Spatiotemporal Model of Coral Reefs

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Collaborators / Mentors: Martin Robinson[2], Maria Bruna[2], Laurel Larsen[1]

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Why Study Coral ?

Coral reef systems are **critical and complicated**

25% of marine life began in a reef

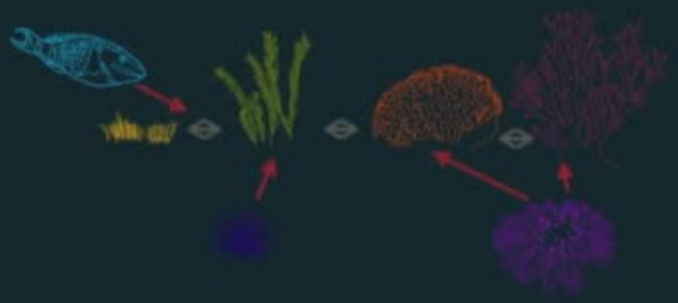
Billion dollar industry (UNEP, 2018).

Projected temperature increases -> more coral mortality

Intriguing nonlinearities

Overview

Coral Reef Introduction



Underlying ODEs

$$\frac{dM}{dt} = aMC - \frac{gM}{M+T} + \gamma MT$$

$$\frac{dC}{dt} = rTC - dC - aMC$$

$$\frac{dT}{dt} = \frac{gM}{M+T} - \gamma MT - rTC + dC$$

Overview

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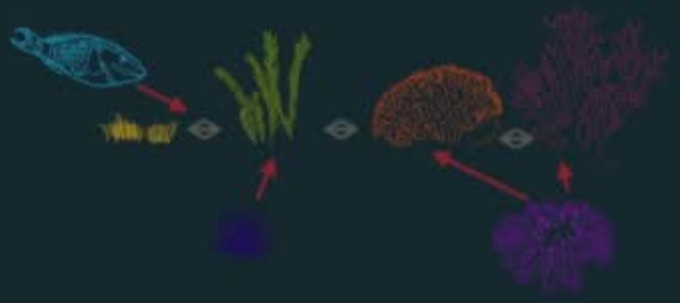

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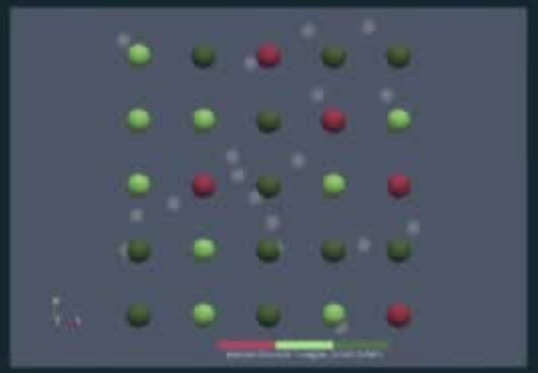
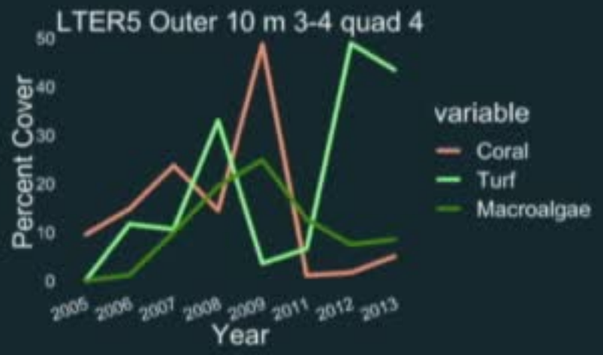
Space and Stochasticity



Reef Representation



The Coral Organism and its symbiont

Drawing inspired by diagram on algaeresearchsupply.com

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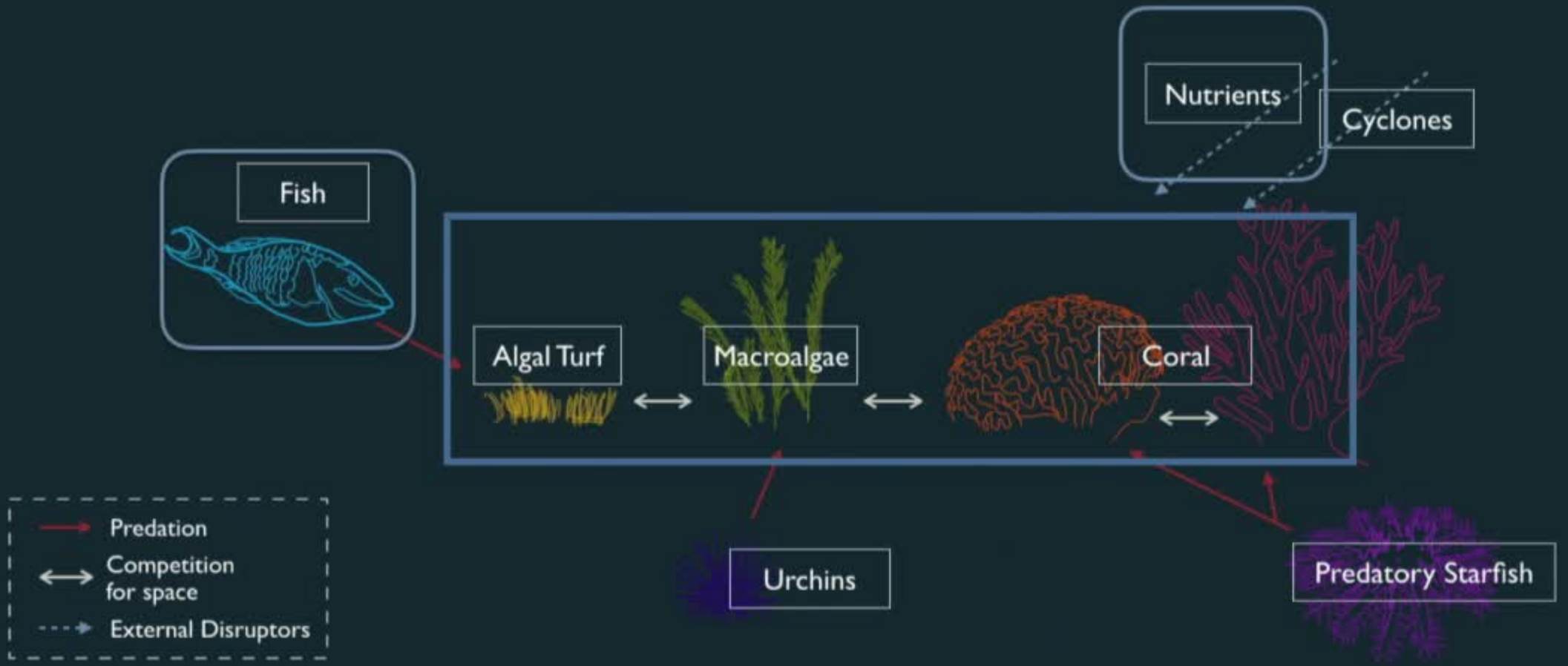
Coral Reef Predation and Competition



Coral Reef Predation and Competition Equations

Mumby, Hastings, Edwards 2007

$$\frac{dM}{dt} = aMC - \frac{gM}{M+T} + \gamma MT$$

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M Macroalgae

C Coral

T Turf

r Growth rate of coral over turf

d Death rate of coral

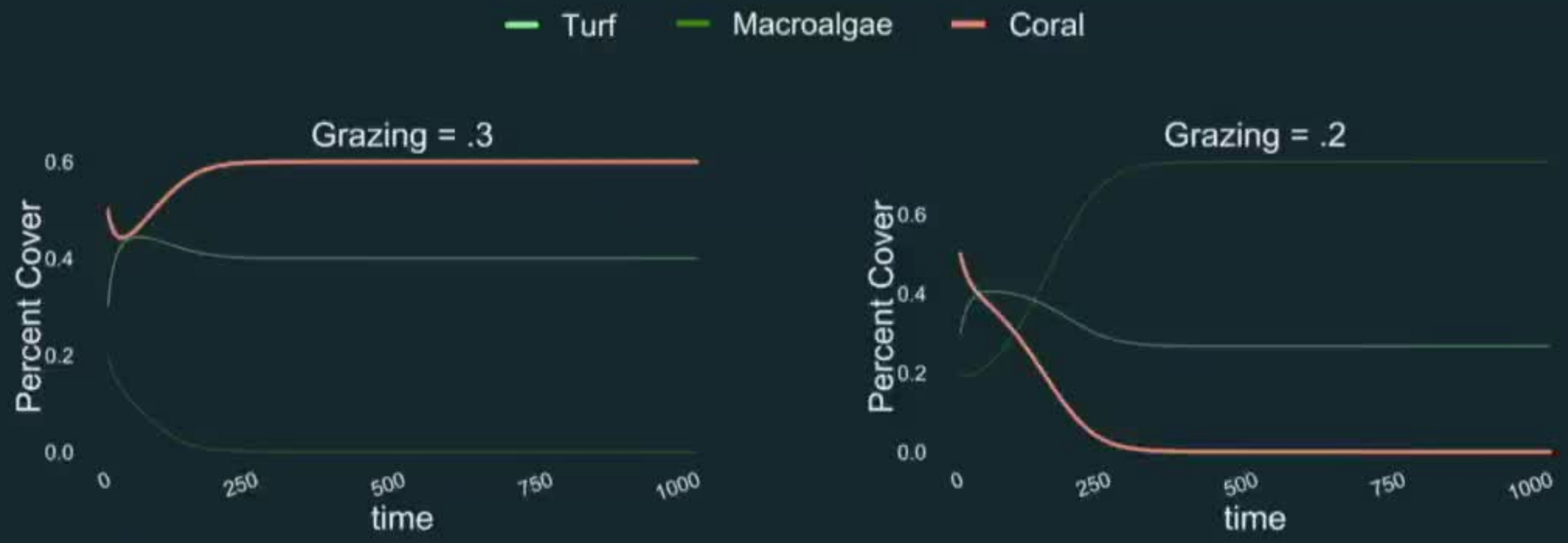
a Growth rate of macroalgae over coral

g Rate of grazing

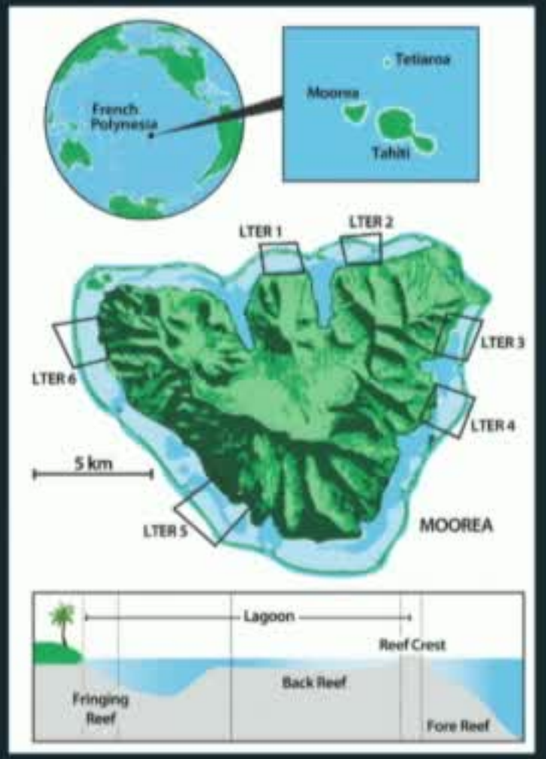
γ Growth rate of macroalgae over turf

Mumby, P. J., Hastings, A. and Edwards, H. J. (2007) 'Thresholds and the resilience of Caribbean coral reefs', *Nature*, 450(7166), pp. 98–101. doi: 10.1038/nature06252.

Equations are Deterministic
Show Bifurcation through grazing parameter changes



Coral Surveying : Moorea, French Polynesia



Source: "Biological and Physical Interactions on a Tropical Island Coral Reef: Transport and Retention Processes Around Moorea, French Polynesia" J.J. Leichter et al.

Source: Criobe station, SO CORAIL http://observatoire.criobe.pf

Toy Model Development: Does spatial discretization allow for how to model meta-stability between ecological regime shifts

$$\frac{dM}{dt} = aMC - \frac{gM}{M+T} + \gamma MT$$

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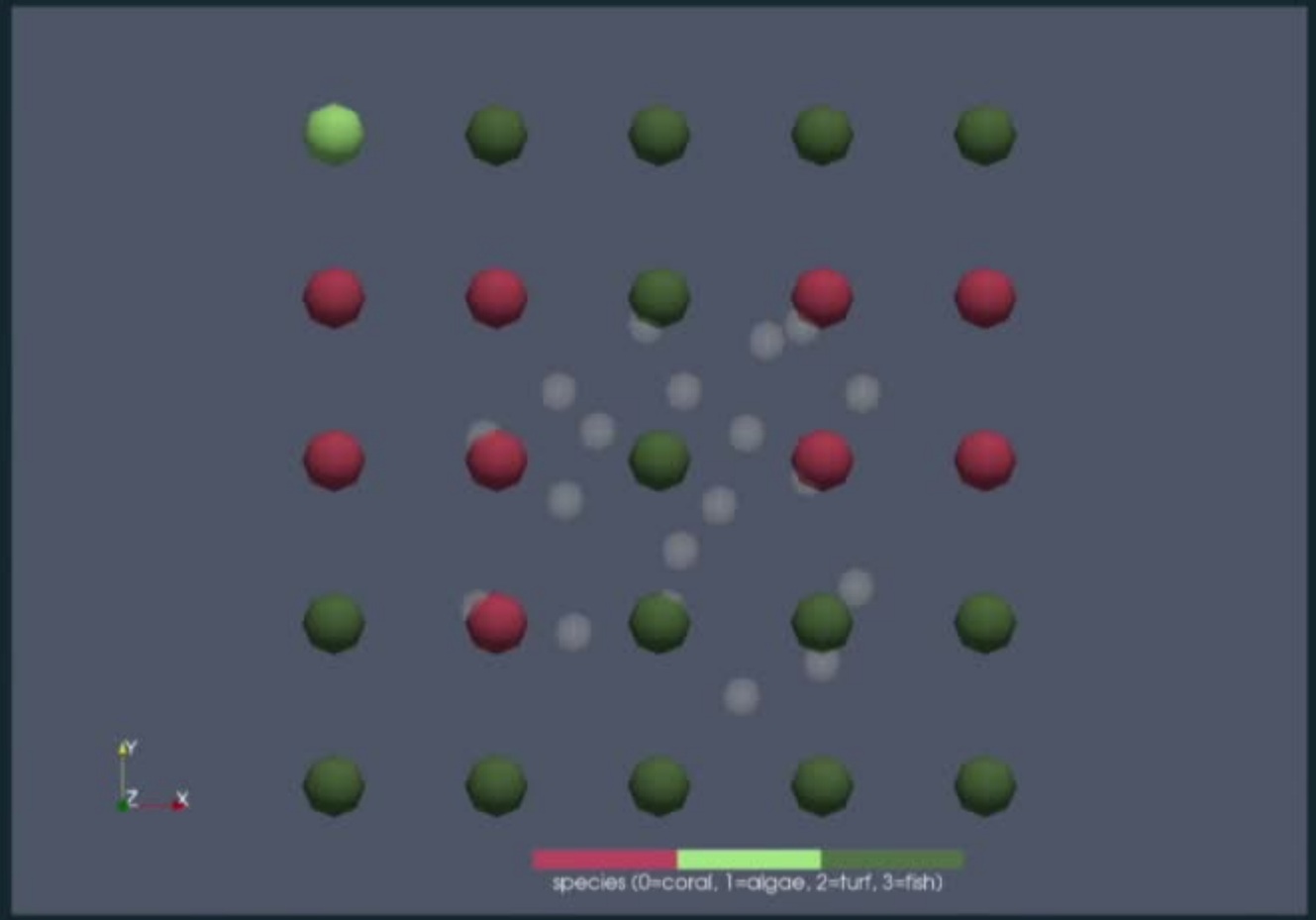
Our Model



Grid Update

```
U = random.uniform(0,1)

if Coral
    if U < d * grid_dt:
        Change to Turf
    if U < d * grid_dt + a * density_macroalgae * grid_dt:
        Change to Macroalgae
if Turf
    if U < gamma * grid_dt * density_macroalgae :
        Change to Macroalgae
    if U < (gamma * grid_dt * density_macroalgae] +
            r * grid_dt * density_coral:
        Change to Coral
if Macroalgae
    if U < g * density_grazers * grid_dt:
        Change to Turf
```

r Growth rate of coral over turf

d Death rate of coral

a Growth rate of macroalgae over coral

g Rate of grazing

γ Growth rate of macroalgae over turf

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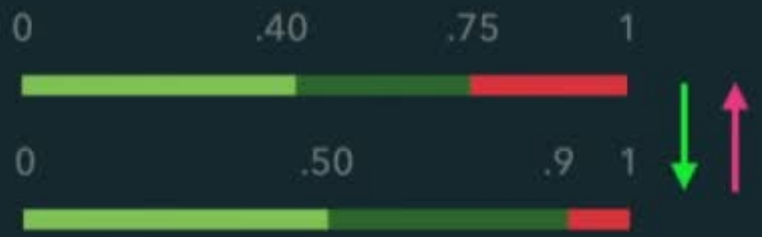

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a Growth rate of macroalgae over coral

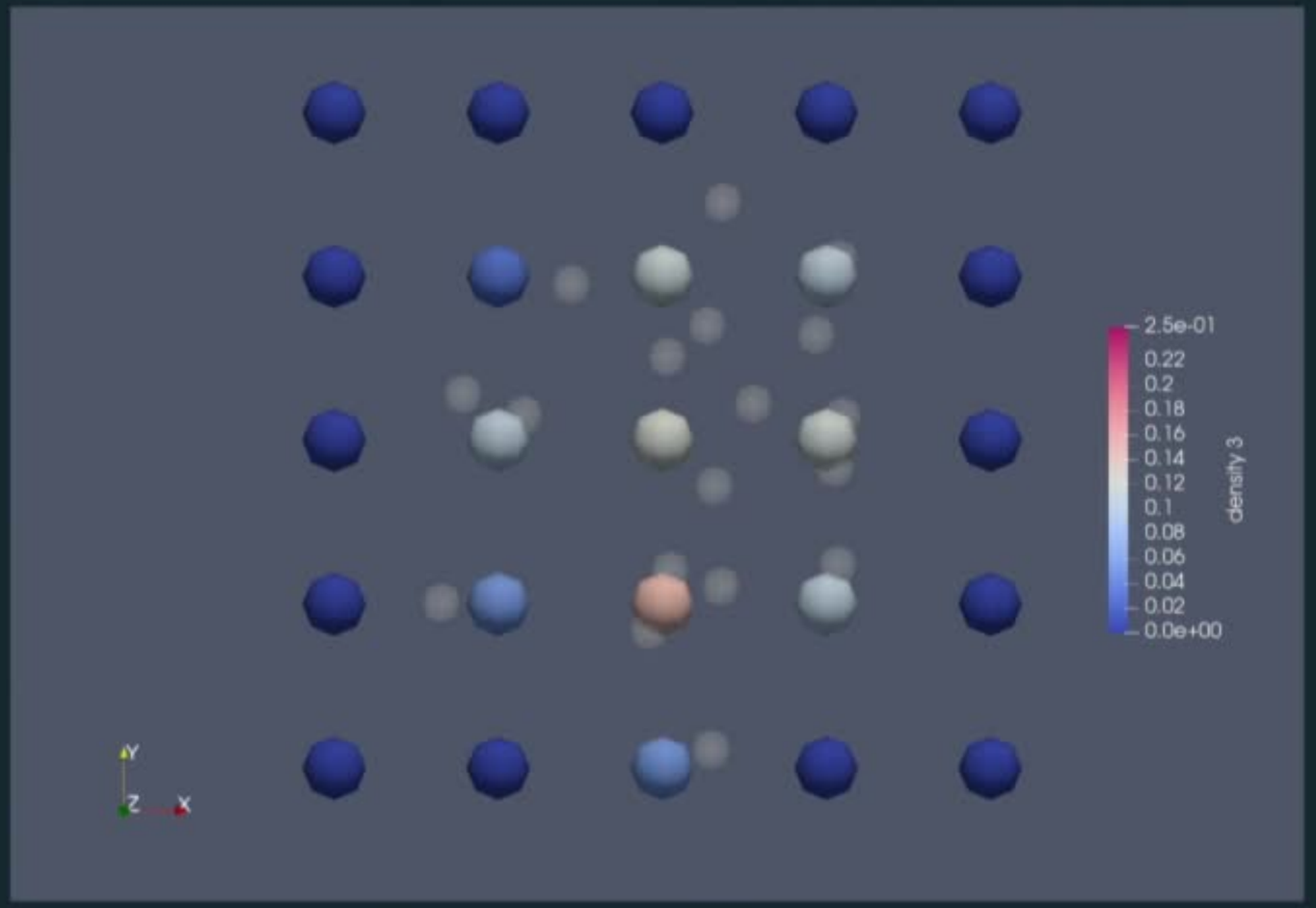
g Rate of grazing

γ Growth rate of macroalgae over turf

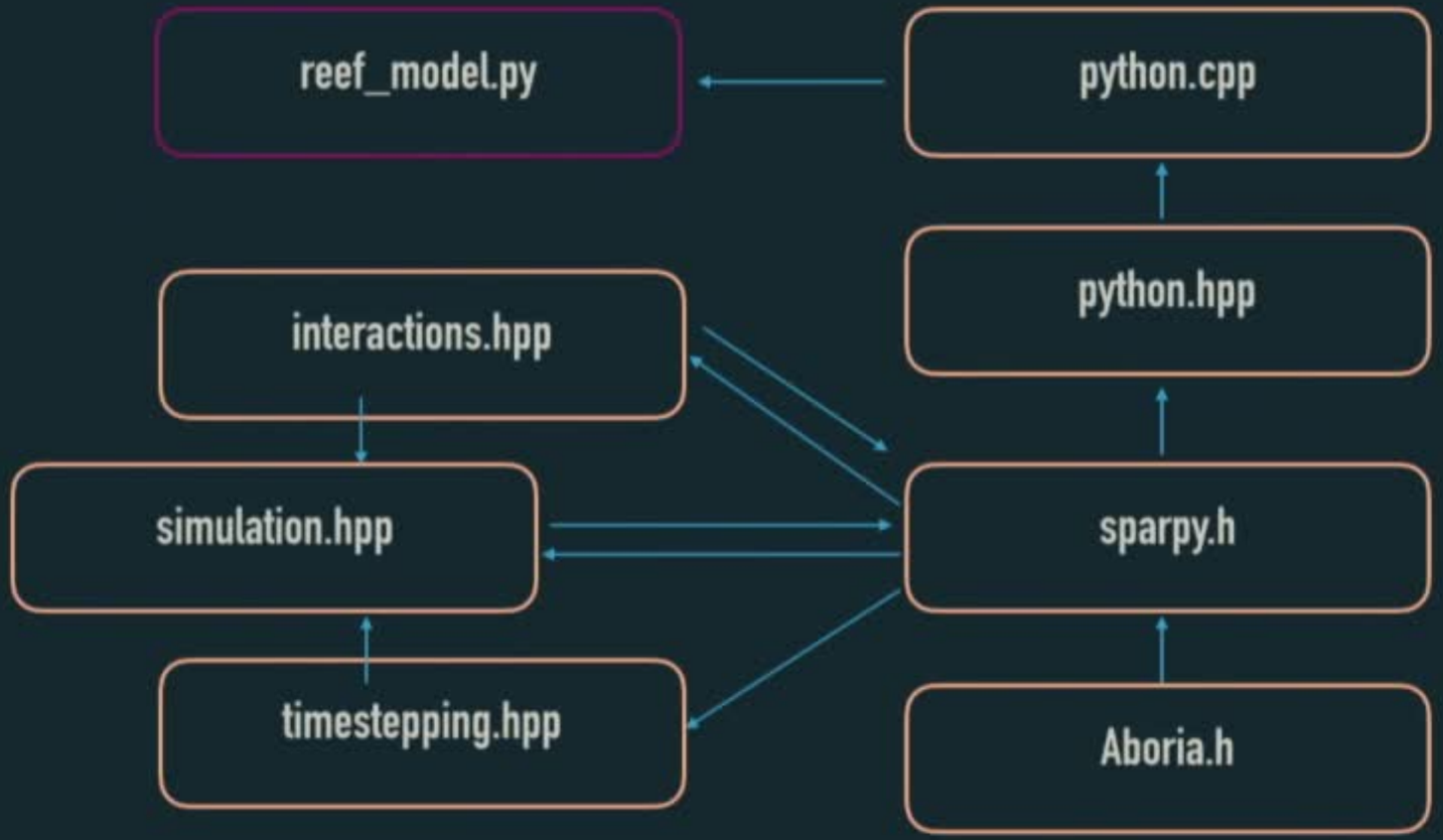
Introduction of Spatial Variability and Stochasticity

Model Objects	Coral, Macroalgae, and Turf are all the same object with the following attributes: Type (C, M, T, F), Velocity, Neighboring types
Random variable U	For initial grid setup, initial fish velocity, and grid update
Morse force $= C_r * e^{(-r/l_r)} - C_a * e^{(-r/l_a)}$	For fish movement (attraction to coral and macroalgae, repulsion from turf, and attraction/repulsion to each other for "flocking" movement
Neighborhood search	For particle interactions and weights in grid update

Density Knowledge



C++ Backend

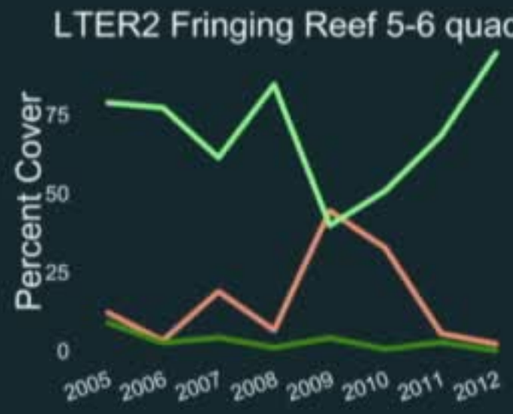

reef_model.py
python.cpp
python.hpp
interactions.hpp
simulation.hpp
sparpy.h
timestepping.hpp
Aboria.h

Edmunds, P. of Moorea Coral Reef LTER. 2019. MCR LTER: Coral Reef: Long-term Population and Community Dynamics: Corals. ongoing since 2005. knb-lter-mcr.4.37 doi:10.6073/pasta/7216fdcde85b630d1b4548b677d9b1d86.

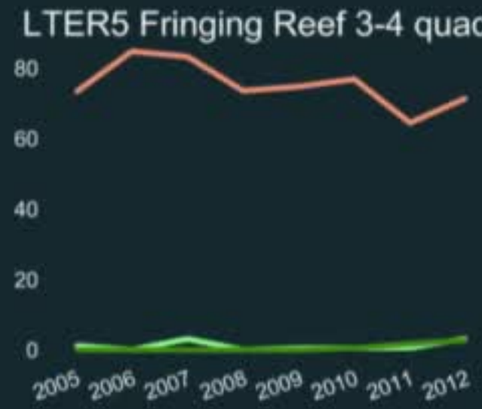
Variety in Reef "Types"

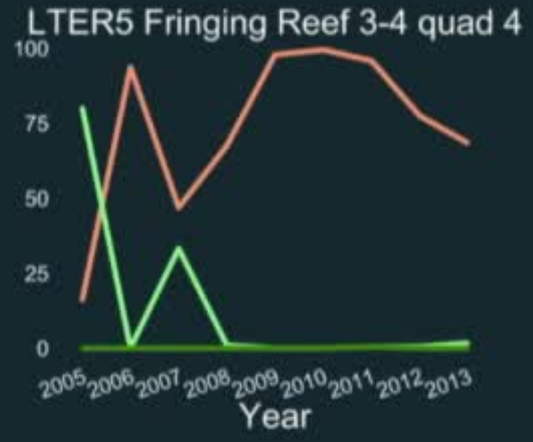
Turf Macroalgae Coral

Algae Favoring



Coral Favoring





Edmunds, P of Moorea Coral Reef LTER. 2019. MCR LTER: Coral Reef: Long-term Population and Community Dynamics: Corals, ongoing since 2005. knb-lter-mcr.4.37 doi:10.6073/pasta/7216fcde858630d1b4548b677d9b1486

Variety in Reef "Types"

Turf Macroalgae Coral

Algae Favoring

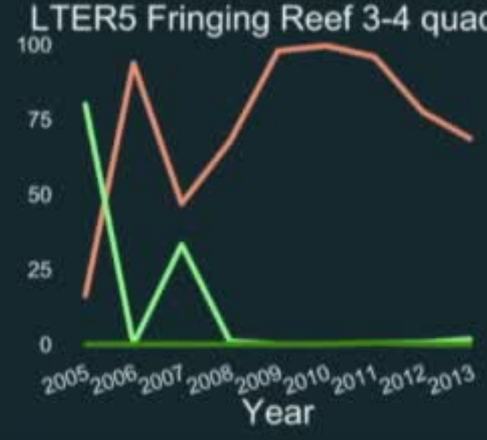
LTER2 Fringing Reef 5-6 quad 7

LTER2 Fringing Reef 5-6 quad 5

Coral Favoring

LTER5 Fringing Reef 3-4 quad 1

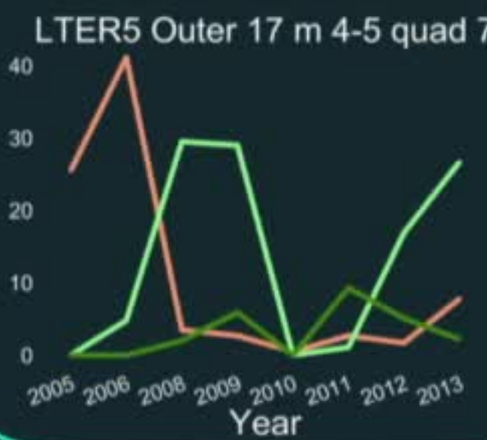
LTER5 Fringing Reef 3-4 quad 4



Variable Outcomes

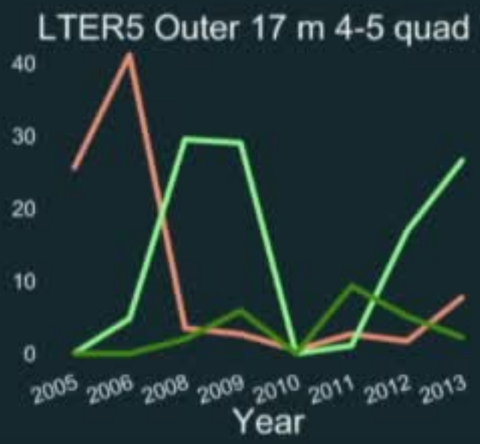
LTER5 Outer 17 m 4-5 quad 8

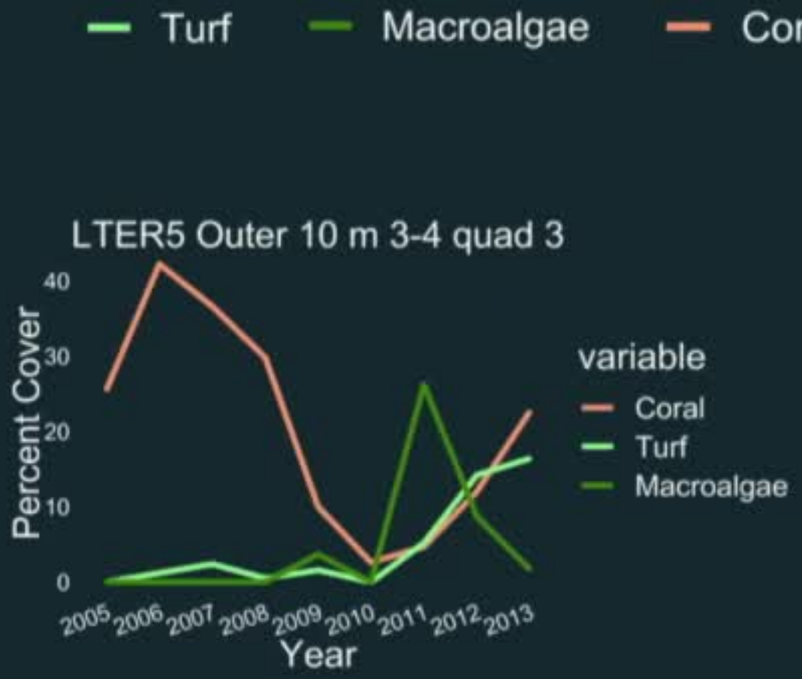
LTER5 Outer 17 m 4-5 quad 7

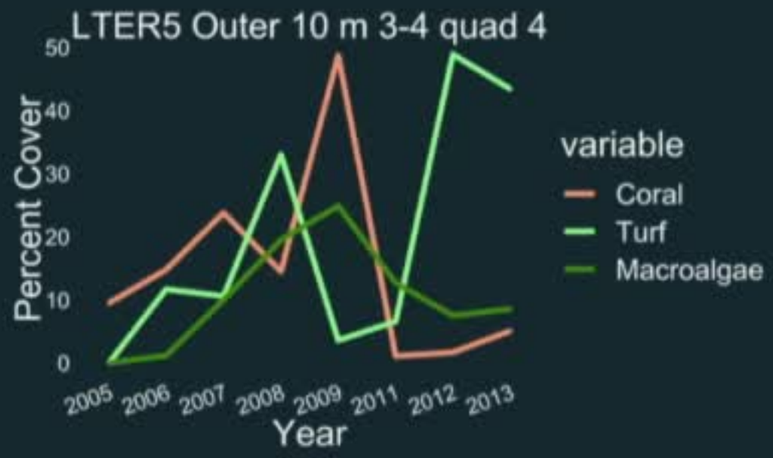


Further Examples of Switching Behavior in Patches of the Same Reef

Variable Outcomes







Original Outputs

Mimicking Switching Behavior

Through weighing stochasticity more heavily by neighboring benthic coverage, including the **same species**, and **increasing number of nodes**

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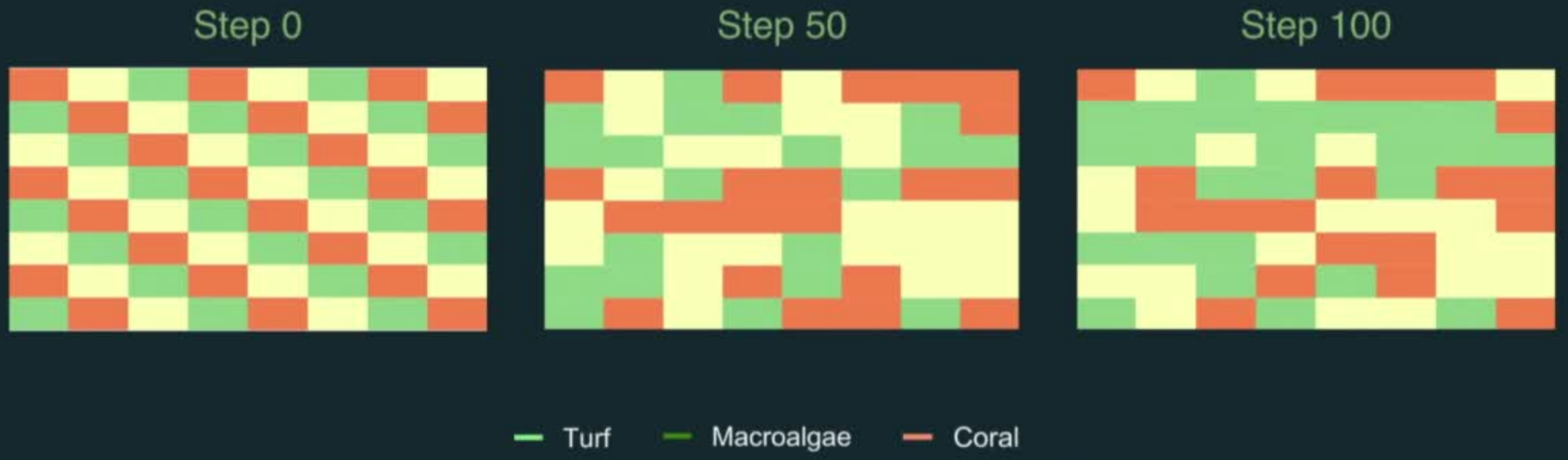
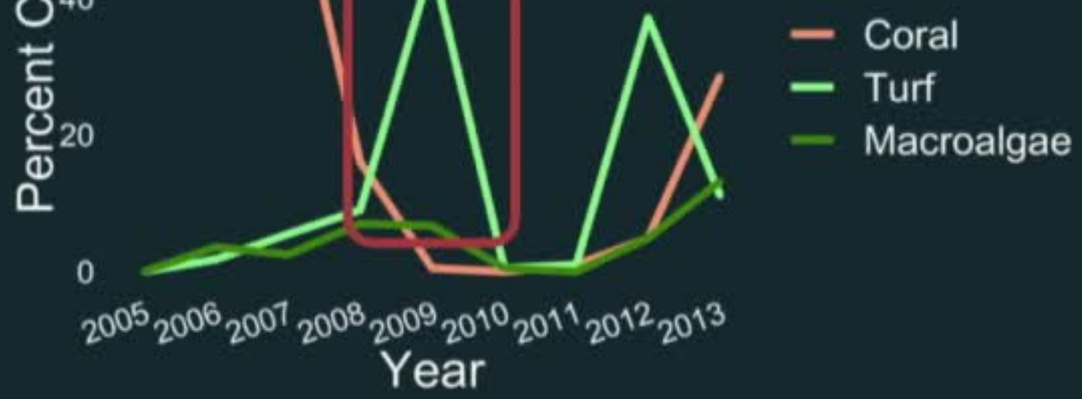


Transfer Entropy (Dreams)



Brooks, A of Moorea Coral Reef LTER, 2016. MCR LTER: Coral Reef: Community Dynamics: Abundance and Species Richness of Fishes Associated with the Coral Porites rus 2000 thru 2011. knb-lter-mcr.1.22 doi:10.6073/pasta/286f844cc890fbbd1915adcbc6895d2d

Alldredge, A of Moorea Coral Reef LTER, 2019. MCR LTER: Coral Reef, Water Column: Nutrients, ongoing since 2005. knb-lter-mcr.1034.9 doi:10.6073/pasta/9328a024f2bf16ecc66024f07dbcc574

Information Flow Examples in Hydrology

Ruddell, B. L., & Kumar, P. (2009). Ecohydrologic process networks: 1. Identification. Water Resources Research, 45(3), doi:10.1029/2008WR007279

Ma, H., Larsen, L. G., & Wagner, R. W. (2018). Ecogeomorphic Feedbacks that Grow Deltas. Journal of Geophysical Research: Earth Surface. https://doi.org/10.1029/2018jf004706

Rinderer, M., Ali, G., & Larsen, L. G. (2018). Assessing structural, functional and effective hydrologic connectivity with brain neuroscience methods: State-of-the-art and research directions. Earth-Science Reviews, 178, 29â€"47. https://doi.org/10.1016/j.earscirev.2018.01.009

Preliminary Results and Takeaways

Stochasticity coupled with (self-inflicting) neighborhood knowledge can keep the system from converging to either coral or turf dominating states

Different models for different parts of the reef

Transfer Entropy still a possibility, need to look at lags and various binning

Stochastic Spatiotemporal model has a lot of exploration potential