FINAL REPORT

PROJECT TITLE: ECOSYSTEM MODELS TO EXPLORE MANAGEMENT OPTIONS FOR KONA'S COASTAL ENVIRONMENTS

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SUMMARY OF PROPOSED RESEARCH

The nearshore marine resources of the Kona region have long provided sustenance and a venue for cultural practices for Hawaiian and non-Native local people. In more recent decades these resources have become central to an expanding tourism industry and provide opportunities for recreational and commercial, in addition to traditional subsistence fisheries (Friedlander et al. 2008). The region's benthic habitats are still considered relatively healthy (Jokiel et al. 2004), with diverse fish populations and few signs of diseased corals (Beets et al. 2010). Contemporary accounts of change however provide evidence that the processes supporting the ecosystems along the Kona region have been severely disrupted, through fishing and coastal development for example, and are facing an increasing number of threats (Marrack et al. 2009, Weijerman et al. 2009). In response, and in addition to existing initiatives that target the protection of natural resources while promoting a healthy economy (Tissot et al. 2004, Tissot et al. 2009), NOAA, in collaboration with local stakeholders, has initiated an Integrated Ecosystem Assessment pilot project for the region.

Integrative Ecosystem Assessments (IEAs) have been proposed as a useful framework to meaningfully inform decisions in marine ecosystem-based management at multiple scales and across sectors (Levin et al. 2008). An IEA is "a formal synthesis and quantitative analysis of information on relevant natural and socioeconomic factors in relation to specified ecosystem management goals" (Levin et al. 2008), and directly supports ecosystem-based management (EBM) of marine natural resources (Levin et al. 2009, Tallis et al. 2010). In contrast to more conventional approaches to resource management, an IEA considers interactions among ecosystem components and recognizes that human activities ought to be guided using collaborative, interdisciplinary, and adaptive methods. As such, IEAs under the EBM framework recognise that an understanding of the whole, not simply the individual components, is necessary to conserve marine ecosystems and the services they deliver (Levin 1999).

Ecosystem models represent an important tool in the implementation of the steps typically required to conduct an IEA (Levin et al. 2009). Specifically, ecosystem models are instrumental to two of the IEA steps outlined in Levin et al. (2009): (i) Risk analysis – ecosystem models can help determine incremental improvements in ecosystem indicators in response to changes in human-induced pressures (Tallis et al. 2010); and (ii) Management strategy evaluation – models can provide the framework with which to evaluate a suite of possible management strategies and help identify which policies and methods have the potential to meet targeted objectives. Ecosystem models are also helpful in highlighting and quantifying trade-offs between different sectors (e.g., ecological and socioeconomic) (Fulton et al. 2007) resulting from current and future management decisions. By integrating data from such a variety of sectors they also permit the identification of data gaps and key risks and uncertainties based on current data availability.

Under NOAA grant number NA10NMF4520325 we proposed to develop two ecosystem models, using the widely used and freely available software Ecopath with Ecosim (www.ecopath.org):

(i) A 'reef' model focusing on the shallow inshore reef environment of the Kona region. This model's original intent was to
   a. define the food web structure of the Kona region's reef system through trophic modelling;
   b. assemble time series data of nutrient input to the coastal zone;
   c. assemble catch (and effort) time series data for target species in the region;
   d. assess the potential impacts to this environment of increased nutrient input deliveries as a result of expanding development.

(ii) A 'coastal' model to include both the inshore and more offshore environment of the Kona region. This model's proposed intent was to
   a. Define the food web structure of the Kona region coastal system through trophic modelling;

b. Assemble catch (and effort) time series data for target species, focusing on species that are important to the recreational and commercial fisheries operating off the coast;

c. Investigate alternative management options that combine conservation objectives (e.g., maximise ecosystem integrity) with fishing practices (e.g., maintain a given economic objective, maintain specific catch of given targeted species);

d. Evaluate trade-offs between different sectors based on the implementation of alternative fishing strategies with differing management objectives.

Aim of Proposed Research

The project's overarching goal was to develop a 'reef' and a 'coastal' ecosystem model for the Kona region to assist in the sustainable management of western Hawaii 's natural marine resources by conserving the natural environment while ensuring economic opportunities. Given data constraints at the scale of the Kona 'coastal' model the original work's intent was slightly modified. Unexpected synergistic opportunities allowed for collated data for (ii) above to significantly contribute to the development of the Hawaiian Longline Fishing Ground Model (HLFG). Through the development of the HLFG model we explored the individual and synergistic ecological effects of climate change and fishing pressure over time.

Methods and Results

Study area

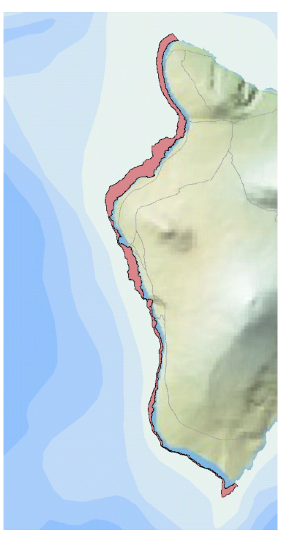

Figure 1 – Reef model area

The Kona, or west coast of Hawai'i, extends from the district of South Kohala in the north to Ka'u in the south.

The 'reef model' was delineated as encompassing the area stretching the entire coast, from approximately 'Upolu point to Ka Lae (South point), encompassing all waters from the low water tide mark down to depths of ca. 100m. Based on available bathymetric data and in collaboration with the Center for Coastal Monitoring and Assessment's Biogeography Branch, we: (i) calculated model area between the coast and the 100 m isobath (data from the U.S. Coastal Relief bathymetry surface for Hawaii - Volume 10 http://www.ngdc.noaa.gov/mgg/coastal/grddas10/grddas10.htm), which encompassed about 300 km^2 (Figure 1); (ii) and developed habitat summaries (in m^2) by geographic zone, major geomorphological structure, detailed geomorphological structure, major biological cover and detailed biological cover for the area encompassed between the coast and the 30 m isobaths (Table 1). Dominant wave direction is from the north, but the coastal zone is variously exposed to the effects of wave energy. Groundwater intrusion into the coastal zone is equally varied along the west Hawaiian shoreline. Community composition and diversity reflects the trends of groundwater flux and wave energy (Dollar 1982).

The 'coastal model', based on DAR fishing zone information (zones for which DAR collects data including catch and effort), included 34 fishing areas, stretching from the Kona coast westward for a total area of 41,942 km^2 (Figure 2). For reasons outlined further below, to capitalise on the information and resources collated in this study, all data significantly contributed to the elaboration of an ecopath model of the Hawaiian Longline Fishing Grounds (HLFG). The model area encompassed the portion of the Central North Pacific used by the Hawaii-based pelagic longline fishery, ranging from 170°E to 150°W and from longitude 10° to 40°N. Specifically, we subset the larger study area used by Kitchell et al. (2002) and Cox et al. (2002b) to construct their Central North Pacific Ecosystem model (CNP8). This model contained a surface area of 13,275,700 km^2 and represented the region where over 95% of the Hawaii longline sets occurred.

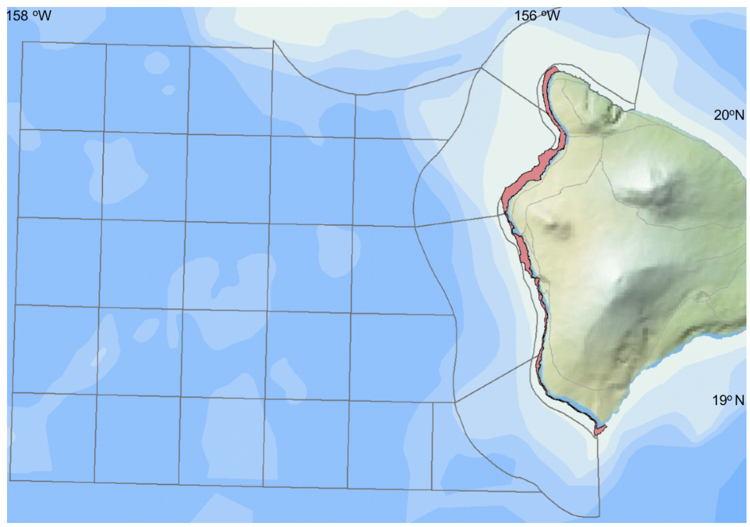

Figure 2 - Coastal ecosystem model area encompassed by the grey DAR boxes, with the reef model area (pink) for comparison.

Table 1 - Area covered by major geormorphological structure types based on Batista et al. (2007)

Geographic Zone	**Area (m^2)**
Bank/Shelf	83,587,560
Bank/Shelf Escarpment	1,997,248
Channel	25,687
Dredged	466,312
Fore Reef	772,258
Land	127,574
Reef Crest	56,489
Reef Flat	3,573,269
Total	*90,606,396*

Major Biological Cover	**Area (m^2)**
Coral	56,738,148
Coralline Algae	1,482,534
Turf	12,372,336
Unclassified	124,542
Uncolonized	18,212,462
Unknown	1,676,374
Total	*90,606,396*

Major Geomorphological Structure	**Area (m^2)**
Coral Reef and Hardbottom	70,593,018
Other Delineations	124,542
Unconsolidated Sediment	18,212,462
Unknown	1,676,374
Total	*90,606,396*

Detailed Biological Cover	**Area (m^2)**
Coral 10%-<50%	42,374,510
Coral 50%-<90%	11,458,476
Coral 90%-100%	2,905,163
Coralline Algae 10%-<50%	1,124,330
Coralline Algae 50%-<90%	358,204
Turf 10%-<50%	1,943,413
Turf 50%-<90%	9,306,502
Turf 90%-100%	1,122,421
Unclassified	124,542
Uncolonized 90%-100%	18,212,462
Unknown Unknown	1,676,374
Total	*90,606,396*

Detailed Geomorphological Structure	**Area (m^2)**
Aggregate Reef	11,297,668
Artificial	124,542
Mud	473,642
Pavement	195,628
Pavement with Sand Channels	466,418
Rock/Boulder	57,683,643
Rubble	156,891
Sand	17,738,821
Scattered Coral/Rock	105,418
Spur and Groove	687,352
Unknown	1,676,374
Total	*90,606,396*

Modelling approach

We used the Ecopath and Ecosim approach (EwE), software version 6.2.0.714 (Christensen and Walters 2004, Christensen et al. 2005, http://www.ecopath.org, Christensen et al. 2008). The foundation of the Ecopath with Ecosim (EwE) suite is a trophic mass balance model - Ecopath - (Polovina 1984, Christensen and Pauly 1992) that creates a static snapshot of the resources in an ecosystem and their interactions, represented by user defined trophically linked biomass 'pools' (Christensen and Pauly 1992). The biomass pools, hereafter referred to as functional groups, consist of a single species, single size/age group of a given species, or species groups representing ecological guilds (sharing similar trophic behaviour, habitats, and other ecological traits). These may be further split into ontogenetic (juvenile/adult) groups that can then be linked in Ecosim.

The idea behind the mass-balance approach is that "at any time within the system, and within the elements of that system, the amounts of matter that flow in must balance the amount that goes out, plus the change in biomass" (Pauly and Christensen 2002 p. 215). Ecopath, therefore, operates under two main assumptions:

(i) That biological production within a functional group equals the sum of mortalities, i.e., on an annual basis, biomass and energy in an ecosystem are conserved (Walters et al. 1997, Walters and Martell 2004a). This relationship can be expressed as follows:

$$B_i \cdot (P/B)_i = \sum_{j=1} B_j \cdot (Q/B)_j \cdot DC_{ij} + Y_i + E_i + BA_i + B_i (P/B)_i \cdot (1 - EE_i) \qquad (1)$$

where B_i and B_j are biomasses of prey (i) and predator (j) respectively; $(P/B)_i$ is the production to biomass ratio, equivalent to total mortality (Z) under most circumstances (Allen 1971); $(Q/B)_j$ is the food consumption per unit biomass of (j); DC_{ij} is the fraction of prey (i) in the average diet of predator (j); Y_i is the total fishery catch rate of group (i); E_i is the net migration rate (emigration - immigration); BA_i is the biomass accumulation rate of group (i); and EE_i is the ecotrophic efficiency, defined as the fraction of production that is consumed within the system or is removed by fishers.

(ii) That consumption within a group equals the sum of production, respiration, and unassimilated foods. This relationship can be expressed as follows:

$$B \cdot (Q/B) = B \cdot (P/B) + (1 - GS) \cdot Q - (1 - TM) \cdot P + B(Q/B) \cdot GS \qquad (2)$$

where GS is the proportion of food unassimilated and TM is the trophic mode expressing the degree of heterotrophy of groups represented within the system - with 0 representing autotrophs, 1 heterotrophs, and intermediate values facultative consumers.

Ecopath then uses a set of algorithms to solve simultaneously n linear equations of the form in equation 1, where n is the number of functional groups. For each functional group, three of the basic parameters: B_i, $(P/B)_i$, $(Q/B)_i$ or EE_i must be known, in addition to the fisheries yield (Y_i), and the diet composition.

Units of the model are expressed in $t \cdot km^{-2} \cdot year^{-1}$ wet weight organic matter for flows, and $t \cdot km^{-2}$ wet weight for biomasses. P/B and Q/B have the dimension $year^{-1}$. For a review of Ecopath with Ecosim's capabilities and limitations see Christensen & Walters (2004) and Plaganyi (2004, 2007).'

Ecosim, is a time-dynamic extension of Ecopath that uses the 'foraging arena' concept (Walters and Juanes 1993, Walters et al. 1997, Walters and Martell 2004b) to model predator-behaviour and its effect on consumption rates. The module uses a system of time-dependent differential equations, where biomass fluxes amongst functional groups are calculated as a function of time by accounting for changes in predation, consumption, and emigration rates, as well as fishing (Christensen and Pauly 2004). For each group, biomass growth rate is expressed as:

$$\frac{dB_i}{dt} = \left(\frac{P}{Q}\right)_i \cdot \sum Q_{ji} - \sum Q_{ij} + I_i - \left(M_i + F_i + e_i\right) \cdot B_i \tag{3}$$

where $(P/Q)_i$ is the gross efficiency; M_i is the natural non-predation mortality rate; F_i is the fishing mortality rate; e_i is the emigration rate; I_i is the immigration rate; and B_i is the biomass of the functional group (i). Calculations of consumption rates Q_{ij} are based on "foraging arena" theory, where the biomass of prey (i) is divided into vulnerable and non-vulnerable pools to predation (Walters and Kitchell 2001, Walters and Martell 2004b). Low vulnerability rates to predators imply donor-driven (prey is limiting), density-dependent interactions. High rates, on the other hand, indicate predator-driven interactions where (a) the behaviour of both prey and predator have weaker effects on limiting predation rates; (b) predation mortality is proportional to the product of prey and predator abundance; and (c) the predator's initial biomass is low compared to its carrying capacity (Christensen et al. 2005). Typically, models are calibrated by adjusting foraging arena parameters until model predictions fit observed trends.

Previous data and gleaned information had indicated that 1990 would constitute a good 'start year' for both models. However, few or no field data, particularly for reef fish, were found to be available prior to the early 2000s to estimate biomass for trophic groups included in the reef model. Moreover, DAR fishing data (with paperwork approved in June 2011), which were to constitute the key time series to fit reef model output data to, were found to be very patchy, particularly with reference to effort data. As a result, together with NOAA PIFSC collaborators on this project, it was decided 2004 would constitute the reef model's start year, as good field data were available then. The year 1990 was kept as start year for the costal model.

To balance the models, changes were first made to the diet matrix, as diet compositions represent only snapshots of the feeding habits of individual species and are likely to be relatively variable based on location and time periods of data collection. The models required only required minor adjustments and were considered balanced when: (i) ecotrophic efficiencies (EE) were smaller than one; (ii) values of the production to consumption ratio (P/Q) for functional groups were between 0.05 and 0.35, with the exception of groups with fast growth rates (higher ratios), and top predators with lower values (Christensen et al. 2005)

Model parameters and functional groups

a. Reef ecosystem model

Following consultation with stakeholders in Hawai´i, the food web structure of the Kona region reef system was defined through a total of 30 species or species groups: Hawaiian monk seals, cetaceans sharks and rays, green sea turtles, large pelagics, reef pelagics, reef piscivores, roi, bottomfish, planktivores, sessile invertebrate feeders, mobile invertebrate feeders, detritivores, corallivores, reef herbivores, yellow tangs (*Zebrasoma flavescens*, adults and juveniles as separate multi-stanza groups), kole (*Ctenochaetus strigosus* , adults and juveniles as separate multi-stanza groups) urchins, crown-of-thorns, benthic invertebrates, octocoral, corals, macroalage, crustose coralline algae, turf algae, zooplankton, phytoplankton, and detritus (see Table 2).

Species were aggregated based on ecological similarities (species that share habitats/discrete feeding particularities), to align with existing monitoring programmes, and to help address – where data were available – the questions of interest for management purposes. The three issues that were raised most often were the role and potential impact (i) of the introduced roi (*Cephalopholis argus*) on local reef fish populations; (ii) of the addition of nutrients on primary producers, particularly due to expanding development, through submarine groundwater discharge; (3) of the aquarium trade over the model area.

The following summarises principal key experts contacted, where applicable, and information collected:

Monk seals — Key experts: Jessica Aschettino (Robin Baird, Charles Littnan)

Data on (i) number of animals that can reasonably be assumed to be within the area over the course of a year; (ii) P/B estimates; (iii) Q/B estimates and (iv) diet information.

Cetaceans — Key experts: Jessica Aschettino (Robin Baird, Justin Viezbicke)

Data on (i) number of animals that can reasonably be assumed to be within the area over the course of a year; (ii) P/B estimates; (iii) Q/B estimates and (iv) diet information.

Note that in most instances only qualitative information, if any, is available on the diet of most cetaceans utilising the nearshore waters of the Big Island.

Sea turtles — Key experts: George Balazs and Stacy Hargrove

Established standards and protocol for relevant turtle information for the Kona coast and finalised biomass estimates for the Kona coast. P/B, Q/B and diet inputs were taken from a previous model developed for Kaloko Honokōhau (Wabnitz et al. 2010).

Reef fish — Key experts: Eric Brown, Alan Friedlander, David Ham, Bill Walsh, Ivor Williams, Jill Zamzow

Division of Aquatic Resources (DAR) and NOAA PIFSC Coral reef Ecosystem Division (CRED) data kindly and generously provided by Bill Walsh and Ivor Williams were summarised and analysed. One 'caveat' to the dataset is that reef sites visited on a regular basis for monitoring purposes were specifically selected to determine whether the aquarium trade has an impact on local resources or not. In other words, most sites are characterised by high coral cover (good recruitment habitat for juveniles, the main target for the marine aquarium trade). Moreover, although a general idea is given about what the habitat consists of, it is difficult, based on the data provided, to extrapolate site data reliably to the entire coast and according to NOAA habitat classes. Following initial discussions with Alan Friedlander at a meeting in May 2011, he very kindly and generously agreed in June 2011 to provide his underwater visual census data for all Kona coast site. These data include, for each transect, habitat categories as per the NOAA classification. A few data manipulations were performed to the original dataset including separating out roi, including juvenile yellow tang and kole categories based on size recorded (between 0 and 10cm, B. Walsh pers. comm.). According to Friedlander et al. (2007) uncolonized hard bottom was defined as habitat having <10% live coral cover (and colonized hardbottom as hard bottom having >10% live coral). NOAA habitat shapefile data from a mapping study conducted in 2007 was extracted and matched to the definition above to calculate proportions of different habitat types.

For all fish, and both datasets, species were aggregated as per defined functional groupings. DAR biomass data was provided in units of weight per area. For Alan Friedlander's datasets, biomass per unit area was derived by summing all available data and dividing by the relevant number of transects. Average biomass per year for each species (or for each functional group) was calculated as the pooled sum over the given year, divided by the number of transects (per habitat type). This method follows Bill Walsh's approach to analyzing WHAP and other resource census data; i.e., biomass data get pooled for the year and then divided by 4 for the number of transects, 4 for the number of rounds (i.e., number of times sites get visited per year), and by 23 for the number of sites along the coast. All selected sites are non-random, thus usually transects are across high coral cover habitats (Jill Kamkow pers. comm.).

For instances where P/B was equal to only natural mortality (M), estimates were taken directly from the literature, or derived using the empirical formula of Pauly (1980). For exploited species, fishing mortality values were initially based on DAR fishing data. However, as calculated catches and associated mortality rates were extremely low and not in keeping with known exploitation rates experienced by coastal stocks, final input values were informed by Friedlander & Parrish (1997) and set in consultation with local experts. This did not apply for yellow tangs.

Where possible, the consumption rate for each functional group was obtained through field studies; otherwise it was estimated from empirical equations such as those available in FishBase (www.fishbase.org). The diet matrix was constructed using data from field studies in Hawai‘i, preferentially the west coast of the Big Island. Where no such data were available, the matrix was complemented with information obtained from the literature for the same species in similar ecosystems.

For P/B, Q/B and diet proportions of functional groups consisting of more than one species, values were calculated accounting for the biomass contribution of a given species to the functional group overall.

Urchins

This functional group was composed of the most frequently reported urchins during surveys, namely *Echinometra mathaei*, *Echinothrix* spp. (i.e. *E. diadema* and *E.calamaris*), *Heterocentrotus mammilatus*, and *Tripneustes* gratilla, Abundance data were derived from the literature and informed for a selection of species by DAR data – reported as average from a number of key monitoring sites (Walsh et al. 2010). Note that Walsh et al. (2010) did not record *E. mathaei*, the most abundant species recorded at Kaloko (M. Weijerman pers. comm.).

Numbers were then converted to biomass based on published test size–weight relationships. P/B values were assumed to be equal to natural mortality rates with a very low fishing mortality (informed by DAR data) and based on published empirical relationships. Depending on the species, Q/B rates were derived based on feeding experiments and/or rates reported for the same species in other parts of the world. *Heterocentrotus mammilatus* was assigned the same Q/B rate as *Echinothrix* spp. Diet data were derived from the published literature.

As with fish, values for P/B, Q/B and diet proportions of functional groups consisting of more than one species were calculated accounting for the biomass contribution of a given species to the functional group overall.

Crown-of-thorns

Abundance data were informed by DAR data (Walsh et al. 2010). Biomass was estimated based on the assumption that an individual weighs on average 466 g.

P/B, Q/B and diet data were derived from values in the published literature.

Benthic invertebrates

Hardly any data have been published for benthic invertebrate abundances on reefs. As such we let the software ecopath derive a value for B - based on established diet relationships and an EE value of 0.95.

P/B, Q/B and diet data were derived from values in the published literature.

Octocorals

Biomass data were informed by DAR data (Walsh et al. 2010) and published empirical relationships. Note that octocoral (*Sarcothelia edmonsoni*) cover is localised, with its distribution concentrated around developed areas near Kiona, and its virtual absence around undeveloped shoreline areas.

P/B, Q/B and diet data were derived from values in the published literature.

Corals

Biomass data were derived based on percent cover and surface area data extracted from the shallow water habitat atlas compiled by Battista et al. (2007) and supplemented with published empirical relationships. The total live coral area estimated in this way corroborates benthic surveys conducted in 2003 and 2007 by DAR all along the west coast of the Big Island. Note however that Walsh et al. (2010) highlight significant coral cover decline for the northern region, probably in part due to a strong winter storm in 2004, and/or to a sedimentation event in 2006 that affected a number of sites.

P/B, Q/B and diet data were derived from values in the published literature.

Benthic primary producers

Key experts: Thomas Sauvage, Claude Payri

Biomass data were derived based on percent cover and surface area data extracted from the shallow water habitat atlas compiled by Battista et al. (2007) and supplemented with empirical relationships obtained from field experiments (T. Sauvage pers. comm.).

P/B values were derived from the published literature and adjusted according to expert opinion.

Zooplankton

Key experts: Brian Hunt, Paul Bienfang

From a review of the literature, it emerged that very few data exist for zooplankton abundance/biomass for the reef zone. Estimates were informed by the results of the few studies available (site specific) and extrapolated to be representative of the whole coastal system based on the guidance of experts.

Phytoplankton (and nutrient dynamics)

Key experts: Jason Adolf, Paul Bienfang, Philippe Binder, Megan Dailer, Henrieta Dulaiova, Eric Grossman, Craig Glenn, Mark Kimura, Karen Knee, Kara Osada, Richard Peterson Jeff Polovina, and Tracy Wiegner

Initial trial approaches to develop primary production time series from ~1997 onwards for Globe Colour, Aqua and SeaWiFs were abandoned due to scale mismatch. From a review of the literature, it emerged that very few data exist for phytoplankton abundance/biomass for the reef zone. Estimates were informed by the results of the few studies available (site specific) and extrapolated to be representative of the whole coastal system based on the guidance of experts. Discussions with researchers from the University of Hawaiʻi at Hilo involved in an EPSCoR funded project (http://www.epscor.hawaii.edu/ender) indicated that data are currently being collected to fill this important gap. Discussions also highlighted that the modelling of (increased) nutrient delivery on phytoplankton dynamics and potential ramifications of such changes at the level of the foodweb was in conflict with a number of students' projects with similar objectives. Most of these projects were just starting or about to start in 2011 with all collected data constituting critical elements of a number of theses. Hence, to limit potential conflict it was determined that the modelling of changes in nutrient dynamics on the ecosystem would not be possible within the proposed timeframe (see also text below)[i].

Fisheries

Key experts: Bill Walsh, aquarium fishermen, David Ham, Alan Everson, Mike Lameier & Jonatha Giddens

In June 2011, DAR provided fisheries data (including effort) for all exploited food fish and species exploited for the aquarium trade for the time period 1990- 2010. Catch time series were compiled for all DAR coastal fishing areas for which data were available by (i) finding appropriate common names for listed Hawaiian names, (ii) grouping fish species by functional group categories (see above), (iii) summarising data from 1990 onwards for each fishing area (100, 101, 102 and 103) by functional group included within the reef model boundaries (this necessitated the estimation of the proportion, and thus associated catch, of certain fishing areas included within the modelled area). Effort and CPUE time series were also derived. Note effort data in number of hooks were not reliable and in term of number of hours, for all gears combined (with all trolling categories merged as catch was reported according to three different trolling categories prior to 2003), data seem to have been reported regularly only from 2002 onwards (Figure 4).

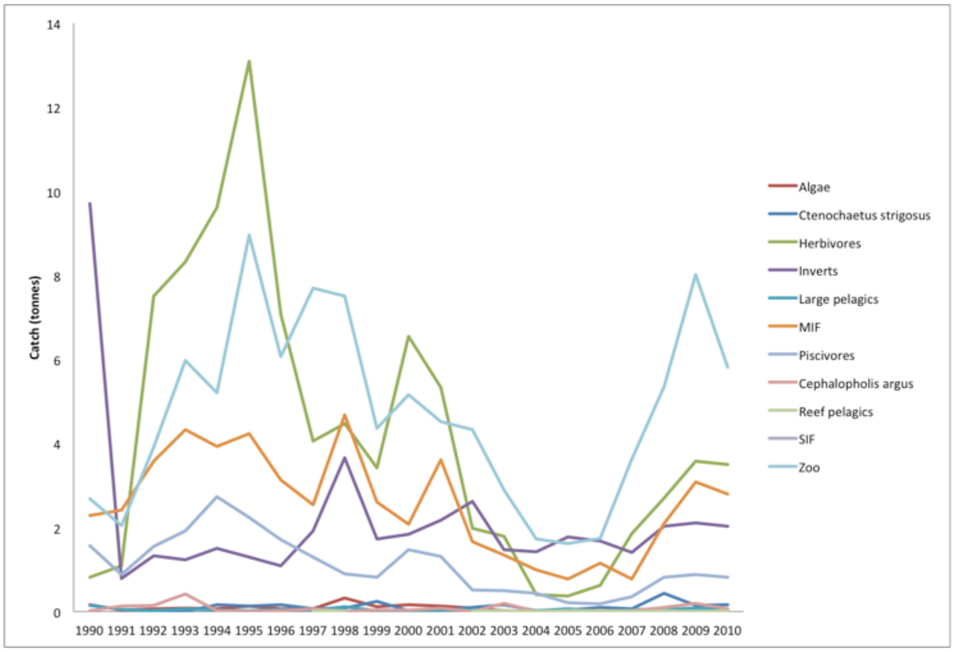

Figure 3 – Total catch in tonnes for the reef model and derived from DAR data for relevant functional groups. MIF: Mobile Invertebrate Feeders; SIF: Sessible Invertebrate Feeders; Zoo: zooplanktivores

Most species caught were pelagic, with trolling dominating effort statistics. Once pelagic species unlikely to be caught within reef model boundaries were removed total catch (and effort) was driven by reef pelagic (inshore handing) (not shown).

Given that the DAR fisheries boxes extended past the limits of our model boundary a large proportion of reported catch included species not considered in our simulation efforts. We also noted that most of the reef pelagic targeted were never recorded on any of transects for which we had field data.

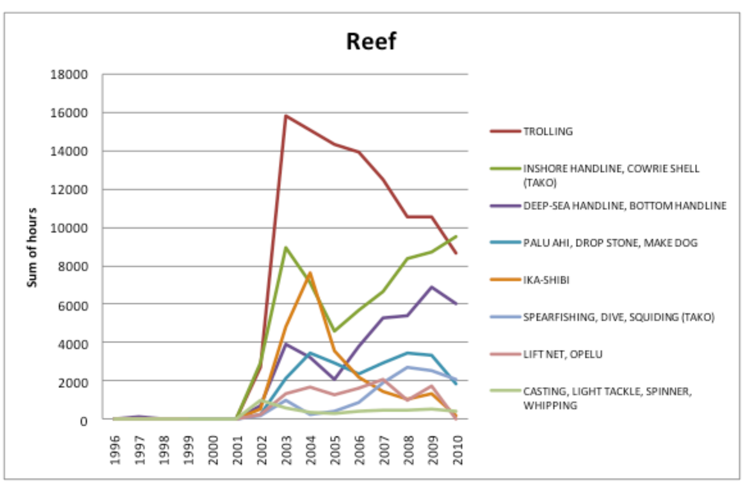

Figure 4 – Effort data (as number of hours) per main gear categories from 1996 onwards for the reef area

Once catch (in tonnes) was divided by the appropriate surface area to obtain catch per unit area as needed for input into ecopath, the resulting values and corresponding fishing mortality values were too small to be reasonable given known fishing pressure on the Kona coast. Hence, we decided to augment the dataset by assuming heavily exploited species to have an F approximately equal to M, while moderately exploited species were assumed to have an F equal to M/2 or less (C. Walters, pers. comm.).

For the aquarium trade data, the top 98% of catch consisted of a few species were allocated to the relevant functional groups. As all data were available as number of pieces collected, the following steps were taken to convert these to biomass: (i) local fishermen kindly provided the average size at collection of the top species; (ii) a literature review was undertaken to compile length-weight relationships for the different species; and (iii) multiply average weight by number of pieces collected for each species.

Table 2 – Trophic parameters for all functional groups of the balanced reef model. Model outputs are presented in bold. B: biomass (t km^2); TL: trophic level; P/B: productivity to biomas ratio (year^{-1}); Q/B: consumption rate (year^{-1}); EE: ecotrophic efficiency. Ytang: yellow tang; MIF: Mobile Invertebrate Feeders; SIF: Sessle Invertebrate feeders; COT: crown of thorns; CCA: crustose coralline algae; Invts: invertebrates. The yellow tang and kole groups were linked via "multi-stanza"

Group name	Trophic level	Biomass (t/km²)	P/B (/year)	Q/B (/year)	EE
Monk seals	3.838	0.001	0.183	11.410	**0.057**
Cetaceans	3.208	0.312	0.143	11.089	**0.071**
Green turtles	2.001	0.036	0.109	8.063	**0.268**
Sharks and rays	3.452	0.100	0.547	3.500	**0.013**
Large pelagics	3.709	0.176	0.804	4.074	**0.630**
Reef pelagics	3.392	0.093	1.022	4.809	**0.677**
Piscivores	3.277	1.061	0.523	4.946	**0.782**
Roi	3.265	0.397	0.410	5.700	**0.552**
Bottomfish	3.307	0.004	0.540	3.900	**0.540**
MIF	3.138	2.053	1.053	8.272	**0.745**
SIF	3.281	0.093	1.440	10.032	**0.573**
Corallivores	3.438	0.501	1.673	12.181	**0.475**
Herbivores	2.020	7.097	0.790	18.648	**0.700**
Yellow tang	2.000	1.780	0.660	35.100	**0.589**
YTang_Juv	2.000	0.460	0.881	74.405	**0.943**
Detritivores	2.000	0.231	1.080	27.700	**0.132**
Kole	2.000	1.271	1.550	31.000	**0.285**
Kole_Juv	2.000	0.392	1.581	57.845	**0.858**
Zooplanktivores	2.973	0.613	1.780	14.736	**0.670**
COT	3.540	0.034	0.411	9.000	**0.025**
Urchins	2.001	100.000	0.484	8.290	**0.031**
Benthic Invts	2.177	**8.741**	2.910	15.250	0.950
Coral	2.549	81.957	1.095	2.100	**0.074**
Octocoral	2.364	0.100	0.600	4.630	**0.571**
CCA	1.000	1.580	1.777	0.000	**0.886**
Macroalgae	1.000	10.170	9.824	0.000	**0.837**
Turf algae	1.000	35.000	20.000	0.000	**0.843**
Zooplankton	2.020	1.240	219.000	949.000	**0.498**
Phytoplankton	1.000	3.290	325.460	0.000	**0.802**
Detritus	1.000	100.000			**0.670**

Following up on preliminary enquiries into CREEL survey data, it was decided that the general setup of the surveys did not lend itself to generate good estimates of total catch for the modelling purposes sought here, especially given the timeframe of the study.

Nutrient dynamics

One of the major objectives of this proposal was to determine the possible impacts of nutrient loading through groundwater discharge (SGD) due to large-scale development along the Kona coast. Submarine groundwater discharge (SGD) is an important land-to-ocean pathway for nutrients, such as nitrate, silicate and phosphate. Introduction of new bioavailable nutrients from SGD into coastal waters can alter the ecosystem's nutrient balance, and may result in increases in phytoplankton or macroalgae growth that in turn can cause other ecological shifts in biological species' composition (Valiela et al. 1990). To investigate such potential impacts, considerable effort was expanded in reviewing the available literature, and meeting/corresponding with researchers whose work focuses on nutrient dynamics along the Kona coast (e.g., Craig Glenn, Henrieta Dulaiova, Karen Knee, Megan Dailer, Eric Grossman, Richard Peterson).

Currently published data do not lend themselves to develop robust input parameters. From several meetings with the above named experts the overwhelming impression was that, although nutrient contribution to the coastal zone through groundwater fluxes is no doubt significant, the quantitative estimates of such contributions are currently unclear. Perhaps most importantly it appears that the dissipation of coastal ocean nutrient concentrations by physical, rather than biological, processes may modulate the effects of potential future increases in nutrient inputs. Indeed, Knee et al. (2010) found conservative behaviour of nutrients in the coastal zone, suggesting a very low biological uptake of nutrients – due to possibly advection, stratification and limitation of phytoplankton productivity by micronutrients. Other preliminary data also suggest that the physical longevity and residence time of phytoplankton along the Kona coast control primary productivity (C. Glenn, pers. comm.). Given that submarine groundwater discharge is typically less saline than seawater, uptake by benthic primary producers is likely to be reduced. Discussions with key experts also highlighted that a number of different groups, under different umbrellas, have and will be collecting a vast array of data on nutrients (incl. nitrite, nitrate, phosphate, silica) and related oceanographic parameters (incl. salinity, dissolved oxygen, temperature) along the Kona coast; primarily at Kaloko Honokōhau and Kiholo Bay. Unfortunately, the timeframe of our respective studies did not allow for these researchers' data to be published (a stated prerequisite for collaboration) in time and integrated into our modelling efforts. As indicated above, to limit potential conflict it was determined that the impact of changes in nutrient dynamics would not be further developed within the remit of this study.

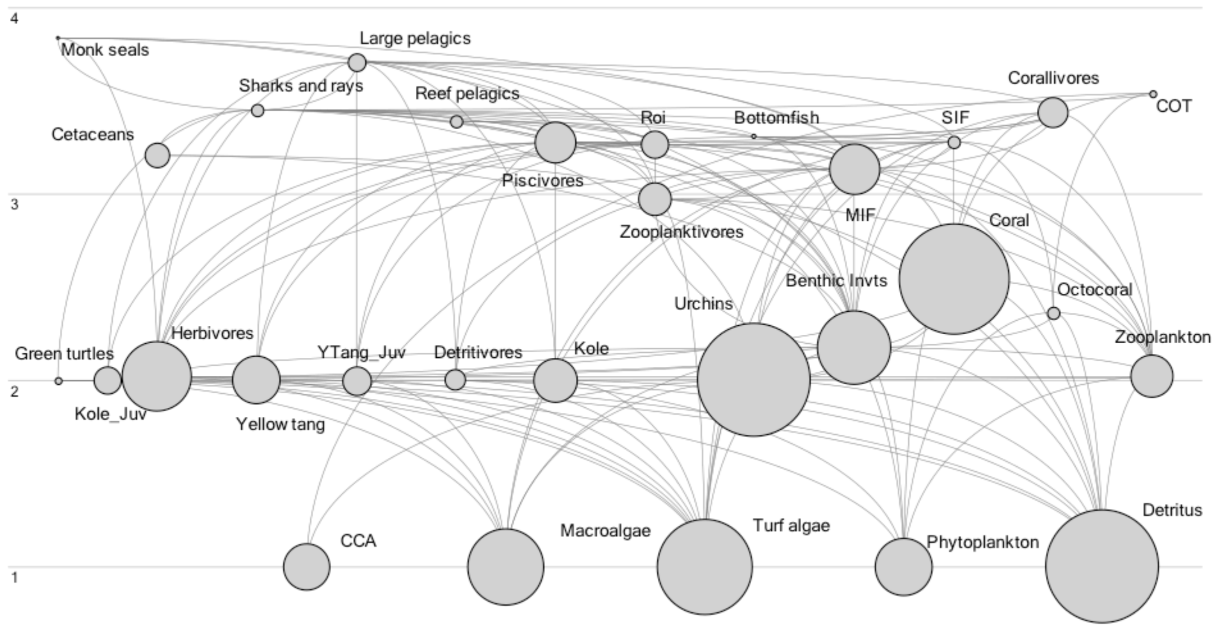

Figure 5 - Trophic flows within the Kona reef ecosystem. Each functional group is identified by a circle whose size represents the relative biomass of that group within the system. The light grey horizontal lines and associated numbers represent trophic levels; lines connecting individual functional groups represent trophic links. YTang = yellow tang; Juv = juvenile; COT = crown of thorns; CCA = crustose coralline algae; Invts = invertebrates

Sea urchins (*Tripneustes gratilla, Echinometra mathaei, Heterocentrotus mammilatu*s, and *Echinothrix* spp.) accounted for the largest proportion of total living biomass in the system (39%). Fish only accounted for 6.3% of total biomass, with herbivores contributing most (57%) followed by MIF (13%). Transfer efficiencies (TE), summarize the proportion of consumption that is passedup a food web. The TE is the ratio between the production of a given trophic level and the preceding trophic level (Pauly and Christensen 1995). The mean transfer efficiency in the ecosystem as a whole was 6.0%, with the same value applying to flows originating from detritus and from primary producers. Not surprisingly consumption by urchins had the biggest impact on resources (31%). Total fisheries catches (excluding invertebrates and algae) accounted for 6% of total fish biomass. Total catches had a mean trophic level of 2.891 (Table 3).

Table 3 – A number of statistics that describe the Kona reef ecosystem

Sum of all consumption	2655.289	t km^{-2} yr^{-1}
Sum of all exports	456.132	t km^{-2} yr^{-1}
Sum of all respiratory flows	1438.313	t km^{-2} yr^{-1}
Sum of all flows into detritus	1378.255	t km^{-2} yr^{-1}
Total system throughput	5928.029	t km^{-2} yr^{-1}
Mean trophic level of the catch	2.891	
Calculated total net primary production	1873.481	t km^{-2} yr^{-1}
Total primary production/total respiration	1.303	t km^{-2} yr^{-1}
Total biomass (excluding detritus)	258.781	t km^{-2}
Total catches	0.991	t km^{-2}
Connectance Index	1.18	
System Omnivory Index	0.118	

b. Coastal ecosystem model

To allow for comparisons with existing simulations (e.g., Cox et al. 2002a, Kitchell et al. 2002), the model was parameterised to represent an average annual situation in 1991.

Key experts who provided valuable information and/or guidance over the course of model development included Mélanie Abecassis, Jessica Aschettino, Robin Baird, Anela Choy, Jeff Drazen, Evan Howell, Brian Hunt, Isaac Kaplan, Evgeny Pakhomov, and Brian Popp.

The coastal zone model was initially delineated based on DAR fishing zone information (zones for which DAR collects data including catch and effort), encompassing 34 fishing areas, stretching from the Kona coast westward for a total area of 41,942 km^2. However,

i. A literature review and discussion with key experts quickly highlighted that for that 'small' a pelagic area, biomass information for a number of critical functional groups was lacking or of poor quality (e.g., mesopelagic mollusks and crustaceans, mid-trophic level fish, zooplankton, phytoplankton). A significant amount of time was spent reviewing the literature and setting up a protocol to determine the proportion of biomass for top predators (all tunas, marlins, swordfish and other billfish), estimated from stock assessments for the North Pacific, that should be apportioned to the area encompassed within the coastal model. This proved quite challenging, given the size of the area over which the stock assessments have been conducted and the size of the pelagic model box in comparison, and the different types of fisheries operating. Although, EE can be provided instead of biomass, leaving Ecopath to calculate the missing term, a number of key stakeholders felt that this would significantly reduce credibility in the model, especially given the (a) size of the model area and (b) few time series available against which to fit the model;
ii. The fitting times series were to consist of DAR CPUE or effort data, which were not obtained until June 2011. Catches were aggregated based on the functional groups defined (Figure 6). In most instances, once catch was divided by model surface area, the resultant yield was extremely small, when compared with expected values. Analysis of effort data did not produce reliable results.

The resultant model structure and draft input parameters presented a poor basis from which to simulate with confidence the potential impact of changes in fishing mortality on mid-trophic level stocks and/or changes in primary production on the system overall, within the allocated time frame. In consultation with local project collaborators, it was decided that collated data and the remainder of the project time should be used to contribute significantly to the development of the Hawaiʻi Longline Fishing Ground (HLFG) Ecopath model. The objective of the HLFG model development was to explore the individual and synergistic ecological effects of climate change and fishing pressure over time. Specifically the HLFG model was combined with climate model output to create four scenarios with varying fishing and climate pressures through the year 2100. The results from these scenarios were used to understand how climate and fishing could possibly change the ecosystem structure, as well as what effects these pressures may have on the Hawaii-based pelagic longline fleet through the remainder of the 21st century.

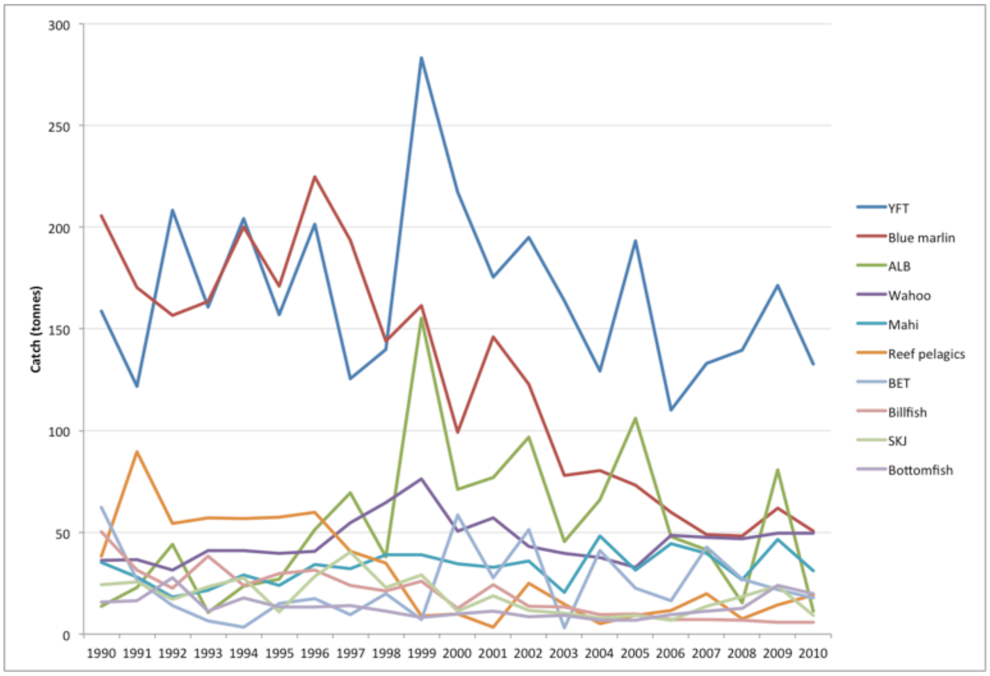

Figure 6 – DAR catch time series for the most important species from 1990 to 2010. YFT: yellowfin tuna; ALB: albacore tuna; BET: bigeye tuna; SKJ: skipjack tuna

Definition of functional groups was guided by the inclusion of representative ecological guilds (i.e., those species that best characterise the system) and the need to include groups that would best reflect potential impacts of fishing on the system over time. Indeed, Polovina et al. (2009) showed that Hawaiʻi-based longline fisheries registered a decline in the catch per unit effort of top predators from 1996 to 2006, whereas catch rates of mid trophic level groups (mahi mahi and sickle pomfret) increased over the same time period.

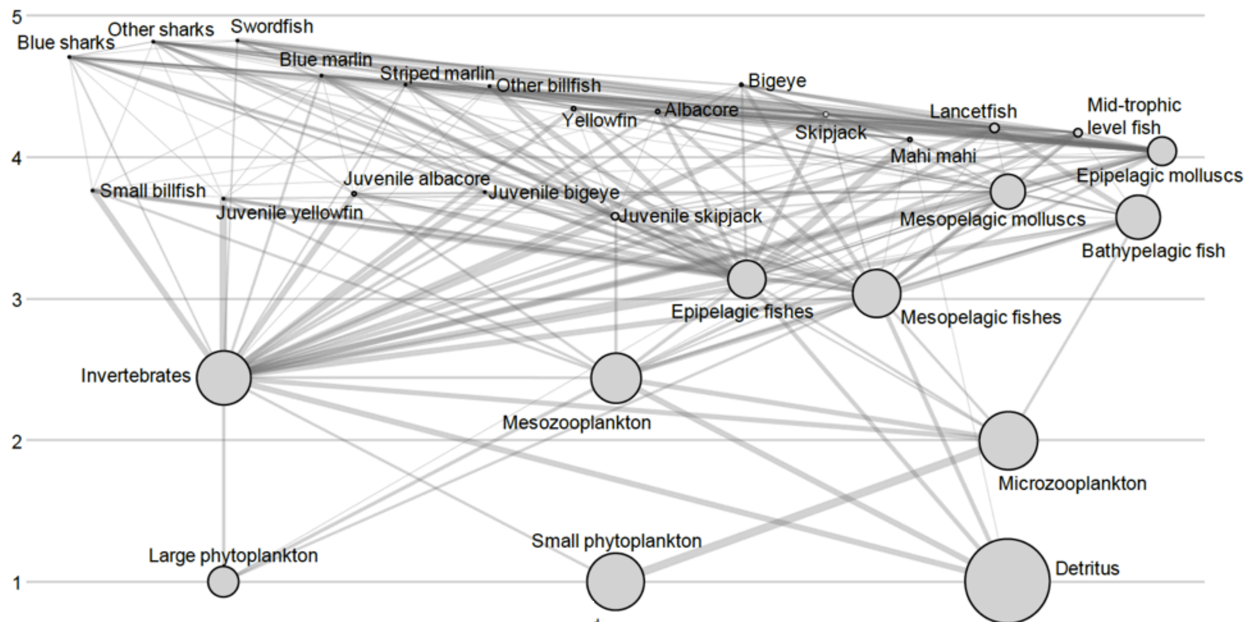

Figure 7 - Trophic flows within the HLFG ecosystem. Each functional group is identified by a circle whose size represents the relative biomass of that group within the system. The light grey horizontal lines and associated numbers represent trophic levels; lines connecting individual functional groups represent trophic links. ZP: Zooplankton; PP: Phytoplankton; mid TL: Mid trophic level fish; Juv: juveniles; Epi: epipelagic; Meso: mesopelagic

The HLFG's main model structure, including most of the Ecopath functional groups and initial biological parameters, were adapted from the CNP8 model used in Cox et al. (2002) and updated for use in Essington (2007).

The ecosystem was described through a combination of 28 groups (Table 4 and Figure 7). All biomass parameters for species/groups were estimated as close to 1991 as possible. For a number of species biomass estimates were informed by data from stock assessments, for which the geographic area considered is generally the entire WCPO. Within this overall area, each assessment adopts a region based spatial stratification methodology. Biomass estimates were taken from the regions in each assessment that covered the HLFG modelled area. For the majority of fish species P/B = M + F. Natural mortality rates were taken directly from the literature, or derived using the empirical formula of Pauly (1980). P/B values calculated using FishBase were checked against fishing mortality estimates if available, to ensure that the total mortality value was realistic and larger than reported F values. Q/B values were sourced primarily from Fishbase, with values based on Palomares and Pauly (1989), with the exception of a few tuna species for which values were augmented with information gleaned from the published literature. For P/B, Q/B and diet proportions of functional groups consisting of more than one species, values were calculated accounting for the biomass contribution of a given species to the functional group overall. EE values were either taken from existing models or estimated by the model. Diet data were sourced from the literature, internal studies and reports, FishBase, or taken from existing ecosystem models in similar regions of the Pacific. Most of the available data pertained to studies conducted off the eastern or westernmost Pacific, where diet items in examined tuna and other top predator species are likely to be composed of a greater proportion of coastal species than from individuals caught in the Central North Pacific. Expert opinion was therefore used to modify the diet matrix accordingly.

All data sources used to obtain the final biological parameters required in the model are included in the Appendix of "Climate change and fishing impacts on the Central North Pacific ecosystem" by EA Howell, CCC Wabnitz, JP Dunne, and JJ Polovina, currently under review in the journal Climactic Change.

Table 4 – Trophic parameters for all functional groups of the balanced HLFG model. Model outputs are presented in bold. B: biomass (t km^2); TL: trophic level; P/B: productivity to biomas ratio ($year^{-1}$); Q/B: consumption rate ($year^{-1}$); EE: ecotrophic efficiency. Biomass for blue shark, swordfish, blue marlin, striped marlin, all tuna species were derived from stock assessment data. Biomass for mahi-mahi, lancetfish and mid-trophic level fish were estimated from CPUE data. The four adult and juvenile tuna groups were linked via "multi-stanza"

Group name	TL	B	PB	QB	EE
Blue shark	4.7	0.0019	0.42	1.5	**0.44**
Other shark	4.8	0.002	0.32	2.8	**0.25**
Swordfish	4.8	0.0018	0.35	3.3	**0.26**
Blue marlin	4.6	0.0005	0.47	3.8	**0.68**
Striped marlin	4.5	0.0006	0.47	3.8	**0.36**
Other billfish	4.5	**0.0004**	0.81	6.1	0.4
Small billfish	3.8	**0.0027**	1	10	0.6
Yellowfin	4.4	0.0196	0.4	10.6	**0.29**
Juvenile yellowfin	3.7	0.0011	0.5	26.3	**0.82**
Albacore	4.4	0.0152	0.4	9.6	**0.4**
Juvenile albacore	3.7	0.0182	0.35	14.9	**0.75**
Bigeye	4.5	0.0041	0.5	8.2	**0.31**
Juvenile bigeye	3.8	0.003	0.6	14.7	**0.79**
Skipjack	4.3	0.0208	1.9	32.6	**0.19**
Juvenile skipjack	3.6	0.0643	5.5	69.3	**0.84**
Mahi mahi	4.1	**0.0236**	1	8.5	0.6
Lancetfish	4.2	**0.0852**	0.47	2.3	0.6
Mid-trophic level fish	4.2	**0.0726**	0.6	4.1	0.6
Epipelagic fish	3.1	2	2	9	**0.57**
Invertebrates	2.4	**8.1**	8	25	0.8
Epipelagic molluscs	4	0.9	3.5	10	**0.85**
Mesopelagic fish	3	5	2	10	**0.86**
mesopelagic molluscs	3.8	1.6	4	10	**0.75**
Bathypelagic fish	3.6	**3.67**	1.5	7	0.85
Mesoscale zooplankton	2.4	5.81	9.85	25	**0.81**
Microscale zooplankton	2	11.13	25	60	**0.44**
Large phytoplankton	1	1.13	120	-	**0.35**
Small phytoplankton	1	10.59	180	-	**0.36**
Detritus	1	100	-	-	**0.08**

TRAVEL

Colette Wabnitz was hosted as a visiting scientist at PIFSC January 10th through March 15th and June 6th until July 18th, 2011 to capitalise on interactions with local collaborators and to be able to analyse DAR fisheries data provided by PIFSC.

OUTREACH AND DISSEMINATION

During her time hosted as a visiting scientist at PIFSC (January 10th – March 15th), Colette Wabnitz gave a 45 minute presentation on the project, including a brief overview of the Kona IEA initiative, at the University of Hawaii at Manōa.

Colette Wabnitz presented key findings from this study at the Kona Symposium held on the Big Island September 15-16, 2011 (presentation appended at the end of this document).

A manuscript entitled "Climate change and fishing impacts on the Central North Pacific ecosystem and Hawaii-based pelagic longline fishery" by E.A. Howell, C.C.C. Wabnitz, J.P. Dunne and J.J. Polovina is currently under review at Climactic Change. The majority of work expanded for the coastal model fed directly into the model presented in this paper. Results from the same model were also presented by J.J. Polovina at the International Workshop on Climate and Oceanic Fisheries in the Cook Islands in October 2011.

FINANCIAL REPORTS

All financial reports are up-to-date.

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[i] Note that Colette Wabnitz has maintained contact with key experts and has been working, past the timeframe of this study, toward coupling a simulation model for ocean primary production based on local data developed at UHilo and the Ecopath model developed under this grant agreement. Note also that preliminary information seem to suggest that, should available data allow this, phytoplankton should perhaps be split into two groups – small and large phytoplankton, as these respond differently to nutrient inputs.

Ecosystem models for Kona's reef and pelagic environments – ecological tools with management applications

Kona Symposium

September 15-16th 2011

COLETTE C. C. WABNITZ

NOAA Pacific Island Fisheries Science Centre

Fisheries Centre, University of British Columbia

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Overview

I. Kona Integrated Ecosystem Assessment (IEA)

Quantitative synthesis and analysis to inform specific management goals

II. Ecological modelling

Use freely available software to paramaterise food webs & investigate impact of stressors

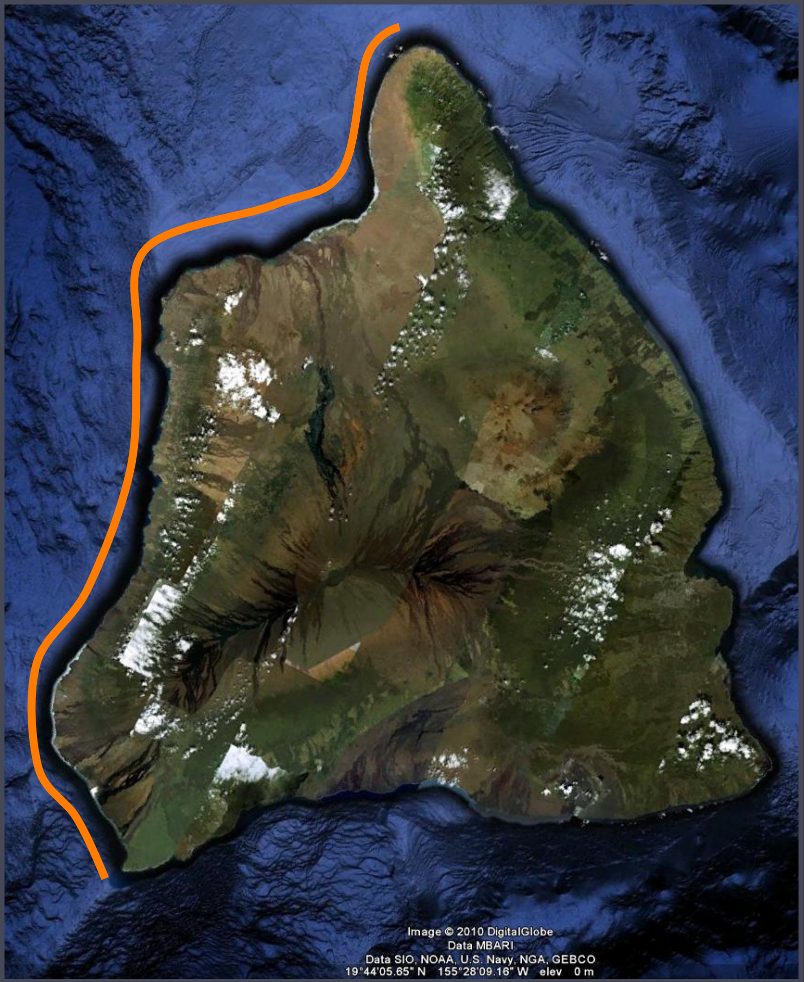
III. Kona reef system

IV. Kona coastal (pelagic) system

Kona Integrated Ecosystem Assessment (IEA)

Purpose of IEA

Synthesis and **quantitative analysis** of information
specifically in relation to identified **ecosystem management goals** for a region



Specific objectives

- Understand how systems work
- Identify data and research gaps
- Understand the impact of stressors

Ecosystem context - Ecopath with Ecosim

www.ecopath.org

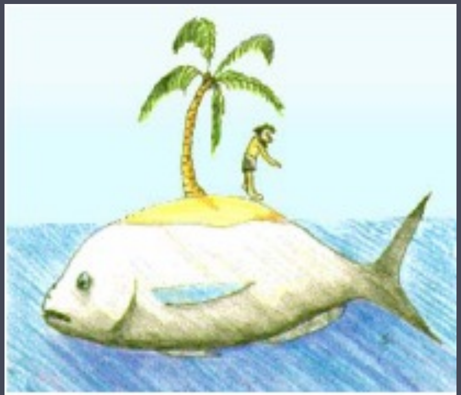
Tool applied worldwide to describe ecosystem structure and functioning for the analysis of food webs and a number of ecological issues

Ecopath with Ecosim contains 3 main routines

I. ECOPATH: mass balance

II. ECOSIM: time dynamic

III. ECOSPACE: time dynamic and spatially explicit (2D)



No fish is an island…

Polovina (1984) Coral Reefs; Pauly et al. (2000) ICES J. Mar. Sci.; Christensen and Walters (2004) Ecol. Model.

Study areas

Study area(s)

Reef model
Pelagic model - offshore to just before Cross seamount

Reef model

SCOPING
- Define boundaries
- Define species / species groups for inclusion
- Define issues the model should help address

Boundaries

0 – 100m depth from north to south

Surface area ~ 300 km^2

Species groups

Ecologically sensible

In line with existing programmes

Help address management concerns

Management questions

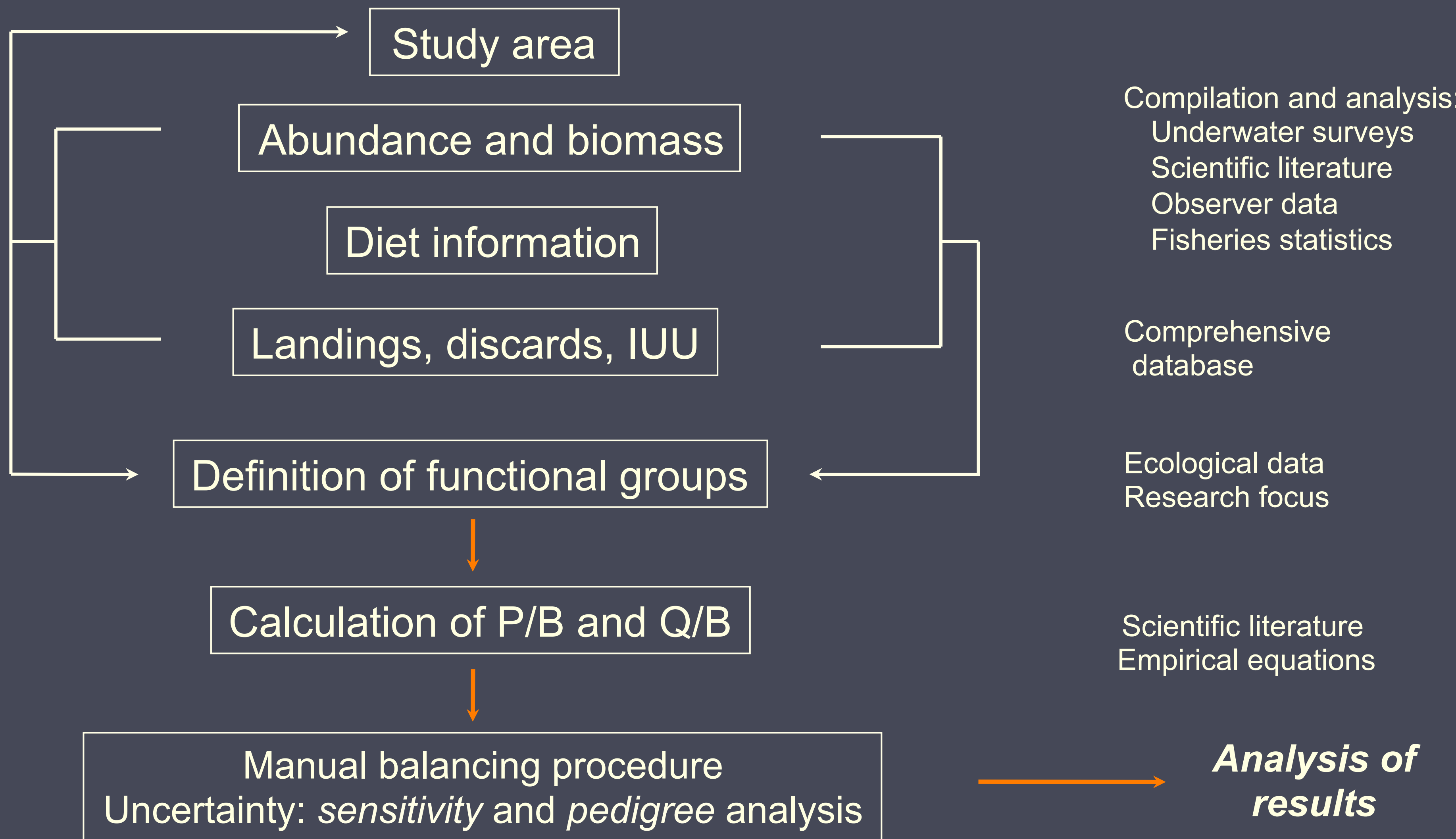
Role of roi

Provision of nutrients through submarine groundwater discharge (SGD)

Aquarium trade

Ecopath - Model set up

Kaloko model



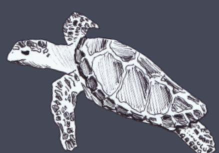
Reef model species groups

Defined 30 groups total


Monk seals


Cetaceans


Sharks and rays


Green turtles


Kole
Adults & juv


Yellow tang
Adults & Juv


Roi


Corallivores


Sessile
Invertebrate
Feeder (SIF)

Bottomfish


Detritivores


Zooplanktivores

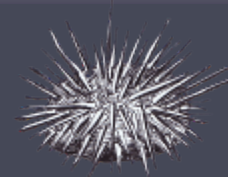

Piscivores

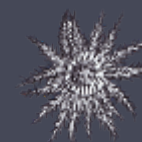

Mobile
Invertebrate
Feeder (MIF)


Herbivores

Reef pelagics

Large pelagics


Urchins

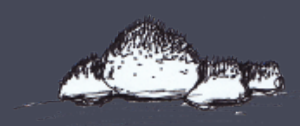

Crown of thorns


Octocoral


Coral


Crustose
coralline algae


Macroalgae


Turf


Zooplankton


Phytoplankton

All drawings: © M. Bailey

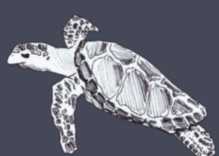
Reef model species groups

Defined 30 groups total


Monk seals


Cetaceans


Sharks and rays


Green turtles


Kole
Adult & juv


Yellow tang
Adult & juv

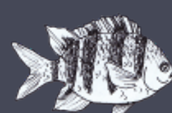

Roi


Corallivores


Sessile
Invertebrate
Feeder (SIF)

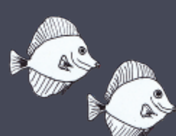
Bottomfish


Detritivores


Zooplanktivores

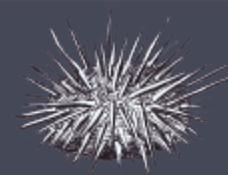

Piscivores

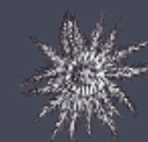

Mobile
Invertebrate
Feeder (MIF)


Herbivores

Reef pelagics

Large pelagics


Urchins


Crown of thorns


Octocoral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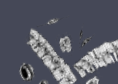
Crustose
coralline algae


Macroalgae

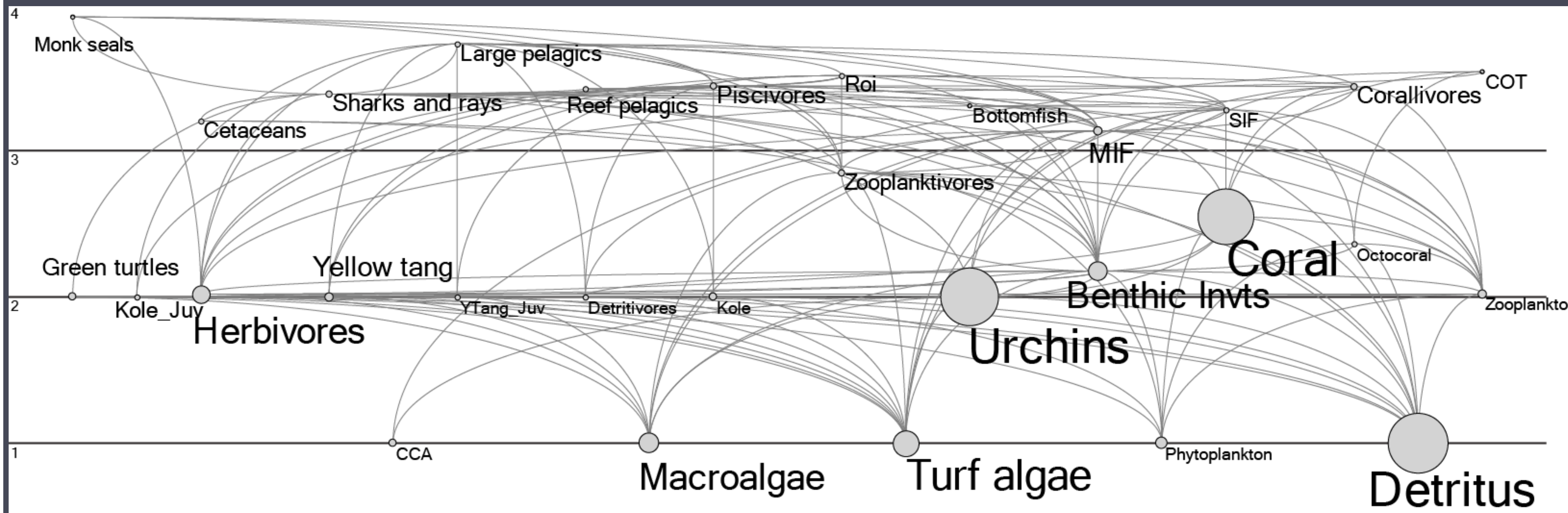

Turf


Zooplankton


Phytoplankton

All drawings: © M. Bailey

Reef model structure



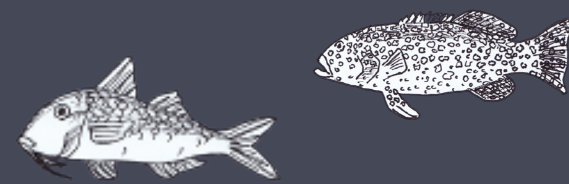
Parameter	Value
Trophic level range	1 – 3.8 (monk seals)
Total living biomass	259 t km^{-2}
Transfer efficiency	6%
Mean trophic level of the catch	2.9
Total catches	0.99 t km^{-2} year^{-1}

Reef model further findings

Biomass

38% of total living biomass

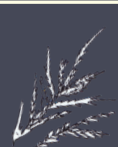
90% of herbivores

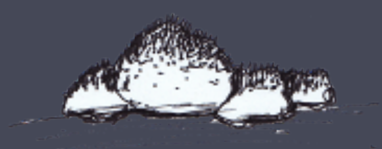


Harvested species (incl. reef and large pelagics)

6% of total living biomass

Production





Algal groups
35% of system production
84% turf algae

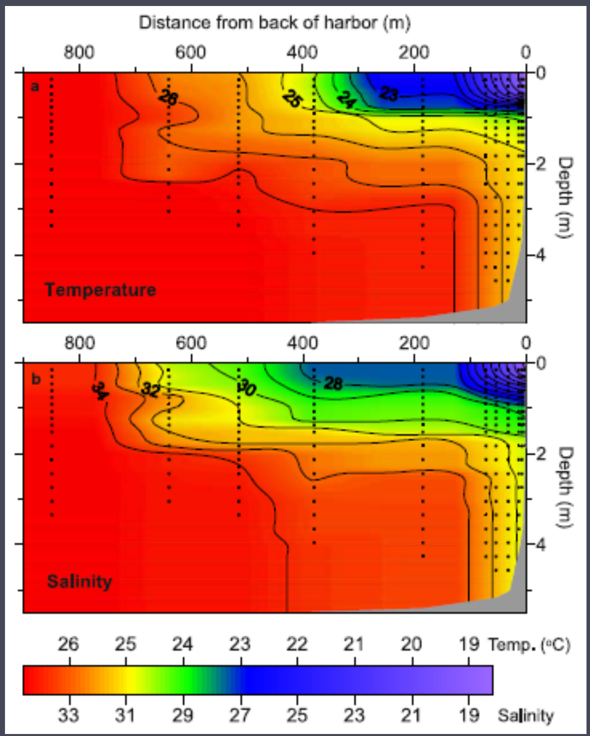
Wabnitz et al. (2010) MEPS

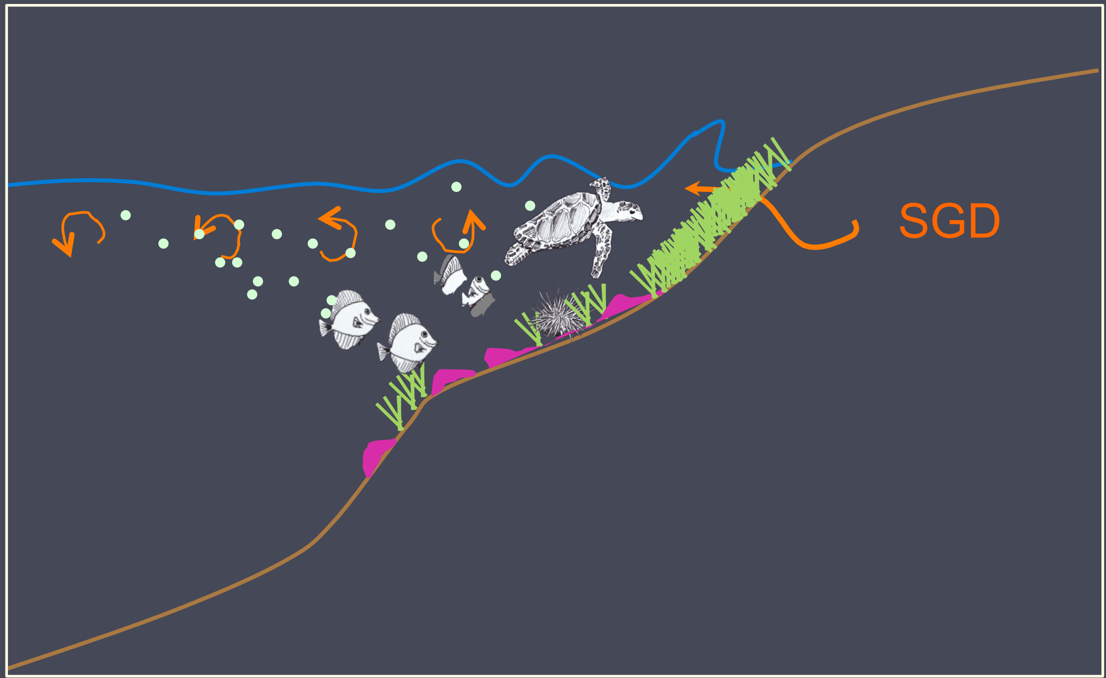
Submarine Groundwater Discharge (SGD)

Flow of fresh groundwater and re-circulated seawater -

Primary source of freshwater and nutrient inputs along the coast

Development → Higher nutrient concentrations
→ Greater productivity of primary producers
→ Potential to disrupt ecosystem function





Knee et al. (2010) Limnol. Oceanogr.; Judy Walker Kona Symp.

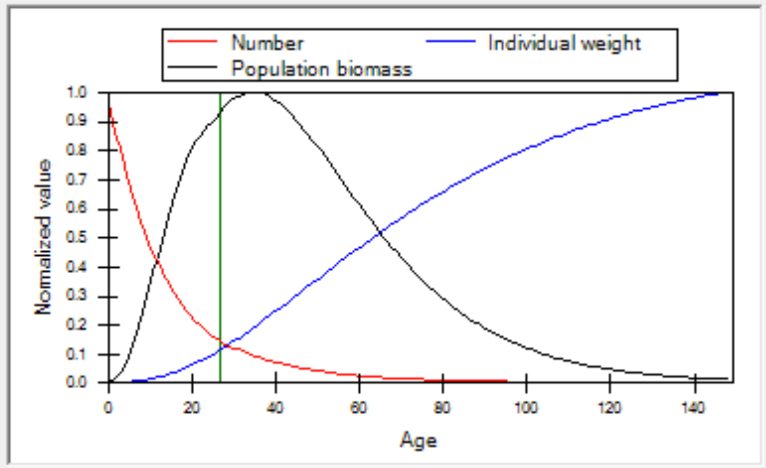
Aquarium trade

Aquarium trade

98% of fish traded composed of 11 species
90% of trade – catches of yellow tang and kole
Most of the catch composed of juveniles – 5-10cm

Biomass - fish survey data, both juveniles and adults

Stanza group: 2: Ytang
Curvature parameter, K (annual), from VBGF: 0.270
Recruitment power: 1.000
Relative biomass accumulation rate (BA/B): 0.000
Wmaturity/Winf: 0.0900
Forcing function for hatchery stocking: Ecosim required
Fixed fecundity



	Group name	Age, start (months)	Leading	Biomass (t/km²)	Z (/year)	Consumption / biomass (/year)
15	YTang_Juv	0	☐	0.0512	0.881	74.41
14	YTang	27	☑	0.198	0.660	35.10

Claisse et al. (2009) MEPS

Reef model – Lessons learned, gaps & future

Urchins

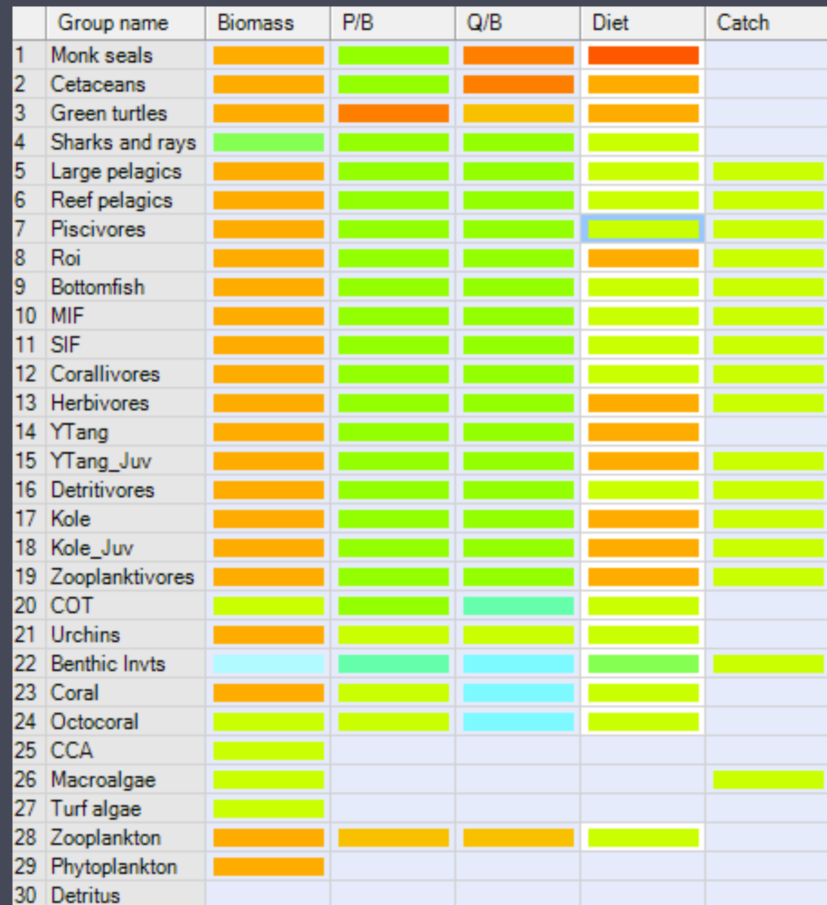
Obtain abundance data, length-weight measurements, diet composition & consumption rates

Zooplankton / phytoplankton

augment existing datasets especially for biomass, production & consumption rates

Algal groups

augment existing datasets especially for biomass and production rates



Overall index - 0.54

All Ecopath models 0.164 – 0.676

Collection of such information would maximise model usefulness and predictive power

Coastal model

Boundaries

Defined by DAR fishing areas (to just before Cross Seamount)

Surface area ~ 42,000 km^2

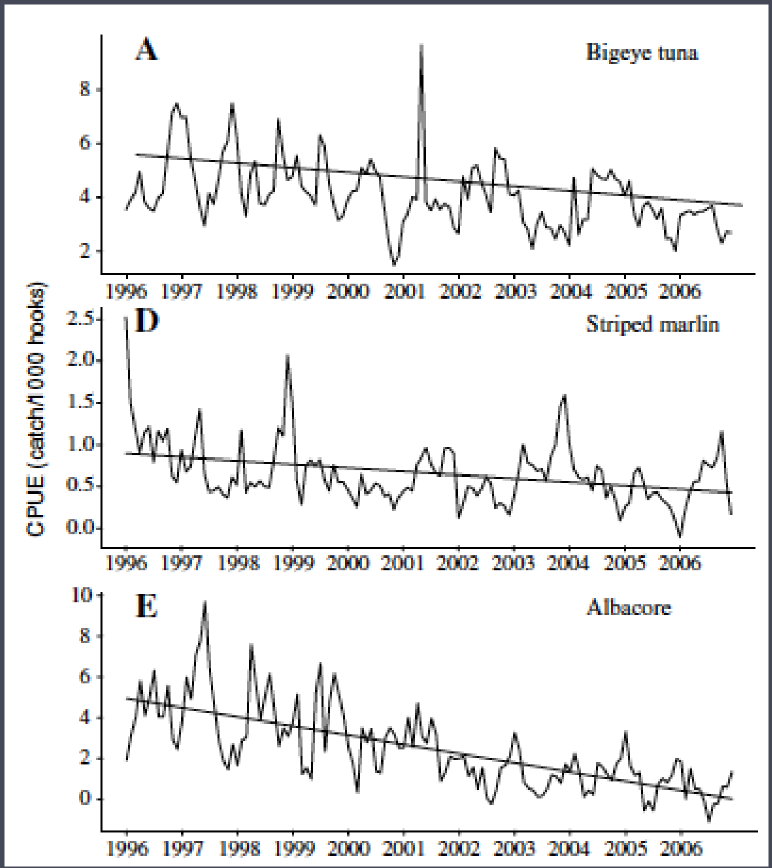
Polovina et al. (2009) Fishery Bulletin

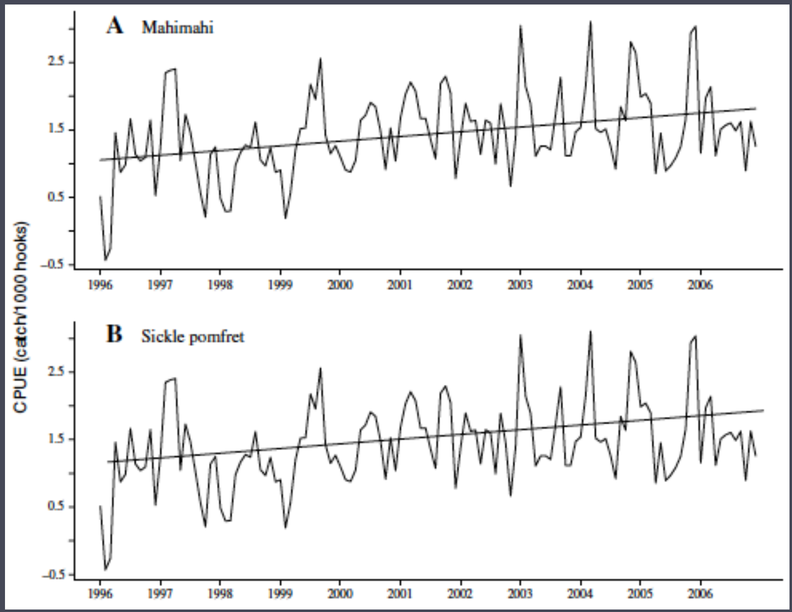
All drawings © M. Bailey

Coastal model

Species groups
Ecologically representative guilds

Fishing impact





Allow comparison/integratuon with Hawaii Longline Fishing Ground (HLFG) model

Polovina et al. (2009) Fishery Bulletin

Coastal model

- Marine mammals
- Blue sharks
- Other Sharks
- Swordfish
- Blue marlin
- Striped marlin
- Other Billfish (adults & juv.)
- YFT (adults & juv.)
- BET (adults & juv.)
- ALB (adults & juv.)
- SKJ (adults & juv.)
- Large pelagics
- Reef pelagics
- Bottomfish
- Mahi mahi
- Lancetfish
- Mid Trophic Levels
- Epipelagic Fish
- Epipelagic Mollusks
- Mesopelagic Fish
- Mesopelagic Mollusks
- Crustaceans
- Bathyforage
- Large / Small Zooplankton
- Large / Small phytoplankton

- Monk seals
- Cetaceans
- Green turtles
- Sharks and rays
- Large Pelagics
- Reef pelagics
- Piscivores
- Roi
- Bottomfish
- MIF
- SIF
- Corallivores
- Herbivores
- ZFI
- ZFL_Juv
- Detritivores
- Cstrig
- Cstrig_Juv
- Zooplanktivores
- Crown of thorn starfish
- Urchins
- Invertebrates
- Coral
- Octocoral
- Crustose Coralline Algae
- Macroalgae
- Turf
- Zooplankton
- Phytoplankton

Conclusions

Models are a valuable addition to the IEA process

quantitatively synthesise data about a system
highlight existing data / research gaps – inform future efforts
help us understand interactions among species within a system
involve stakeholders
inform management decisions

Models should be dynamic living tools

need to be vetted by regional experts
improved by new data and time series
adapted to answer new questions as they arise

Thank you!

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Colette.wabnitz@gmail.com