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Data provider acknowledgements

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Glossary

Resilience - the ability of an ecosystem to resist and recover from disturbance

Herbivory - the consumption of algae on a coral reef

Predation - the consumption of animals on a coral reef

Functional group - the role that a collection of fish species play in modifying coral reef ecosystems through consumption, competition, and habitat modification

Off-reserve - locations outside of marine reserves

Marine reserve - a physical area within which fishing activities are forbidden

Unfished biomass - the maximum average potential total reef fish biomass on a coral reef

Collapsed - the loss of 90% (or more) of unfished biomass on a given coral reef

Recovered - the maintenance of 90% (or more) of unfished biomass on a given coral reef

Browsers - reef fishes that primarily consume macroalgae

Scrapers/excavators - reef fishes that remove reef substrate while consuming living material on the reef surface

Grazers - reef fished that primarily consume turf algae

Planktivores - reef fish that primarily consume plankton

Detritivores - reef fish that primarily consume detritus (dead organic material)

Macro-invertivores - reef fish that primarily consume small invertebrates

Micro-invertivores - reef fish that primarily consume large invertebrates

Macroalgae - large, leathery algae, usually with a prominent frond and stalk

Turf algae - fine filamentous algae

Trophic level - the average number of steps between a consumer and plant material in a food web

Functional return - the relative increase in log-biomass of a functional group, relative to their log-biomass at a given baseline, across a defined range of total reef fish biomass

```
#
#  models.py
#
#  Joint MPA and Remote unfished biomass model
#
#  Created by M. Aaron MacNeil on 11/11/14.
#  Copyright (c) 2014 AIMS. All rights reserved.
#

import sys
import os
from data import *
from pymc import *
import numpy as np
import pdb


#------------------------------------------------ Global priors
# Uninformed
#gamma_0 = Uniform('unfished_biomass', lower=1, upper=15, value=6)
# Global intrisic biomass levels - priors from PNAS paper
gamma_0 = Normal('unfished_biomass', mu=pnas_prior, tau=pnas_tau)
sd_0 = Uniform('gbiom_sd', lower=0., upper=100., value=1.)
tau_0 = Lambda('gbiom_tau', lambda sd=sd_0: sd**-2)

#"""
# Nussiance parameters
beta_10 = Normal('hard_coral', mu=0.0, tau=0.001, value=0.0)
beta_11 = Normal('hard_coral2', mu=0.0, tau=0.001, value=0.0)
beta_12 = Normal('hard_coral2', mu=0.0, tau=0.001, value=0.0)
beta_3 = Normal('atoll', mu=0.0, tau=0.001, value=0.0)
beta_50 = Normal('productivity', mu=0.0, tau=0.001, value=0.0)
beta_51 = Normal('productivity2', mu=0.0, tau=0.001, value=0.0)
beta_52 = Normal('productivity3', mu=0.0, tau=0.001, value=0.0)
#"""

#"""
# Data-provider effect
delta_0 = Normal('delta0', mu=0.0, tau=0.001, value=0.0)
sd_d0 = Uniform('provider_sd', lower=0., upper=100., value=1.)
tau_d0 = Lambda('provider_tau', lambda sd=sd_d0: sd**-2)
rho0 = Normal('provider', mu=delta_0, tau=tau_d0,
value=np.ones(nprovider))
rho_0 = Lambda('rho_0', lambda r0=rho0: r0-np.mean(r0))
#"""

#------------------------------------------------ Marine reserve recovery
submodel
# Minimum biomass
gamma_1 = Normal('min_biomass', mu=4.599065, tau=0.01, value=4.599065)
# Rate of intrinsic biomass growth within reserves
gamma_2 = Uniform('intrinsic_growth', lower=-1, upper=3, value=.1)

# Mean model
```

```
mu = Lambda('mu', lambda K=gamma_0, r=gamma_2, mb=gamma_1, b10=beta_10,
b11=beta_11, b12=beta_12, b3=beta_3, b50=beta_50, b51=beta_51,
b52=beta_52, r0=rho_0[Imp]: K/(1+((K-mb)/mb)*np.exp(-r*mreserve_age)) +
b10*mhard_coral + b11*mhard_coral**2 + b12*mhard_coral**3 + b3*matoll +
b50*mproductivity + b51*mproductivity**2 + b52*mproductivity**3 + r0)


# 'Observation' error
bio_sd = Uniform('bio_sd', lower=0, upper=1000, value=2.)
bio_tau = Lambda('bio_tau', lambda sd=bio_sd: sd**-2)
# Likelihood
Yi = Normal('Yi', mu=mu, tau=bio_tau, value=m_lbiomass, observed=True)


#------------------------------------------------ Remote location
submodel
# Local variation
sd_lr = Uniform('lr_sd', lower=0., upper=1000., value=1.)
tau_lr = Lambda('lr_tau', lambda sd=sd_lr: sd**-2)
# Location-scale estimates
eta_0 = Normal('eta0', mu=gamma_0, tau=tau_lr,
value=np.ones(nrlocation)*6.)
eta0c = [Lambda('eta0__%s'%(rlocation[i]), lambda e0=eta_0[i]: e0) for i
in xrange(nrlocation)]

# Mean model
mu_r = Lambda('mu_r', lambda e0=eta_0[Irl], b10=beta_10, b11=beta_11,
b12=beta_12, b3=beta_3, b50=beta_50, b51=beta_51, b52=beta_52,
r0=rho_0[Irp]: e0 + b10*rhard_coral + b11*rhard_coral**2 +
b12*rhard_coral**3 + b3*ratoll + b50*rproductivity + b51*rproductivity**2
+ b52*rproductivity**3 + r0)

# 'Observation' error
bior_sd = Uniform('bior_sd', lower=0, upper=1000, value=2.)
bior_tau = Lambda('bior_tau', lambda sd=bior_sd: sd**-2)
# Likelihood
Zi = Normal('Zi', mu=mu_r, tau=bior_tau, value=r_lbiomass, observed=True)


#------------------------------------------------ Management type
submodel
# Management parent priors
#res_mu= Normal('res_mu', mu=6, tau=0.001, value=6.1)

# Location variability
#sd_resmu = Uniform('resmu_sd', lower=0., upper=1000., value=1.)
#tau_resmu = Lambda('resmu_tau', lambda sd=sd_resmu: sd**-2)
# Location-scale estimates
res_l = Normal('res_location', mu=6., tau=0.01,
value=np.ones(nrslocation)*6)
res_lx = [Lambda('res_location__%s'%(res_location[i]), lambda
b0=res_l[i], B0=gamma_0: np.exp(b0)/np.exp(B0)) for i in
xrange(nrslocation)]
```

```
# Mean model
res_mu = Lambda('res_mu', lambda b0=res_l[Irsl], b10=beta_10,
b11=beta_11, b12=beta_12, b3=beta_3, b50=beta_50, b51=beta_51,
b52=beta_52, r0=rho_0[Izp]: b0 + b10*res_hard_coral +
b11*res_hard_coral**2 + b12*res_hard_coral**3 + b3*res_atoll +
b50*res_productivity + b51*res_productivity**2 + b52*res_productivity**3
+ r0)

# 'Observation' error
res_sd = Uniform('res_sd', lower=0, upper=1000, value=2.)
res_tau = Lambda('res_tau', lambda sd=res_sd: sd**-2)
# Likelihood
Gi = Normal('Gi', mu=res_mu, tau=res_tau, value=res_lbiomass,
observed=True)


#------------------------------------------------ Fished submodel

# Average fished prior
#zeta_0 = Normal('fished_average', mu=3, tau=0.001, value=3.1)

# Local variation
#sd_lf = Uniform('lf_sd', lower=0., upper=1000., value=1.)
#tau_lf = Lambda('lf_tau', lambda sd=sd_lf: sd**-2)
# Location-scale estimates
kappa_0 = Normal('kappa_0', mu=4.0, tau=0.01, value=np.ones(nfl)*4.0)
Kappa = [Lambda('Kappa__%s'%(flocation[i]), lambda k=kappa_0[i]: k) for i
in xrange(nfl)]

# Mean model
mu_k = Lambda('mu_k', lambda k0=kappa_0[Ifl], b10=beta_10, b11=beta_11,
b12=beta_12, b3=beta_3, b50=beta_50, b51=beta_51, b52=beta_52,
r0=rho_0[Ifp]: k0 + b10*fhard_coral + b11*fhard_coral**2 +
b12*fhard_coral**3 + b3*fatoll + b50*fproductivity + b51*fproductivity**2
+ b52*fproductivity**3  + r0)

# 'Observation' error
fc_sd = Uniform('fc_sd', lower=0, upper=1000, value=10.)
fc_tau = Lambda('fc_tau', lambda sd=fc_sd: sd**-2)
# Likelihood
Ki = Normal('Ki', mu=mu_k, tau=fc_tau, value=flbiomass, observed=True)


#======================================================= POSTERIORS

#------------------------------------------------ Proportions of B0
# Management
res_mgmtx = [Lambda('mgmt__%s'%(res_mgmt[i]), lambda b0=res_l[Imresl==i],
B0=gamma_0: np.exp(np.mean(b0))/np.exp(B0)) for i in xrange(nmgmt)]
# Fished
F_ari = Lambda('F_ari', lambda B0=gamma_0, k0=kappa_0:
np.exp(k0)/np.exp(B0), trace=False)
F = [Lambda('F__%s'%(flocation[i]), lambda F=F_ari[i]: F) for i in
xrange(nfl)]
```

```
# Restricted
R_ari = Lambda('R_ari', lambda B0=gamma_0, l0=res_l:
np.exp(l0)/np.exp(B0), trace=False)
R = [Lambda('R__%s'%(res_location[i]), lambda R=R_ari[i]: R) for i in
xrange(nrslocation)]

#------------------------------------------------ Recovery times
# Time to recovery from initial biomass
@deterministic(plot=False)
def AR_90(K=gamma_0, r=gamma_2, mb=gamma_1):
    # Log-scale equivalient of 90% of arithmetic B0
    k0 = np.log(.9*np.exp(K))
    return np.log(((K/k0)-1)/((K-mb)/mb))/-r

# Virtual reserve age - fished
@deterministic(plot=False)
def VAf(K=gamma_0, r=gamma_2, mb=gamma_1, K0=kappa_0):
    # Keep things sane incase of random zeros
    k0 = array([min(max(mb,k),K) for k in K0])
    return np.log(((K/k0)-1)/((K-mb)/mb))/-r

# Virtual reserve age - restricted
@deterministic(plot=False)
def VAr(K=gamma_0, r=gamma_2, mb=gamma_1, K0=res_l):
    # Keep things sane incase of random zeros
    k0 = array([min(max(mb,k),K) for k in K0])
    return np.log(((K/k0)-1)/((K-mb)/mb))/-r

# Times to recovery - fished
TR90_f = Lambda('TR90_f', lambda t90=AR_90, vage=VAf: t90-vage)
TR90x = [Lambda('fTR90__%s'%(flocation[i]), lambda tr=TR90_f[i]: tr) for
i in xrange(nfl)]
# Times to recovery - restricted
TR90_res = Lambda('TR90_res', lambda t90=AR_90, vage=VAr: t90-vage)
TR90y = [Lambda('rTR90__%s'%(res_location[i]), lambda tr=TR90_res[i]: tr)
for i in xrange(nrslocation)]

#======================================================== PLOTTING
POSTERIORS
#"""
# Marine reserve recovery
global_model = Lambda('global_model', lambda K=gamma_0, r=gamma_2,
mb=gamma_1:
K/(1+((K-mb)/mb)*np.exp(-r*pred_x)))
# Unfished biomass - arithmetic
global_B0 = Lambda('global_B0', lambda b0=gamma_0: np.exp(b0))
#"""
```

Supplementary Table 1 | Data provider locations and contact information.

Provider	Localitie(s)	Year(s)	Contact
University of Hawaii	Ducie, Easter Is, Farquhar, Hawaii, Henderson, Oeno, Pitcairn Is, Salas y Gomez	2002-2012	Alan Friedlander friedlan@hawaii.edu Fisheries Ecology Research Lab, Department of Biology, University of Hawaii, Honolulu, HI 96822 USA
NOAA Coral Reef Ecosystem Division	Agrihan, Alamagan, Asuncion, Baker, Farallon de Pajaros, French Frigate, Guam, Guguan, Hawaii, Howland, Jarvis, Johnston, Kauai, Kingman, Kure, Lanai, Laysan, Lisianski, Maro, Maug, Maui, Midway, Molokai, Necker, Niihau, Oahu, Ofu & Olosega, Pagan, Palmyra, Pearl & Hermes, Rose, Rota, Saipan, Sarigan, Swains, Tau, Tinian, Tutuila, Wake Is	2005-2009	Ivor Williams Ivor.Williams@noaa.gov Coral Reef Ecosystems Division, NOAA Pacific Islands Fisheries Science Center, Honolulu, HI 96818 USA
Wildlife Conservation Society	Fiji	2012	Stacy Jupiter sjupiter@wcs.org Wildlife Conservation Society, Marine Programs, Bronx, NY 10460 USA
Newcastle University	Antigua, Belize, Bonaire, Curacao, Dominican Republic, Hondouras, Jamaica, Saint Lucia	2010-2011	Steve Newman steve.newman@newcastle.ac.uk School of Marine Science and Technology, Newcastle University, Newcastle upon Tyne NE1 7RU UK
Centre of Excellence for Coral Reef Studies	Ahus, GBR, Great Chagos Bank, Karkar, Maldives, Peros Banhos, Salomon, Seychelles	2008-2011	Nick Graham nick.graham@jcu.edu.au Australian Research Council Centre of Excellence for Coral Reef Studies, James Cook University, Townsville, QLD 4811 Australia