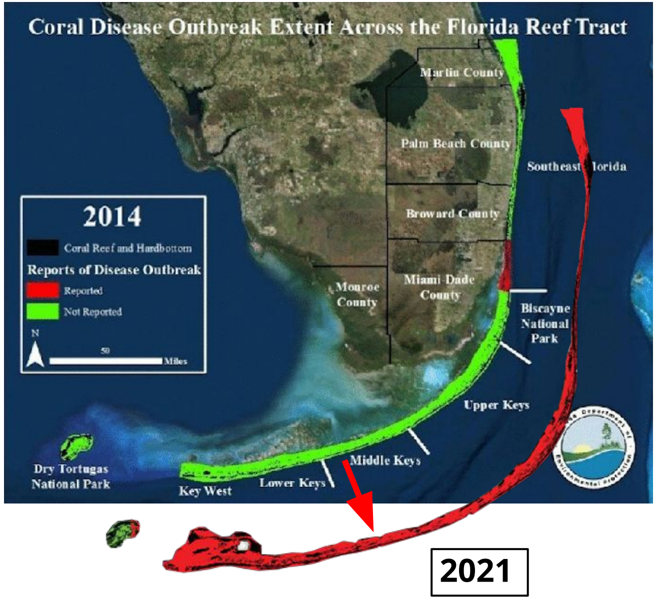
Disentangling coral disease and coral larvae connectivity to inform reef restoration in Florida.

Thomas Dobbelaere, Daniel M. Holstein, Erinn M.Muller, Lewis J. Gramer, Luke McEachron, Sara D Williams, Emmanuel Hanert

thomas.dobbelaere@uclouvain.be

Since 2014, Florida corals have been affected by the Stony Coral Tissue Loss Disease (SCTLD)



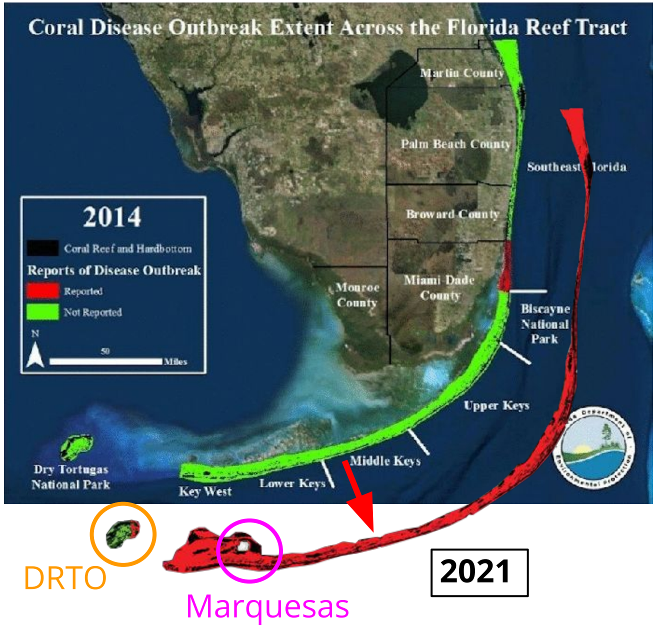
At least 22 reef building species affected

Decline in living coral tissue area of ~60% on impacted reefs.

Up to a 95% decrease in density of susceptible species on affected reefs

⇒ **Largest coral disease outbreak on record.**

Since 2014, Florida corals have been affected by the Stony Coral Tissue Loss Disease (SCTLD)



At least 22 reef building species affected

Decline in living coral tissue area of ~60% on impacted reefs.

Up to a 95% decrease in density of susceptible species on affected reefs

⇒ **Largest coral disease outbreak on record**.

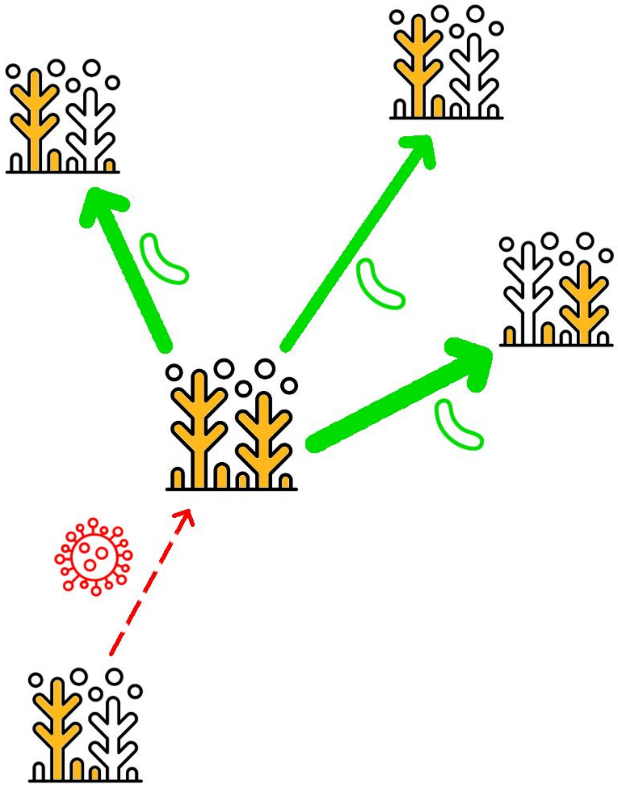
...BUT the spread of SCTLD apparently stalled between the Marquesas and the Dry Tortugas (DRTO) in 2020 (until May 2021)

It is thus urgent to restore reefs while preventing SCTLD to strike back

Larval exchanges between reefs promote the resilience of the network

However, the SCTLD is likely water-borne

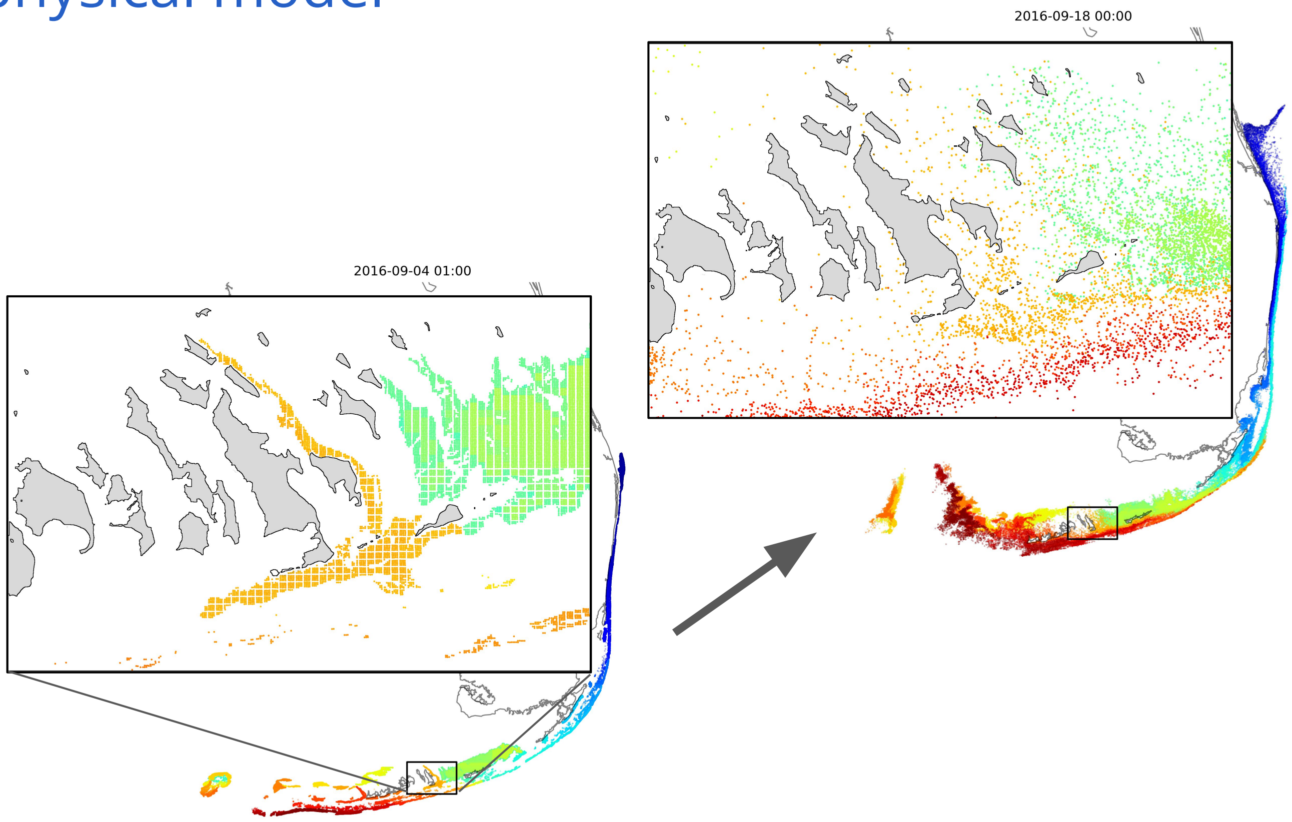
⇒ Identify reefs that are **good larval sources** for the network while being **weak potential sinks of disease** agent



To do so, we simulated the transport of coral larvae and disease agents with a biophysical model

Monthly **connectivity matrices** for **SCTLD** between May 2018 and May 2021

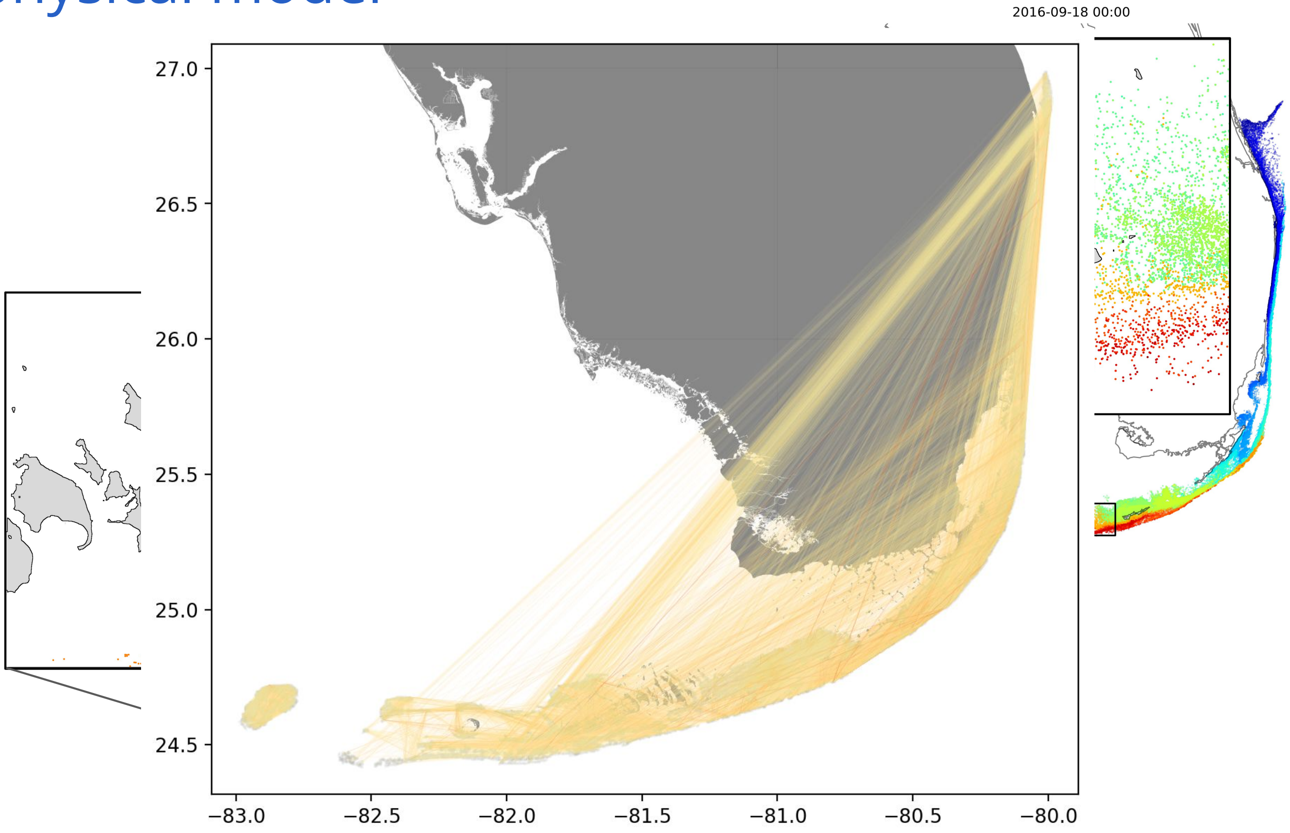
Connectivity matrices for **3 spawnings events** of *Acropora cervicornis*, *Dendrogyra cylindrus* and *Orbicella faveolata* in 2018, 2019 and 2020



To do so, we simulated the transport of coral larvae and disease agents with a biophysical model

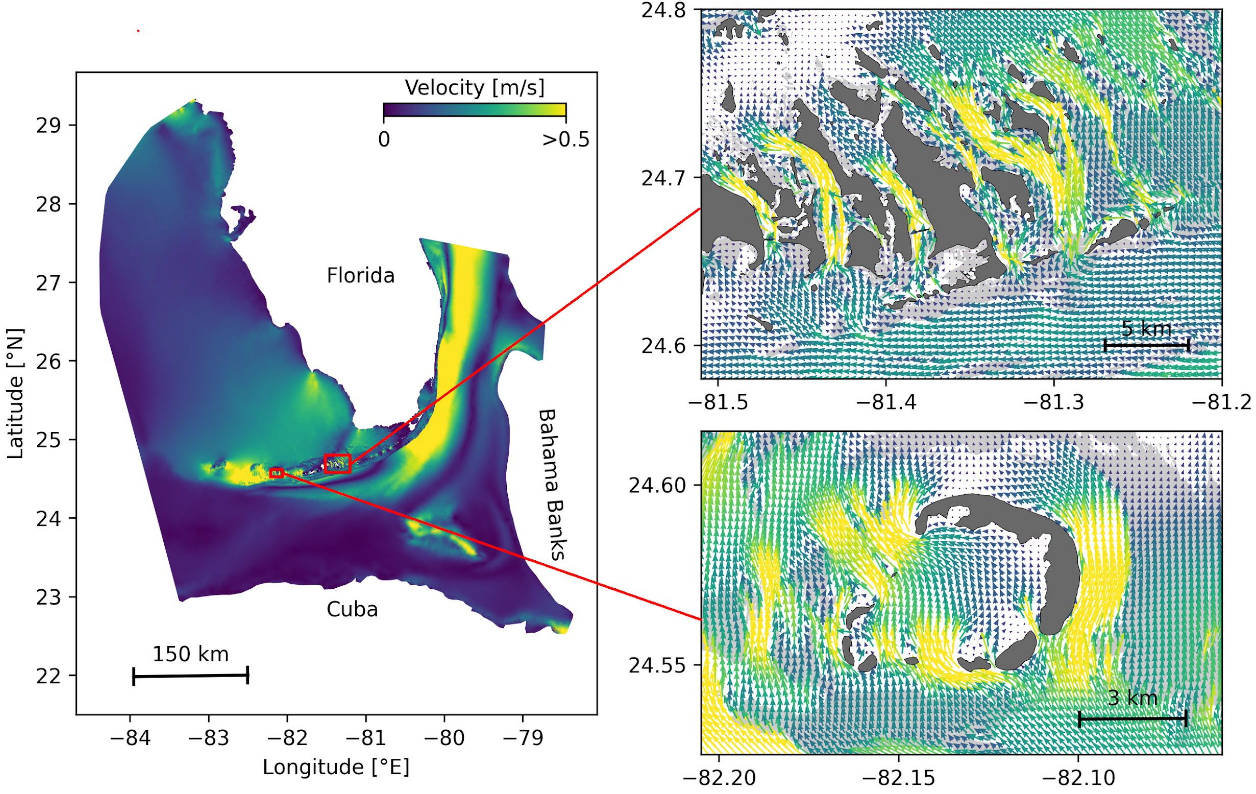
Monthly **connectivity matrices** for **SCTLD** between May 2018 and May 2021

Connectivity matrices for **3 spawnings events** of *Acropora cervicornis*, *Dendrogyra cylindrus* and *Orbicella faveolata* in 2018, 2019 and 2020



We simulated the ocean circulation at the reef scale with the coastal ocean model SLIM

SLIM simulates the circulation around reefs and islands with a resolution of 100m (~10x more than existing models)



We then developed a restoration index based on the weighted in- and out-degrees for SCTLD and larvae for each reef

Weighted disease in-degree

$$\left.\begin{aligned} D_i^{in} &= k_i^{in,dis} \times \left(\frac{s_i^{in,dis}}{k_i^{in,dis}}\right)^{\alpha^{dis}} \\ C_i^{out} &= k_i^{out} \times \left(\frac{s_i^{out}}{k_i^{out}}\right)^{\alpha} \end{aligned}\right\} \longrightarrow R_i = \frac{C_i^{out} - \beta D_i^{in}}{C_{\max}^{out}}$$

Restoration index

Weighted coral out-degree

We then developed a restoration index based on the weighted in- and out-degrees for SCTLD and larvae for each reef

Weighted disease in-degree

$$D_i^{in} = \boxed{k_i^{in,dis}} \times \left(\frac{s_i^{in,dis}}{k_i^{in,dis}}\right)^{\alpha^{dis}}$$

$$C_i^{out} = \boxed{k_i^{out}} \times \left(\frac{s_i^{out}}{k_i^{out}}\right)^{\alpha}$$

Weighted larval out-degree

Restoration index

$$R_i = \frac{C_i^{out} - \beta D_i^{in}}{C_{\max}^{out}}$$

number of connections (= degree)

We then developed a restoration index based on the weighted in- and out-degrees for SCTLD and larvae for each reef

Weighted disease in-degree

$$D_i^{in} = \boxed{k_i^{in,dis}} \times \left(\frac{\boxed{s_i^{in,dis}}}{k_i^{in,dis}} \right)^{\alpha^{dis}}$$

$$C_i^{out} = \boxed{k_i^{out}} \times \left(\frac{\boxed{s_i^{out}}}{k_i^{out}} \right)^{\alpha}$$

Weighted larval out-degree

Restoration index

$$\longrightarrow R_i = \frac{C_i^{out} - \beta D_i^{in}}{C_{\max}^{out}}$$

number of connections (= degree)

sum of connection weights

We then developed a restoration index based on the weighted in- and out-degrees for SCTLD and larvae for each reef

Weighted disease in-degree

$$\left.\begin{aligned} D_i^{in} &= \boxed{k_i^{in,dis}} \times \left(\frac{\boxed{s_i^{in,dis}}}{k_i^{in,dis}}\right)^{\boxed{\alpha^{dis}}} \\ C_i^{out} &= \boxed{k_i^{out}} \times \left(\frac{\boxed{s_i^{out}}}{k_i^{out}}\right)^{\boxed{\alpha}} \end{aligned}\right\} \longrightarrow R_i = \frac{C_i^{out} - \beta D_i^{in}}{C_{\max}^{out}}$$

Restoration index

Weighted larval out-degree

number of connections (= degree)

sum of connection weights

relative importance of degree versus connection weight

We then developed a restoration index based on the weighted in- and out-degrees for SCTLD and larvae for each reef

Weighted disease in-degree

$$\left.\begin{aligned} D_i^{in} &= \boxed{k_i^{in,dis}} \times \left(\frac{\boxed{s_i^{in,dis}}}{k_i^{in,dis}}\right)^{\boxed{\alpha^{dis}}} \\ C_i^{out} &= \boxed{k_i^{out}} \times \left(\frac{\boxed{s_i^{out}}}{k_i^{out}}\right)^{\boxed{\alpha}} \end{aligned}\right\} \longrightarrow R_i = \frac{C_i^{out} - \boxed{\beta} D_i^{in}}{C_{\max}^{out}}$$

Weighted larval out-degree

Restoration index

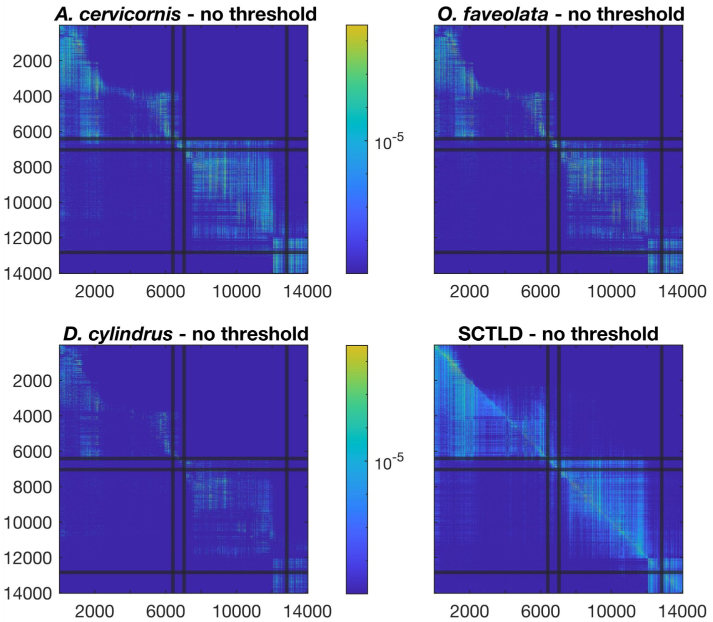
Relative importance of disease risk (susceptibility to disease)

number of connections (= degree)

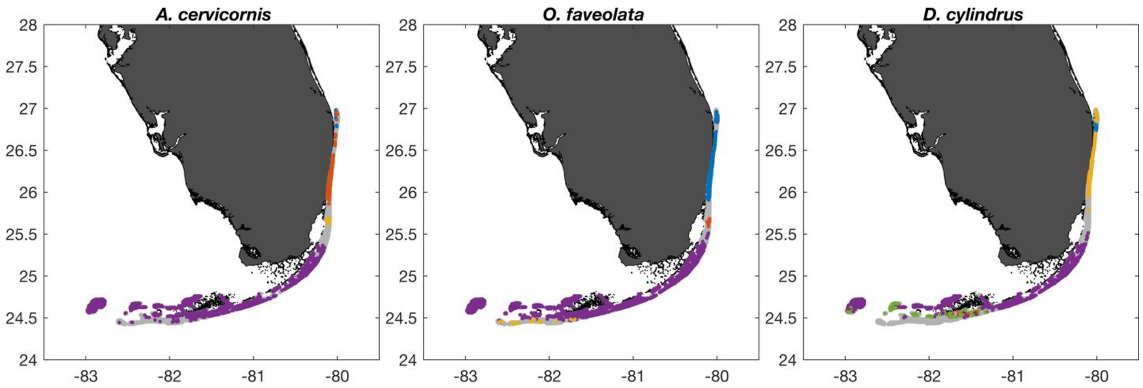
sum of connection weights

relative importance of degree versus connection weight

Connectivity analysis suggests that all reefs are reachable by the disease pathogen and reveals more fragmented network for D. cylindrus



Mean connectivity matrices: SCTLD has stronger connections while *D. cylindrus* exhibits weak connections compared to the other two species

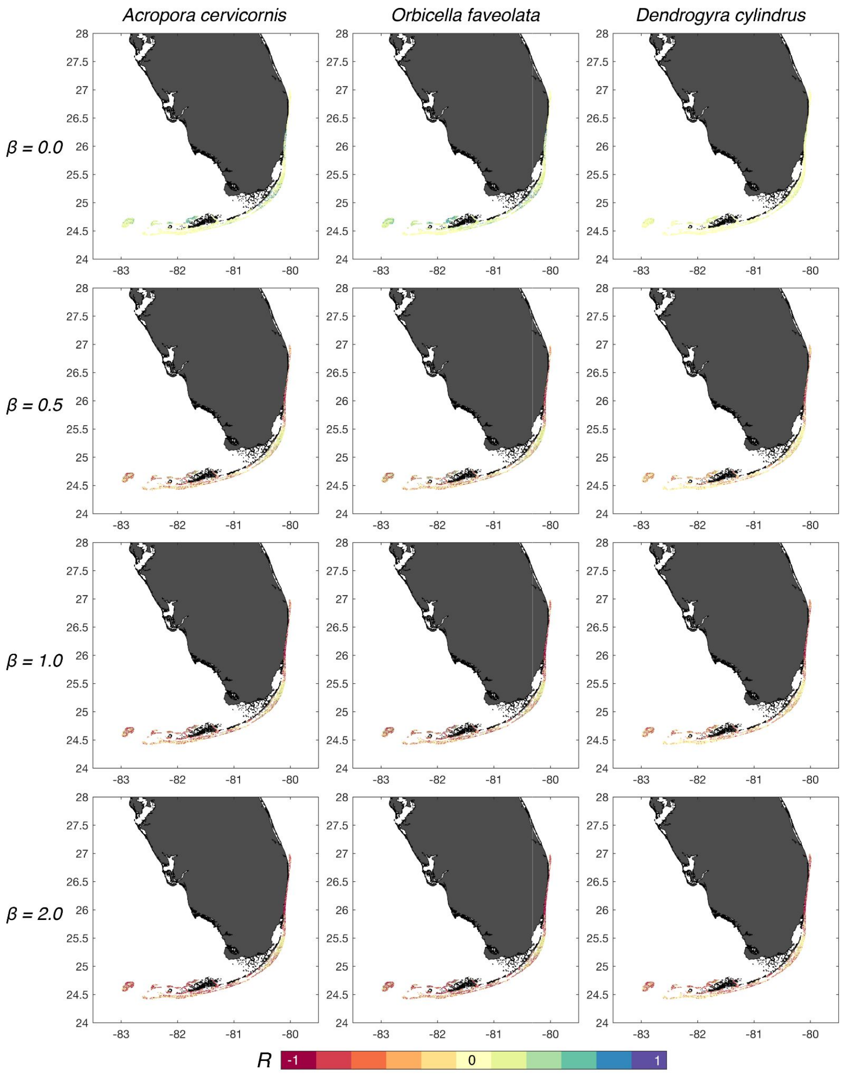


Strongly connected communities (SCC):

Consistent separation between the North of the Florida Reef Tract and the Florida Keys

Notably smaller SCC in the Keys for D. cylindrus

Averaged SCTLD network has a single SCC covering the whole FRT ⇒ can potentially reach any reef



Some reefs have consistent restoration index values across species for different values of β

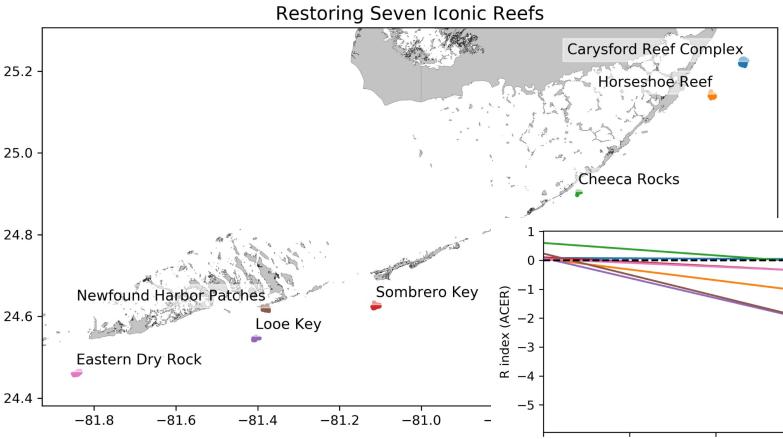
Reefs in the **Upper Keys** generally have **low restoration index** value

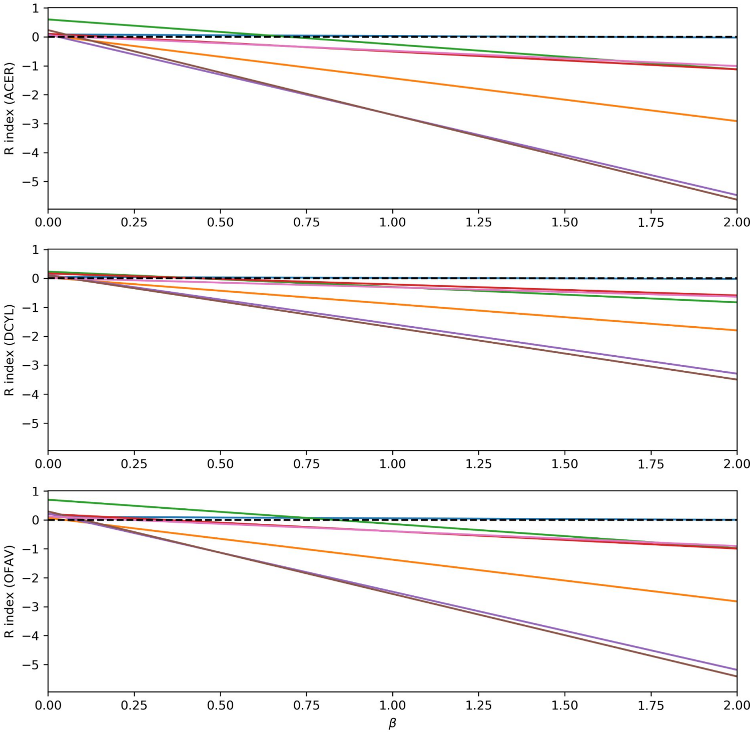
Some reefs exhibit **high restoration index** values even with **high β** for all species ⇒ **attractive for ecosystem-based restoration**

Similar spatial patterns between *O. faveolata* and *A. cervicornis* ⇒ possible **coupled restoration ?**

R can be used to assess the susceptibility of restored reefs to disease

Seven iconic reefs selected for restoration in the Florida Keys based on their ecological services, connectivity and genetic complexity





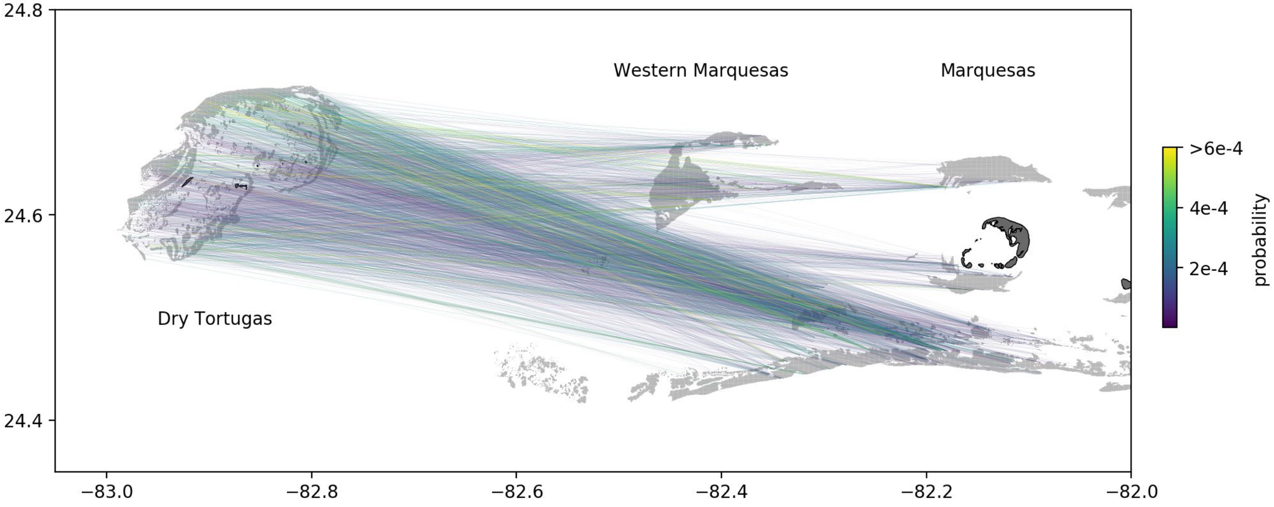
Our results suggest that:

Carysford Reef and Cheecah Rocks are more protected against disease (R > 0 when β < 0.4)

Horseshoe Reef and Looe Key are more susceptible to disease (R < 0 when β < 0.1)

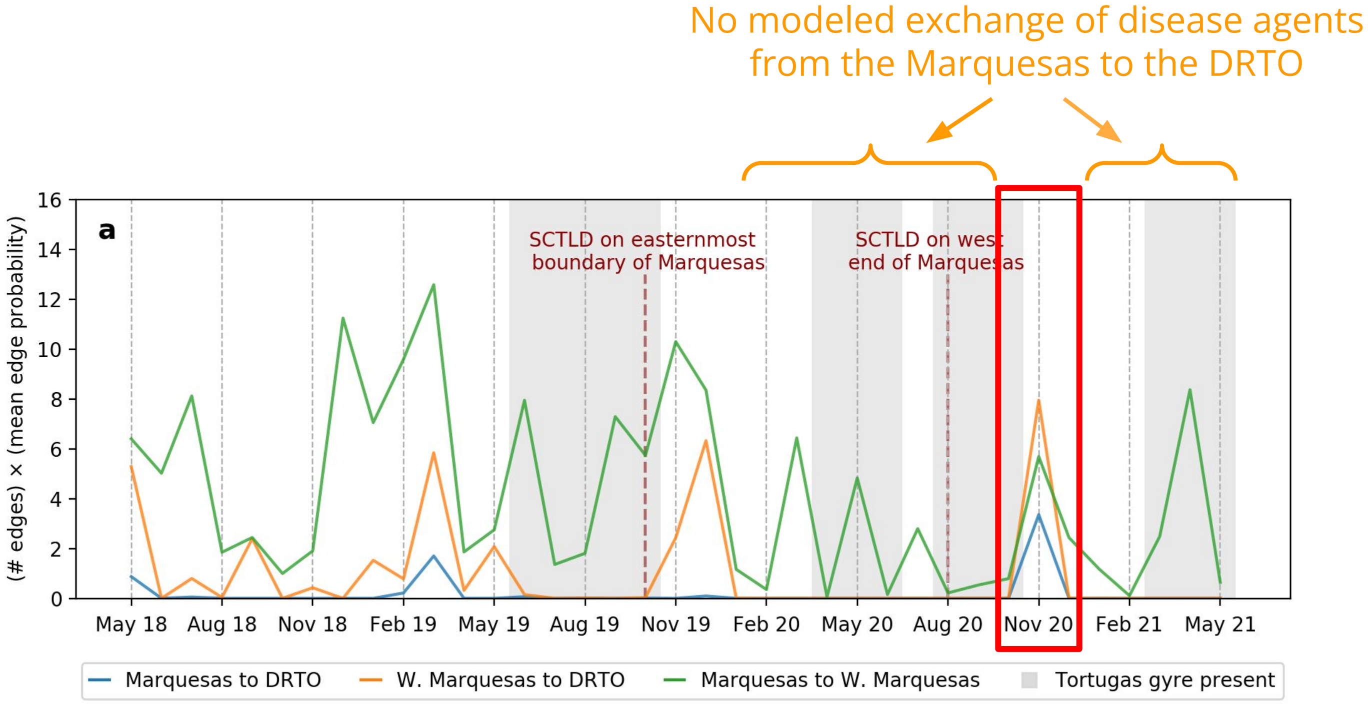
Furthermore, disease connectivity can be used to study the timing of the propagation of the disease from the Marquesas to the DRTO

We analyzed the temporal evolution of the number of hydrodynamic-predicted connections between the Marquesas and the DRTO in the disease network as well as their strength



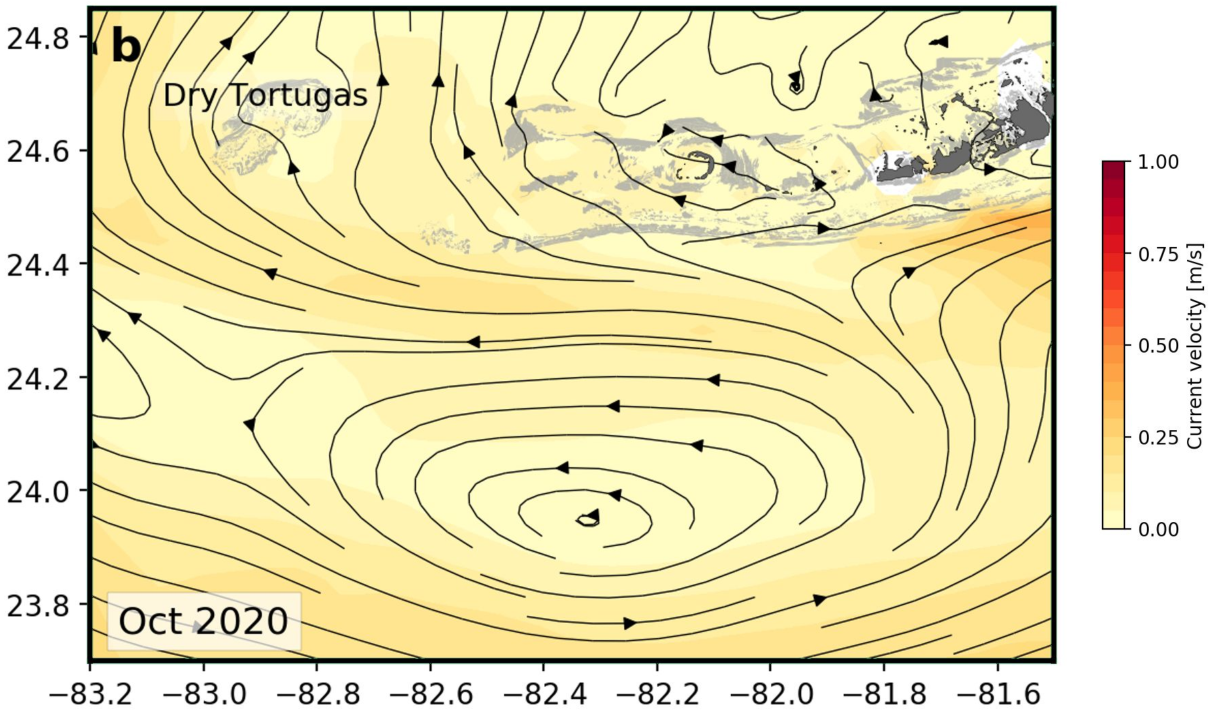
Our results suggest that disease agents probably reached the DRTO in November 2020

Our results indicate that the connectivity between the Marquesas and the Dry Tortugas is strongly impacted by the local eddy activity



Our results suggest that disease agents probably reached the DRTO in November 2020

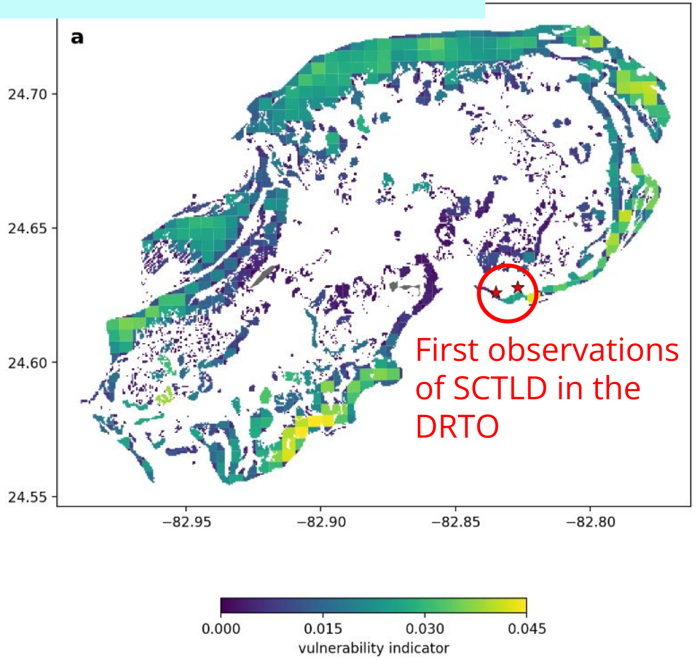
Our results indicate that the connectivity between the Marquesas and the Dry Tortugas is strongly impacted by the local eddy activity



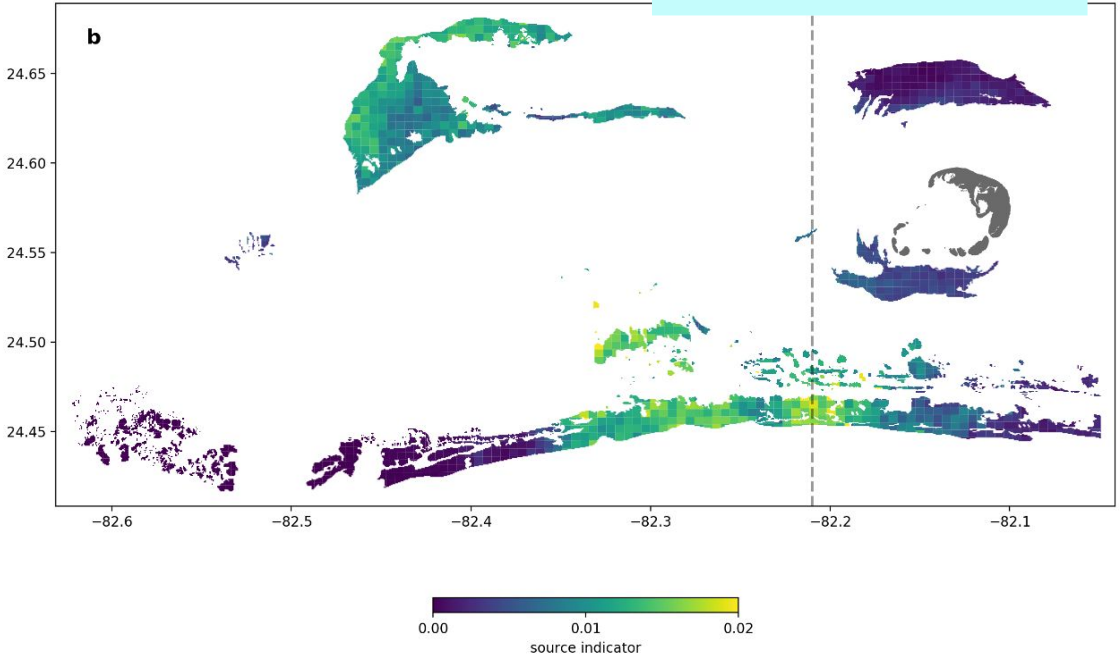
By summing the strengths of all incoming and outcoming connections, we can identify the regions most likely to initiate the propagation of SCTLD to the DRTO

Reefs most likely to get affected on eastern DRTO

Reefs of the southern Marquesas most likely to propagate SCTLD



First observations of SCTLD in the DRTO



In brief

We used a high resolution bio-physical model to build restoration metrics taking larval connectivity and disease risk into account.

D. cylindrus is especially at risk due to its high susceptibility to the SCTLD and fragmented larval connectivity.

Reefs with high R value for all species are good potential candidates for restoration although complementary studies taking coral species distribution and density into account are required.

Hydrodynamic-predicted disease network can help to understand the timing of the propagation of the disease throughout Florida