I. Report Title: Recovery modeling for anthropogenic impacts on Hawaiian coral reefs.

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II. Abstract.

This project developed a preliminary numerical recovery model for use in ecological studies and in natural resource damage evaluations related to natural and anthropogenic injuries to Hawaiian coral reefs. The model is based on the successful NOAA CCFHR injury recovery models first developed for the Florida Keys. The first phase of this project generated the required demographic rates (growth, mortality, recruitment) for Hawaiian corals using existing archived time series photoquads obtained during the past 7 years. Recruitment is defined as the addition of individual colonies within the photoquad. Growth and partial mortality was calculated using image analysis software. These data were incorporated into the model and tested. Preliminary results are very encouraging as the model is producing recovery curves that are realistic in terms of recovery time and final coral cover in the final steady state. Further field testing is required, with a need for additional data on larger colonies and more data from certain habitats. The quantitative model could be used in evaluating damage caused by events such as storm events, Crown of Thorns starfish outbreaks, ship groundings, dredge and fill projects, oil spills or other impacts. These spatially explicit models focus on percent coral cover to estimate recovery to baseline (the condition that would exist if not for the injury). The model output is designed to include the recovery time and the shape of the recovery curve.

III. Executive Summary

This project succeeded in producing a preliminary numerical recovery model for reef corals on Hawaiian coral reefs that can be used to estimate the recovery time for damaged reefs. A large data base of demographic data on Hawaiian corals was developed as part of the project. These data are incorporated into the recovery model and can be used to estimate population response to damage in a variety of Hawaiian habitats. Preliminary runs of the model produce output that is consistent with field observations of recovery time and final coral cover at various locations.
IV. Purpose

A. Detailed description of the HCRI research priority addressed:

This project addressed Research Priority Item 4 (Pollution): “calculate the recovery time of a typical Hawaii biotic reef that has been damaged. A recovery time model for Hawaiian coral reefs would also be very useful in establishing and supporting damage claims concerning reef injuries due to a variety of other anthropogenic disturbances including sediment spills and dredge and fill operations. The recovery times will be similar no matter what the initial cause of the mortality, provided that the causative factor has been removed”

B. Objectives of the project.

The overall goal was to develop coral population models for various habitats based on natural recruitment, mortality and growth data. These models can be used to make recovery estimates. Such quantitative estimates based on best available information are useful in planning mitigation strategies and in determining compensatory damages in dealing with coral injuries in Hawaii. Our specific objectives were to:

1) Generate coral demographic data (recruitment, growth, and mortality) for abundant species in major habitat types using archived CRAMP photoquadrat images and other data supplemented by additional size-frequency field data;

2) Use the demographic data to develop Hawaiian coral reef recovery models based on the existing NOAA CCFHR recovery model that was developed for the Florida Keys.

V. Approach

A. Detailed description of the work that was performed.

The first goal of the project which is to “Generate coral demographic data (recruitment, growth, and mortality) for abundant species in major habitat types using archived CRAMP photoquadrat images and other data supplemented by additional size-frequency field data.” This was accomplished with data recorded for a total of 3947 coral colonies. The mean growth for all colonies combined was 1.6 cm yr\(^{-1}\) which is a value similar to growth rates measured by other investigators. Recruitment (all sites combined) was 1.2 m\(^2\) \(\text{yr}^{-1}\). Survival (all sites combined) was 70% \(\text{yr}^{-1}\). All of these are values in good general agreement with other work and confirm the appropriateness of the methodology. These data have been compiled into spread sheets and will be archived along with the digital images at NODC.

The second goal of the project was to develop the recovery model. The model is a probability-based spatial model written in SAS (see Appendix for sample code). Briefly, the model tracks the identity of each pixel in a matrix, the dimensions of which may be defined by the user. During each iteration, the model queries each pixel and applies probabilistic demographic parameters (growth, recruitment, and mortality) to each pixel. The fate of each pixel is determined by drawing a random number from a uniform distribution between 0 and 1. That random number is compared to the probability for the demographic parameter, and the pixel grows, dies, or becomes a new recruit as appropriate.
For the present simulations, a 100 x 100 matrix was used. Model runs assumed an empty initial matrix (i.e., all space was open and able to be colonized) and a pixel size of 5 x 5 cm. Probabilistic demographic parameters were derived from the field observations. Annual mortality was reported as a percentage, so these raw values were used directly in the model. Recruitment data were reported as number per m$^2$; these data were converted to number per 25 cm$^2$ for model input. The model assumes that once a recruit occupies a pixel, that pixel is fully occupied. The field growth data were reported as cm$^2$/year. Growth rates for the model were determined by calculating the number of years it would take to occupy 25 cm$^2$, using positive growth rates only (a pixel cannot be partially occupied; instead partial mortality is reflected in the model by death of adjacent pixels within a colony). The calculated time was converted to a probability, and divided by 8 (the number of pixels adjacent to a queried pixel). In each time step the model applies growth, then mortality, then recruitment. This sequence ensures that new recruits occupy a single pixel and neither grow nor die until the next time step.

Model runs of 100 annual time steps were conducted for each of four species (Montipora capitata, Porites lobata, Porites compressa and Pocillopora meandrina) for each of the 12 reef sites for which field data were collected. Each species/site combination was modeled independently; future model runs will simulate multiple species to be run simultaneously.

B. Project management:

The CRAMP database is maintained by Dr. Eric Brown with a back-up maintained by Dr. Kuulei Rodgers. Lea Hollingsworth, a Ph.D. candidate developed methodology for measuring changes in each photoquad over time. Dr. Brown trained and supervised Ms. Hollingsworth and was responsible for the QA/QC of the photoquad data. Additional field work (model assessment and verification) was conducted by Drs. Jokiel and Rodgers. Dr. Piniak iworked with development of the model and incorporated the data into the CCFHR models for the Hawaii region. All data are deposited in the NODC.

VI. Findings

During the first phase of the project a considerable breakthrough was made by Lea Hollingsworth in developing the methodology to utilize the “Image J” computer software program (a free download from NIH that operates on Windows, Macintosh and UNIX computer systems – [http://rsb.info.nih.gov/ij/](http://rsb.info.nih.gov/ij/)) instead of Sigma Scan, to measure coral demographics (growth, recruitment, mortality, partial mortality, fusion events and fission events).

The Sigma Scan program we had initially planned to use for this project had several aspects that made it difficult and cumbersome to use. Namely these were:

1. Polygon shapes that are generated to trace the outer boundaries of the corals are not editable during the tracing process or after completion.
2. The coral must be re-traced prior to being measured to correct minor mistakes made during the tracing process.

3. Once a coral has been measured, the polygon cannot be removed unless the program is closed and all unsaved work is lost.

4. Traces cannot be refined under higher magnification to improve the precision of the measurement.

5. Irregular features (holes, petroglyphs shrimp trails, damaged areas, worm tubes, oysters, etc.) cannot be subtracted from the initial trace around the outer boundary of the coral.

6. Traced corals are overlaid with a solid color (Fig. 1) which makes it difficult for another observer to verify that a coral has been precisely traced and that the species of the coral has been correctly identified.

7. Once the entire photoquad has been processed, traced overlays for an individual coral cannot be viewed independently.

Fig. 1: Section of a photoquadrat that has been processed using A) Sigma Scan and B) Image J. Note the area circled in green. The outline trace between neighboring corals is not visible in the Sigma Scan processed image. However, in the Image J processed image, the borders are clearly visible.
All of above mentioned problems with the Sigma Scan program have been overcome by using the “Region of Interest” (ROI) feature in Image J. The ROI feature preserves the outline and position of a traced coral as a fully editable file. Any mistakes made during the tracing process can be corrected once the trace has been completed. The data collector can also zoom in at a higher magnification and edit (add, move, or delete) the points to improve the precision of the trace (Fig. 2).

ROI files can be named to coincide with the identification number of the corresponding coral. These ROI files, in turn, can be saved in a ROI zip folder for subsequent review/analysis/editing/use. In addition, the traces outline the outer boundary of the coral instead of overlaying it with a solid color (Fig. 1). Therefore, another observer can quickly and easily verify the precision of the trace and the identification of the coral species. Being able preserve individual traces, verify the data, and review/edit the ROI files has greatly improved the QA/QC for the data collection part of this project.

Another advantage of using the ROI feature is in the analysis of subsequent images (later years) for a given photoquad site. The ROI files from the previous year can be imported into the subsequent image, edited to accommodate the change in size (Fig. 3.), and saved in a new ROI zip folder for that current year. Thus the time consuming process of generating new traces for each coral is avoided. In addition, the use of the previous year’s ROI files serves as a built-in quality control step in the identification of corals for subsequent measurements which are used to determine the rate of growth, and the frequency of mortality, partial mortality, fusion and fission events. “Phoenix effect” corals (corals that suffer a partial mortality event and leave behind a small undetectable remnant of living tissue; the coral appears dead, but later images show the coral has survived.) that might otherwise be classified as new recruits are similarly easy to identify using ROI files from previous years.
Fig. 2. A ROI file that has been edited to improve the precision of a trace.

Fig. 3. A) Coral with a ROI trace (the fine yellow line around the outer border of the coral). B) The same ROI trace in image 2A, that has been imported into the photoquad image for the subsequent year. C) The same ROI trace and coral in image 2B. The ROI is in the process of being edited to accommodate the change in size from the previous year.

Examples of processed images from Honolua, Maui are shown as Figs. 4-5. There is a dramatic change each year in the size and shape of the corals, so it is a very dynamic system. Individual colonies come and go rapidly, yet over time the mean coverage at each of the CRAMP monitoring sites remains relatively steady from year to year under normal conditions.
Fig. 4. Image J processed photoquad image from the 1999 Honolua North 3m 01 site.

Fig. 4. Image J processed photoquad image from the 2000 Honolua North 3m 01 site.
The model is running successfully and a series of test runs have been completed with very nice results. For example, Fig. 7 shows the recovery time for the four dominant species at Puamana, Maui. At this site *Montipora capitata*, a very fast growing incrusting species reaches its maximum population in 20 years while slower growing *Porites lobata* takes up to 60 years to recover. *Porites compressa*, the finger coral, grows relatively fast but is a branching species and is broken readily by major storm surf events. Thus its response time is slower at this site (60-80 years) is far less than at wave sheltered locations.

A second example shown in Fig. 8 compares the population response of a single species at a number of sites. Note that the poorest growth and development is at Kakahaia, which is a reef flat site off south Molokai that is highly impacted by sediment. Coral cover is very low at this site as the model simulates. In contrast, the development and growth of *Porites lobata* is very high at Honolua, which is a very rich marine protected area on Maui. The intermediate result at Pupukea, Oahu is from another marine protected area that is heavily impacted by North Pacific Swell during the winter months. Heavy wave action limits coral development at this site. So the preliminary model does give us realistic results, with the final population number in agreement with the present coral cover. Certainly the demographic data will continue to be refined and
there will be modifications to the program to allow other manipulations of the response such as intermittent disturbances.

**Fig. 8.** Model output for one species (*Porites lobata*) at various sites.

This type analysis shown in Fig. 8 can be used to answer the basic question as to which of the four species is best suited to each site, or which site is best (and worst) suited for each species—and how that compares to the percent cover data for each site).

### Model refinements

The results presented here are for a basic single-species demographic model. Future versions of the model could be improved in several ways. First, the current model draws probabilities randomly from a uniform distribution. This incorporates some stochasticity into the model, but environmental variability may be better captured by using the field data to define non-uniform probability distributions. Sample sizes for each species were often insufficient to statistically define a probability function, and sites were not pooled to increase sample size since the population dynamics for a species were highly site-specific (see results). Therefore, additional data collection for most species would be necessary to derive probability distributions from field data.

A second model refinement would be to determine the sensitivity of the model to spatial resolution. Demographic parameters are calculated depending on pixel size. For example, in the field data recruits were reported as number per m$^2$. Counting a recruit in the field data depends on the size at which that colony becomes observable and identifiable in the photoquadrat. Assuming that occurs when a coral is ~2 cm in diameter, that new recruit would occupy ~3.1 cm$^2$. For ease of calculation, the model simply assumed that a recruit fully occupies the 5 x 5 cm pixel. One alternative would
have been to apply growth and mortality rates to the newly visible recruit until it obtains
a size of 25 cm². However, this would effectively eliminate recruitment for many of the
species observed, and the model requires a recruitment parameter to function. A
second option would have been to reduce the pixel size to that of an observable recruit.
However, that would unduly limit the amount of area available for growth—a new recruit
in a 2x2 cm pixel would only have 32 cm² (8 adjacent pixels at 4 cm² each), and certain
species exceeded that growth rate at certain sites (Porites lobata and P. compressa at
Palaau, for example).

Future model runs will simulate multiple species assemblages simultaneously rather
than individual species. The current data collection effort included only corals.
However, data should also be generated for other benthic categories (macroalgae,
crustose coralline algae, etc.) to more effectively simulate dynamics of the entire reef
community. A multispecies model would also improve the simulation of ecological
events—for example, different initialization matrices could be used to compare recovery
of a disturbed community (an empty matrix) with that of an unaffected reference
community (in which the initial matrix reflects community composition of the reference
habitat at the time of the injury).

VII. Evaluation

The goals for the first phase of the project have been met and we are continuing to
compile data that will be used in the model.

Indicators of success.

We have already received several requests about the methodology we have developed
for analyzing coral reef photoquadrat images and model results. Dr. Robert Richmond
requested information about the program being used as several of his collaborators are
interested in tracking coral disease lesions. Lea Hollingsworth provided Dr. Richmond
with a brief overview of the program and demonstrated its use. Shino Ogawa (Masters
student, Zoology Department, University of Hawaii at Manoa, working under Dr. John
Stimson) asked Lea to demonstrate the use of Image J to analyze photoquadrat
images. Shine is measuring the competitive interaction (growth and mortality) between
corals and zoanthids for her graduate work. Dr. John Stimson mentioned that his Ph.D.
student, Nadiera Sukraj, needs to analyze photoquadrat images for her doctoral work.
He thought Nadiera might find the techniques and methodology we have developed
useful for her work. We have developed a step-by-step guide for using Image J to
analyze coral reef photoquadrat images. The guide is in the testing phase (it has been
provided to individuals who have no prior experience with the Image J program. They
have been asked to process a photoquad image by following the guide and provide
feedback about the ease of its use). Once the tests are complete, we will make the
guide available as a PDF download on the CRAMP website. Discussions with
managers on applications of the model are ongoing and leading to further development
and refinements. The model is being tested. A paper for submission to a peer-
reviewed journal is being prepared and a funding application for continuing this work is
in preparation.
VIII. Recommendations to managers.

The population model is a valuable tool for determining the length of time needed for a destroyed or damaged reef to recover. The preliminary model can be applied to many situations. Further demographic data are needed because the response of the output is determined by the accuracy of recruitment, growth and mortality estimates for each species of coral. These parameters will vary with environment (wave exposure, depth, etc.). Some demographic data such as growth and mortality rates for very large coral heads is presently lacking, but will be obtained in the near future through further field work. The model will become increasingly valuable as the demographic data base of estimates for additional habitats and environments are developed.

IX. Dissemination of Project results:

A. Results to date involve only the first phase of the model development and testing. There is considerable complexity to the model and there is a need to gather additional data on growth and survival of very large coral heads that were too big to fit within the photoquads. There will be continued development and collaboration with others in the scientific and management community as the model is refined.

B. Publications and presentations during project period:


Ku’ulei Rodgers and Lea Hollingsworth made a public presentation at Hanauma Bay public information and outreach on July 19, 2007.
Appendix—sample model code (for Kamalo Porites lobata run)

/*

PROGRAM INFORMATION

PROJ: Coral Injury Recovery Modelling—HCRI

DESC: Simulates the recovery of injured coral reefs.

AUTH: Gary Fisher, modified by Greg Piniak

DATE: 2008-01-05

INPUTS/OUTPUTS

INs: The DATA directory is ‘C:\Greg\Fisher\Greg Piniak\HCRI\DATA’.

This directory contains the input datasets and the parameter file.

OUTs: The output is a SAS dataset containing the percent recovery DATA.

*/

proc datasets lib=work kill;
quit;

dm 'clear log';
dm 'clear output';

proc printto log="c:\temp\BatchSASLog.log" new;
run;
options ls=250 ps=2000 nocenter nodate FORMDLIM="";title;
options nomlogic nomprint nomtrace nosymbolgen spool;
libname msm "C:\GREG\FISHER\Greg Piniak\HCR\Data";

%macro Batch(
	dsn /*Data Set Name*/,
	sy  /*Time Period*/,

rr  /*Recruitment Rate*/,

gr  /*Growth Rate*/,

im  /*Individual Mortality*/,

rinit /*Return Interval */,

modelrun /* Model Run*/,

spp)/* spp id*/;

proc iml symsize=160000000 worksize=500000000;

/* This module initializes the model */

start coral_injury_files(nr, nc, p) global(modelrun&modelrun,p0,aliveFract,z);

use &dsn;

read all var num into p ;

p0=p;

modelrun&modelrun=p;

nr=nrow(p);
nc=ncol(p);
aliveFract=j(&ts+1,2,0);
aliveFract[1,1]=0;
aliveFract[1,2]=0;
do i = 1 to &ts;
-aliveFract[i+1 ,1]= i;
end;
z=aliveFract;
finish;

/* Recruitment Rate module */
start rr(p,rr,nr,nc);
do i=1 to nr;
do j=1 to nc;
if p[i,j] =0 then do;
if uniform(-1) >= (1-rr) then  p[i,j] = 1;else p[i,j]=0;
end;
end;
end;
finish;

/* Growth module */
start growth(p,nr,nc,modelrun&modelrun);
do i=2 to nr-1;
do j=2 to nc-1;
/* The seed for the uniform function is set to -1. This will draw values from the system clock */

*x1;
if (P[i,j]=1 & P[i-1,j-1]=0) then P[i-1,j-1]=uniform(-1);
   if (p[i-1,j-1]>(1-\&gr) & p[i-1,j-1]<1.00) then p[i-1,j-1]=1.00;
*x3; if (P[i,j]=1 & P[i+1,j-1]=0) then P[i+1,j-1]=uniform(-1);
   if (p[i+1,j-1]>(1-\&gr) & p[i+1,j-1]<1.00) then p[i+1,j-1]=1.00;
*x7; if (P[i,j]=1 & P[i-1,j+1]=0) then P[i-1,j+1]=uniform(-1);
   if (p[i-1,j+1]>(1-\&gr) & p[i-1,j+1]<1.00) then p[i-1,j+1]=1.00;
*x5; if (P[i,j]=1 & P[i+1,j+1]=0) then P[i+1,j+1]=uniform(-1);
   if (p[i+1,j+1]>(1-\&gr) & p[i+1,j+1]<1.00) then p[i+1,j+1]=1.00;
*x8;
if (P[i,j]=1 & P[i-1,j]=0) then P[i-1,j]=uniform(-1);
   if (p[i-1,j]>(1-\&gr) & p[i-1,j]<1.00) then p[i-1,j]=1.00;
*x4;
if (P[i,j]=1 & P[i+1,j]=0) then P[i+1,j]=uniform(-1);
   if (p[i+1,j]>(1-\&gr) & p[i+1,j]<1.00) then p[i+1,j]=1.00;
*x6;
if (P[i,j]=1 & P[i,j+1]=0) then P[i,j+1]=uniform(-1);
   if (p[i,j+1]>(1-\&gr) & p[i,j+1]<1.00) then p[i,j+1]=1.00;
*x2;
if (P[i,j]=1 & P[i,j-1]=0) then P[i,j-1]=uniform(-1);
   if (p[i,j-1]>(1-\&gr) & p[i,j-1]<1.00) then p[i,j-1]=1.00;
end;
end;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
/* Counter routine */
p=choose(p<1 ,0,p);/* This change fractional values to zero // or keep value of p*/
/* counter */
modelrun&modelrun= choose(p>0,modelrun&modelrun + 0.001,p);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
finish;

/*Individual Mortality Module*/
start im(nr,nc,p,p0);
do i=1 to nr;
do j=1 to nc;
    if p[i,j] =1 then do;
        p[i,j]=uniform(-1);
        if p[i,j] >= &im then p[i,j]=1; else p[i,j]=0;
    end;
end;
finish;

/* AliveFract Module */
start aliveFract(p,p0,aliveFract,i);
    aliveFract[i+1,2] = (sum(p>=1)) / (sum(p0>=0)) ;
    return(aliveFract);
finish;

/* OutputData Module */
start OutputData(p,modelrun&modelrun,z);
    create pout&modelrun(genmax=&ts) from p;
    append from p;
    close pout&modelrun;
    create z from z;
    append from z;
    close z;
    counter = p + modelrun&modelrun;
    create counter(genmax=&ts) from counter;
    append from counter;
    close counter;
finish;

/**************************** Main ***************************************************/
call coral_injury_files(nr,nc,p);

/* use i variable for time */
do i= 1 to &ts;
    call growth(p,nr,nc,modelrun&modelrun);

call im(nr,nc,p,p0);

call rr(p,&rr,nr,nc);

z=aliveFract(p,p0,aliveFract,i);

call OutputData(p,modelrun&modelrun,z);

end;

quit;

/***************************************************************************/

/*Graphics routines***************************************************************************/

goptions device=win rotate=landscape;

proc sql noprint; select max(col2) as maxpercentrecovery into :vref from z;quit;

data z;

  format dsn $20.;

  set z;

  dsn="&dsn”;

  ts=&ts;

  gr=&gr;

  rr=&rr;

  im=&im;

  rinit=&rinit;

  model=&modelrun;

  spp=&spp;

run;
symbol value= dot h=1 i=join color=red;

axis1 order=(0 to 1 by .1)
   label=(font=swissb HEIGHT=1 angle=90 "Percent Cover" j=c)
   value=(HEIGHT=1 font=swissb);

axis2 order=(0 to &ts by 20)
   label=(font=swissb HEIGHT=1 "Timesteps")
   value=(HEIGHT=1 font=swissb);

proc gplot data=z(rename=(col1=timestep col2=percentrecovery));
plot percentrecovery*timestep/regeqn haxis=axis2 vaxis=axis1 ;
/*title " Patch Dynamics Model with Three Storm Events";*/
title;
run;
quit;

/* Percentrecovery dataset *******************************************/
proc append base=percentrecovery data=z;run;

/* Housecleaning *******************************************************
proc datasets library=work ;
    save greg percentrecovery;
run;
quit;
*/
*libname patch clear;
%mend;

/**********Batch Driver*****************************************************/
data null;
set msm.kamalo (firstobs=1 obs=1);/* border intentionally set to missing values*/
    call execute( '%Batch(' || dsn || ','||ts|| ','||rr ||','||gr ||','||im ||','||rinit||','|| modelrun
      ||','|| spp ||' )');
run;
/****************************Export*********************************************/
data percentrecovery;
set percentrecovery;
rename col1=x col2=y;
run;
/*proc export data=percentrecovery outfile="c:\temp\percentrecovery.csv" dbms=CSV replace;*/
/*run;*/

/****************************Maximum Percent of Recovery*************************/
proc printto ;run;
/*******Maximum Percent of Recovery***********************************/
proc sql; Title'Maximum Percent of Recovery';
    select spp,
max(y) as maxpercentrecovery

from percentrecovery

group by spp;

Title;

quit;

%inc "C:\GREG\FISHER\Greg Piniak\HCRI\Programs\MS Area Graph3.sas";

/* Housecleaning***********************************************
*/

/*

proc datasets lib=work kill;quit;

*/