# Identifying and characterising coral reef “oases”

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# Supporting information

## Appendix 1.

We used numerical simulations to evaluate a wide range of empirical possibilities of coral reef trajectories. The simulations were intended to capture the behaviour of long-term coral cover dynamics based on four predetermined model scenarios considered as representative of trajectories observed from long-term monitoring of reefs: (1) linear trends (i.e., where coral cover declines or increases linearly; (2) nonlinear oscillations, (3) phase shifts (i.e., where coral cover declines suddenly and remains low); and (4) long-term stability (i.e., where coral cover can vary from year to year, but does not increase or decrease significantly over time). For each scenario, we generated 30 random values for coral cover for a thirty-year time-series. The model parameters were chosen to return values of coral cover between 0 and 65%, a range that is representative of contemporary average values from the Caribbean and Indo-West Pacific.

### Stable

For sites exhibiting stable coral cover () in year , we generated 30 random values about an intercept () with variation (), for a thirty-year time-series as follows:

where is the standard deviation about . The intercept is chosen from either a normal () or uniform distribution (), determined by a fair coin flip.

The R function to return a stable time series is:

##' cc = upper value of coral cover, used in normal or uniform distribution (40)  
##' yrs = number of years in the time series (30)  
##' rnorm\_theta = probability of observing a zero or one (0.5)  
##' (for the coin flip)  
  
stable\_simF <- function(cc = coral\_cover, yrs = number\_yrs, rnorm\_theta = 0.5){  
   
 coin\_flip <- sample(c(0, 1), size = 1, prob = c(rnorm\_theta, 1 - rnorm\_theta))  
   
 # If coin\_flip is 0, sample from normal distribution:  
 if(coin\_flip == 0){  
 cc = rnorm(1, mean = cc, sd = 5)}  
   
 # Otherwise, sample from a uniform distribution:  
 if(coin\_flip == 1){  
 cc = runif(1, max = cc, min = 5)}  
   
 # Choose the starting coral cover sd from a normal distribution  
 cc\_sd = 0.1 \* cc # make standard deviation 10% of starting coral cover  
 cc\_sd = rnorm(1, mean = cc\_sd, sd = 0.5)  
   
 # Change cc\_sd if below some arbitrary threshold  
 cc\_sd = ifelse(cc\_sd < 0.1, 0.1, cc\_sd)  
   
 # Get time series  
 y = rnorm(number\_yrs, mean = cc, sd = cc\_sd)  
   
 # Assemble data frame  
 sim\_df <- data.frame(year = 1:number\_yrs,   
 w = cc - y, slope = 0, intercept = cc,   
 y = y)  
   
 return(sim\_df)  
}

### Phase shift

For sites exhibiting a phase shift, a new intercept () and variation () was selected at a year chosen randomly between year 10 and year 30 () of a thirty-year time-series as follows:

where is the new standard deviation about . The effect of the phase shift is to reduce the coral cover to a value chosen uniformly between 1 and half of the original .

The R function to return a phase shift is:

##' cc = upper value of coral cover, used in normal or uniform distribution (40)  
##' yrs = number of years in the time series (30)  
##' rnorm\_theta = probability of observing a zero or one (0.5)  
##' (for the coin flip)  
##' shift\_min = the earliest year in which a phase shift can begin (10)  
##' shift\_max = the latest year in which a phase shift can begin (30)  
  
phase\_shift\_simF <- function(cc = coral\_cover, yrs = number\_yrs, rnorm\_theta = 0.5,   
 shift\_min = 10, shift\_max = 30){  
   
 coin\_flip <- sample(c(0, 1), size = 1, prob = c(rnorm\_theta, 1 - rnorm\_theta))  
   
 # If coin\_flip is 0, sample from normal distribution:  
 if(coin\_flip == 0){  
 cc = rnorm(1, mean = cc, sd = 5)}  
   
 # Otherwise, sample from a uniform distribution:  
 if(coin\_flip == 1){  
 cc = runif(1, max = cc, min = 5)}  
   
 # Choose the starting coral cover sd from a normal distribution  
 cc\_sd = 0.1 \* cc # make standard deviation 10% of starting coral cover  
 cc\_sd = rnorm(1, mean = cc\_sd, sd = 0.5)  
   
 # Change cc\_sd if below some arbitrary threshold  
 cc\_sd = ifelse(cc\_sd < 0.1, 0.1, cc\_sd)  
   
 # Get time series  
 y = rnorm(number\_yrs, mean = cc, sd = cc\_sd)  
   
 # Now choose when the phase shift happens  
 begin\_shift = floor(runif(1, min = shift\_min, max = shift\_max))  
   
 # Get the new coral cover mean  
 cc\_new = runif(1, max = 0.5\*cc, min = 1)  
   
 # Get the coral cover sd, similar to old sd  
 cc\_sd\_new = rnorm(1, mean = cc\_sd, sd = 0.1)  
   
 # Change cc\_sd\_new if below some arbitrary threshold  
 cc\_sd\_new = ifelse(cc\_sd\_new < 0.1, 0.1, cc\_sd\_new)  
   
 # Get phase shift time series  
 y\_new = rnorm(number\_yrs, mean = cc\_new, sd = cc\_sd\_new)  
   
 # Assemble data frame  
 sim\_df <- data.frame(year = 1:number\_yrs,   
 w = cc - y, slope = 0, intercept = cc,   
 y = y) %>%   
 mutate(y = ifelse(year < begin\_shift, y, y\_new))  
   
 return(sim\_df)  
}

### Linear trend

For sites exhibiting a linear trend in coral cover, a slope (m) was also selected randomly with a thirty-year time series determined by the equation for a line, as follows:

where is the standard deviation about .

The R function to return a linear trend is:

##' cc = upper value of coral cover, used in normal or uniform distribution (40)  
##' yrs = number of years in the time series (30)  
##' rnorm\_theta = probability of observing a zero or one (0.5)  
##' (for the coin flip)  
##' trend = slope of the linear trend (-0.5)  
##' trend\_sd = standard deviation for the trend (0.25)  
  
linear\_simF <- function(cc = coral\_cover, yrs = number\_yrs,   
 trend = linear\_trend, trend\_sd = linear\_trend\_sd,   
 rnorm\_theta = 0.5){  
   
 coin\_flip <- sample(c(0, 1), size = 1, prob = c(rnorm\_theta, 1 - rnorm\_theta))  
   
 # If coin\_flip is 0, sample from normal distribution:  
 if(coin\_flip == 0){  
 cc = rnorm(1, mean = cc, sd = 5)}  
   
 # Otherwise, sample from a uniform distribution:  
 if(coin\_flip == 1){  
 cc = runif(1, max = cc, min = 5)}  
   
 # Choose the starting coral cover sd from a normal distribution  
 cc\_sd = 0.1 \* cc # make standard deviation 10% of starting coral cover  
 cc\_sd = rnorm(1, mean = cc\_sd, sd = 0.5)  
   
 # Change cc\_sd if below some arbitrary threshold  
 cc\_sd = ifelse(cc\_sd < 0.1, 0.1, cc\_sd)  
   
 # Random variation for each time point  
 w <- rnorm(number\_yrs, mean = 0, sd = cc\_sd)   
   
 # Random value for slope  
 slope <- rnorm(1, mean = trend, sd = trend\_sd)  
   
 # Random value for intercept (i.e., the starting coral cover)  
 intercept <- rnorm(1, cc, sd = cc\_sd)  
   
 ## Get time series  
 y <- slope \* x + intercept + w  
   
 # Assemble data frame  
 sim\_df <- data.frame(year = 1:number\_yrs,   
 w = w, slope = slope, intercept = intercept,   
 y = y)  
   
 return(sim\_df)  
}

### Oscillations

Finally, we used a cosine curve to simulate oscillations over time:

with an amplitude (), period () and horizontal shift (). In this equation, represents the vertical shift of the cosine curve. Note that the is 30 instead of 40 as previously, to prevent unusually high coral covers due to the oscillations.

The R function to return oscillations is:

##' cc = upper value of coral cover, used in normal or uniform distribution (30)  
##' yrs = number of years in the time series (30)  
##' rnorm\_theta = probability of observing a zero or one (0.5)  
##' (for the coin flip)  
##' trend = slope of the linear trend (0)  
##' trend\_sd = standard deviation for the trend (0)  
##' amp = amplitude  
##' period (years) [for a 30 yr time series, a period of 30 results in a U] (40)  
  
non\_linear\_simF <- function(cc = coral\_cover, yrs = number\_yrs,   
 trend = linear\_trend, trend\_sd = linear\_trend\_sd,   
 rnorm\_theta = 0.5, amplitude = amp){  
   
 coin\_flip <- sample(c(0, 1), size = 1, prob = c(rnorm\_theta, 1 - rnorm\_theta))  
   
 # If coin\_flip is 0, sample from normal distribution:  
 if(coin\_flip == 0){  
 cc = rnorm(1, mean = cc, sd = 5)}  
   
 # Otherwise, sample from a uniform distribution:  
 if(coin\_flip == 1){  
 cc = runif(1, max = cc, min = 5)}  
   
 # Choose the starting coral cover sd from a normal distribution  
 cc\_sd = 0.1 \* cc # make standard deviation 10% of starting coral cover  
 cc\_sd = rnorm(1, mean = cc\_sd, sd = 0.5)  
   
 # Change cc\_sd if below some arbitrary threshold  
 cc\_sd = ifelse(cc\_sd < 0.1, 0.1, cc\_sd)  
   
 # Random variation for each time point  
 w <- rnorm(number\_yrs, mean = 0, sd = cc\_sd)   
   
 # Random value for slope  
 slope <- rnorm(1, mean = trend, sd = trend\_sd)  
   
 # Random value for intercept (i.e., the starting coral cover)  
 intercept <- rnorm(1, cc, sd = cc\_sd)  
   
 # Phase shift  
 phase\_shift = runif(1, 0, 0.25) \* pi  
   
 # Amplitude  
 amp = rnorm(1, mean = amp, sd = amp\*0.5)  
   
 # Period  
 period = rnorm(1, mean = period\_yrs, sd = period\_yrs\_sd)  
   
 # Vector representing the nonlinear trend  
 cs = amp \* cos(2\*pi\*1:number\_yrs/period + phase\_shift)  
  
 # Get time series  
 y <- slope \* x + intercept + w + cs  
  
 # Assemble data frame  
 sim\_df <- data.frame(year = 1:number\_yrs,   
 w = w, slope = slope, intercept = intercept,   
 y = y)  
   
 return(sim\_df)  
}

![Time series of coral cover from numerical simulations representing four different reef trajectories (n = 100 per trajectory).](data:application/pdf;base64,)

Time series of coral cover from numerical simulations representing four different reef trajectories (n = 100 per trajectory).