# Modeling Benthic Carbonate Sedimentation on Biological Principles

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"In the end, the geo is … a consequence of the eco in carbonates".

## Rationale

Carbonate systems have biological levels of complexity. The producers are diverse and occupy their environments and communities opportunistically - not passively like clastic sediment particles. The creation of carbonate geomaterials from seawater chemistry is almost entirely mediated by the metabolic processes of organisms. Whether those organisms are present at a site is determined by environmental (niche) and historical (dispersal, recruitment, mortality) events.

While carbonate production can be scaled approximately to physical environmental parameters (depth, temperature; e.g., Demicco & Klir 2001, Jl Petrol. Sci. Eng. 31, 135–155), modeling using this approach is rules-based and often fails if extended from the central (coral-reef) concepts. Models of benthic carbonates in general (e.g., shelf margin bryozoan mounds, maerl beds, cold-water coral thickets, Halimeda banks) must include the habitat tolerances, growth, calcification, reproduction, mortalities and interactions of the actual creatures. In short, a population ecology model is required.

## Application of a Population Model

The classic population interaction model– e.g., rabbits as prey for foxes – is the Lotka-Volterra arrangement of coupled ordinary differential equations (ODE). However, for benthic carbonate-producers, most of which are skeletonized, bottom-attached, and colonial, competition is more subtle and in terms of space and nutrition. It acts primarily via relative growth rates, spawning success, overgrowing capabilities, and recuperation after extreme events. The predators tend to be partial grazers rather than annihilators of colonies. Different reproductive strategies (e.g., planktonic release of propagules, binary fission in situ, colony extension, and regenerative cloning) and the time from settlement of propagules until later reproduction are both important, and require population models with size-maturity cohorts that determine growth rates, mortalities, carbonate production.

## Goals, Strategy

The present model – called numericCARBONATE (nC) – is being developed to explore the role of population ecology in carbonate sedimentation. It is a numerical experimental tool which may be operated alone, but could be 'bolted on' to some existing carbonate models. Thus, it is compatible with the CSDMS Carbonate Workbench concept.

For now nC is being applied only to present-day environments and taxa, under steady-state conditions. Episodic (~decadal) events such as storms or mass coral bleachings are factored in. Once steady-state operation is validated, then we will include sea-level change and geological histories.

The project will validate outputs against drill core records, specifically those in the Funafuti tradition ("www.tuvaluislands.com") and of the Integrated Ocean Drilling Program (IODP; see below). nC will compute visual core-logs for comparison to the descriptions and photos of carbonate cores, down to the forms and sizes of corals and other taxa, and the interstitial and sediment materials. We believe it is very important for models to have a set "bar" for their validation.

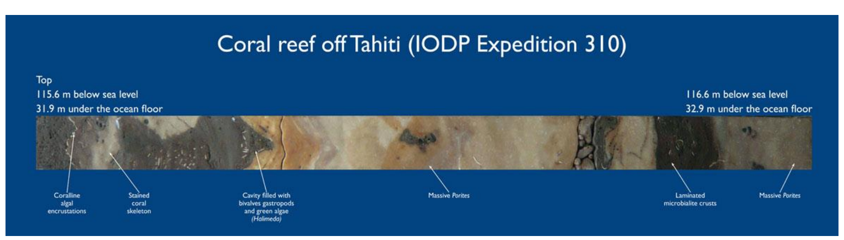



*Fig. 1. Validations of nC will include comparisons with mesoscale descriptions of fossil communities in drill cores of carbonates, for example IODP cores from Tahiti (IODP Expedition 325 Scientists, 2010. IODP Prel. Rept., 325. doi:10.2204 /iodp.pr.325.2010), Great Barrier Reef, the Great Australian Bight cold-water carbonates, and NE Atlantic coral mounds.*

## The Geological View

As organisms establish, grow and die, skeletal production and destruction create new geomaterials. In some locations the skeletons are locked together in frameworks; in others they are loose or broken and can be transported. The vertical accumulation of carbonate is a matter of organism growth rates and solidification of the foundations. nC handles accumulation in 4 bins at the seafloor: the underground, loose sediment layer, and framework understorey and superstructure. The contribution of organisms accumulated in these bins is available for sediment transport and diagenesis routines (both yet to be implemented).

## Formulation

A Lotka-Volterra (L-V) system is implemented as follows:

1. A taxon's areal cover indicates it's stock. It's capacity to release spawn, collect light and nutrients, suffer from grazing, and interact with neighbours scale with the stock size. Growth, mortality and recruitment are expressed as changes in the area covered.
2. Each taxon competes against all others, so the L-V system can be written in pairwise 'them vs us' form, instead of solving large numbers of simultaneous ODE at each step.
3. The basic time step is 1 year and the populations are modelled in bursts - for instance over 20 years.
4. Outputs include population histories, summaries of faunal composition and stocks, and maps of bottom type and accumulation.

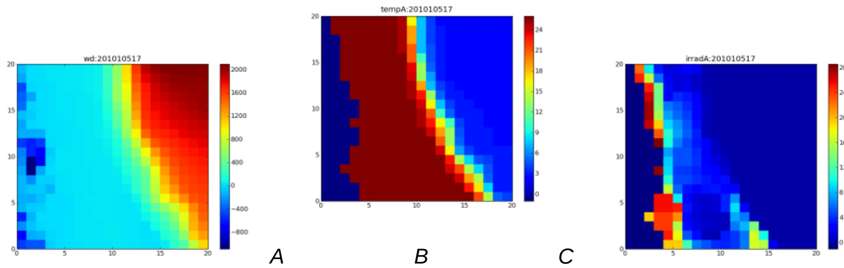



*Fig. 2. Maps of environmental variables for the model areas, computed at start of model runs from global datasets. A. Water Depth (m), b. Bottom Temperature (deg C), c. Benthic PAR irradiance (µmol photons m-2 s-1 available for photosynthesis).*

## Habitat Suitability

Suitable habitat is a major restriction on facies of benthic carbonates, whether warm-water coral reefs, cold-water coral mounds, or bryozoan shelf banks. Although our knowledge of limiting factors is incomplete, few populations fully occupy their potential physical and trophic ranges, for many reasons, past and current (e.g. dispersal and habitat histories, competition, predation, community dependencies). In addition, habitats are not homogeneous: growth, reproduction and survival may be optimal in 'central' parts, while competition may dominate at the margins.

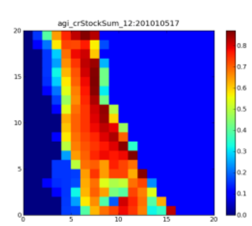
nC uses a set of global datasets to compute habitat suitability: water depths (GEBCO 1nm), ocean temperature and nutrient chemistry (WOA05), irradiance and chlorophyll (MODIS AQUA), surface wave climate (WAVEWATCH III), internal wave dissipation (from WHOI), and substrate types (dbSEABED). We are seeking more layers, especially for tidal and geostrophic flows.

Environmental sub-maps are compiled at model start-up (e.g., Figs 2a-c). Sea-surface PAR is transformed to benthic irradiance after Gattuso et al. 2006 (Biogeosciences, 3, 489–513, 2006). Temperature and nutrient (nitrate) are extracted from WOA05 for bottom waters only.

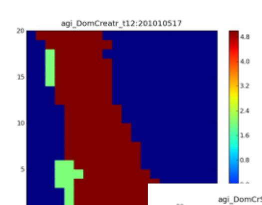
## Biological Knowledge-Base (KB)

A population ecology model demands detailed information about the life strategies, habitats and dimensions of organisms. Fortunately, large amounts of data are available, including from published papers and systems such as ReefBase, FishBase, OBIS, MARBEF and GBIF. Aquarium keepers often report on the physical environmental limitations of species. nC focusses on dominant 'marker' taxa. After considering using genera, guilds, communities and functional groups, we opted for a firm footing in the modeling using only verifiable, species-level information.

We built a prototype KB for 12 taxa, describing variables such as Colony Size, (Environmental Preferences) Temperature, (Reproduction) Spawn Production Rate, Mortality Rates. The environmental ranges are described using values, linear sets, or fuzzy terms. Routines for checking and reconciling the KB data are built into the model.




A




B,C

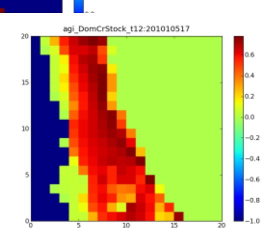
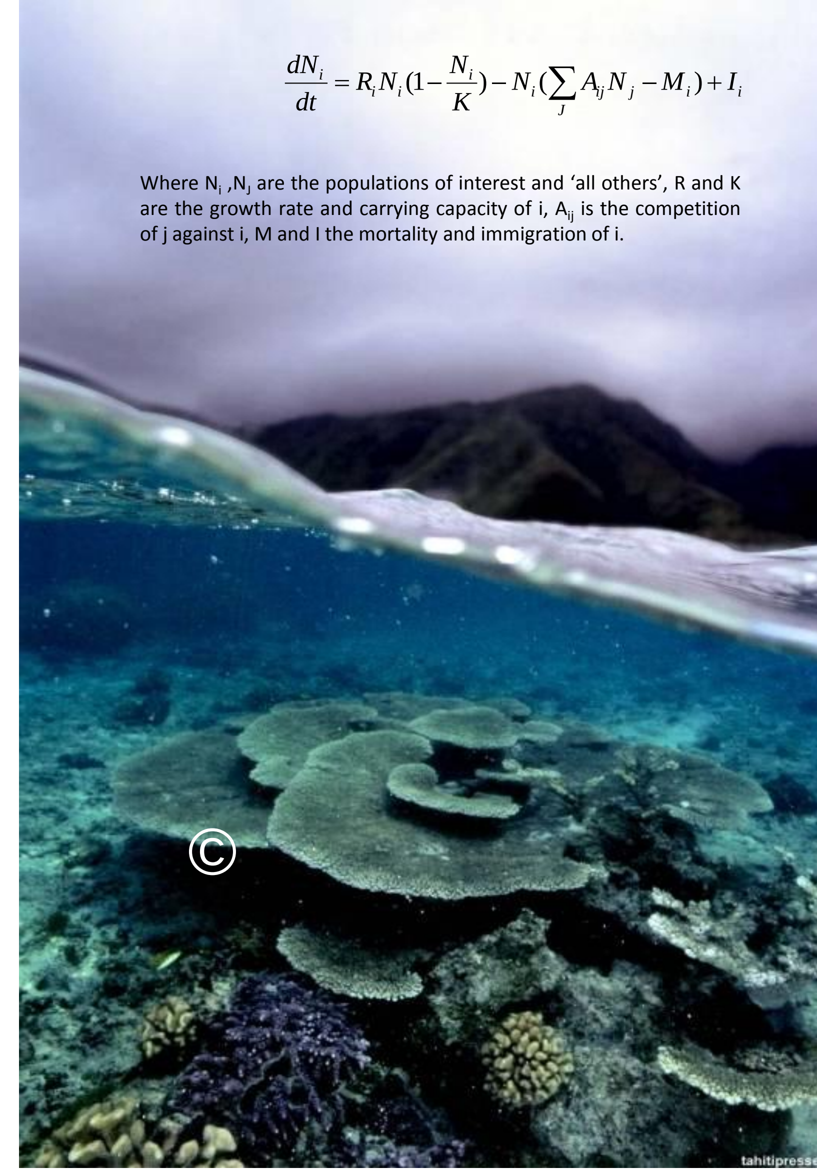



*Fig. 3. Some model outputs. A. Total habitation by carbonate organisms, as % area coverage. B,C. The dominant species, and their abundances. In this case the most widespread is Halimeda, representing green calcified algae (5), and Porites, representing hermatypic corals (2). Agincourt Reef-Cairns region, GBR.*



$$\frac{dN_i}{dt} = R_i N_i \left(1 - \frac{N_i}{K}\right) - N_i\left(\sum_j A_{ij} N_j - M_i\right) + I_i$$

Where $N_i$ ,$N_j$ are the populations of interest and 'all others', R and K are the growth rate and carrying capacity of i, $A_{ij}$ is the competition of j against i, M and I the mortality and immigration of i.



*Fig. 4. Formulation and view at Tahiti, area of Ocean Drilling into coral reefs.*

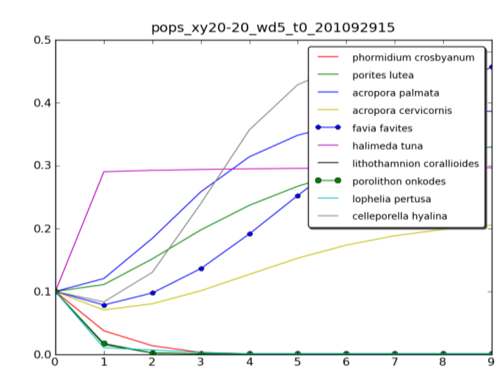
## Results

Here we report on early development stages for the model. Population behavior appears to be well-constrained (Fig. 5) and reacts to events such as mortalities. The restrictions from habitat suitability are effective. The growth and calcification is producing realistic accumulation values. Elementary outputs of community composition and stocks are being produced (Fig. 3).

The models can be run for almost any location (currently Chagos Bank, Lord Howe Island, Midway Atoll, Agincourt Reef GBR) with minimal setup time. Grid resolution has been tested between 500m and 10km for up to 100x100 cells, and runs to 240 years have been achieved in times <10 minutes.

Work in the immediate future will be to improve topographic (water depth) resolution near existing reefs, implement code for immigration and mortality events, and add more key marker taxa to the knowledge base.

*Fig. 5. Plots of population growth at model spin-up till 10 years for a shallow water depth, warm-water, low latitude site. By the model, Halimeda quickly establishes, reef corals increase steadily over 5 years, others in the KB fade out quickly. The community matures to an Acropora-Favia assemblage with bryozoa and Halimeda. The model accuracy is likely to be 0.1 (fractional coverage by area) .*

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*With thanks to Tahiti Press (Papeete, Tahiti) for permission to use the scene-setting photograph.*