A 3-D cellular depositional model of platform evolution delivered at fine scale

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Abstract

Satellite and field observations suggest modern, shallow carbonate depositional systems to be self-organized, yet the processes generating such behavior are not fully understood. A 3-D forward model of carbonate reef growth rooted in cellular automata simulates landscape evolution through time. Synthetic landscapes are generated over spatial extents of several kilometers through time scales of millennia at meter-scale resolution. Classes in the model include biotic (e.g., branching and massive coral communities, algal communities) and abiotic (e.g., unconsolidated sand) carbonate factories. Environmental factors include relative sea level and light intensity, and ecological controls are based on life history traits for the biological facies. Ecological processes within the model include mortality and colonization rates, transition probabilities between facies, and rates of vertical accretion. The algorithm results in a self-organized landscape whose lateral geometries emulate those observed in nature, such as rims and reticulate structures. Visualizations can be produced by accessing topographic and facies maps generated at each time step. This project's goals are 1) to investigate which configurations of environmental parameters result in specific spatial motifs, 2) examine the effects of environmental perturbations on reef construction, and 3) understand the importance of biological and physical regimes on the generation of geomorphological features.

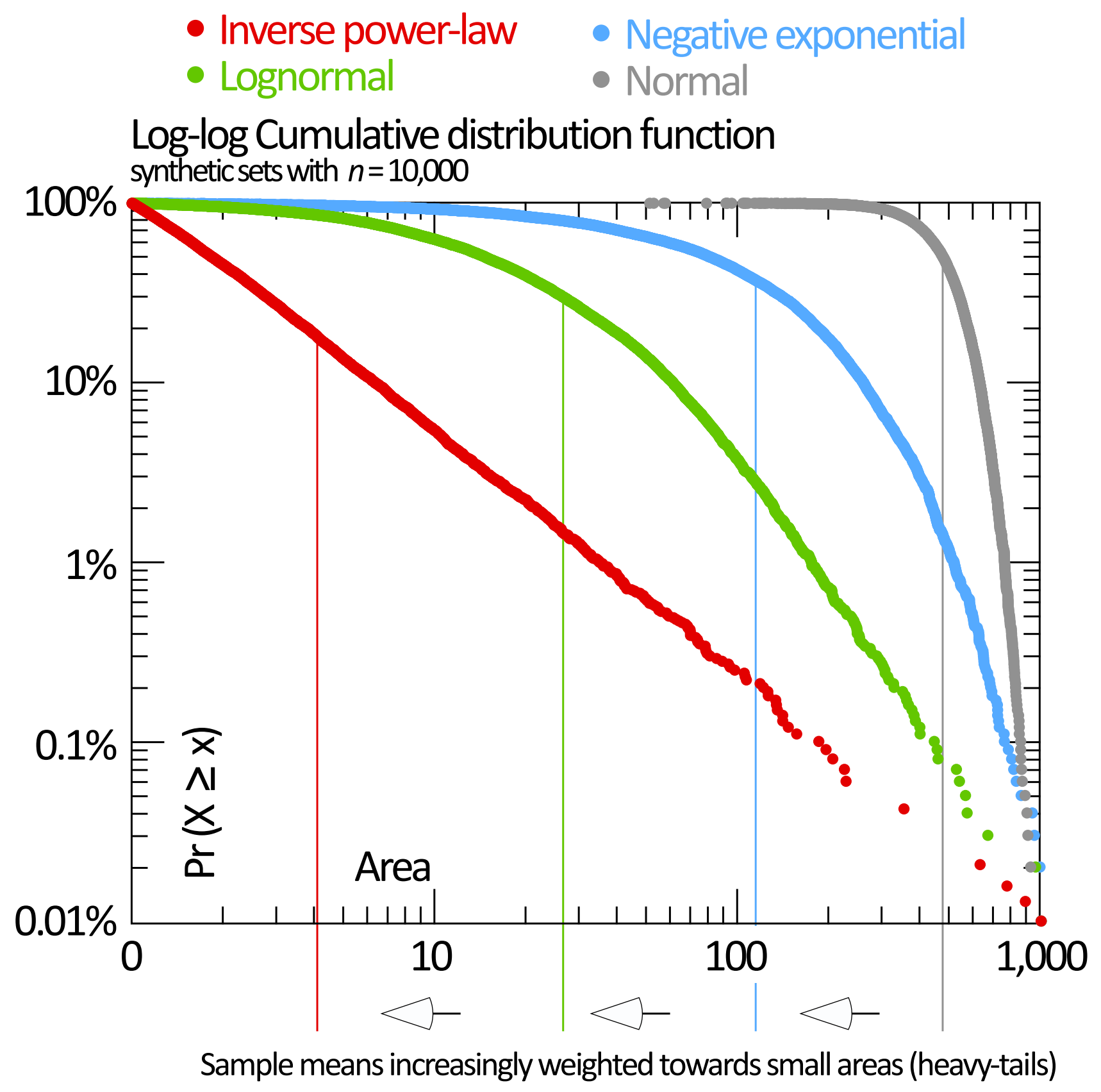
Motivation

Carbonate accumulation on platform tops generate landscapes whose geometric properties follow heavy-tailed size frequency distributions. These statistical models describe situations when there are many small objects and few very large bodies causing means to be low and variance to be high. Carbonates have been found to exhibit such behavior in both the vertical (Wilkinson et al. 1999; Burgess and Pollitt 2012) and the horizontal (Purkis et al. 2012). However, the underlying processes generating these vertical and horizontal patterns remain unclear.

An exponential distribution is a stochastic model describing the time between a pair of consecutive events in a Poisson process, in which the events occur constantly and independently. Lithofacies thickness distributions follow such a pattern and result from both stochastic and deterministic processes (Wilkinson et al. 1999; Burgess and Pollitt 2012). Wilkinson et al. showed that the thickness frequency distribution could be explained purely by a Poisson process. Burgess and Pollitt demonstrated via a forward model that deterministic rules generate exponential distributions. However, simulations generated the desired pattern at a lower frequency than is observed in vertical outcrops. This difference was attributed to the simplicity of the model and suggested more complex models (e.g., 3-d versus 1-d) that better represent physical processes are necessary to fully understand the generation of exponential distributions.

The areal extents of geobodies in carbonate landscapes exhibit a similar pattern of many small bodies and few large bodies. Besides the exponential model, two alternative descriptions for such a pattern are the power law and lognormal distributions. While all three models have similar expressions, their underlying mathematical structures differ, and thus, they have different real-world interpretations. Under a power law, the function is proportionate to itself thereby implying scale invariance. Alternatively, a variable follows the lognormal model when its logarithm is normally distributed. The interpretation here is that the pattern results from the multiplication of independent random variables. All three of these heavy-tailed models have been observed across a range of scientific fields, and they may have similar appearances when visually inspected.

This statistical properties of the carbonate geometries hints at the underlying mechanisms generating the landscapes. As models for carbonate landscape evolution rooted in physical processes are developed, their mathematical structure should be calibrated to exhibit the aforementioned distributions thereby emulating the real-world. Once the forward models are calibrated, simulations using different environmental parameter regimes can be performed to quantify the environment's influence on landscape evolution thus allowing validation by comparing simulations' geometries to those of carbonate landscapes observed via satellite and *in situ* observation.



Right: Examples of the cumulative frequency distributions for normal, inverse-power law, negative exponential, and log-normal distributions plotted on a log-log scale. The percent of geobodies below a given size (y-axis, log scale) decreases as the size increases (x-axis, log scale). A power law distribution appears the decrease linearly while the other distributions will have some curvature.

Goals

(1) Construct a 3-D cellular depositional (forward) model capable of generating geometric patterns that are similar to those encountered in natural systems

(2) Grain of a meter and extent of several kilometers

(3) Capable of initiating from featureless or pre-existing topography

(4) Emulate geologic realism with a focus on rims, reticulates, and debris aprons

(5) Biologically relevant rule-sets determine landscape development

(6) Simultaneously investigate the relationship between vertical and lateral extents of carbonate landscapes

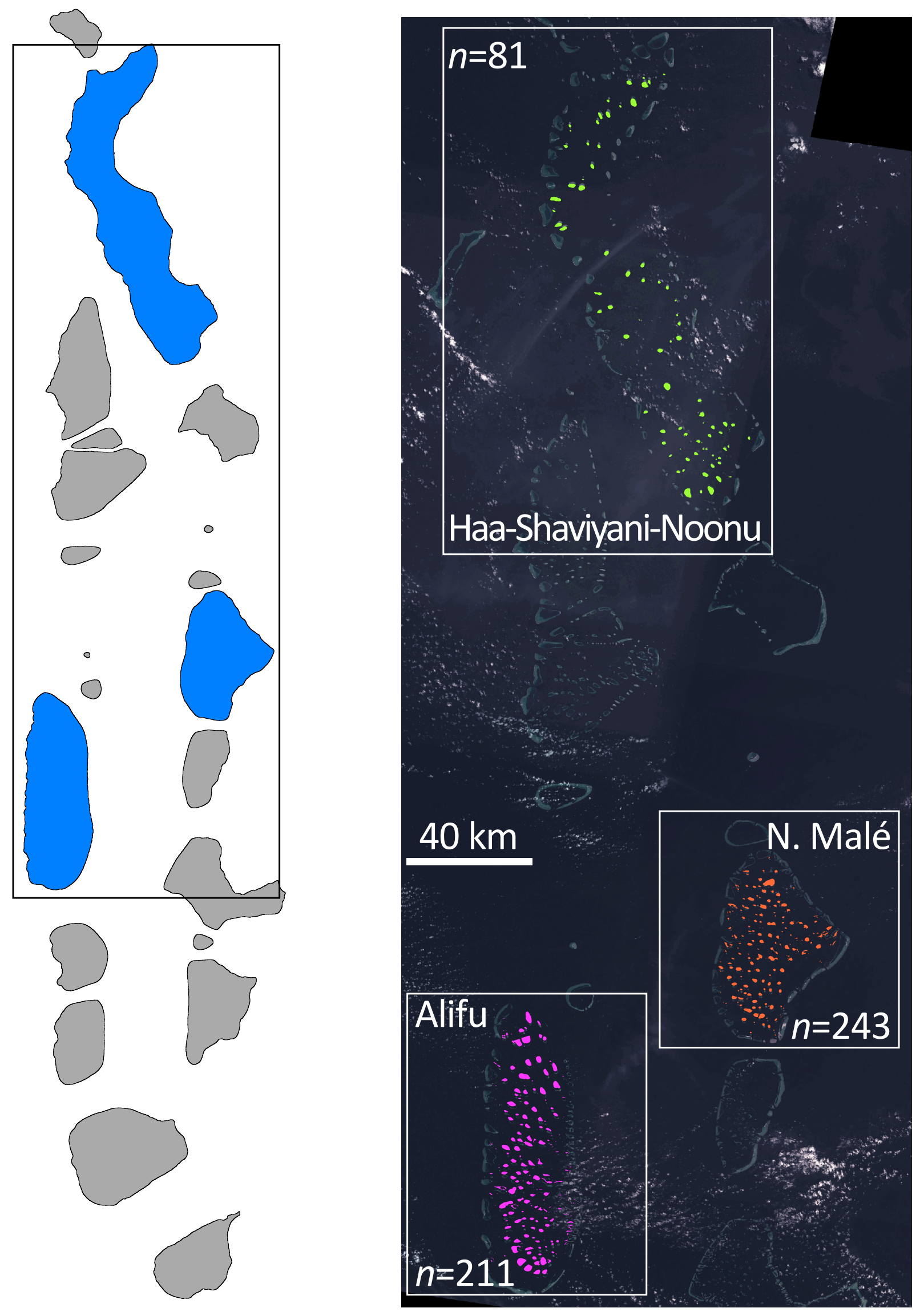
Features

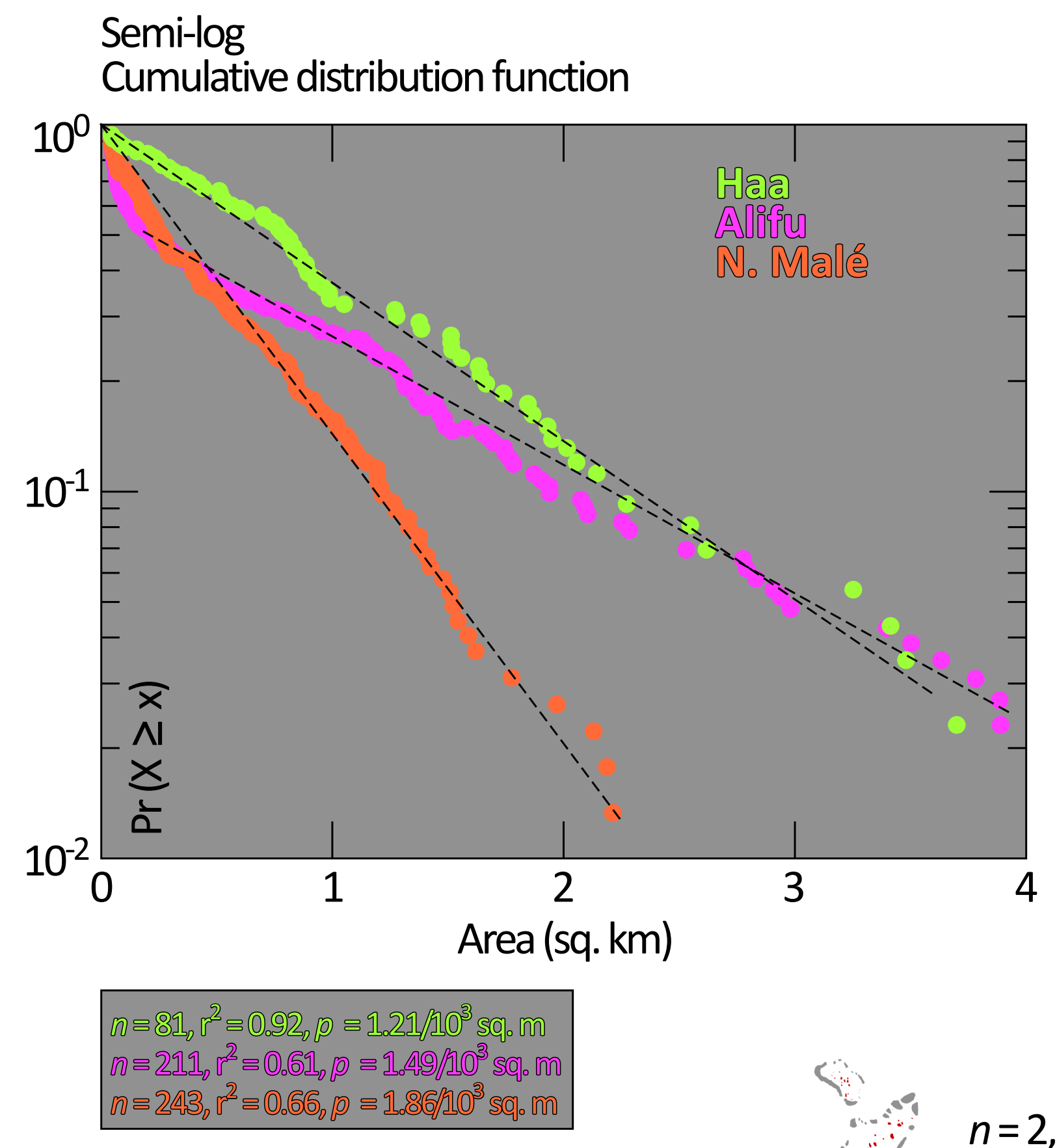
(1) A field of cells with an attributed value describing the status or condition of each modeled location

(2) Structured connections between cells

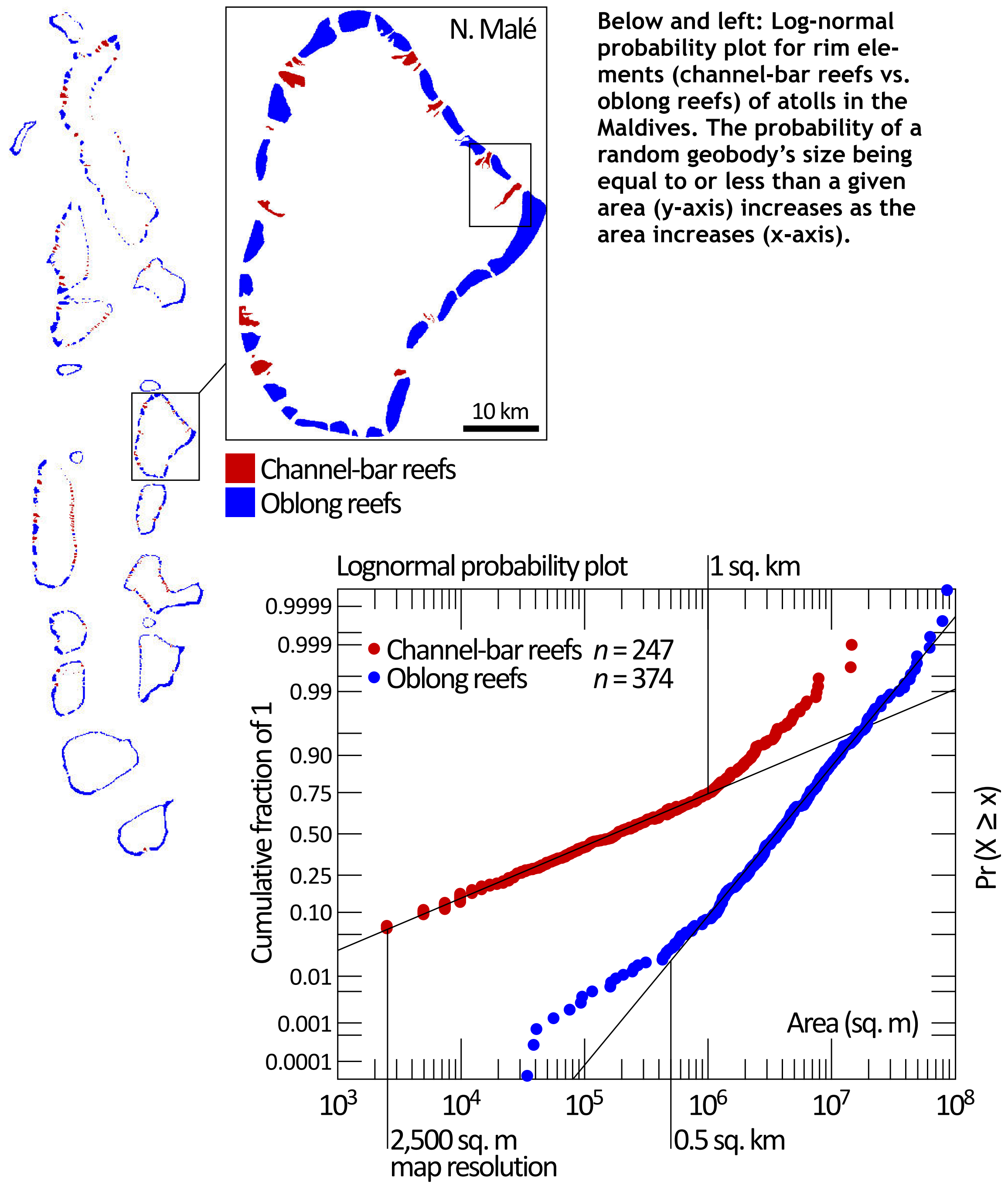
(3) A suite of mathematical rules that govern change within the system

(4) Iteratively updated through cycling 'model years'

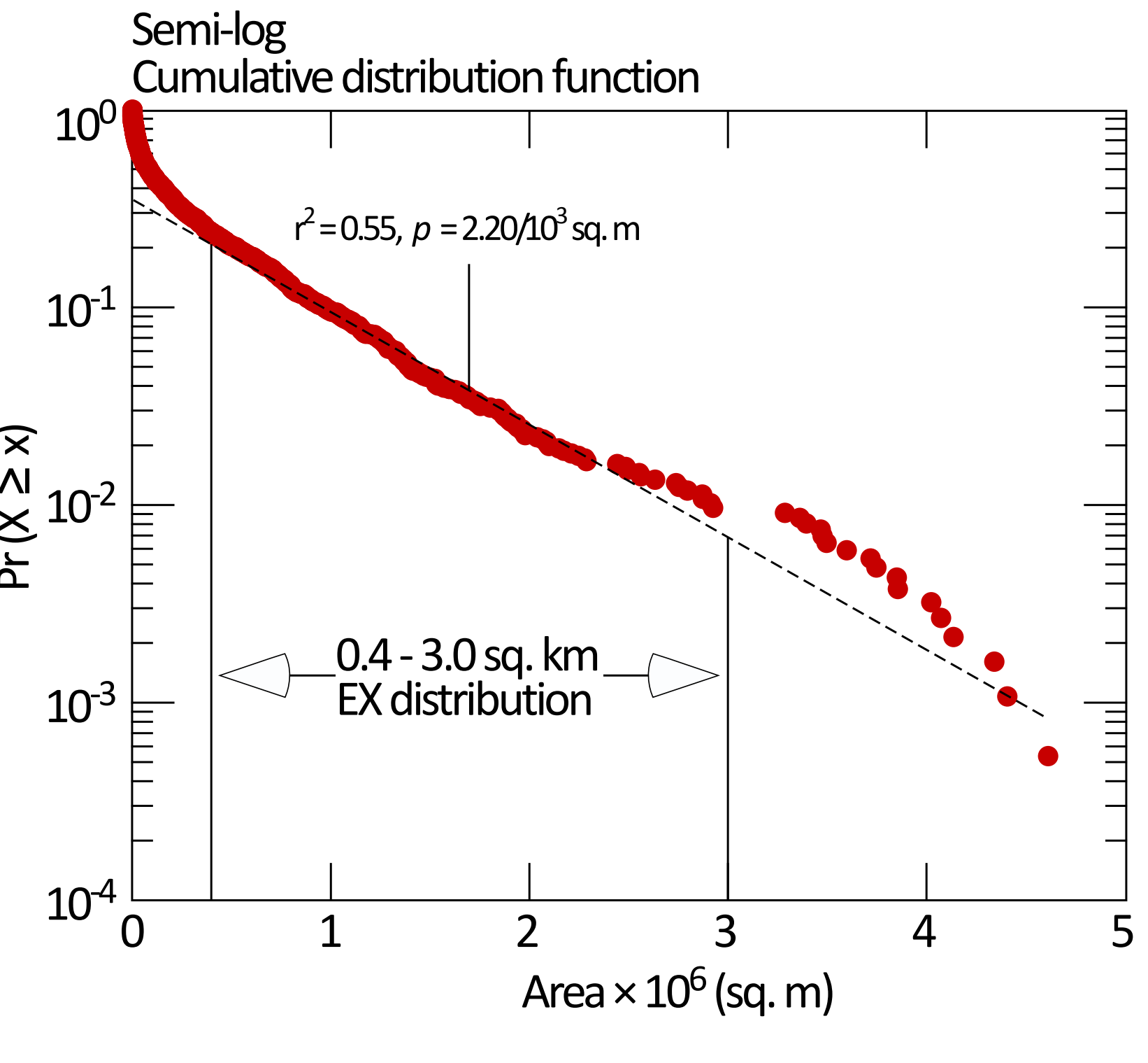




Above and left: The cumulative frequency distributions for patch reefs in three atolls in the Maldives.



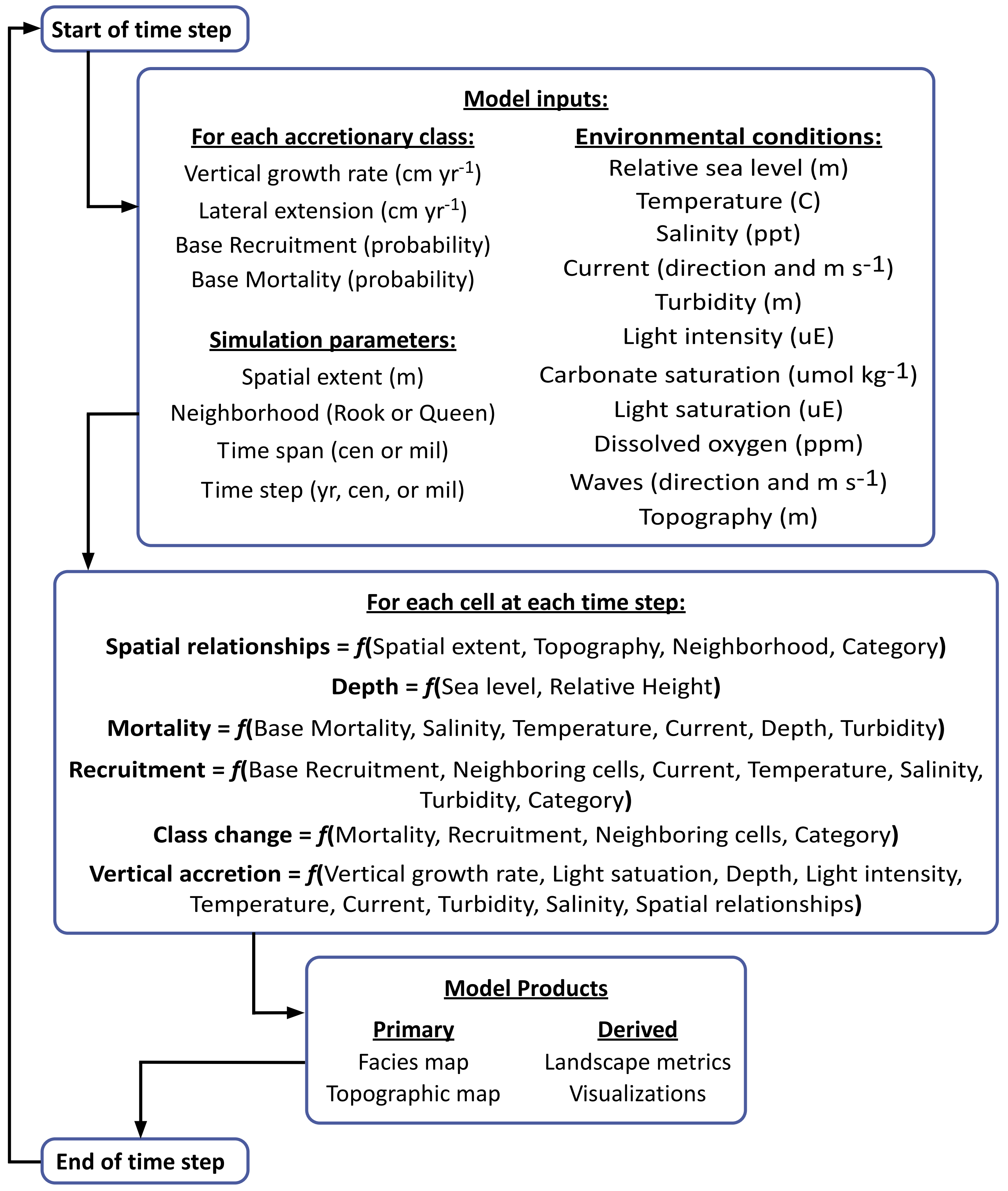
Below and left: Log-normal probability plot for rim elements (channel-bar reefs vs. oblong reefs) of atolls in the Maldives. The probability of a random geobody's size being equal to or less than a given area (y-axis) increases as the area increases (x-axis).



Below and right: Semi-log cumulative distribution function for patch reefs within the lagoons of atolls in the Maldives. The percent of patch reefs below a given size (y-axis) decreases as the size increases. In this case, the plot demonstrates the presence of a log-normal distribution.

Model overview

The outline below illustrates the model's basic framework. The user defines the accretionary classes, their internal properties, the environmental conditions (either static or dynamic), and the simulation's parameters. The algorithm uses this information to generate fields for the spatial arrangement of benthic classes and their relative height at each time step based on the fields from the previous time step.



Start of time step

Model inputs:

For each accretionary class:
Vertical growth rate (cm yr^{-1})
Lateral extension (cm yr^{-1})
Base Recruitment (probability)
Base Mortality (probability)

Simulation parameters:
Spatial extent (m)
Neighborhood (Rook or Queen)
Time span (cen or mil)
Time step (yr, cen, or mil)

Environmental conditions:
Relative sea level (m)
Temperature (C)
Salinity (ppt)
Current (direction and m s^{-1})
Turbidity (m)
Light intensity (uE)
Carbonate saturation (umol kg^{-1})
Light saturation (uE)
Dissolved oxygen (ppm)
Waves (direction and m s^{-1})
Topography (m)

For each cell at each time step:

Spatial relationships = *f*(Spatial extent, Topography, Neighborhood, Category**)**

Depth = *f*(Sea level, Relative Height**)**

Mortality = *f*(Base Mortality, Salinity, Temperature, Current, Depth, Turbidity**)**

Recruitment = *f*(Base Recruitment, Neighboring cells, Current, Temperature, Salinity, Turbidity, Category**)**

Class change = *f*(Mortality, Recruitment, Neighboring cells, Category**)**

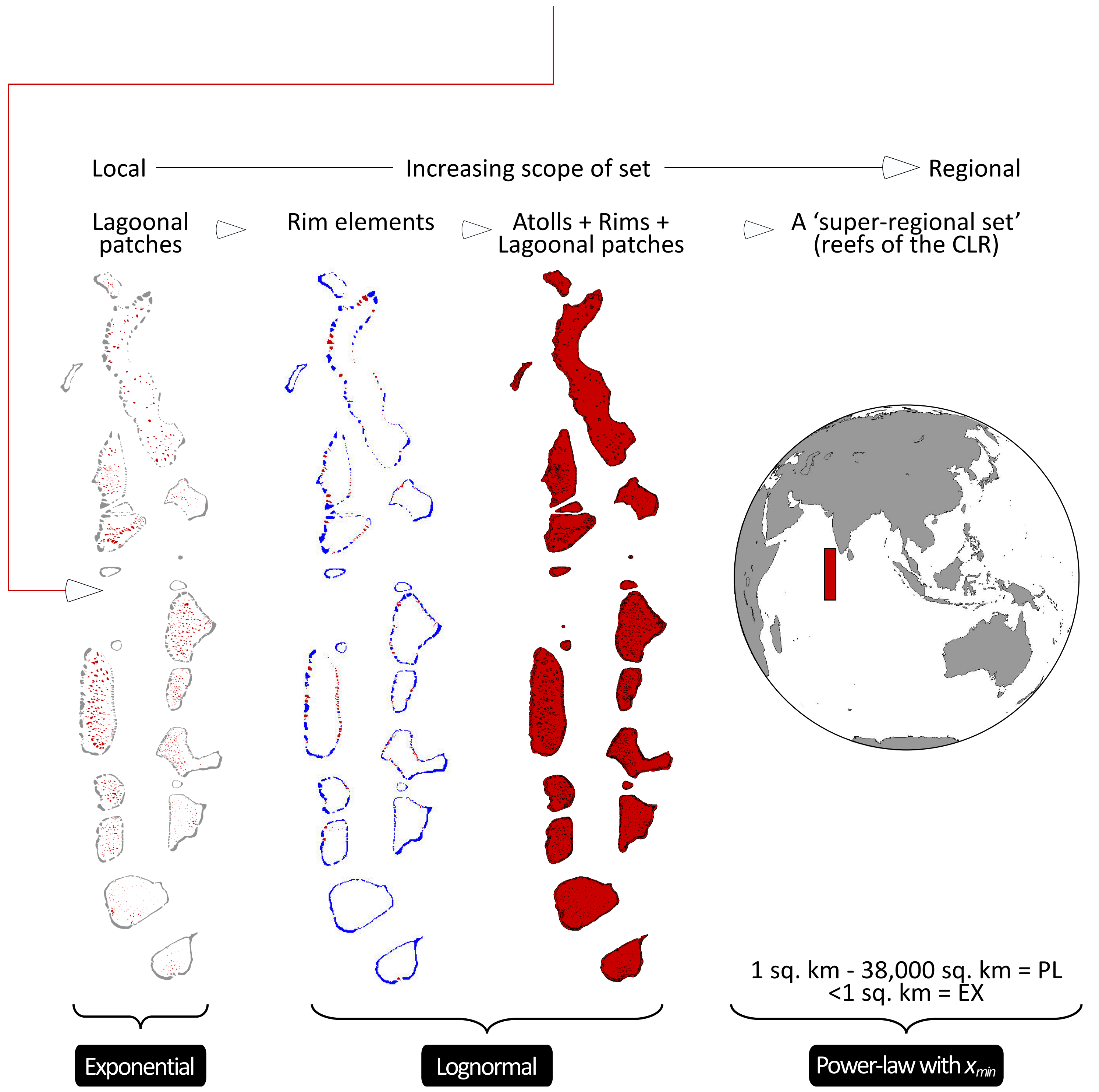
Vertical accretion = *f*(Vertical growth rate, Light satuation, Depth, Light intensity, Temperature, Current, Turbidity, Salinity, Spatial relationships**)**

Model Products

Primary
Facies map
Topographic map

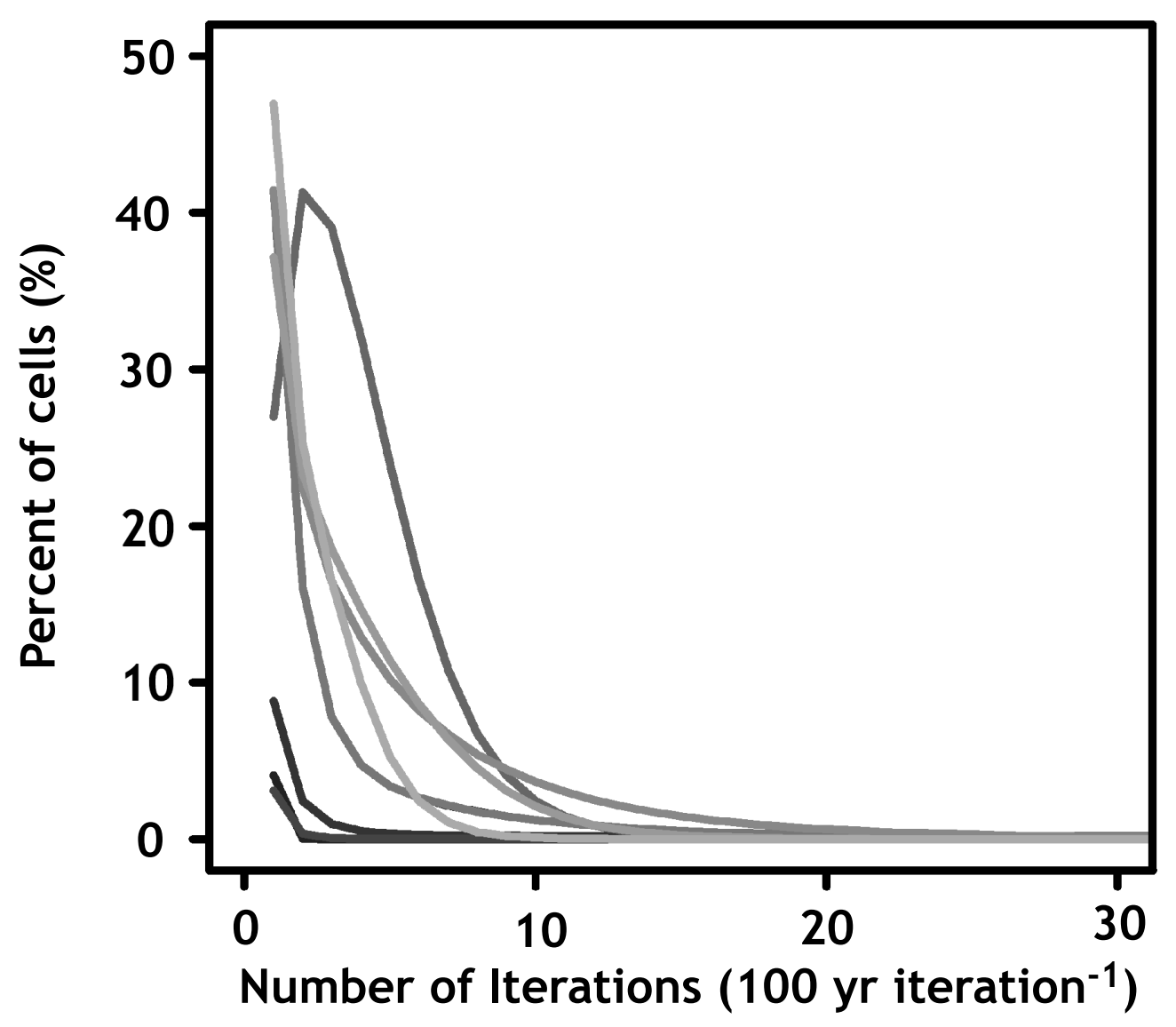
Derived
Landscape metrics
Visualizations

End of time step

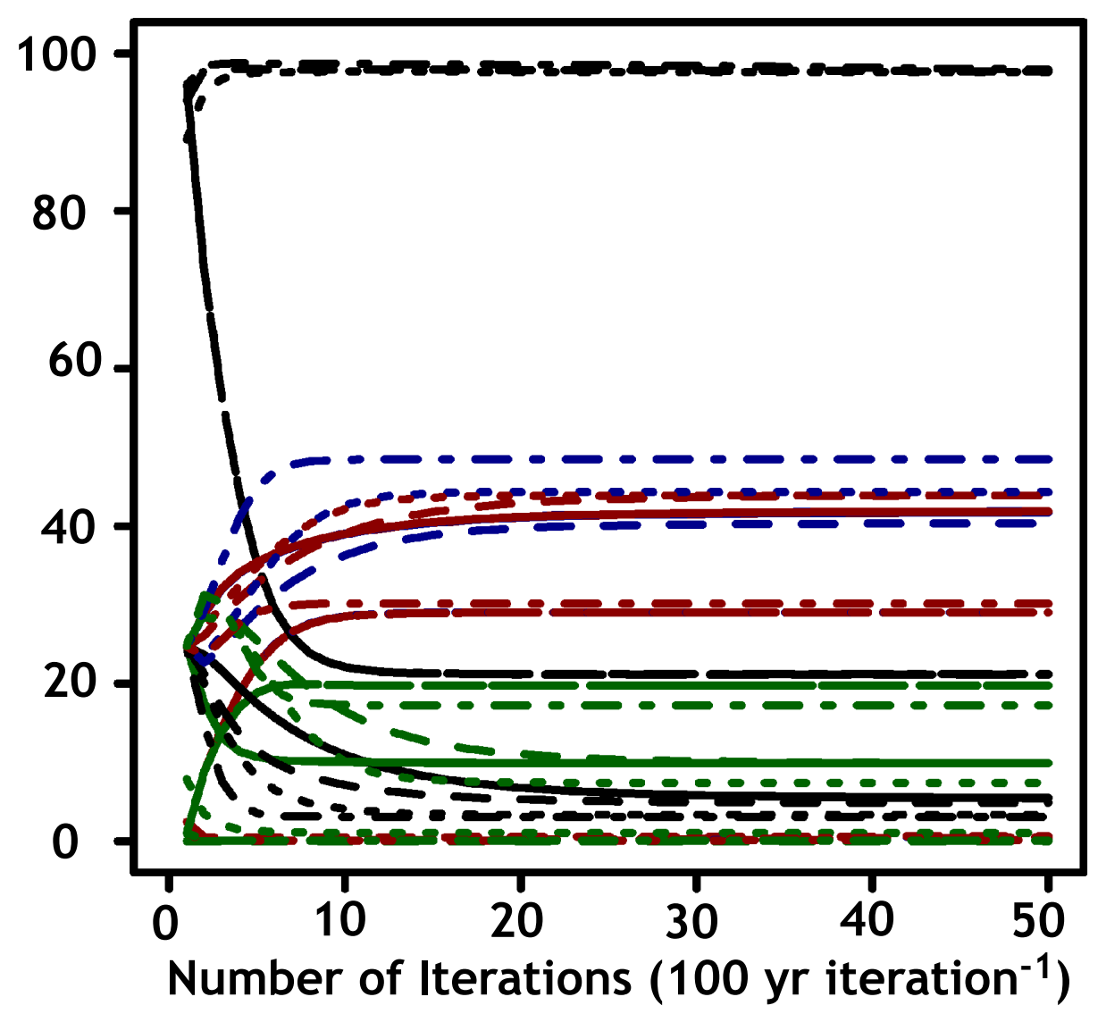


Stabilization/Self-organization

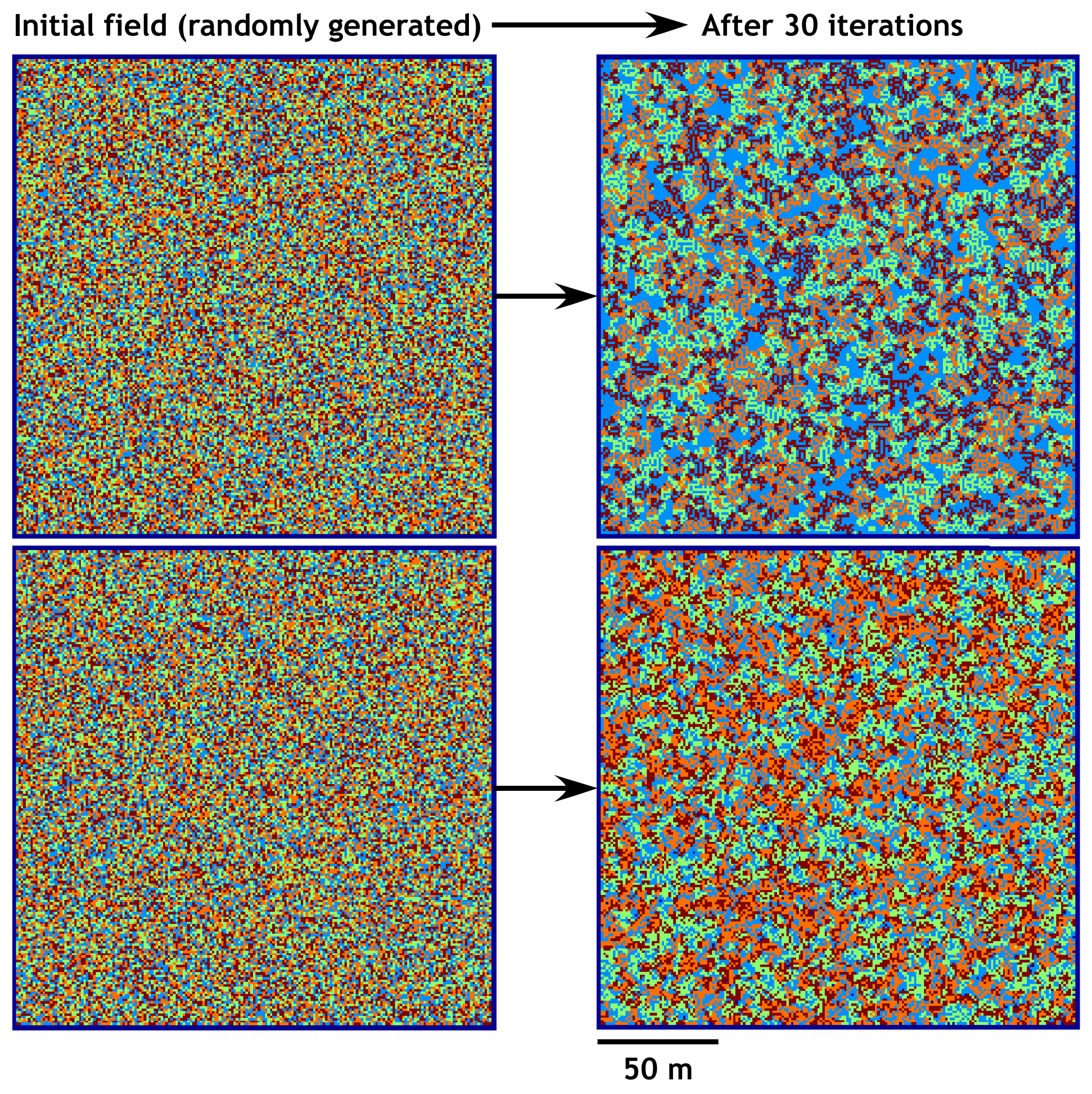
Through a set of rules rooted in ecological and geologic knowledge, the model produces a self-organized mosaic of accretionary classes. This is demonstrated by the number of cells whose accretionary class changes in each subsequent time step.



Above: The instability of the benthic field over time for 10 simulations as illustrated by the percent of cells whose state changed from one iteration to the next.



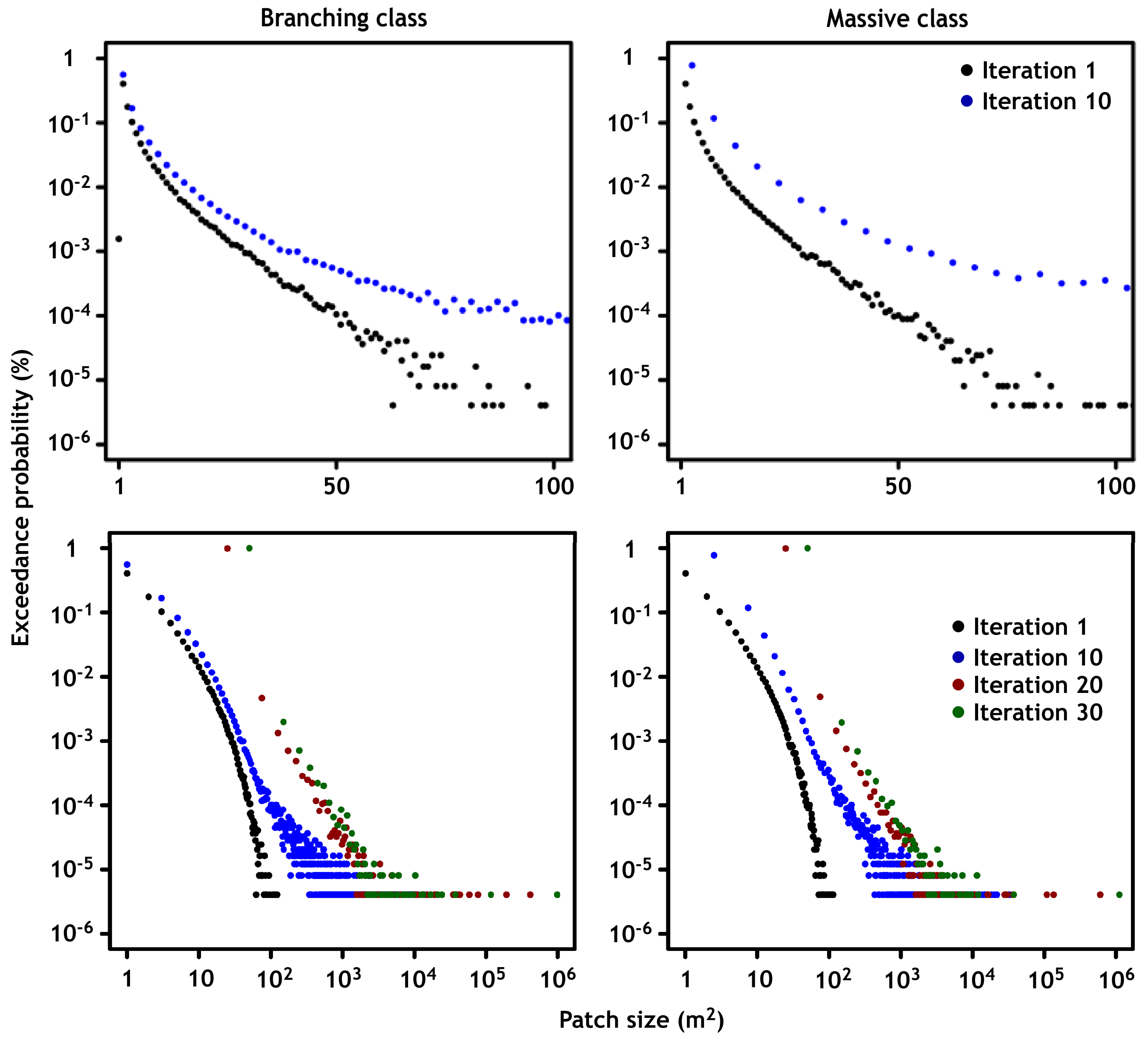
Above: The stability of the benthic field over time for 10 simulations as illustrated by the percent of cells with a given accretionary state.



Right: Examples of landscapes formed through a self-organized rule applied over to the landscape over time. Beginning with a random generated field (left column), the model moves forward in time. At each step, the model looks at each cell and its neighboring cells to determine the facies class in the next iteration. The top row follows a deterministic self-organized rule (Burgess), and the bottom row follows a stochastic rule-set. After 30 iterations, both rule sets have shifted from totally random to relatively stable groupings of classes.

Geometric properties

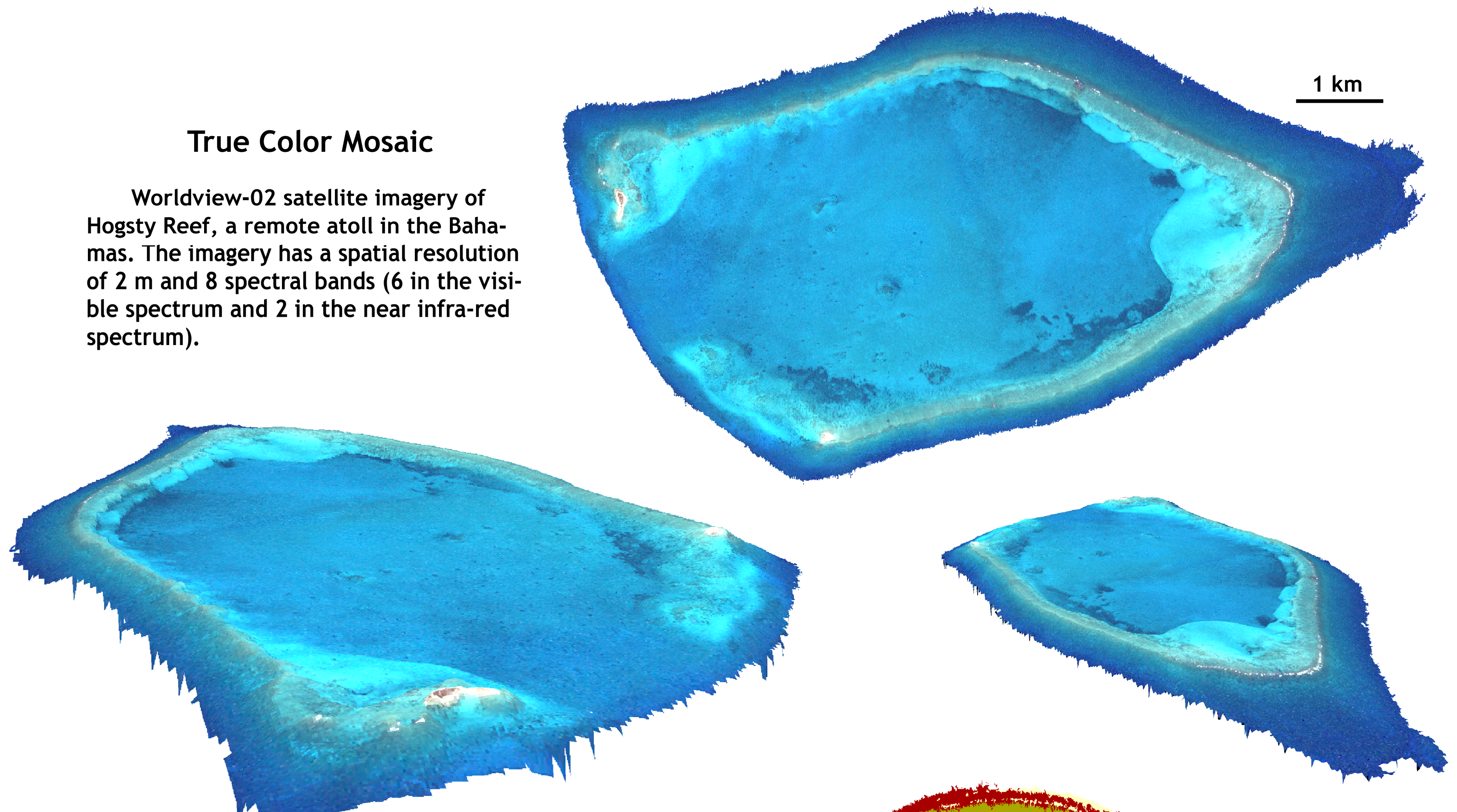
The size distribution for the modelled reef build-ups versus their frequency is best described by heavy-tailed distributions (e.g., lognormal, exponential, and power law). This result is in accordance with observations from the real-world. Future model developments will seek to understand the influence of multiplicative growth processes on creation of patch reef complexes that follow different heavy-tailed distributions with the aim to understand the subtle biotic processes that switch a size-frequency distribution from exponential to power law.



Above: The size frequency distribution for branching and massive accretionary classes from four steps spanning 30 iterations (3000 years). The distributions shift the right as time increases.

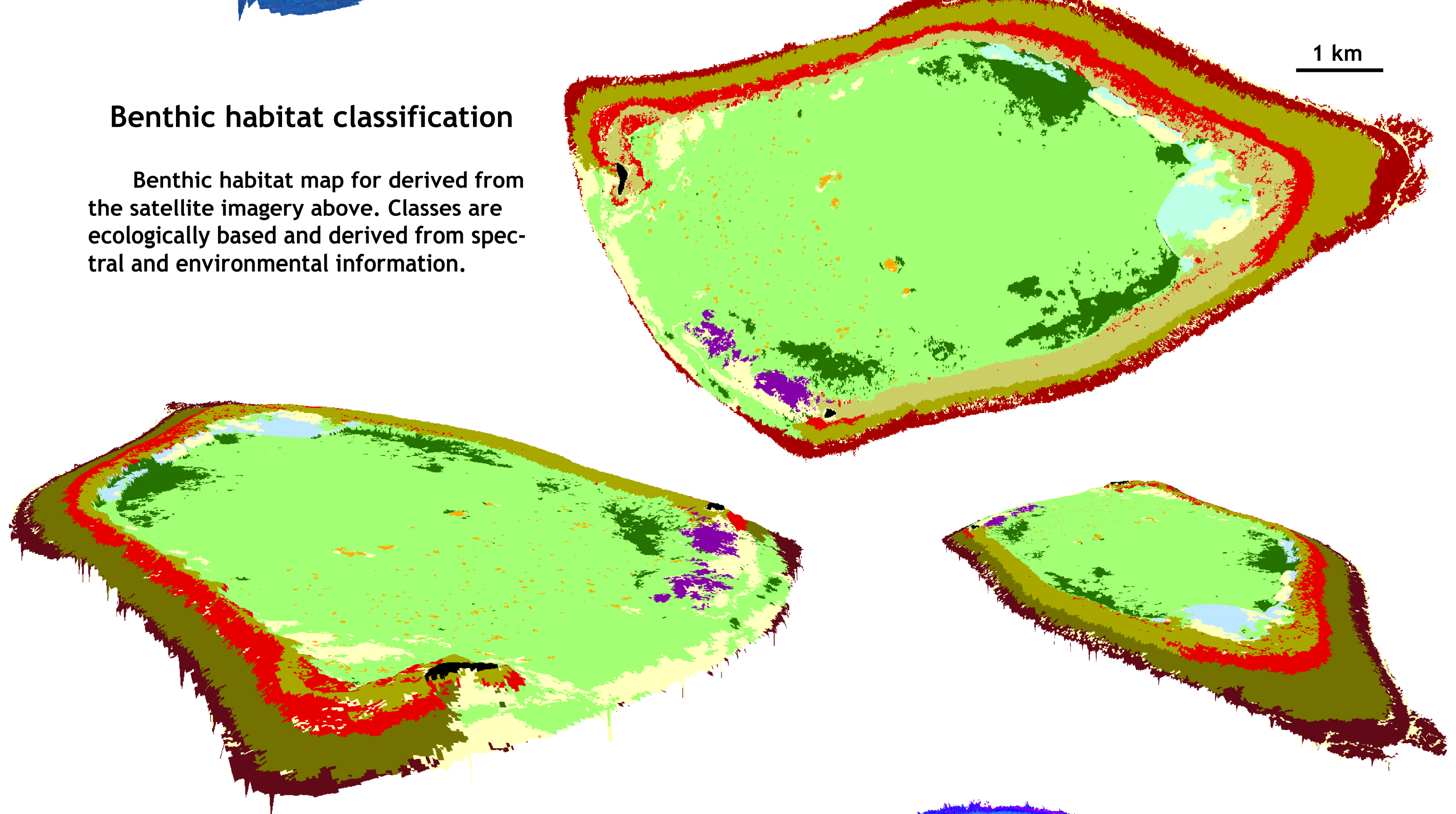
Remotely-sensed imagery

Carbonate landscapes in shallow waters (above 25 m depth) have been regularly imaged over the last 30 years as part of on-going efforts to map the resource distributions to support marine conservation. These ocean color data provide spectral information on the seafloor composition and water depth in the observed areas. Over time, improved technology led to finer spatial and spectral resolutions in the imagery thereby increasing the information available for mapping. Concurrent developments in image processing and mapping techniques improved the accuracy of the resultant geospatial products. Investigations of these benthic composition (e.g., sand, seagrass, coral community, etc.) and bathymetry maps demonstrate re-occurring statistical properties, such as the frequency of geobodies' sizes following heavy-tailed distributions. In the near-term, these observations of real-world landscapes can be integrated into carbonate modeling systems as stochastic processes for calibration and validation. The long-term goal is to replace the stochastic elements with deterministic rule-sets rooted in physical, chemical, and biological processes.



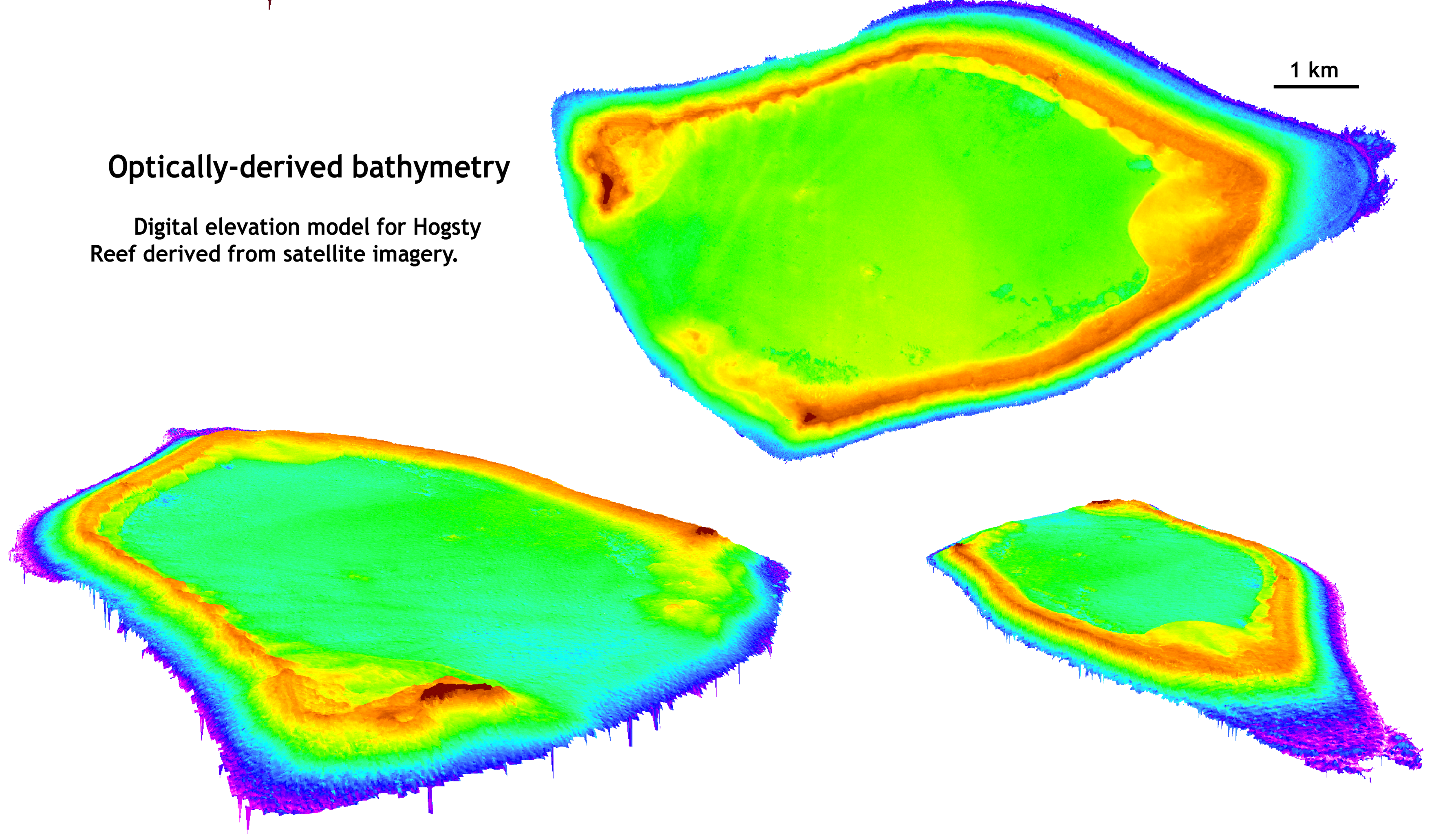
True Color Mosaic

Worldview-02 satellite imagery of Hogsty Reef, a remote atoll in the Bahamas. The imagery has a spatial resolution of 2 m and 8 spectral bands (6 in the visible spectrum and 2 in the near infra-red spectrum).



Benthic habitat classification

Benthic habitat map for derived from the satellite imagery above. Classes are ecologically based and derived from spectral and environmental information.

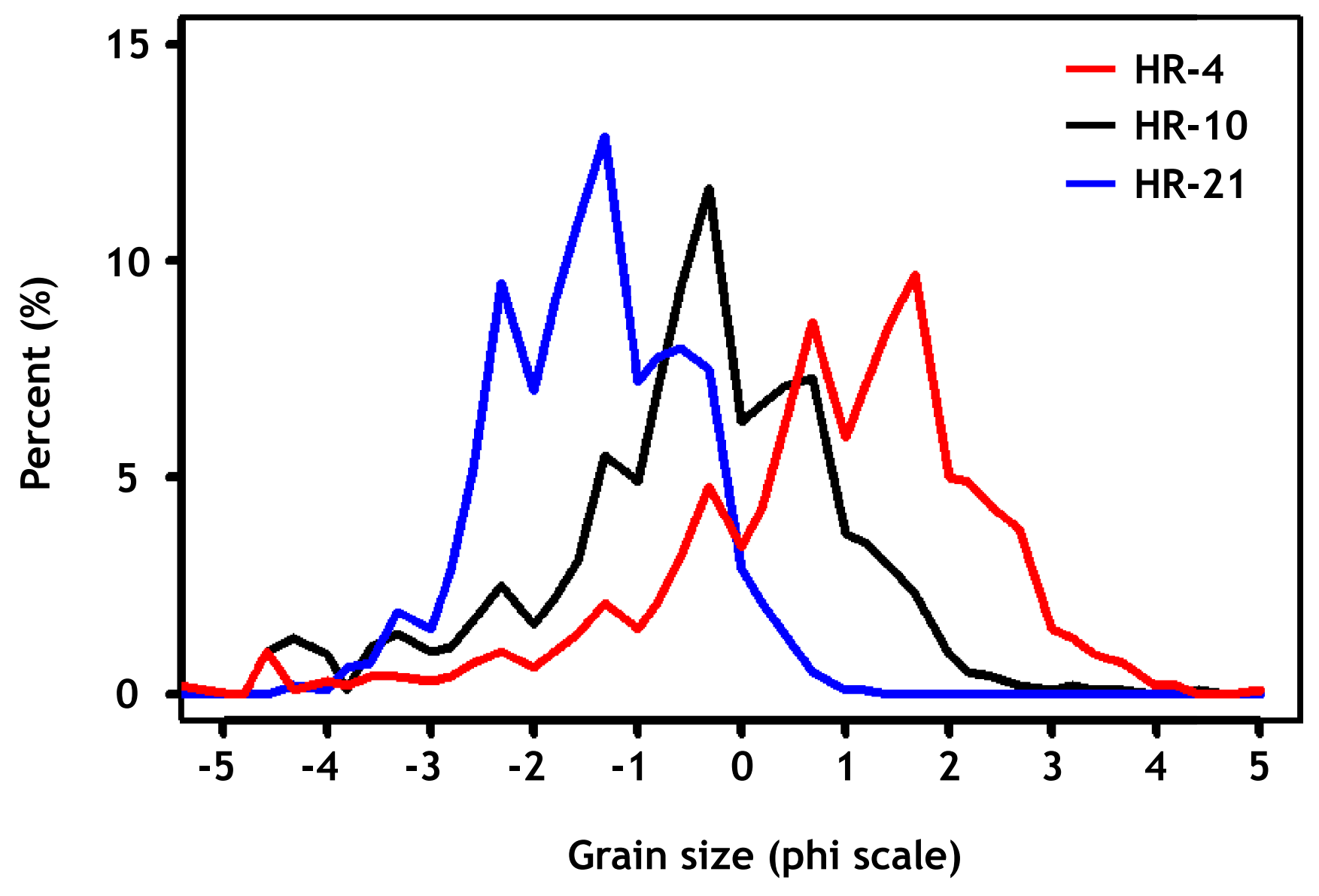


Optically-derived bathymetry

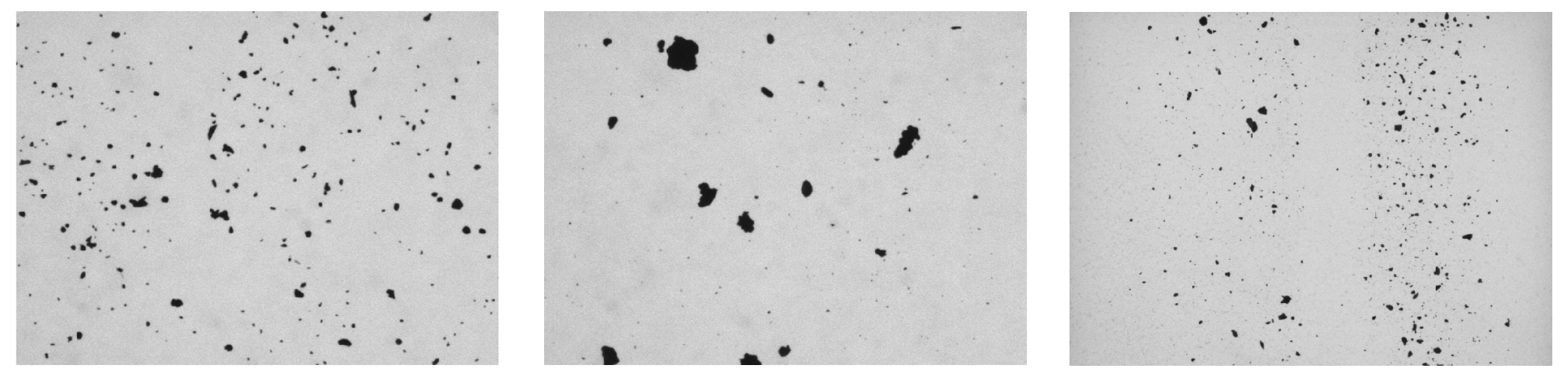
Digital elevation model for Hogsty Reef derived from satellite imagery.

In situ sediment sampling

The spatial distribution of sediment is critical in determining the carbonate factories' spatial arrangement, and a sediment grain's characteristics (e.g., size, shape, composition, etc.) provide information on its origin. Accurate representation of these patterns within a landscape requires thorough sampling, and reliable generalization of environmental factors' influence on the aforementioned spatial patterns requires multi-site sampling. To this end, we gather samples from remote reefs across the Caribbean Sea and Pacific Ocean. The size and shape of grains are assessed using a Camsizer (Retsch Technology GmbH). The resulting statistics are geolocated allowing them to be matched with habitats and depths from benthic habitat and bathymetric maps, respectively. Sediment distribution maps are created with geospatial interpolation.



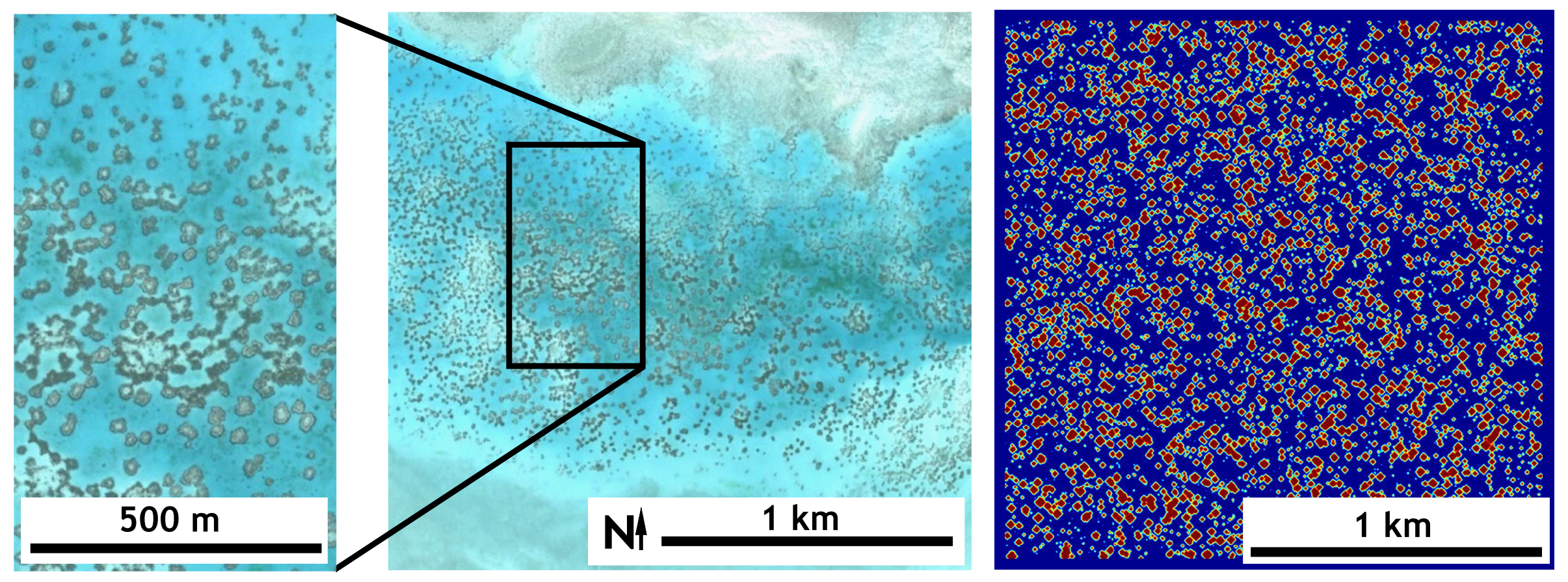
Above and right: Grain size distributions for 3 sediment samples collected at Hogsty Reef, the Bahamas. Pictures of the environments in which the samples were collected are to the right.



Left: Gray-scale images from which the Camsizer calculates the statistics for grain size and shape.

Geologic realism

The topographic features generated by the model resemble real-world examples observed by satellite. Reticulate structures were generated by a combination of stochastic recruitment in a cell and the incorporation of a neighborhood effect on class transitions. Rim structures are emulated by varying the recruitment field from a uniform probability across the platform to one focus on the platform's edges indicating that differences in this spatial distribution of this parameter influences framework geometry.



Right: Examples of patch reefs formed in nature (left) and simulated by the model (far right). Each covers an expanse of a 2 km by 2 km (4 km^{2}).

Summary

Satellite observations of reefs demonstrate that the distributions of their geometric sizes follow heavy-tailed distributions, which can be attributed to the self-organizing properties of these systems and is based around the "law of proportional effect." The presented model emulates lagoonal framework construction by combining depth dependent growth with a conditioned neighborhood influence. Initial results are encouraging and indicate that the simulated reefs have the same geometric properties as natural systems.

Key insights:

[1]A comparatively simple assimilation of logic into a cellular automata is sufficient to generate realistic lagoonal patch reef complexes on time-scales of millennia (Holocene)

[2]The numerical parameters that describe the size-frequency distribution of the simulated build-ups are in good accordance to those observed in real-world systems

[3]Further development is necessary and will focus on simulation of the redistribution of detritus. This advancement will be achieved by coupling a hydrodynamic model to the biologic automata