, 1 hour, 1 day

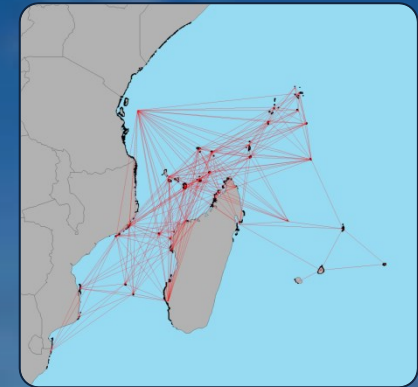
2- Connectivity matrix processing

Connectivity matrices



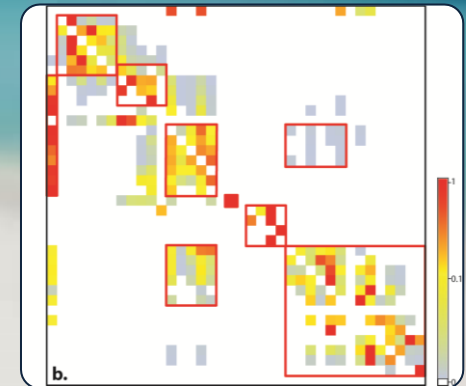
1

Edge list features



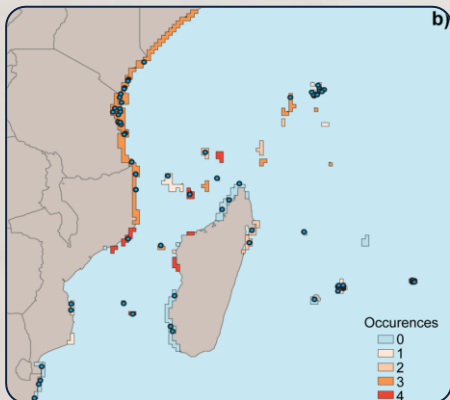
2

Migration matrices



Betweenness centrality index

4



Clustering

3



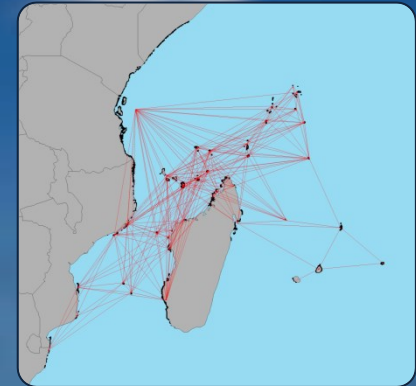
2- Connectivity matrix processing

1

Edge list features

Linking connected pair of sites

- i) the peak concentration of larvae,
- ii) the length of the segment (i.e. distance)
- iii) the direction of the flow



Regional connectivity:

$$\text{Connectance} = \frac{\sum \text{connexions réalisées}}{\sum \text{connexions possibles}}$$

2- Connectivity matrix processing

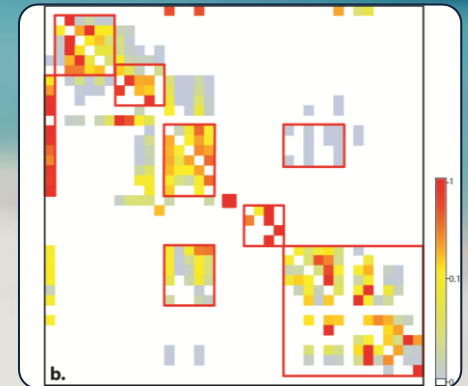
Migration matrix of imports

→ proportion of larvae coming in from each site

Migration matrix of export

→ proportion of larvae exported to each site

2 Migration matrices



2- Connectivity matrix processing

- **Clustering** : task of grouping a set of objects in such a way that objects in the same group (called a cluster) are more similar to each other than to those in other groups
→ Discover the natural groupings of a set of objects
- **APCluster tool (R)** : « affinity propagation » method

No need to determine the number of clusters

Developed to cluster images of faces, detect genes in microarray data, identify cities that are efficiently accessed by airline travel etc

Clustering

3



2- Connectivity matrix processing

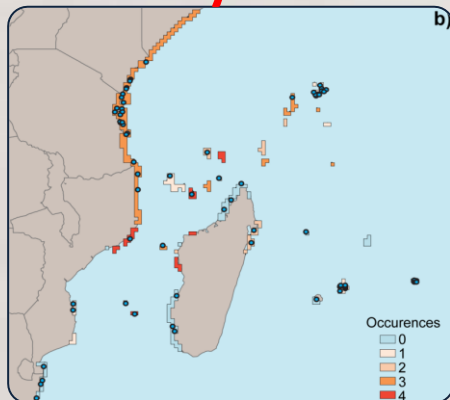
Identification of the most important nodes of the network

Central sites, acting as gateway for spreading individuals through the network
= stepping stones

High BC \rightarrow important sites for multigenerational connectivity

**Betweenness
centrality index**

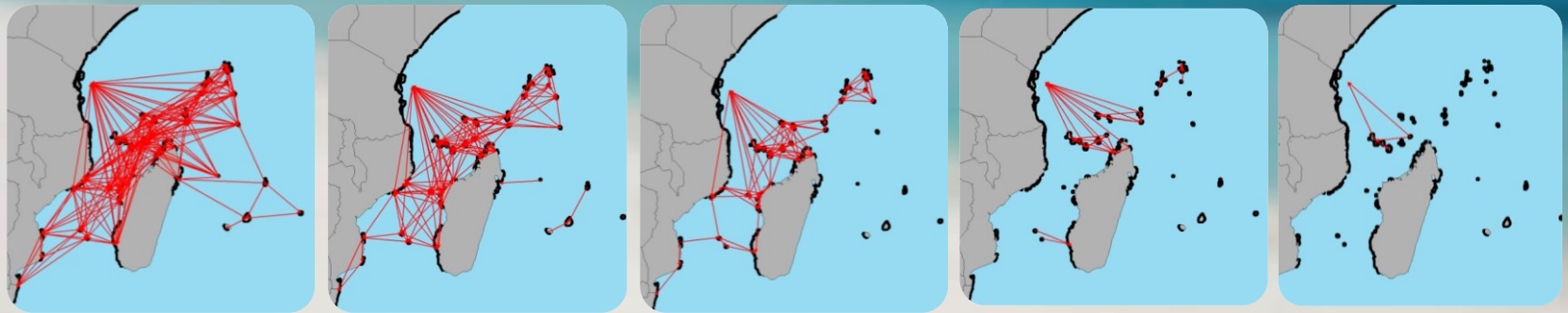
4



***igraph* tool (R)** : BC metric measures the proportion of shortest paths between nodes that pass through a given node

3- Habitat degradation scenarios

Exploratory assessment of different scenarios concerning habitat degradation consequences on coral reef ecosystems connectivity patterns, to better inform anticipatory planning and management of coastal and marine resources



Habitat degradation

20%

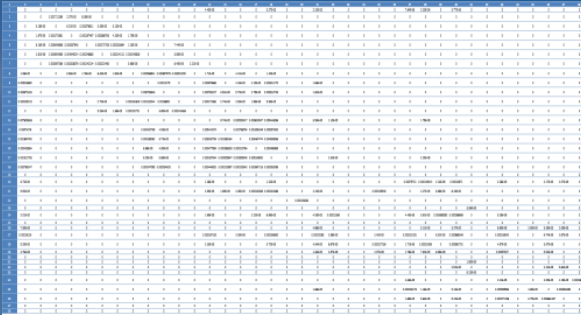
50%

70%

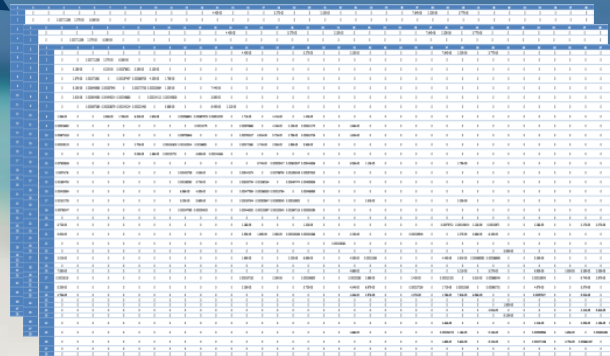
90%

3- Habitat degradation scenarios

Connectivity matrix

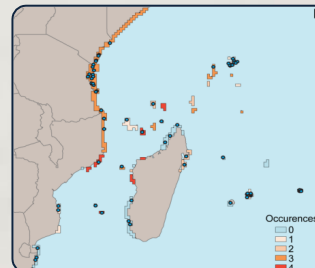


Connectivity matrix
(Degradation indices = 20, 50, 70, 90 %
Connectivity threshold= 10^{-5})

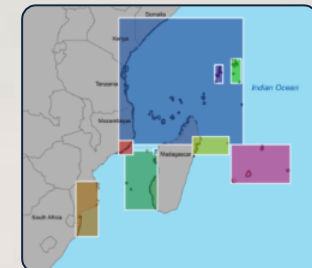


Connectance rate

Betweenness centrality
index



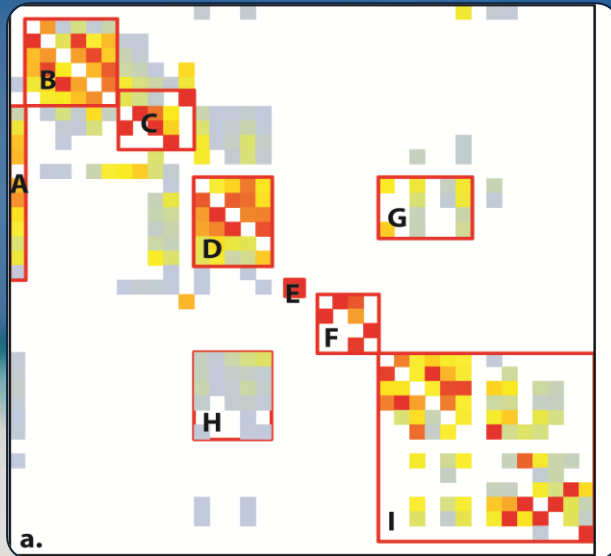
Clustering



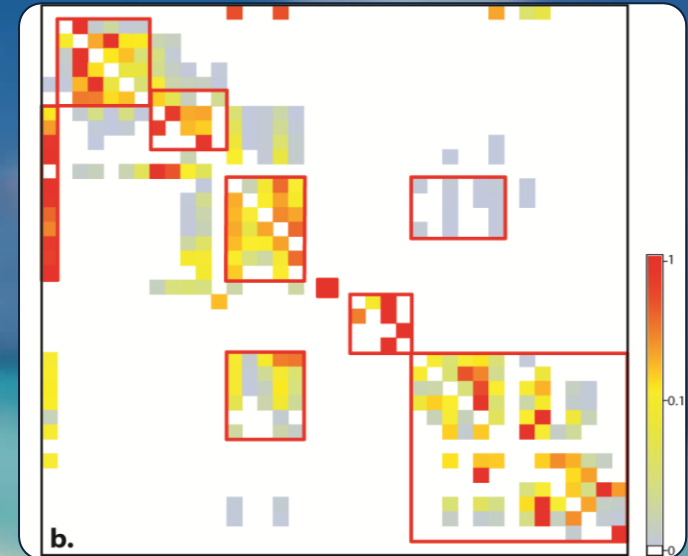
RESULTS



MIGRATION MATRICES (PLD = 30 d)



a. Imports of larvae



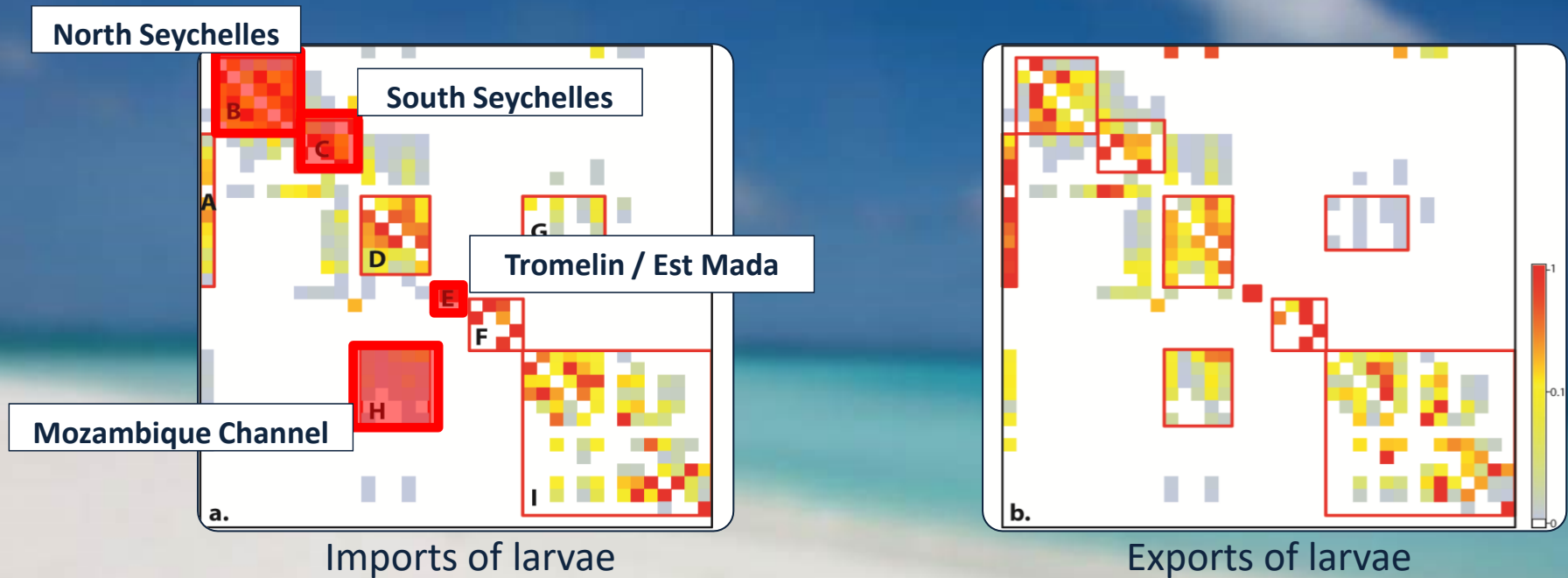
b. Exports of larvae

8 sub-regions by visual inspection:

- A: Comoros, South Seychelles, North tip of Madagascar and East African Coast;
- B: North Seychelles;
- C: South Seychelles;
- D: Comoros, North tip of Madagascar and the North of the Mozambique channel;
- E: Tromelin to East Madagascar;
- F: Mascarene archipelago;
- G: From Comoros region to the middle of the Mozambique Channel;
- H: From the middle of the Mozambique Channel to Comoros region;
- I: reefs of the middle and South of the Mozambique channel.

- Low regional connectivity
- High interconnectivity within sub-regions

MIGRATION MATRICES (PLD = 30 d)

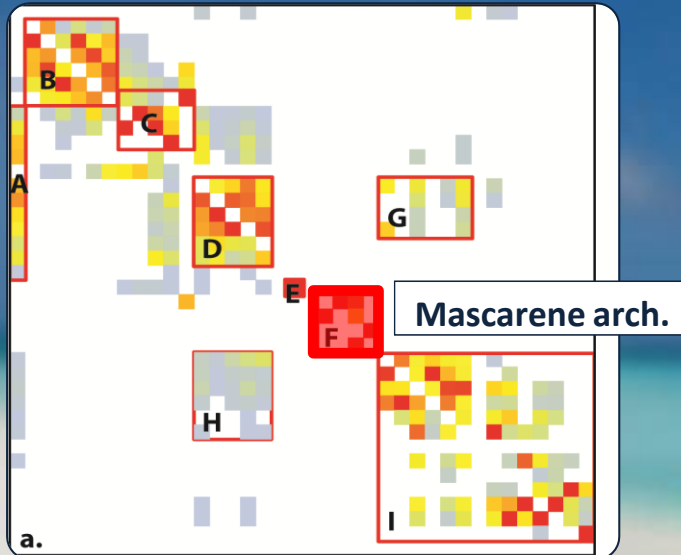


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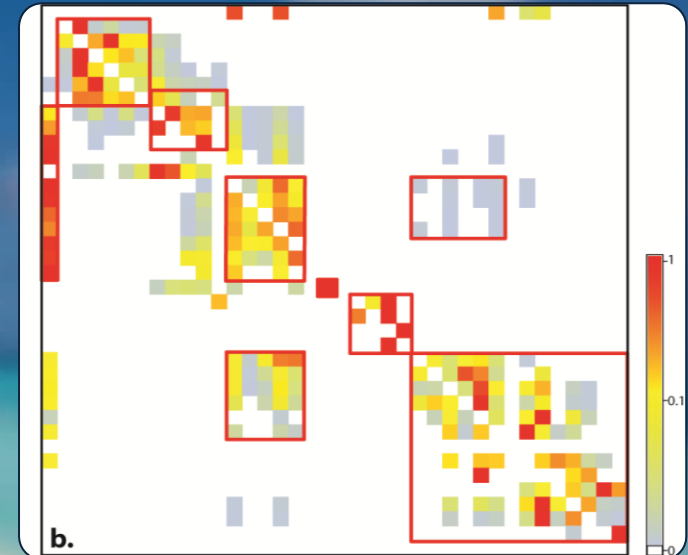
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Imports of larvae



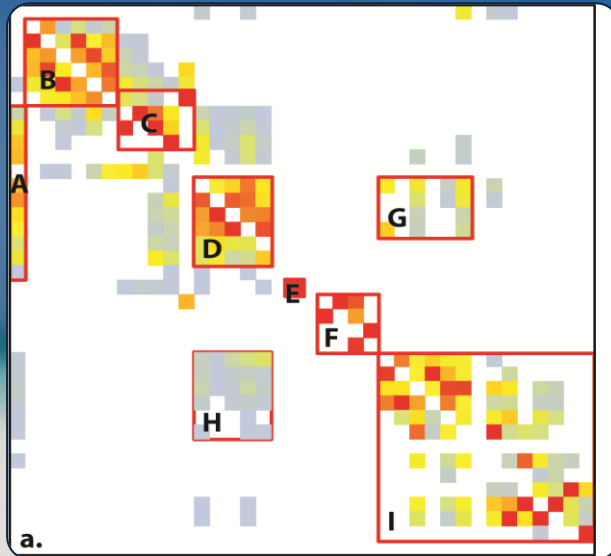
Exports of larvae

8 sub-regions by visual inspection:

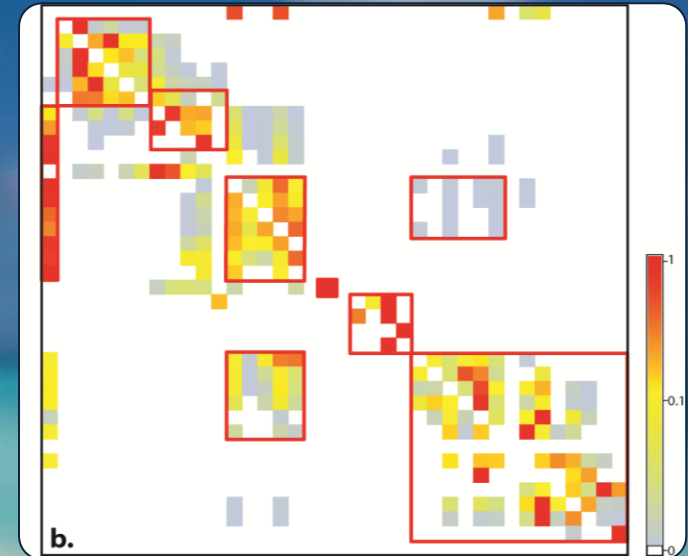
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MIGRATION MATRICES (PLD = 30 d)



a. Imports of larvae



b. Exports of larvae

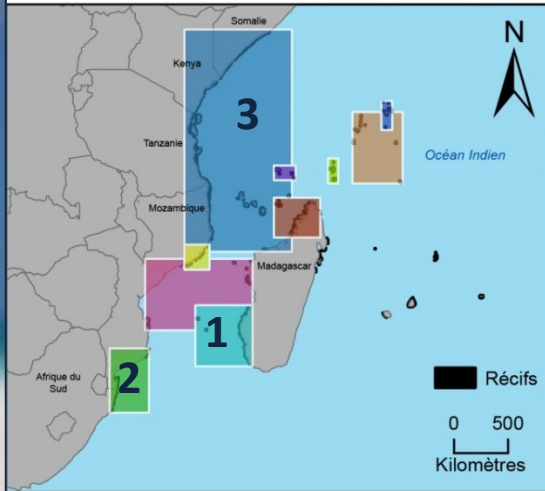
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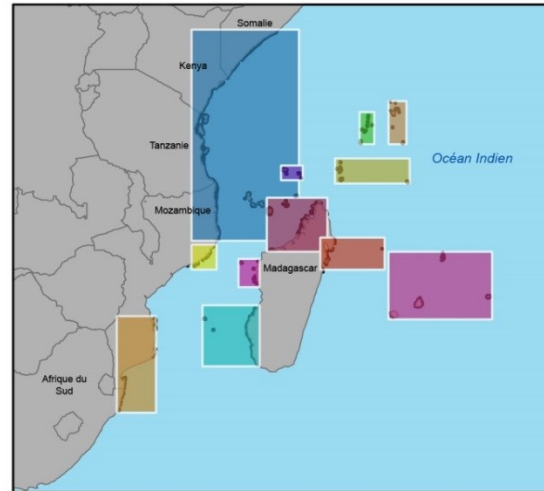
When PLD \nearrow , nb of connections \nearrow

CLUSTERING

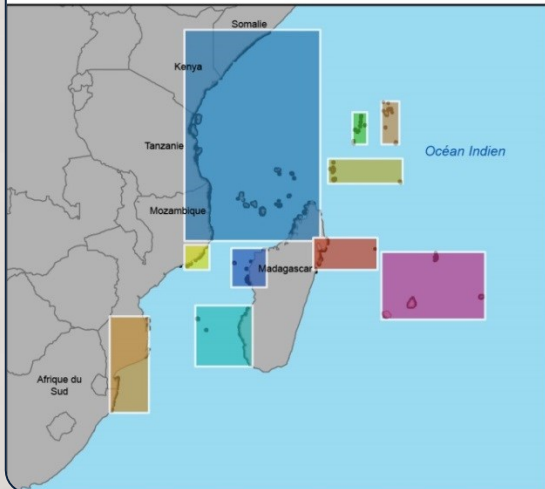
DVL = 10 jours, 10 clusters



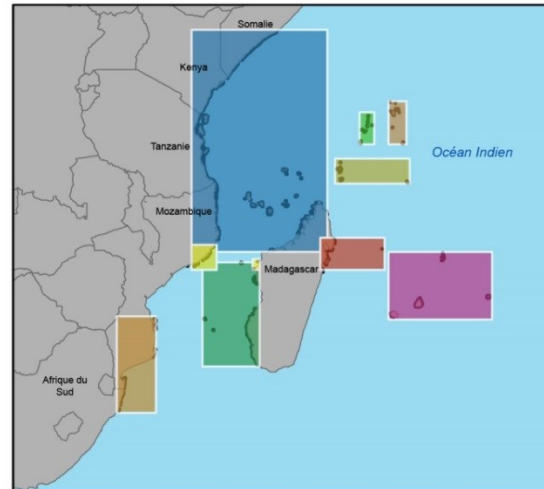
DVL = 20 jours, 12 clusters



DVL = 30 jours, 10 clusters



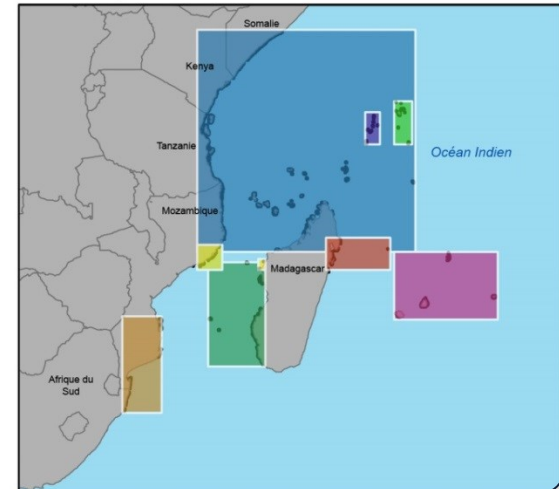
DVL = 40 jours, 10 clusters



Clusters depend on PLD

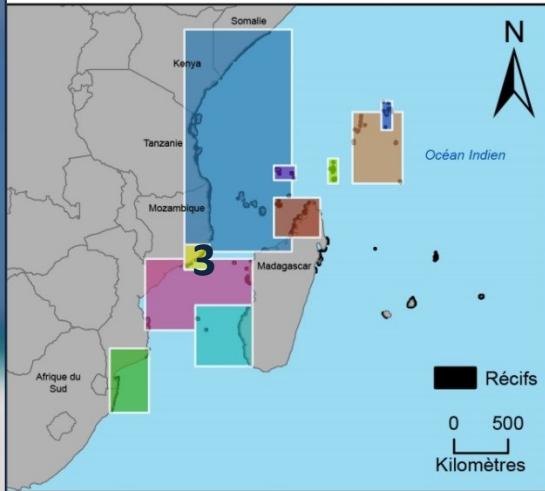
PLD \nearrow , clusters size \nearrow :
1, 2, 3

DVL = 50 jours, 9 clusters

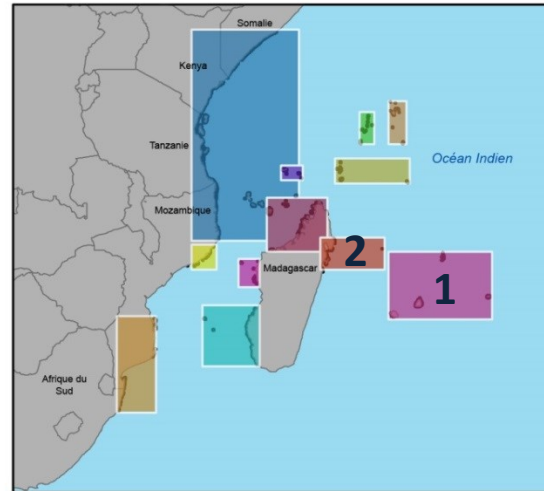


CLUSTERING

DVL = 10 jours, 10 clusters

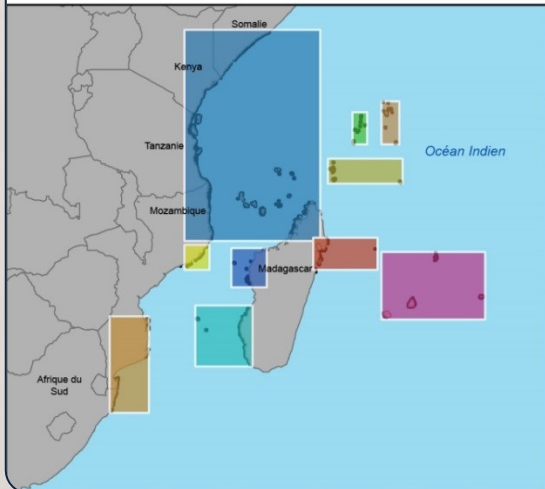


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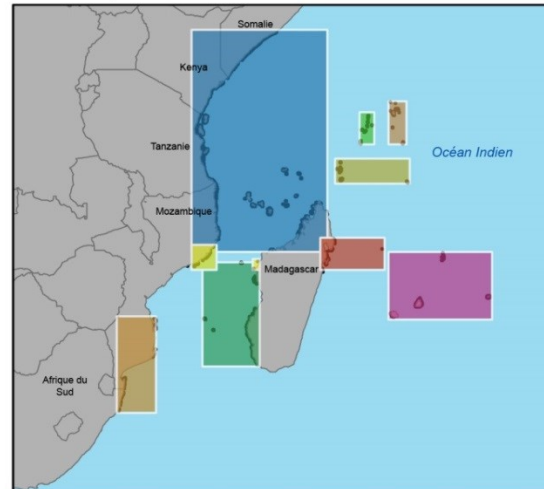


Some don't change : 1, 2, 3

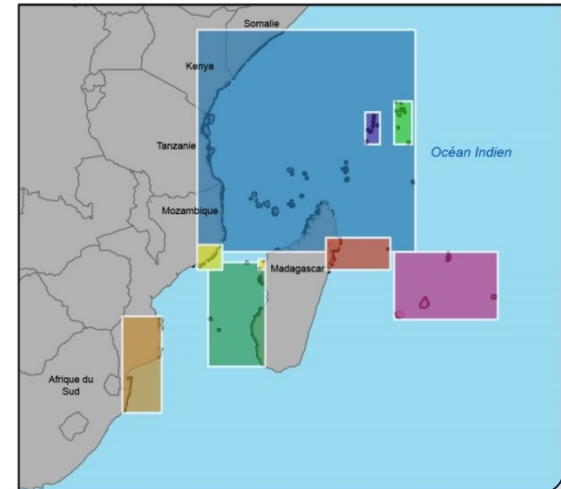
DVL = 30 jours, 10 clusters



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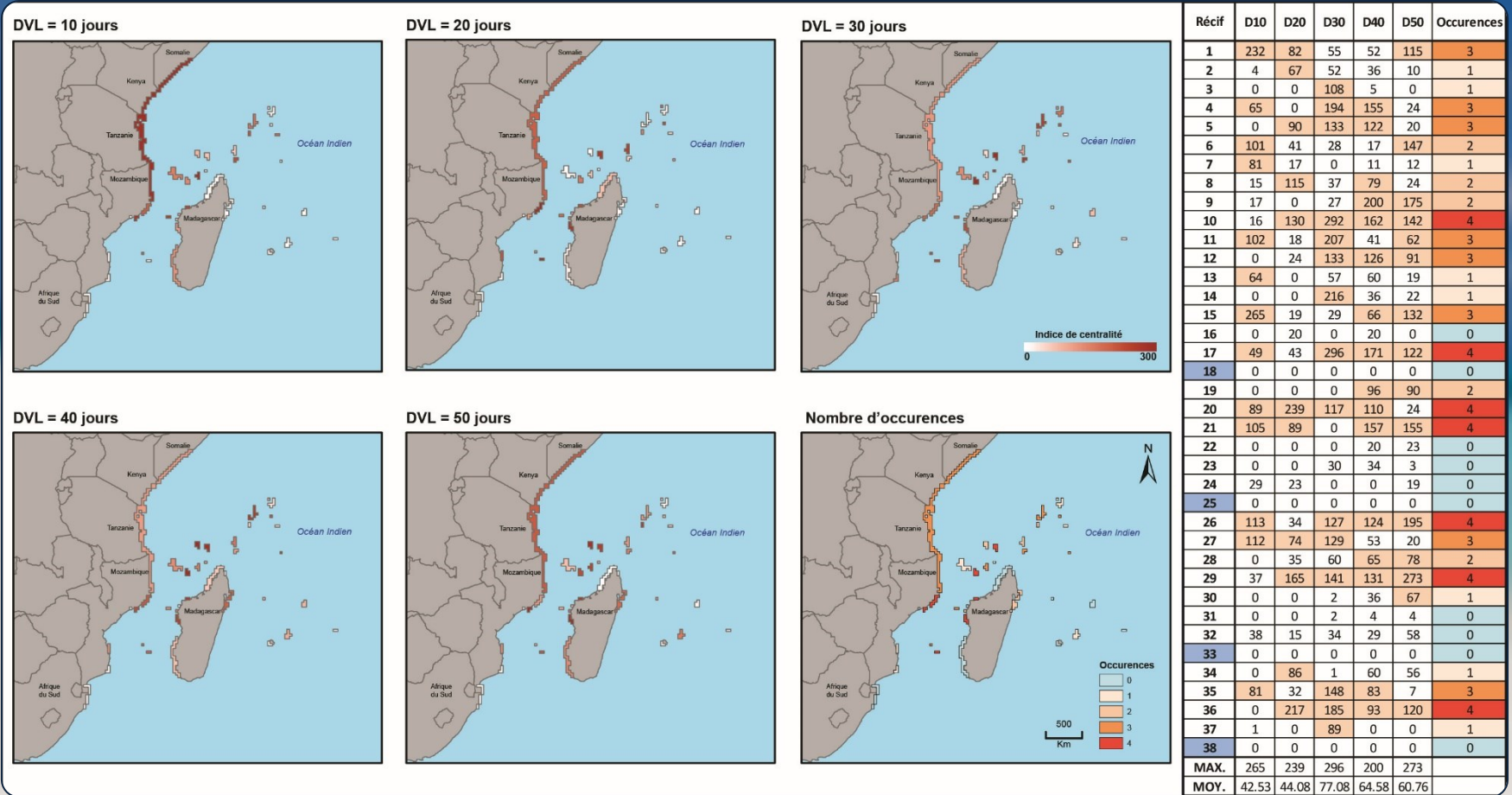
DVL = 50 jours, 9 clusters



Regional connectivity in the Indian Ocean

Centrality depend on PLD

BETWEENNESS CENTRALITY



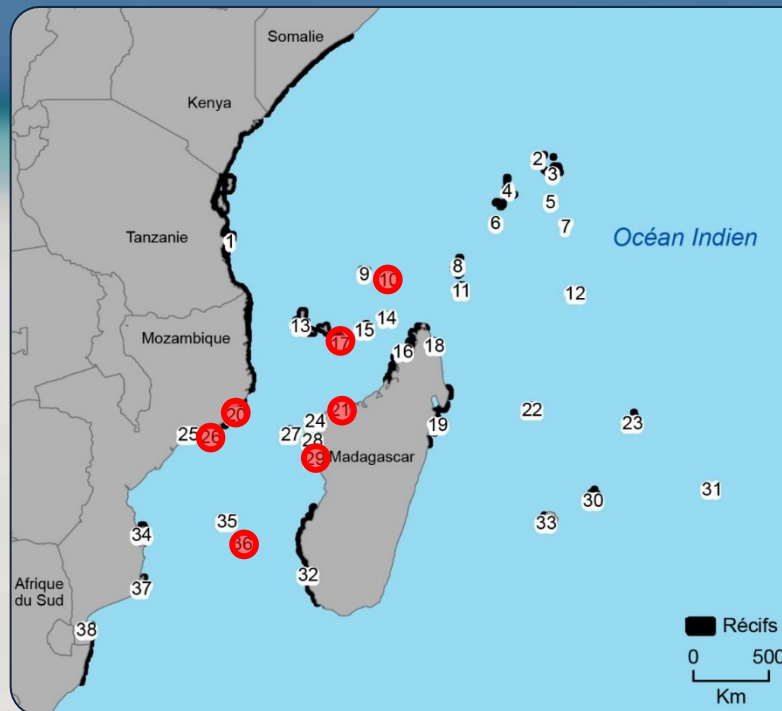
Reefs in the network with high betweenness centrality are gateways through which individuals have to pass in order to spread to other nodes, and therefore may be the most important for multigenerational connectivity within the region

Regional connectivity in the Indian Ocean

BETWEENNESS CENTRALITY

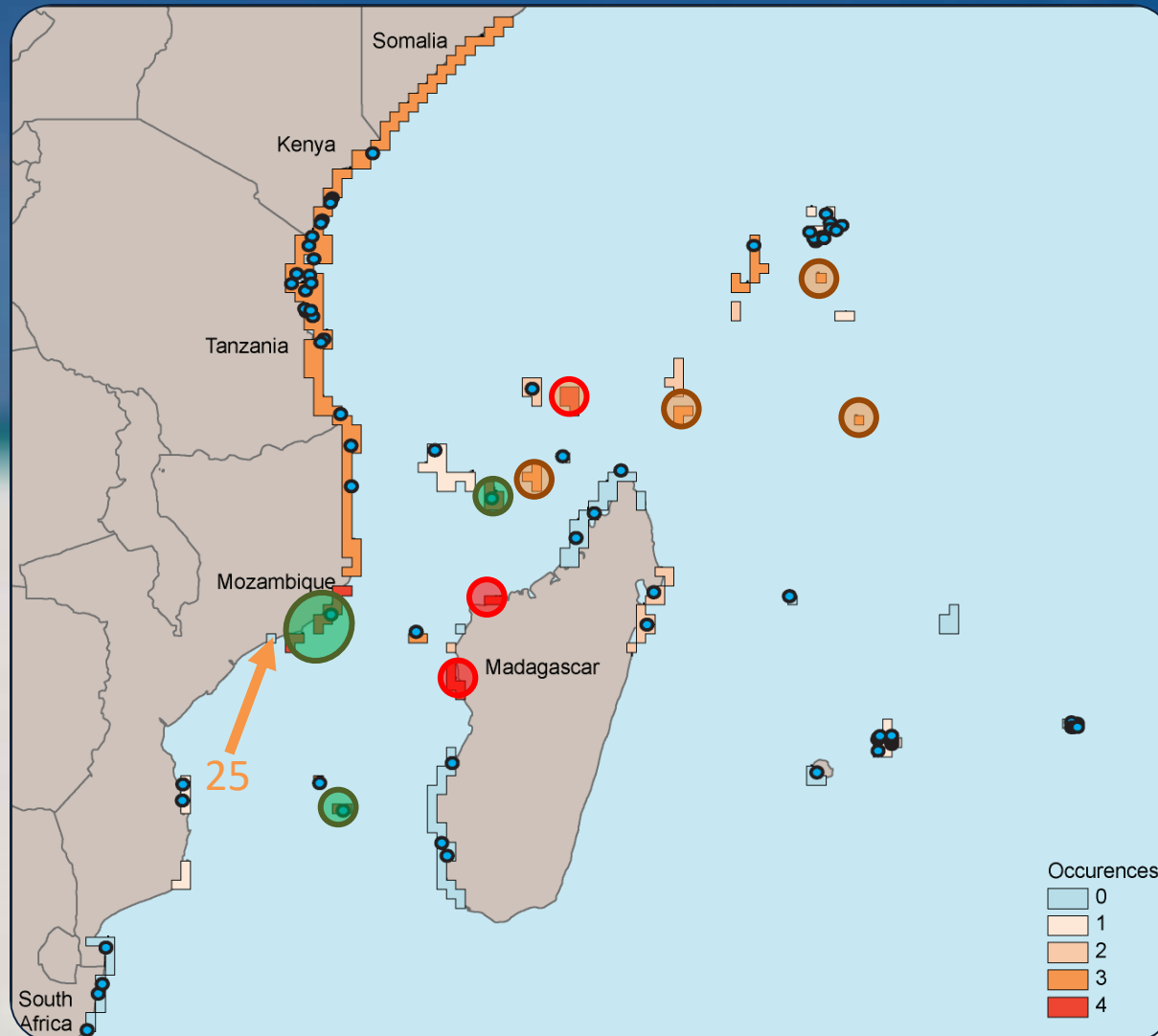
7 reefs : Occurrences = 4 → the most important for multigenerational connectivity within the WIO

Récif	D10	D20	D30	D40	D50	Occurrences
1	232	82	55	52	115	3
2	4	67	52	36	10	1
3	0	0	108	5	0	1
4	65	0	194	155	24	3
5	0	90	133	122	20	3
6	101	41	28	17	147	2
7	81	17	0	11	12	1
8	15	115	37	79	24	2
9	17	0	27	200	175	2
10	16	130	292	162	142	4
11	102	18	207	41	62	3
12	0	24	133	126	91	3
13	64	0	57	60	19	1
14	0	0	216	36	22	1
15	265	19	29	66	132	3
16	0	20	0	20	0	0
17	49	43	296	171	122	4
18	0	0	0	0	0	0
19	0	0	0	96	90	2
20	89	239	117	110	24	4
21	105	89	0	157	155	4
22	0	0	0	20	23	0
23	0	0	30	34	3	0
24	29	23	0	0	19	0
25	0	0	0	0	0	0
26	113	34	127	124	195	4
27	112	74	129	53	20	3
28	0	35	60	65	78	2
29	37	165	141	131	273	4
30	0	0	2	36	67	1
31	0	0	2	4	4	0
32	38	15	34	29	58	0
33	0	0	0	0	0	0
34	0	86	1	60	56	1
35	81	32	148	83	7	2
36	0	217	185	93	120	4
37	1	0	89	0	0	1
38	0	0	0	0	0	0
MAX.	265	239	296	200	273	
MOY.	42.53	44.08	77.08	64.58	60.76	



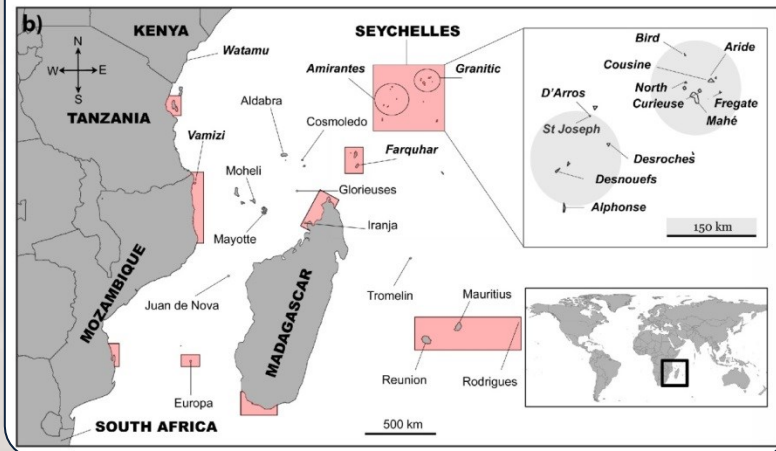
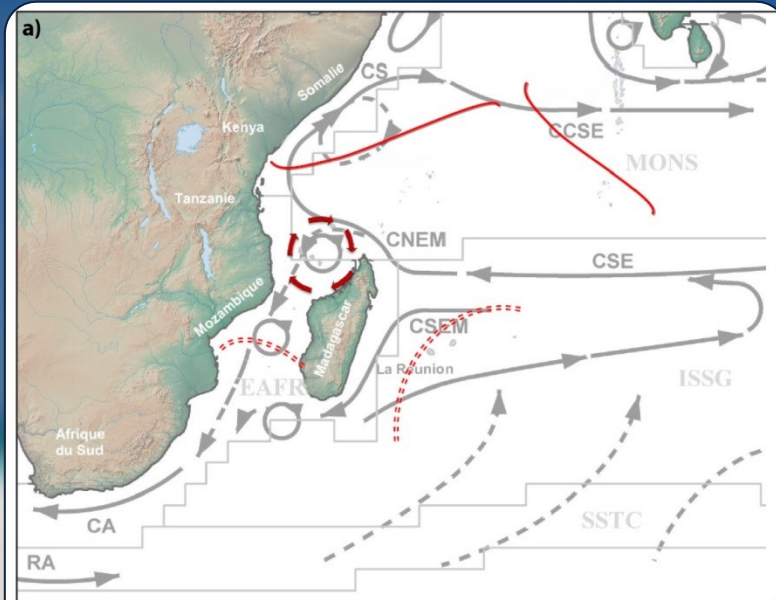
1	Mozambique/Tanzanie Kenya/Somalie	20	Angoche
2	Bird	21	Majunga
3	Seychelles	22	Tromelin
4	Poivre	23	Saint Brandon
5	Platte	24	Besalampy
6	Alphonse	25	Pebane
7	Coëtivy	26	Moma
8	Providence	27	Juan de Nova
9	Aldabra	28	Maintirano
10	Cosmoledo	29	Masoarivo
11	Farqhar	30	Maurice
12	Agalega	31	Rodrigues
13	Comores	32	Morondava - Anakao
14	Glorieuses	33	La Réunion
15	Geyser bank	34	Bazaruto arch.
16	NW tip of Madagascar	35	Bassas da India
17	Mayotte	36	Europa
18	Nosy Ankomba / Anko	37	Maxixe
19	Masoala peninsula Ste Marie	38	Maputo bay to Santa Lucia

Regional connectivity in the Indian Ocean



- Only 3 sites of high centrality (Nb. O = 4), hosts an MPA ●
Europa, Mayotte, Moma, Angoche
 - Other high centrality sites can be considered as priority sites for MPA implementation ●
Cosmoledo, Majunga, Masoarivo
 - 4 more sites can be added : Nb. O = 3 ●
Platte, Farqhar, Agalega Geyser
- + Reef 25 (Pebane)
completely isolated for all PLD

Regional connectivity in the Indian Ocean



Muths et al., 2012 (a); Bourjea, 2014 (b)

- Nb connections ↗ with PLD
- Low regional connectivity
- High interconnectivity within sub-regions (Mozambique Channel, Mascarene archipelago)
- Results congruent with genetic analysis on:

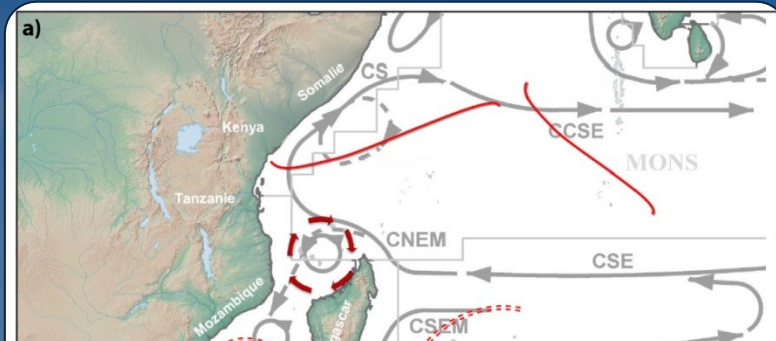
Reef fish → Muths et al. (2011, 2012, 2014):
E.merra, *L. kasmira* et *M. berndti*

Turtles → Bourjea et al. (2007)

Brittle star → Hoareau et al. (2013)

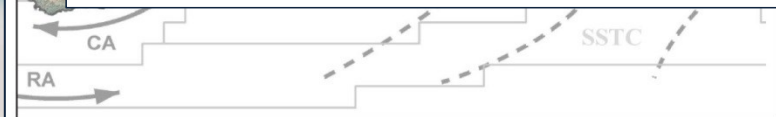
- Results congruent with biogeographic studies → Obura (2012): coral triangle (high diversity - Northern Mozambique Channel)
- Similarities with turtles conservation priority areas → Bourjea (2014)

Regional connectivity in the Indian Ocean



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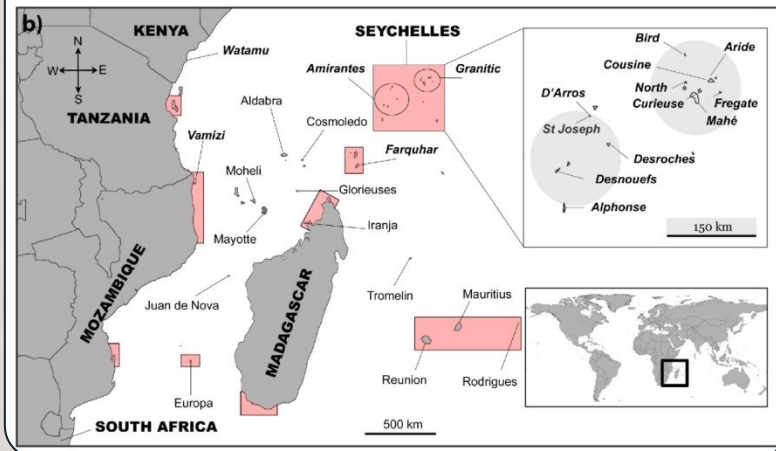
Crucial to have a multi-specific approach at the regional scale to elaborate suitable management plans



E.merra, L. kasmira et M. berndti

Turtles → Bourjea et al. (2007)

Brittle star → Hoareau et al. (2013)



- Results congruent with biogeographic studies → Obura (2012): coral triangle (high diversity - Northern Mozambique Channel)

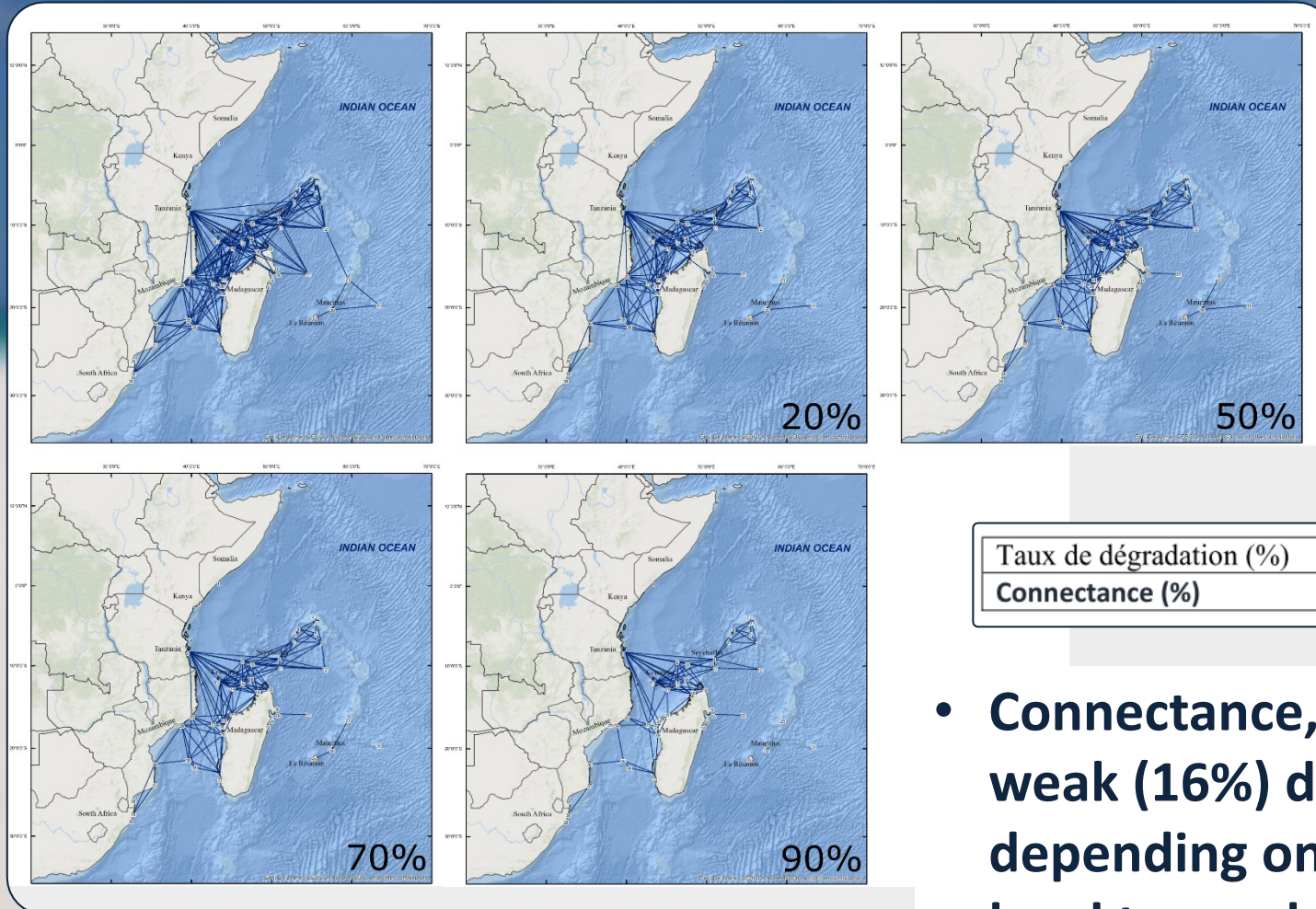
- Similarities with turtles conservation priority areas → Bourjea (2014)



*What about habitat degradation within
the context of increasing pressures?*

HABITAT DEGRADATION SCENARIOS

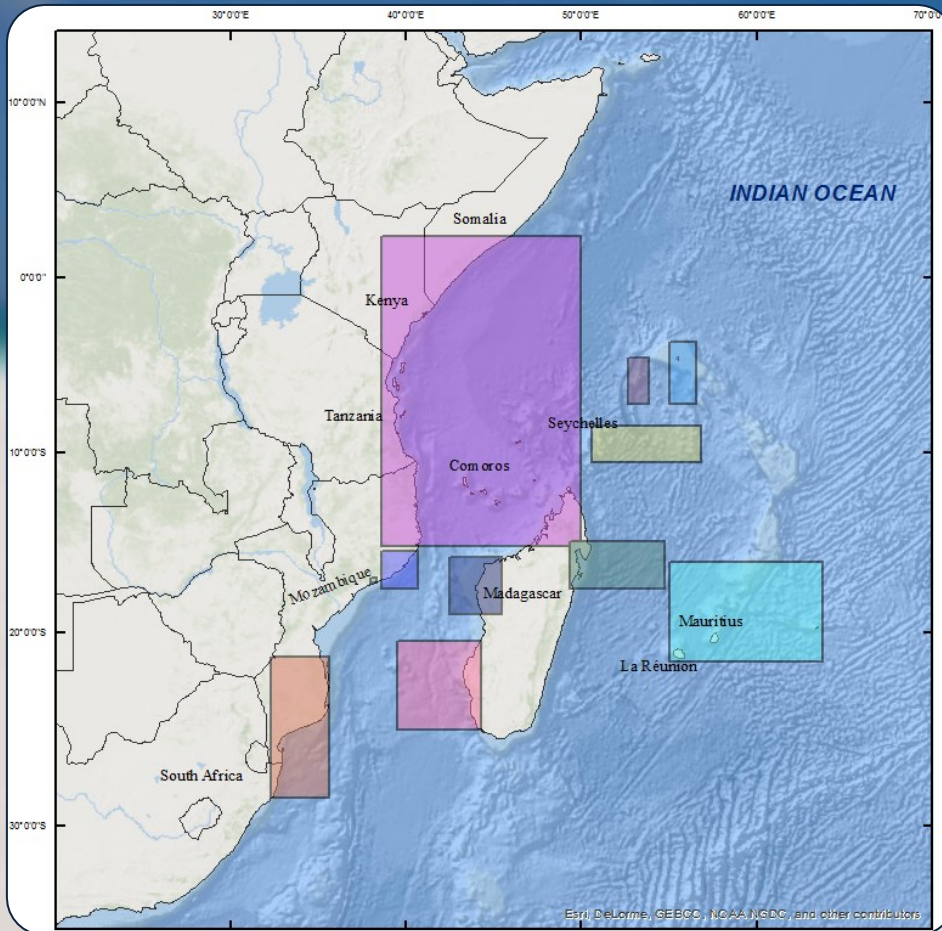
CONNECTANCE



- **Connectance, which is quite weak (16%) decreases depending on degradation level to reach 7%.**

Habitat degradation scenarios

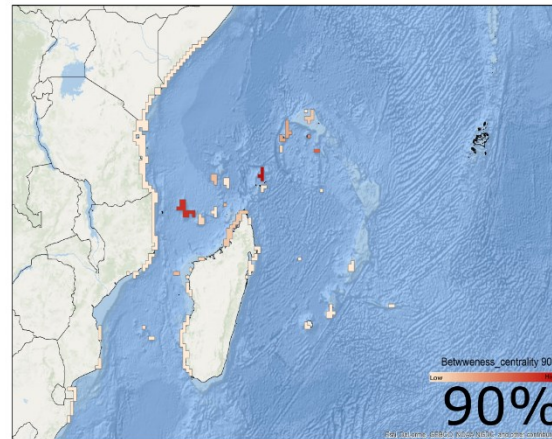
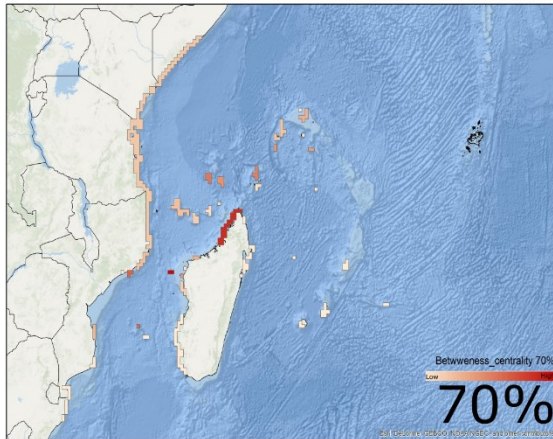
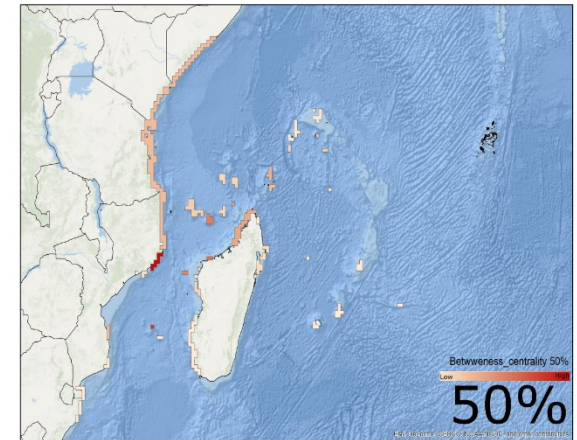
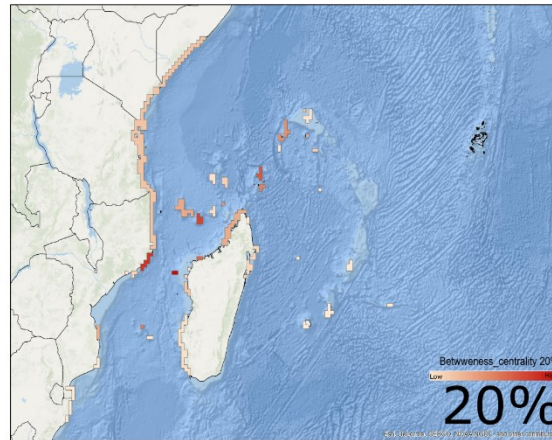
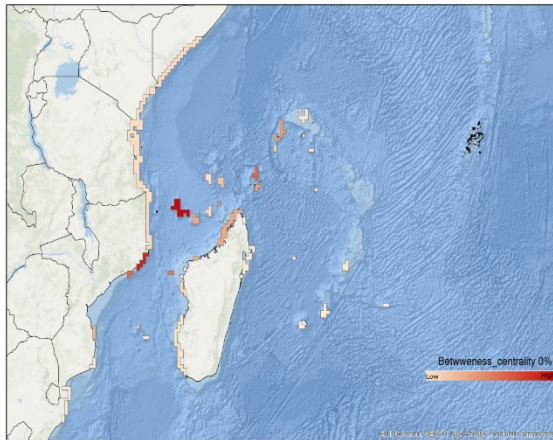
CLUSTERING



- Similar clusters for degradation indices = 20, 50%
- From 70%, Mascarene archipelago islands begin to be completely isolated from the other islands/reefs.

Habitat degradation scenarios

BETWEENNESS CENTRALITY



- Reef centrality change depending on the degradation index
- It completely modifies the network nodes for multigenerational connectivity

PERSPECTIVES



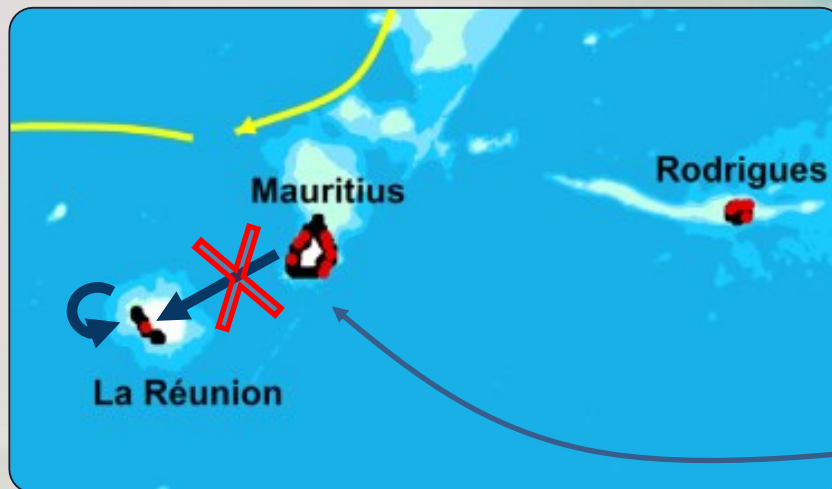
IMPLICATIONS IN TERMS OF MANAGEMENT

This work :

- Highlights the geographic scale of marine connectivity in the WIO
- Provides support for spatial based planning processes and regional cooperation

→ Large scale connectivity : not only self-recruitment, ecosystems are linked

→ MPA implementation has to be designed relatively to connectivity patterns (distinguishing sink/source sites)

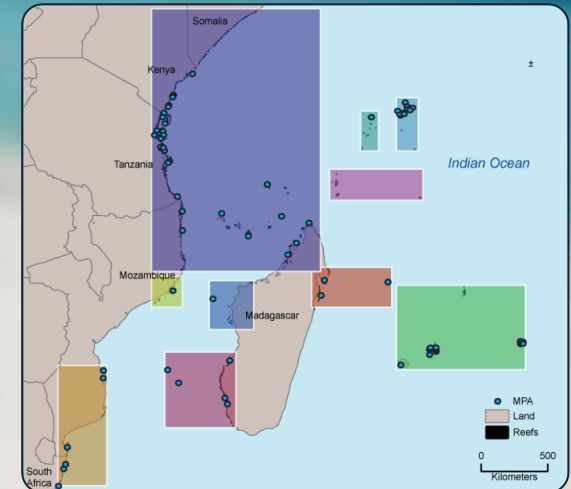


IMPLICATIONS IN TERMS OF INTERNATIONAL COOPERATION

MPA implementation has to be designed as a network and planned at the regional scale to maintain connectivity

→ Implies regional cooperation between governments for effective transnational management - political will

→ The regional scale conservation planning could be set-up through international cooperation, only including groups of countries (corresponding with clustering results for example) **but also through already existing regional instruments such as IOC, Nairobi convention in the IO.**



Or Northern Mozambique Channel initiative / Grand Observatoire de l'OI

Thank you for your attention !

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