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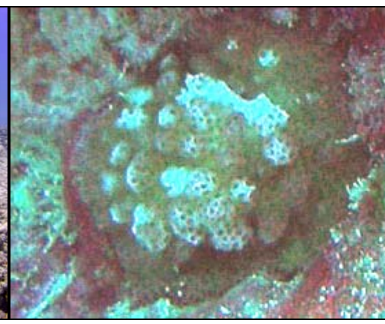
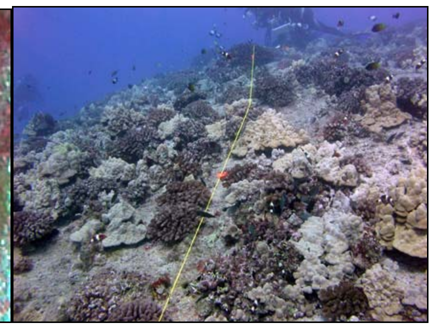
Recovery Projections for Scleractinian Corals Injured in the *M/V Cape Flattery* Incident, Oahu, Hawaii, 2005





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Executive Summary

Recovery of injury to scleractinian corals that resulted from *M/V Cape Flattery* grounding, response and removal activities at Barbers Point, Oahu, Hawaii is estimated for *Montipora* encrusting, *Pocillopora* cauliflower, *P. eydouxi* and *Porites* lobate species groups by individual size categories. Recovery modeling incorporated recruitment and proportional survival rates inferred from attached colony size frequencies in reference areas, measured growth of reference colonies within the incident area, and projected survival and growth of population structure remaining in the incident area. Fundamental assumptions were that average reference population structure adequately reflected spatial and temporal variability inherent in site specific population dynamics, that history, over the long term, would be repetitive, and that parameter estimates would apply, without inhibition, to injured areas. Slower growing *Montipora* encrusting and *Porites* lobate species groups were represented by the largest colonies and displayed the longest projected terminal recovery times (57 and 117 years respectively). Smaller, faster growing *Pocillopora* species groups were projected to recovery much sooner, but were very similar to each other in terminal recovery time estimates (both in 23 years). Approximately 99 % of lost coral abundance (smaller and/or faster growing corals) may be replaced within 21 years. However, resource value associate with the largest colonies will take much longer to replace (up to 117 years). These rates of recovery are not inconsistent with previous projections for Hawaiian reefs. Model augmentation may be needed to address potential inhibition of recovery processes resulting from continued movement of remaining reef debris and lack of topography in specific habitat zones.

Introduction

Injury quantification in natural resource damage assessments covered under the Oil Pollution Act of 1990 must, in general, determine the degree, and spatial and temporal extent of impact to natural resources (the Oil Pollution Act NRDA Regulations, 15 C.F.R. Part 990). Estimates of timing and pathways of natural recovery are fundamental to determining the temporal aspects of resource service losses and to the scaling of restoration actions that may be sought to fairly compensate the public and injured parties. To estimate loss and recovery, some understanding of the state of the resources prior to injury must be gained. In coral reef habitats, pre-injury data on resources is often lacking; thus, nearby reference areas must serve as a proxy for determining and monitoring baseline conditions.

The grounding, response and removal of the 555 ft bulk carrier *M/V Cape Flattery* from February 2 to 11, 2005 outside the entrance channel to Barbers Point Harbor on Oahu, Hawaii resulted in widespread injury to coral reef resources (Kolinski 2005a, b, Kenyon 2005, Polaris Applied Sciences, Inc. 2005, Kolinski et al. 2007). Pre-incident data on the state of the resources was lacking, so quantification of loss was based on comparison of resources between injured and multiple reference areas that surrounded the impact site (Kolinski et al. 2007). Scleractinian corals were measured as abundance of individuals categorized by species and size, and injury was represented in terms of species groups (combinations based on genus, gross morphology and growth rate) and size categories in an effort to ensure some accounting for variation in lost functional attributes (such as topographic complexity, habitat quality, filtering capacity, productivity, reproductive potential, etc.), particularly in determining recovery and restoration needs. Species group and size based data collected from reference communities can be used to infer historic coral population dynamics for injured areas, and serve here as a foundation for modeling the recovery of coral losses based on relevant sizes and species group rates of growth. Site specific data collected in the field thus form the basis for analyses of coral loss and recovery, providing estimates that are directly transferable into models that facilitate determinations of resource equivalency.

Methods

Recovery rates were estimated for the reestablishment of incident related coral loss for *Montipora* encrusting, *Pocillopora* cauliflower, *Pocillopora eydouxi* and *Porites* lobate species groups across habitats injured by *M/V Cape Flattery* grounding and response activities. Significantly lower ($P \leq 0.05$) densities of corals were demonstrated in injured compared to multiple reference areas in these species groups and estimated loss/injury was reported and formed the basis for quantifying recovery needs (Kolinski et al. 2007). Recovery modeling incorporated recruitment and proportional survival rates inferred from attached colony size frequencies in reference areas (those previously used to discern incident related loss), measured growth of reference colonies within the incident area, and projected survival and growth of population structure remaining in the incident area. Fundamental assumptions were that average reference population structure adequately reflected spatial and temporal variability inherent in site specific population dynamics, that history, over the long term, would be repetitive, and that parameter estimates would apply, without inhibition, to injured areas. Model augmentation to address potential inhibition of recovery processes absent adequate primary restoration in specific habitat zones in injured areas was not employed but is discussed.

Recruitment and Proportional Survival

Projections of recruitment and recovery were based on the analysis of coral abundance in individual size frequency categories (longest linear dimension: 0 to < 2 cm, 2 to < 5 cm, 5 to < 10 cm, 10 to < 20 cm, 20 to < 40 cm, 40 to < 80 cm, 80 to < 160 cm and 160 + cm) independently averaged across measured injury site reference areas for individual species groups that displayed significant loss ($P \leq 0.05$) in each of five habitat zones (slope, escarpment area, reef depressions, shelf pavement, *Porites* zone, see Kolinski et al. 2007 for habitat descriptions, relationship to noted injury and data collection methods). Average reference area abundances in each size category for each species group and habitat were proportioned relative to the sum of the 0 to < 2 cm and 2 to < 5 cm categories for *Montipora* encrusting, *Pocillopora* cauliflower and *Porites* lobate groups as a means to estimate "recent" recruit abundance (number of corals < 5 cm diameter) and long-term proportional survival (average abundance in each remaining size category divided separately by the sum of corals < 5 cm). This process assumed the state of the reference population as reflected by measured size categories at a given time represented historic variation in recruitment and survival dynamics, and that this serves as the best available site specific information for projecting future recruitment and survival processes. The average size of each size category was used to represent all colonies within a category (i.e., 2.5 cm, 7.5 cm, 15 cm, 30 cm, 60 cm, 120 cm, with remaining categories defined below).

Species group proportional survival estimates in all cases displayed Type III type survivorship (Deevey 1947). However, in all habitats proportions of *Pocillopora* cauliflower and *P. eydouxi* appeared lower in some of the smaller size classes compared to larger ones, suggesting a historic regional deficit in recruitment or event that disproportionately affected smaller colonies. In these species groups, neighboring size classes were combined and represented by an average size estimated as the weighted mean (based on colony abundances within each initial size class) to maintain the necessary proportional relationship for modeling recovery. In *Pocillopora eydouxi*, category combinations forced recruits to be represented as the weighted average size of 8.1 cm (shelf pavement) and 8.9 cm (escarpment). In *Pocillopora* cauliflower, intermediate size group combinations resulted in 9.4 cm (shelf pavement), 10.2 cm (*Porites* zone), 10.4 cm (reef depressions), 21.9 cm (escarpment) and 26 cm (slope) categories. This process of category collapse appeared logical as it incorporated historic variation and allowed modeling to proceed.

Although *Porites* lobate colonies exceeding 300 cm were observed within the incident and surrounding areas (Kolinski pers. obs.), none was known to exceed 240 cm on reference transects, so the terminal size category for this species group was represented by 200 cm (average of 160 and 240 cm). Similarly, *Pocillopora* cauliflower rarely exceeds 45 cm at Barbers Point and *P. eydouxi* were not known to greatly exceed 100 cm in reference areas. Terminal size categories for these species groups were represented by 42.5 cm and 90 cm respectively. *Montipora* encrusting colonies approaching 160 cm were observed on transects, so 120 cm was used to represent this groups' terminal size category.

Growth

Site specific growth was measured for survivors of 189 reference colonies of *Pocillopora meandrina*, *P. eydouxi*, *Porites evermanni* and *P. lobata* within the immediate vicinity of 18 emergency restoration cement stations established within the injury area and 8 *Montipora patula* and *M. capitata* colonies on re-cemented substrate (see Kolinski 2005b). Longest linear length, perpendicular width and height of each colony were determined using a flexible measurement tape in March and April 2005 and again in July 2006. Distribution maps and photos of each colony ensured all were identified and tracked appropriately. Only colonies measured by a single individual were considered for growth analysis. The fastest linear growth rate in any of the three measured dimensions was selected for each coral for analysis. Colonies that displayed size reductions in all dimensions were not considered (i.e., potential growth was determined for modeling).

Potential confounding effects of differences in depth, site, initial size and injury on rates of growth were examined for *Pocillopora* and *Porites* species groups using a combination of ANOVA, ANCOVA, and regression analysis procedures. A single factor, level of injury, significantly ($P \leq 0.05$) influenced reference colony growth in *Pocillopora meandrina*; thus, only uninjured colonies within this species were considered for determining its' rate of growth. *Porites evermanni* and *P. lobata* data were combined as their rates of growth did not differ significantly ($P > 0.05$; Kolinski in prep.). All selected colonies across habitats and depths were pooled within each species for calculating average growth. The rates of growth of *Pocillopora* and *Porites* species groups corresponded well with those that could be identified in the literature.

The growth rate of *Montipora capitata* (n = 2) and *Montipora patula* (n = 6) was determined by averaging site colony measurements with growth values derived from the literature (Holthus et al. 1986, Jokiel and Tyler 1992), as representative measurements at the site were low and involved substrates that had been cemented. The literature values were higher but determined from colonies in much shallow water where such species tend to display faster growth. An average value of the two species was used to represent growth within the *Montipora* species group as overall averages did not differ significantly ($P > 0.05$). All species used for determining growth rates were well represented within individual species groups (Table 1),

Table 1. Rates of growth for species injured at Barbers Point, Oahu (*estimate partially derived from values in literature; ** total proportion of species' individuals within a species group as measured in pre-assessment reference transects, see Kolinski et al. 2007).

Species group	Species used to represent growth rate	n	Min. Linear Size (cm)	Max. Linear Size (cm)	Average Growth (cm yr^{-1}) ± S.E.	**Species reference site representation within species group (%)
Montipora encrusting	*M. capitata* and *M. patula*				2.29*	99.9
Pocillopora cauliflower	*P. meandrina*	41	6	40	1.99 ± 0.15	99.6
Pocillopora eydouxi	*P. eydouxi*	20	20	94	4.76 ± 2.05	100
Porites lobate	*P. evermanni* and *P. lobata*	40	8	73	1.76 ± 0.21	99.9

In Hawaii, average growth rates of settlers and young recruits appear reduced compared to those of larger colonies (Kolinski 2004, unpub. data, and see Edmunds 2007). Initial time periods necessary for new settlers to establish and grow were estimated as follows: 6 years for *Montipora* encrusting to reach an average of 2.5 cm linear diameter; 3 years for *Pocillopora* cauliflower to reach 2.5 cm; 6 years for *Pocillopora eydouxi* to reach 8.1/8.9 cm, and; 5 years for *Porites* lobate to reach 2.5 cm (see Kolinski 2004 and Grigg and Maragos 1974). Linear growth rates from Table 1 were applied thereafter and considered constant.

Recovery Modeling

Recovery paths were modeled for each size category within a species group to ensure timelines were specific to estimated size based losses and to allow opportunity to compensate for various levels of functional loss associated with different sized corals (i.e., topographic structure, habitat, reproductive potential, filtering, productivity, etc.). The model incorporated timelines necessary for new system recruits to replace losses within specific size categories, but also modified losses based on growth and survival projections of corals that remained within injured habitats following the incident. Remaining colonies numbers were estimated as the difference between average reference habitat specific abundances and estimated injury associated losses (see Kolinski et al. 2007).

Species group growth rates (Table 1) were used to determine the period of time necessary for corals to transfer from each average category size to the next, adding recruit time for modeling new corals through the system. In all cases, time periods that reflected entrance of new system recruits into a given category meant that category reached full recovery in relation to average reference system representation (as average reference numbers were used to define incident loss, natural recruitment and proportional survival in the area). Proportional survival rates derived from reference communities were used to project colony numbers from one category to the next. Data limitations and model construction prohibited abundance projections beyond the average colony size for each category, and assumed the recovering system would not exceed abundances within reference population size categories.

Model results of cumulative recovery and time were combined within each size category across habitats for each species group for direct use in resource equivalency analysis. Results were also combined across size categories within a species group to provide an initial basis for establishing system recovery performance criteria. Graphic representation and resource equivalency analysis (not presented) assume linear relationships between projected inflection points.

Results

Montipora encrusting

Cumulative recovery and associated time estimates for *Montipora* encrusting colonies are provided in Table 2 along with reported loss and percentage of total loss for each size category. Recovery projections range from 6 to 57 years for lost colonies based on average sizes within categories (Table 2, Figure 1). Colonies less than 20 cm diameter accounted for over 90 % of projected loss; recovery of these corals is estimated to occur within approximately 11 years. Resource value associated with larger colony sizes may take approximately 57 years to replace.

Table 2. Projections of proportional recovery of estimated *Montipora* encrusting coral losses by size category (represented by category size averages).

	Size Category Average (cm)						
Year	**2.5**	**7.5**	**15**	**30**	**60**	**120**	**All Sizes**
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2		0.04					0.01
3			0.13				0.03
5	1.00		0.16				0.03
6							0.56
7				0.01			0.56
8		1.00					0.80
10				0.16			0.81
11			1.00				0.94
12				0.19			0.94
13					0.03		0.94
18				1.00			0.99
20					0.05		0.99
23					0.27		0.99
25					0.30		0.99
26						0.02	0.99
31					1.00		0.999
39						0.06	0.999
46						0.08	0.999
49						0.34	0.999
51						0.37	0.999
57						1.00	1.00
Initial Loss	360,674	176,654	106,208	41,051	6,482	626	691,695
% of Total	52.14	25.54	15.35	5.93	0.94	0.09	100

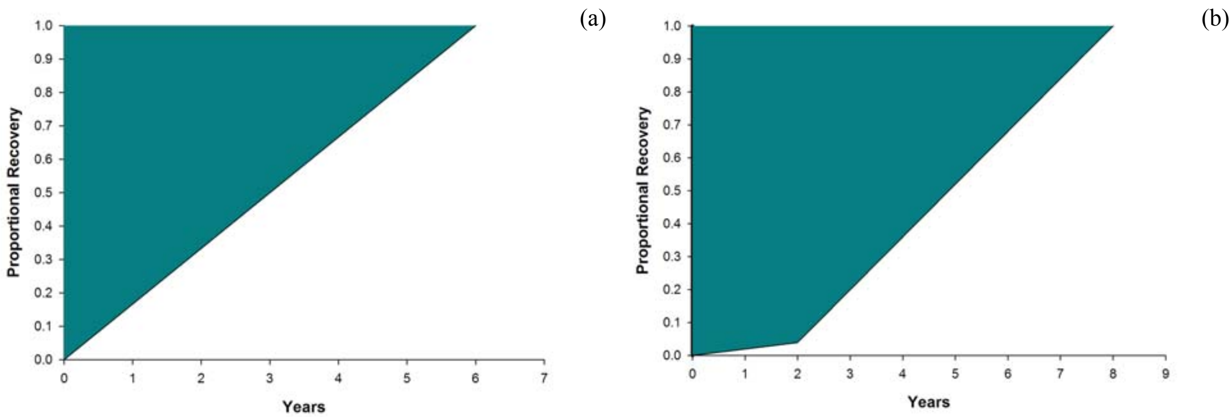

Figure 1. Projections of proportional recovery of estimated *Montipora* encrusting colony losses by size category (represented by category size averages; a = 2.5 cm; b = 7.5 cm; continued on next page).

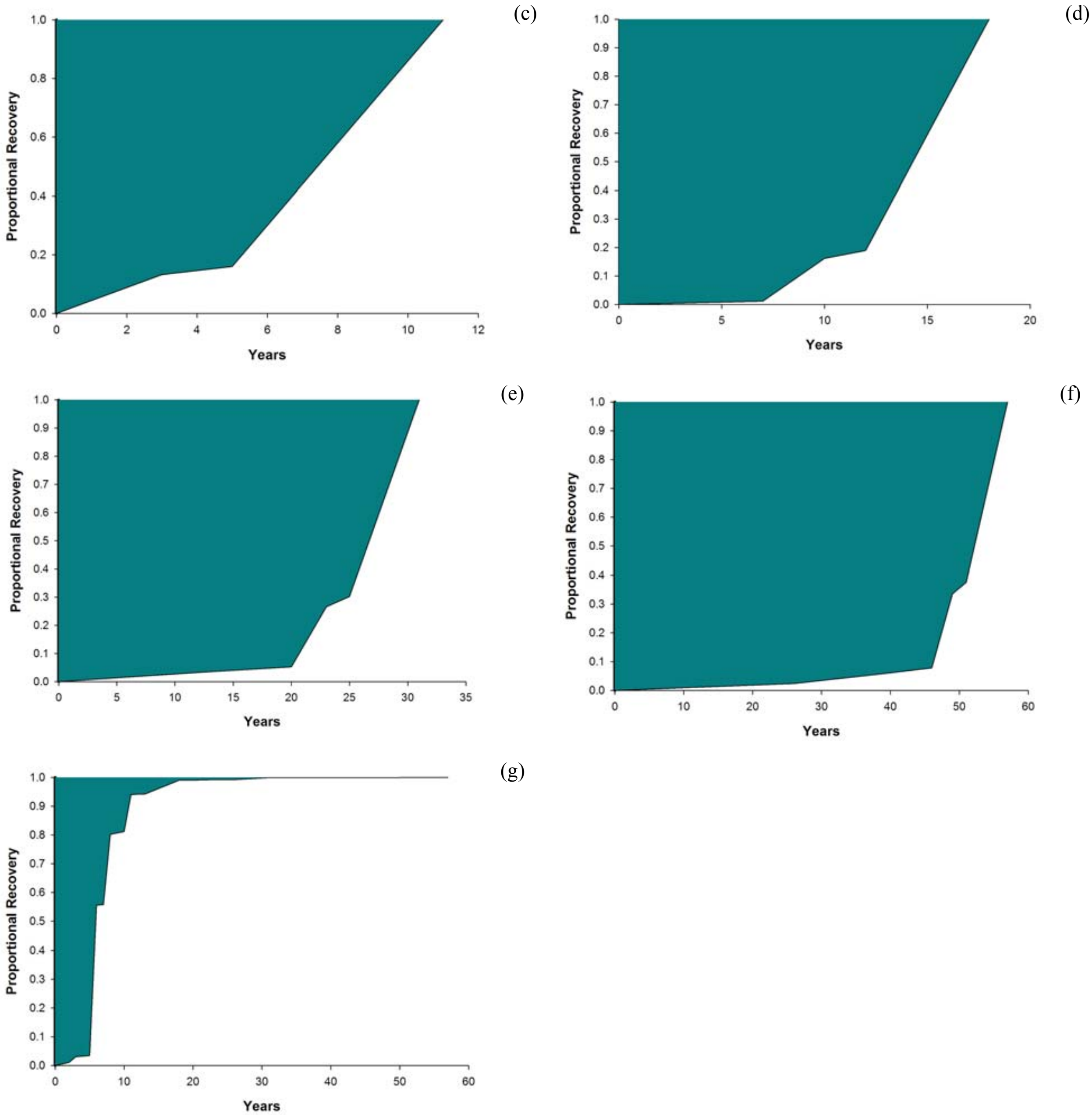

Figure 1 cont. Projections of proportional recovery of estimated *Montipora* encrusting colony losses by size category (represented by category size averages; c = 15 cm; d = 30 cm; e = 60 cm; f = 120 cm; g = all sizes).

Pocillopora **cauliflower**

Recovery projections, estimated loss and percentage of total loss for *Pocillopora* cauliflower colonies are provided in Table 3 and Figure 2. Estimated recovery ranges from 3 to 23 years for the lost colonies based on average size within categories. The majority of colonies less than 20 cm diameter accounted for nearly 90 % of projected loss; recovery of these corals is estimated to occur within approximately 7 years. Resource value associated with larger colony sizes may take approximately 23 years to replace.

Table 3. Projections of proportional recovery of estimated *Pocillopora* cauliflower coral losses by size category (represented by category size averages).

	Size Category Average (cm)					
Year	**2.5**	**9.4/10.2/10.4**	**21.9/26**	**30**	**42.5**	**All Sizes**
0	0.00	0.00	0.00	0.00	0.00	0.00
3	1.00	-0.22				0.66
4		-0.19				0.66
6		0.82			0.04	0.86
7		1.00				0.90
8					0.04	0.90
10			0.82	-0.68	0.14	0.90
12			0.82			0.90
13			0.99			0.90
14				-0.96		0.89
15			1.00			0.89
17				1.00	0.22	0.99
20					0.26	0.99
23					1.00	1.00
Initial Loss	71,708	19,835	4,450	5,498	799	102,290
% of Total	70.10	19.39	4.35	5.37	0.78	100

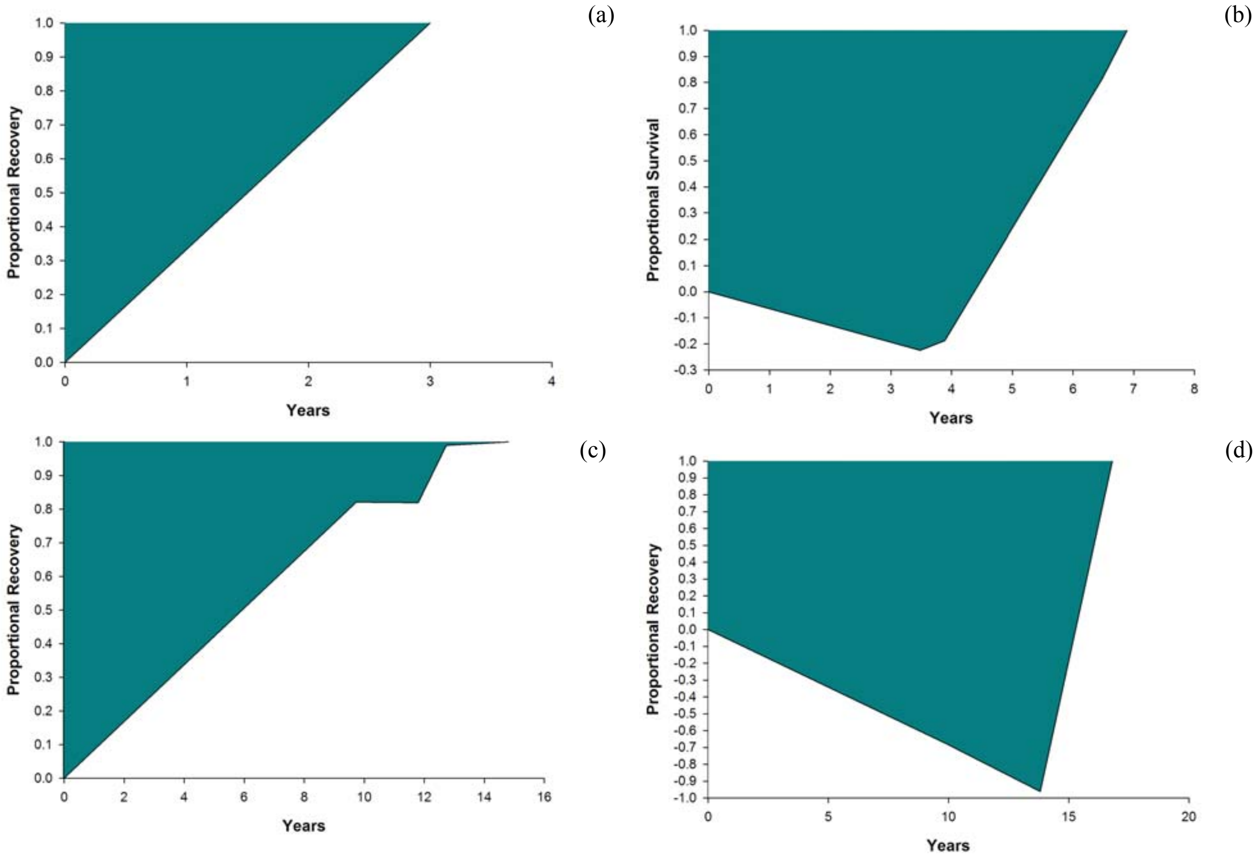

Figure 2. Projections of proportional recovery of estimated *Pocillopora* cauliflower colony losses by size category (represented by category size averages; a = 2.5 cm; b = 9.4/10.2/10.4 cm; c = 21.9/26 cm; d = 30 cm; continued on next page).

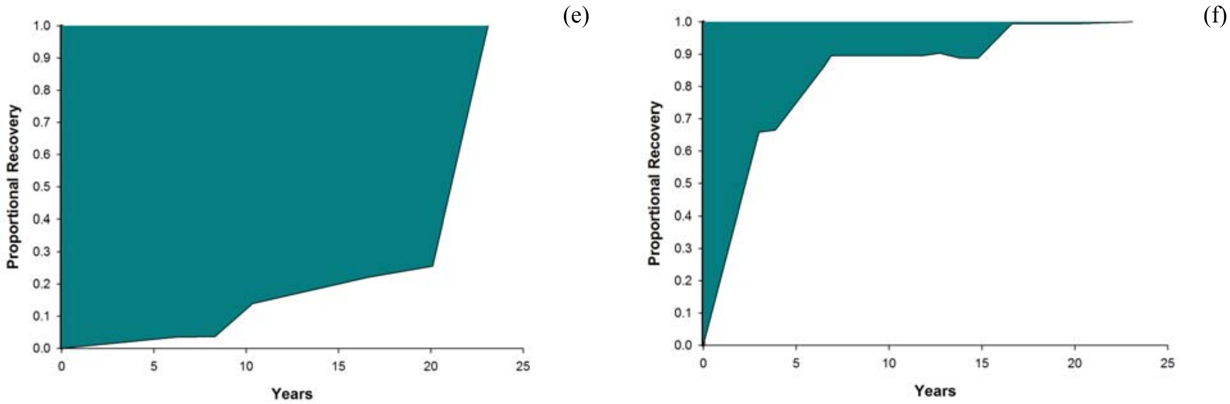

Figure 2 cont. Projections of proportional recovery of estimated *Pocillopora* cauliflower colony losses by size category (represented by category size averages; e = 42.5 cm; f = all sizes).

Pocillopora eydouxi

Cumulative recovery and associated time estimates for *Pocillopora eydouxi* colonies are provided in Table 4 along with reported loss and percentage of total loss for each size category. Recovery projections range from 6 to 23 years for lost colonies based on average sizes within categories (Table 4, Figure 3). Colonies less than 40 cm diameter accounted for nearly 90 % of projected loss; recovery of these corals is estimated to occur within approximately 11 years. Resource value associated with larger colony sizes may take approximately 23 years to replace.

Table 4. Projections of proportional recovery of estimated *Pocillopora eydouxi* coral losses by size category (represented by category size averages).

	Size Category Average (cm)				
Year	**8.1/8.9**	**30**	**60**	**90**	**All Sizes**
0	0.00	0.00	0.00	0.00	0.00
5		0.04			0.01
6	1.00		0.004	-0.03	0.61
11		1.00	0.04		0.90
13				-0.02	0.90
17			1.00	-0.01	0.97
23				1.00	1.00
Initial Loss	29,832	14,740	3,942	1,239	49,753
% of Total	59.96	29.63	7.92	2.49	100

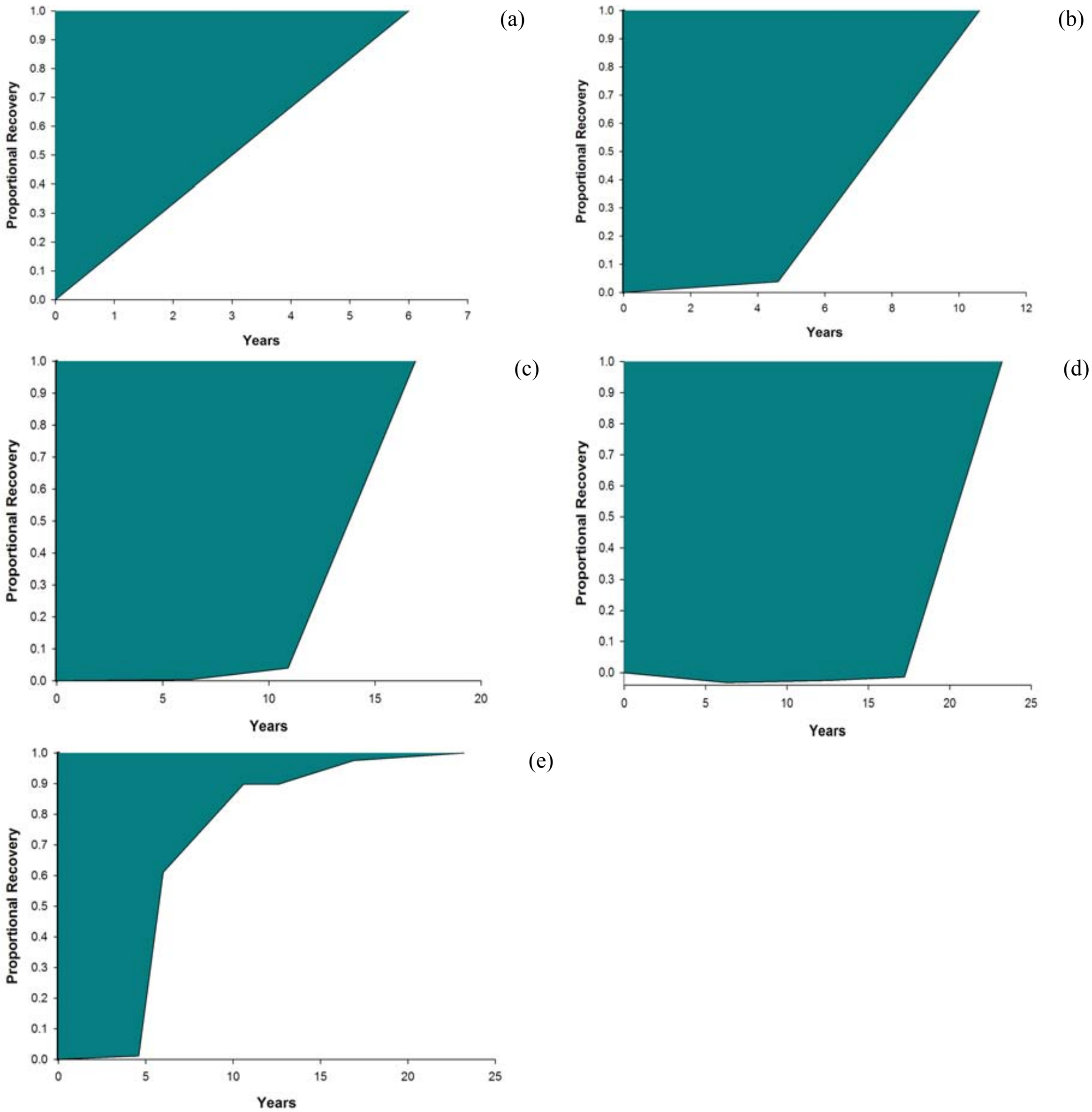

Figure 3**.** Projections of proportional recovery of estimated *Pocillopora eydouxi* colony losses by size category (represented by category size averages; a = 8.1/8.9 cm; b =30 cm; c = 60 cm; d = 90 cm; e = all sizes).

Porites lobate

Recovery projections, estimated loss and percentage of total loss for *Porites* lobate colonies are provided in Table 5 and Figure 4. Estimated recovery ranges from 5 to 117 years for the lost colonies based on average size within categories. Colonies less than 20 cm diameter accounted for nearly 90 % of projected loss; recovery of these corals is estimated to occur within approximately 12 years. Resource value associated with larger colony sizes may take approximately 117 years to replace.

Table 5. Projections of proportional recovery of estimated *Porites* lobate coral losses by size category (represented by category size averages).

	Size Category Average (cm)							
Year	**2.5**	**7.5**	**15**	**30**	**60**	**120**	**200**	**All Sizes**
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3		0.02						0.01
4			0.47					0.16
5	1.00							0.46
7			0.48					0.46
8		1.00						0.71
9				0.01				0.71
12			1.00					0.88
13				0.55				0.93
16				0.56				0.93
17					0.002			0.93
21				1.00				0.97
26					0.01			0.97
30					0.56			0.98
33					0.56			0.98
34						-0.01		0.98
38					1.00			0.99
45							0.02	0.99
51						-0.02		0.99
60						-0.01		0.99
64						0.51		0.996
67						0.47		0.996
72						1.00		0.999
80							-0.01	0.999
97							-0.02	0.999
105							-0.02	0.999
109							0.38	0.9996
112							0.30	0.9996
117							1.00	1.00
Initial Loss	83,951	72,126	91,811	26,202	5,478	1,886	164	281,618
% of Total	29.81	25.61	32.60	9.30	1.95	0.67	0.06	100

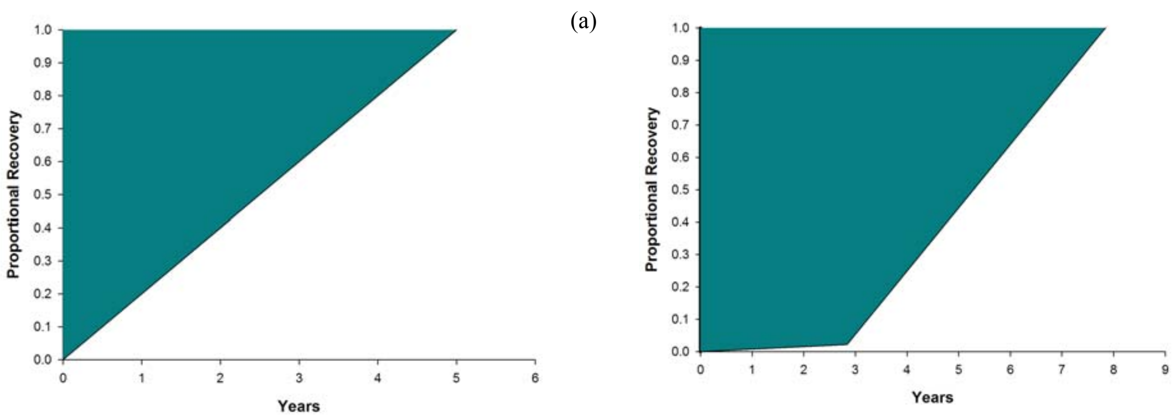

Figure 4. Projections of proportional recovery of estimated *Porites* encrusting colony losses by size category (represented by category size averages; a = 2.5 cm; b = 7.5 cm; continued on next page)

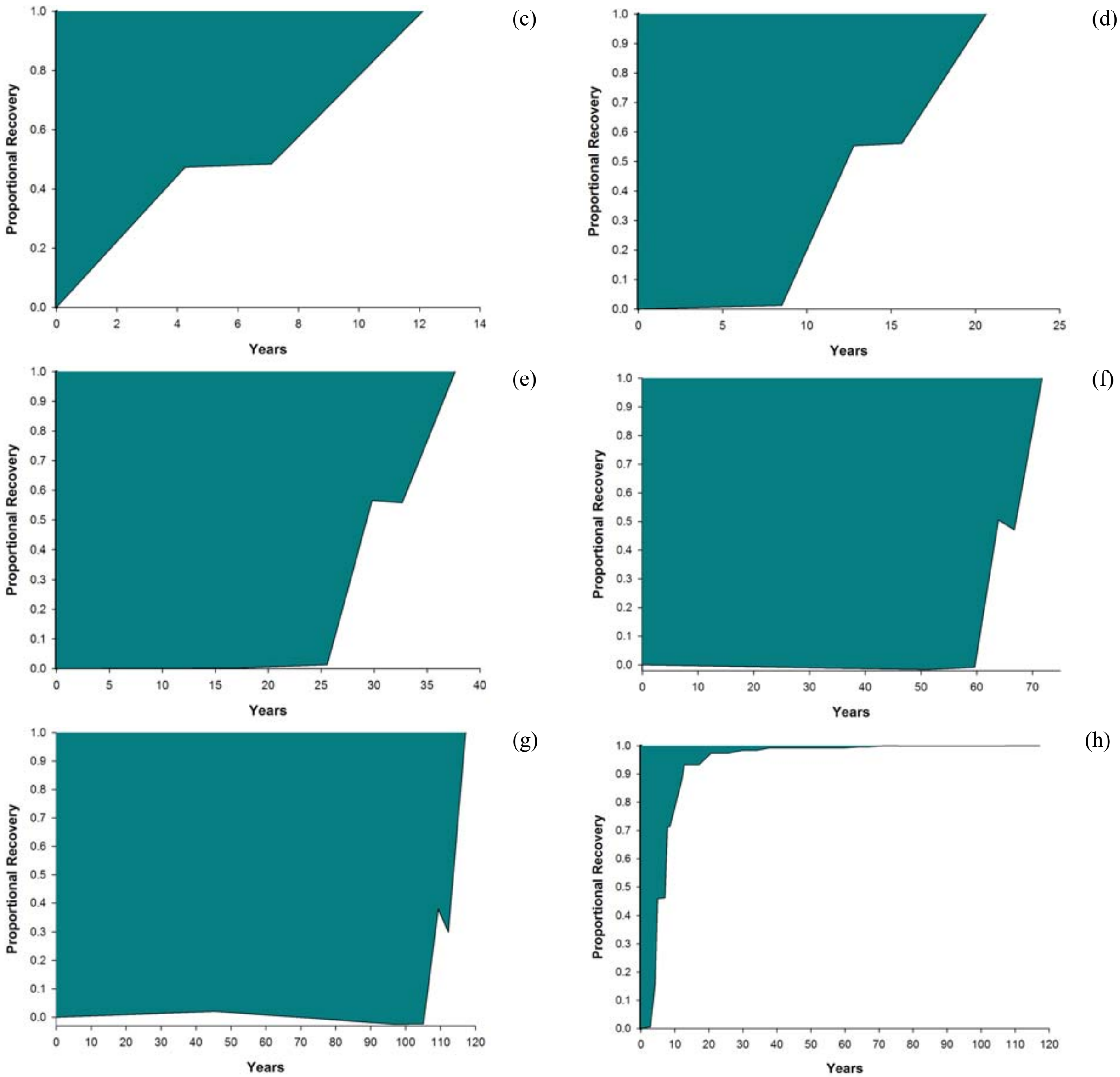

Figure 4 cont.. Projections of proportional recovery of estimated *Porites* encrusting colony losses by size category (represented by category size averages; c = 15 cm; d = 30 cm; e = 60 cm; f = 120 cm; g = 200 cm; g = all sizes).

All Species Groups

An illustration of projected recovery of corals throughout the injured system across species groups is shown in Figure 5. Associated numbers are not supplied so as to maintain focus on the separate qualities provided by the different species groupings and their related sizes. System-wide, 99 % of lost colonies are projected to recovery within approximately 21 years. Resource value associated with the largest lost colonies may take approximately 117 years to replace.

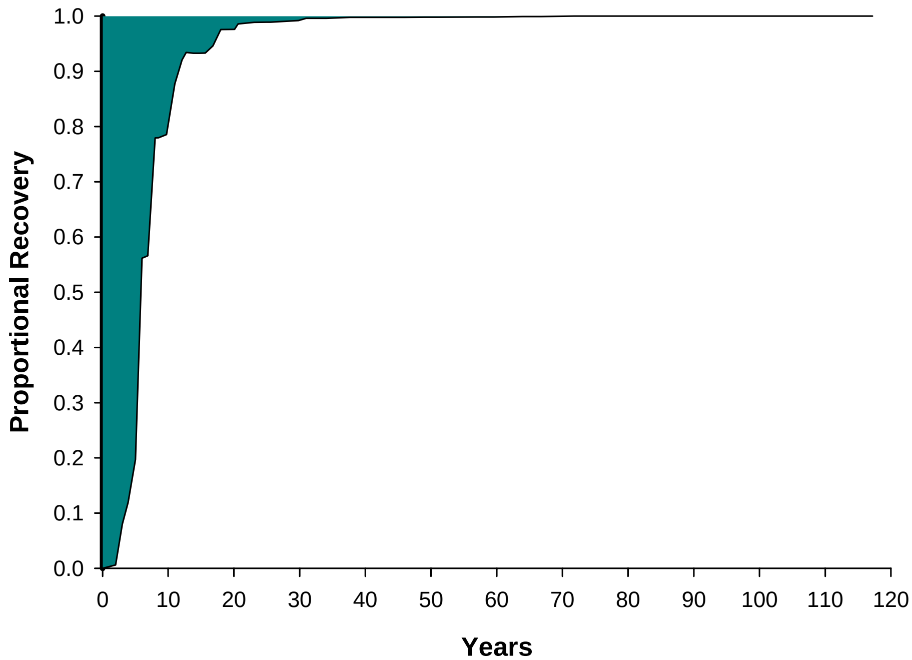

Figure 5. Projection of proportional recovery of coral colony losses within the *M/V Cape Flattery* incident area.

Discussion

History and present system constraints are two factors that need to be considered in projecting future events. In modeling coral reef recovery related to the *M/V Cape Flattery* incident, baseline structure, recruitment, and survival parameters were sought through assessment of reference communities surrounding the incident area (Kolinski et al. 2007). Average parameter values from sampled reference sites within individual habitat zones were assumed to reflect long term coral community dynamics and associated variability in relation to historic events, and provided the best site specific information available from which to model. Growth rates of colonies within the incident zone formed the basis for modeling time in relation to proportional recovery. Forecasts of potential decreases in colony size (Hughes 1984, Hughes and Connell 1986, Fong and Glynn 1998, Hughes and Tanner 2000, Lirman and Miller 2003) were not incorporated as supportive data were not available and variability associated with such a process was assumed to be represented in proportional survival estimates based on average values of individual size categories. There were no data to suggest parameter values would exceed or decline below those indicated by sampled reference populations; so constant recruitment, proportional survival and baseline were assumed.

Coral loss and recovery were measured and modeled as individual species groups (combinations based on genus, gross morphology and growth rate) and size categories in an effort to specify and account for variation in coral function and population dynamic attributes such as topographic complexity, habitat quality, filtering capacity, productivity, reproductive potential and survival probability. This approach of separate categories allows flexibility in exploring compensatory actions that are commensurate with species group and size related attributes. It also maximizes opportunity for some level of direct compensatory restoration and provides a fundamental basis for thoughtful evaluation when considering equity among categories in terms of loss and compensatory replacement.

The models are reflective of population dynamics in habitats free of incident related injury and serve as a basis for recovery consideration. However, they do not account for potential lags or constraints to recovery or future injury that may be associated with the incident. Loss of topography favorable to coral recruitment (Norstrom et al. 2007, see also Gittings et al. 1988) and herbivore shelter may greatly influence the time and path of recovery in the area impacted by the ships' hull beyond that estimated using reference site data. In addition, remaining incident related reef debris may impede recruitment (Gittings et al. 1988, Grigg 1995, Fox et al. 2003, Fox 2004) and reduce survival of corals remaining in the incident area, prolonging recovery. Potential impedance to recovery is difficult to quantify in terms of time absent representative data from this or similar cases, but has been noted in Hawaii (Grigg 1995). Limited restoration of topography and large scale removal of debris has occurred at the incident site. A long-term comparison of recovery in partially restored and un-restored areas may be needed to augment recovery projections. Alternatively, remaining debris might be removed and topography reestablished as a mechanism to address these recovery concerns.

Individual species groups differed in their recovery trajectories due to associated growth rates, distributions among size categories and estimated loss. The slower growing *Montipora* encrusting and *Porites* lobate species groups were represented by the largest colonies and displayed the longest projected terminal recovery times. Smaller, faster growing *Pocillopora* species groups were projected to recovery much sooner, but interestingly were very similar to each other in terminal recovery time estimates. Ecologically, *Pocillopora eydouxi* was represented by diameter sizes just over twice that of *Pocillopora* cauliflower species; however, its' growth rate was over twice as fast, explaining the similarity. Modeling of remaining colonies through the various size categories in some cases resulted in negative recovery for some of the species groups. Such trends represent the effects of disproportionate size based loss over time from an overall population perspective. Recovery gains associated with remaining colonies were also modeled but are less evident within graphs and tables. Evidence of initial recovery does exist at the site in the form of recent *Pocillopora* and *Porites* recruits to cement substrates used in initial primary restoration (Kolinski, unpub. data). Projected recovery rates for individual species groups should serve as a basis for establishing site specific recovery performance criteria that can be monitored over time allowing for future model modification.

The models project full recovery of incident related coral injury within 117 years absent potential inhibition by topographic loss, remaining reef debris, additional system impacts or dramatic changes in modeled parameters. Approximately 99 % of lost coral abundance (smaller and/or faster growing corals) may be replaced within 21 years. Direct comparison of these projections to those previously applied to Hawaiian coral reefs is difficult as few reported estimates are field data based (Grigg and Maragos 1974, Grigg 1985, 1995, Holthus et al. 1986, Dollar and Tribble 2003), all consider coral cover as opposed to abundance and size, recovery is likely to vary between different communities, localities and types of impacts (Done et al. 1991, Connell 1997, Hughes and Connell 1999), and all derived estimates and associated methods remain subject to interpretation and field verification. Previous estimates of coral recovery in Hawaii range from approximately 17 to well over 70 years. Modeled projections for Barbers Point are not inconsistent with these estimates given the limitations for direct comparison.

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