Report of the Hawaii Atlantis Ecosystem Model Planning Workshop held in January 2017, in Honolulu

Mariska Weijerman

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Report of the Hawaii Atlantis Ecosystem Model Planning Workshop held in January 2017 in Honolulu

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Photo front cover Reef scene at Kahekili, Maui, *NOAA photo*

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Background

The development of a spatially-explicit ecosystem model for the insular ecosystems (coral reef and bottomfish) of the Main Hawaiian Islands is an interdisciplinary effort with collaborators from each of the science divisions at NOAA's Pacific Islands Fisheries Science Center (PIFSC), the University of Hawaii, Hawaii Institute for Marine Biology, the international Atlantis community, the NOAA Pacific Islands Regional Office (PIRO), the Hawaii Division of Aquatic Resources (DAR), and the Western Pacific Regional Fisheries Management Council (WPRFMC). The steering committee consists of Mike Seki, Jeff Polovina, Frank Parrish, Rusty Brainard, Charles Littnan, Annie Yau, Justin Hospital, and Mariska Weijerman (Chair). Funding for this project comes from PIFSC and the WPRFMC.

Workshop Goals

As a first step in model development, we need to identify policy-relevant and scientific-relevant questions that can be addressed by the model outcome. Based on those questions, we need to ascertain that the spatial domain of the model has the correct boundaries (both horizontally and vertically) and that the key species (groups) are included. PIFSC hosted this planning workshop to meet the following goals:

1. Identify and prioritize research questions of interest
2. Identify spatial geometry of model (limited to insular ecosystem around MHI from 0 - ~400 m depth)
3. Identify functional species groups / species of ecological or economic interest.

Attendees

Name	*Affiliation*	*Name*	*Affiliation*
Melanie Abecassis	JIMAR/PIFSC-EOP	Frank Parrish	PIFCS-ESD
Rusty Brainard	PIFSC-ESD-CREP	Stacie Robinson	PIFSC-PSD-HMSRP
Jon Brodziak	PIFSC-FRMD-SAP	Marlowe Sabater	WPRFMC
Gery Davis	PIRO-Habitat Conservation	Mike Seki	PIFSC-DO
Matt Dunlap	PIRO-Sustainable Fisheries	Brett Taylor	JIMAR/PIFSC-FRMD-LHP
Adel Heenan	JIMAR/PIFSC-ESD-CREP	Bill Walsh	DAR-Kona
Justin Hospital	PIFSC-ESD-SEP	Mariska Weijerman	JIMAR/PIFSC-ESD-CREP
Hal Koike	DAR-Oahu	Ivor Williams	PIFSC-ESD-CREP
Charles Litnan	PIFSC-PSD-HMSRP	Johanna Wren	JIMAR/PIFSC-ESD-EOP
Tom Oliver	JIMAR/PIFSC-ESD-CREP	Annie Yau	PIFSC-FRMD-SAP

Introduction

The workshop started on Jan 13, 2017 at 8:30 am with a welcome by Mike Seki, Director of PIFSC. Mike explained that NOAA has embraced Ecosystem-based Fisheries Management which requires the synthesis of interdisciplinary data sets and that we must now take into account the realities of climate change and ocean acidification. He explained that regional ecosystem models can simultaneously couple chemical, physical, biological, ecological, and socio-economic dynamics at scales relevant to coastal communities and, therefore, realistically represent patterns and processes affecting marine ecosystems and those who depend on them and explicitly address tradeoffs across ocean use sectors. To meet this high bar for informed management, PIFSC (with Council support) has initiated the effort to parameterize and develop the Atlantis Ecosystem Model to allow for the exploration of the ecosystem effects of changes in the environment, policy options and management strategies. Mike acknowledged everybody's busy schedule and expressed his gratitude that we all made the time and commitment to come and participate in this ambitious effort.

Background presentation on the Atlantis Ecosystem Model

Mariska Weijerman, Ecosystem Modeler in the Coral Reef Ecosystem Program (CREP), presented background information on the Atlantis Ecosystem Model framework. She highlighted the model's complexity, as it encompasses key ecological, hydrological, and human use dynamics making it data intensive (Fig 1). The downside of any complex, full system model is that it increases uncertainties in model output data and is, therefore, only relevant as a strategic tool, i.e. to understand the system's dynamics and evaluate 'What If' scenarios. Mariska explained the intended use of the Hawaii Atlantis ecosystem model as a Management Strategy Evaluation tool and outlined the next steps in model development.

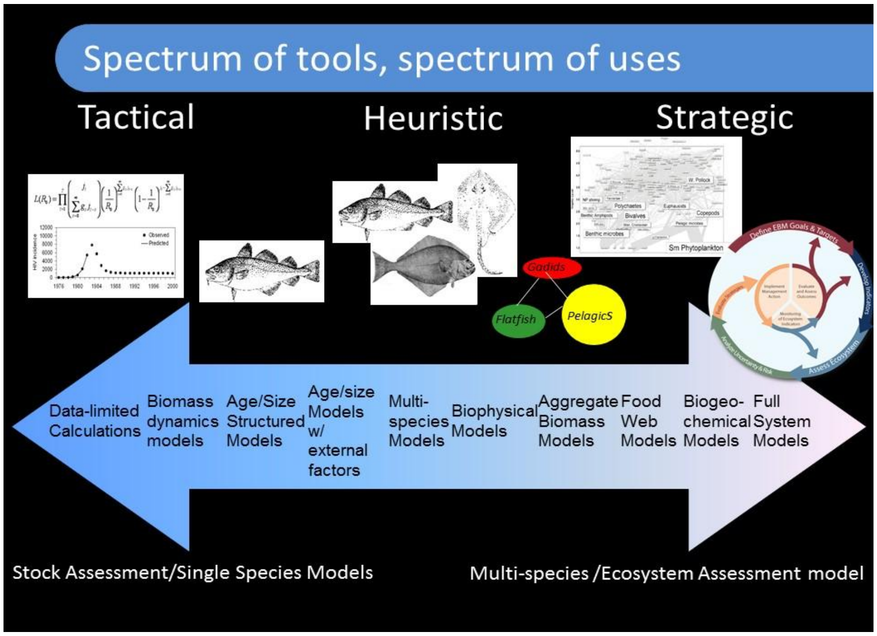


Figure 1-- Spectrum of models and their intended use; from left to right models get more complex, representing the system more realistically at a cost of accuracy in model output. Hence, models to the right of this spectrum are used for strategic purposes, whereas models on the left of this spectrum can be used as tactical tools.

Atlantis consists of several submodules that can be as complex or simple as the user wants (Fig 2). The base of any Atlantis model is the model's geometry. Once this is completed, the oceanographic submodule can be developed. Intentions are to use the Hawaii Regional Ocean Modeling System (ROMS) model output (from Dr. Brian Powell at Oceanography Dept. at UH) as input layer for the hydrodynamic fluxes across the boundaries of each area (box/polygon). In collaboration with Dr. Kirsten Oleson at the Dept. of Natural Resources and Environmental Management (NREM) at UH, existing time series data of spatially-explicit nutrient and sediment influxes will be added as local drivers. Additionally, we will also add United Nations Intergovernmental Panel on Climate Change (IPCC) climate projection trajectories as drivers for change in temperature and possibly pH (CO_2). The biological/ecological submodule characterizes the life history of all species (mostly aggregated in functional groups based on similar life history and diet data), diets, (seasonal) movements, and non-trophic interactions with other species (e.g. space competition of benthic groups). These three submodules are necessary to develop the base Atlantis model. Other model components are optional, such as a dynamic fishery harvest module and for management strategy evaluation, an assessment and management module. Additionally, an economic submodule could be dynamically coupled to influence the fishery fleet (recreational/commercial/ spearfishers/hook and line fishers etc.) or other human user groups (e.g. marine tourism).

Mariska explained how Atlantis can be used for Management Strategy Evaluation (MSE) as it has each of the key components of the adaptive management cycle included in the framework. By using different parameters (within realistic bounds), it is possible to address uncertainty to some extent. Key factors needed for MSE are the identification of alternative management scenarios (specified by managers) and indicators to evaluate the performance of the different scenarios. Indicators will be identified at a later stage in the model development. She also highlighted the importance of communication with the stakeholders at all stages of model development and mentioned the intent to create a website that would be updated approximately every 6 months to inform all interested parties of the progress made.

She continued with an optimistic timeline for a 'simple' (no dynamics human use component) Atlantis model and estimated that is would take 3 to 4 years to develop. She concluded by outlining the workshop goals.

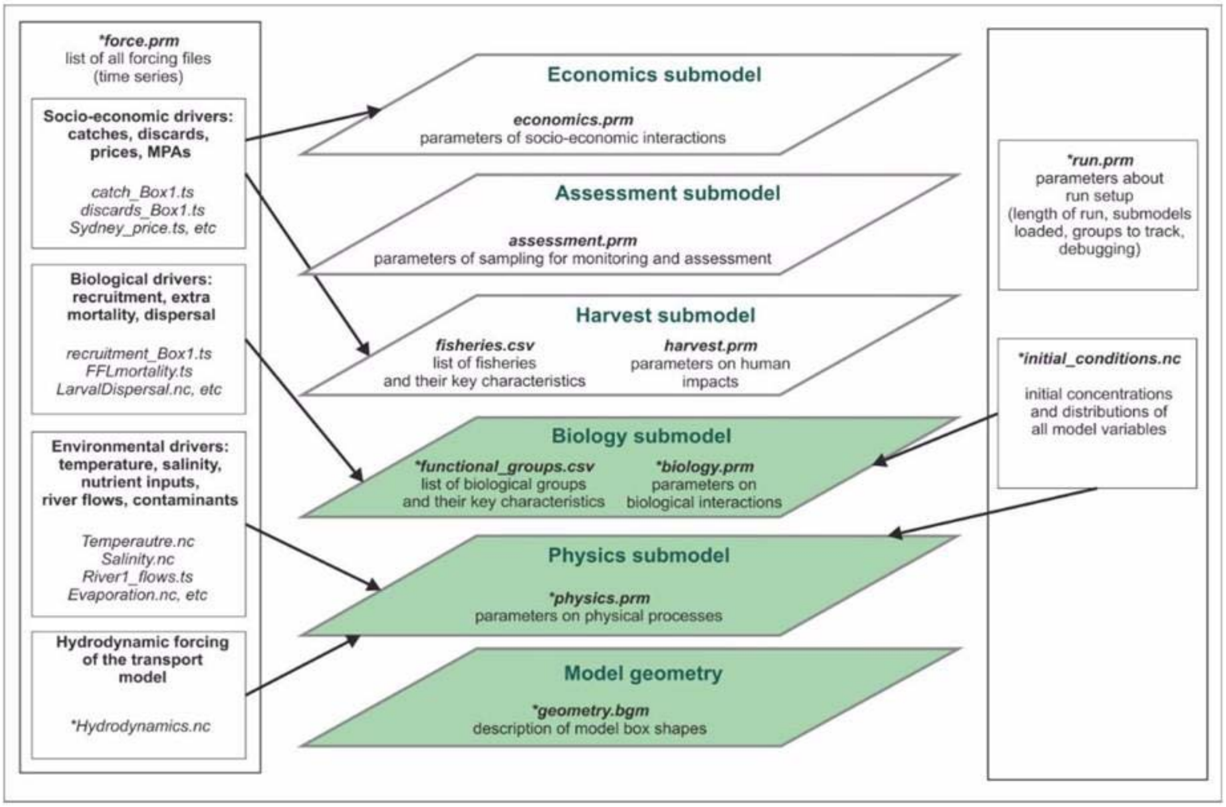


*Figure 2—Schematic representation of the Atlantis model structure and input files. Submodels colored in green are obligatory. Files marked with * are required, others are optional.*

Goal 1. Research/management questions to explore with the MHI Atlantis model

Prior to the workshop, Mariska had sent out five potential discussion topics that could be addressed by the developed model; these were:

1. Assess how an increase in MHI monk seal population may affect the bottomfish fishery
2. Evaluate the socio-economic/ecological tradeoffs of existing bottomfish fishery regulations compared to alternative regulations
3. How are the ecosystem goods and services provided by the shallow (0-30 m) coral reef ecosystems impacted by temperature-sensitive coral species loss?
4. Are coral reef ecosystems more or less resilient to the effects of climate change if there is a larger population of herbivorous parrotfish?
5. Can coral reef ecosystem resilience be changed through spatial management such as no-take areas or Herbivore Enhancement areas?

General discussion points raised (in italics) and addressed:

Success in other models depended on the outline of specific targets. Will this same approach be taken? Yes, two key groups in the MHI Atlantis model are monk seals and bottomfish. Both are already actively managed, and there is a strong interest in sustainably managing them. In follow-up meetings, management targets need to be identified with the relevant management agencies.

Sedimentation and nutrient impacts are important e.g. in relation to herbivory. Will this be included? Yes, through collaboration with UH-NREM, we will be able to include spatially explicit time series data of nutrient and sediment inputs in the entire MHI.

Start with simpler goals for which data are available already before addressing energy, aquaculture impacts, etc. Better to build the maximal model from the start with a view to fill data gaps later. Through today's workshop and follow-up meetings with subject matter experts, we will identify the current status of knowledge and identify data gaps and then, in a case-by-case situation, determine whether to drop or add estimated parameter values. In general, the consensus was to add estimated values and through sensitivity analysis see how important those values are and if it is worth adding resources to get improved values. In the project outputs, there will be a data gaps section that can direct research resources in the future.

What is the time frame for projections? It was agreed to have a 10-20 year timeframe to evaluate tourism and fisheries impacts since this is in line with the effective management of 30% of coastal area by 2030 to which the State of Hawaii has committed. For climate change-relevant questions, we will include 3 different time scales – near, mid, and long term. We discussed the best way to force the model with the existing hydrodynamic data and concluded there were two possible options: (1) loop over the available 2009-2013 ROMS data since 2014 was an anomalous year with high recruitment, and 2015-2016 had anomalously warm water temperatures; (2) to periodically include the anomalous year in a loop (i.e. 2014) as the future norm for storm events and recruitment change. Time series data of nutrient and sediment input are based on projected rainfall. It was argued that these models are likely weak for the coastal interface, and it would be beneficial to have more sophisticated physical oceanographic model output. It was brought up that a PhD student is working on currents throughout the MHI – POST WORKSHOP. However, when reaching out to that person it turned out she is working on surface currents offshore and uses the same (4 x 4 km grid) ROMS model as we suggested to use.

Include seasonal patterns? Atlantis uses 4 seasons to account for seasonality, if species have strong seasonality we can include that.

Organization of questions - have a hierarchy of questions and organize these by threats, or alternatively organize by pressure and drivers. Each question (if applicable) can be subset into questions related to the impacts of drivers individually and cumulatively. The relative importance of the drivers in the system can thus be determined as well as the cumulative effects.

What information is available on movement patterns for those with large home ranges? Some data are available for reef fish. Larger home ranges are generally for larger animals. In the Atlantis model, species are initially distributed according to spatial (seasonal) distributions specified by the user. They can move depending on their home range and in line with the specified distribution or when they are set as “density dependent.” They can move for food where the distance moved depends on swim speed. Additionally, movement can be limited by environmental sensitivities (temperature, salinity, oxygen), and species will leave areas that are not suitable (if they do not encounter a suitable area, they will die). Atlantis cannot allocate probabilities of movement from one polygon to the next; the model is not stochastic. Monk seals would have a home range that spans multiple polygons (or the entire model domain). By making them density dependent we can make them move between polygons when food gets scarce.

Is there a need to include other agencies, forestry for instance, if we are to truly communicate a model that is management relevant? Agencies invited were the agencies directly involved with the management of marine resources since that is what the model addresses. However, Atlantis can evaluate different scenarios of land-based sources of pollution (LBSP) but does not include actions to reduce LBSP.

What has the impact of the Guam model been? Unfortunately, staff turnover in the Guam Division of Aquatic and Wildlife Resources and the Guam coastal zone management agencies had been high, e.g. during Mariska’s visits in 2012, 2014, and 2015, administrators and key staff had been replaced each time. However, the Guam Atlantis model was used by PIRO for permitting in relation to the ongoing military development. To make sure that the MHI Atlantis model would be beneficial to managers, we made sure the model is in line with, and can be used as a support tool to address several state and federal ecosystem plans and mandates (and so decouple it from priorities of administrators/staff), e.g. the Council’s Hawaii Fishery Ecosystem Plan, the Federal Ocean Acidification Research And Monitoring Act, the Magnuson-Stevens Fishery Conservation and Management Act, the Marine Mammal Protection Act, the Endangered Species Act, the Coral Reef Conservation Act, and to operationalize the Governor of Hawaii’s commitment to “effectively protect 30% of Hawaii’s nearshore resources by 2030.” Furthermore, an Atlantis model fits well within several NOAA strategic plans, such as: the NOAA Ocean and Great Lakes OA Plan (2010), the NOAA Fisheries Climate Science Strategy (2015), and the NOAA Pacific Islands Regional Climate Action Plan (2016). Lastly, it also supports goals outlined in the National Marine Fisheries Service Ecosystem Based Fisheries Management Policy and Road Map documents.

Specific discussions points raised per question:

Q1: General agreement

Q2: *There is a perception that the bottomfish are over-regulated (both by catch limits and by BRFA). Alternative management option should include using catch limits and evaluating tradeoffs for different inclusions of BRFAs, e.g. keep half of the existing BRFAs and open the other half for fishing or have even fewer BRFAs.* Mariska will follow up in a later stage with specifics for this management question (i.e. exact options to evaluate and performance indicators).

Q2: *The Council is primarily interested in this question. However, the 30 by 30 initiative (30% of coastal area effectively managed in 2030 target) is triggering interest in relative effectiveness of existing fisheries rules. Therefore, should we expand #2 to include coral reef fishes?* Valid point agreed by all and rephrased Q2 to include reef fish fishery as well as bottomfish fishery.

Q3. There was a short discussion on how to define ecosystem goods and services. It was agreed to include ecosystem services for (dive) tourists and fishers (food, recreation). Specifics will be dealt with later.

Q4: We adapted this question to include all herbivores not just parrotfish.

Q5: General agreement

Agreed upon topics to explore with the Atlantis model are:

1. Assess how an increase in MHI monk seal population may affect the bottomfish fishery and vice versa
2. Evaluate the socio-economic/ecological tradeoffs of existing bottomfish and coral reef fish fishery regulations compared to alternative regulations
3. How are the ecosystem goods and services provided by the shallow (0-30 m) coral reef ecosystems impacted by temperature-sensitive coral species loss?
4. Are coral reef ecosystems more or less resilient to the effects of climate change if there is a larger population of herbivores?
5. Can coral reef ecosystem resilience be changed through spatial management, such as, no-take areas or Herbivore Enhancement areas?

After the coffee break, Mariska gave a short overview of the Guam Atlantis model which included only the shallow (0-30 m) coral reef ecosystem and recreational fishery.

Goal 2: Model Geometry specification

Mariska presented an overview of model geometry around each island based on somewhat homogenous biological (habitat and fish biomass) characteristics (for the shallow 0-30 m boxes) and prevailing oceanographic currents. Additionally, the DAR fishery reporting zones were considered by drawing up the boundaries. These interactive PDF maps were also send prior to the workshop for participants to verify.

Each spatial area/box also has vertical water column layers (Fig. 3). It was agreed that these should be set between day and night behavior, i.e. moving up and down the water column layers.

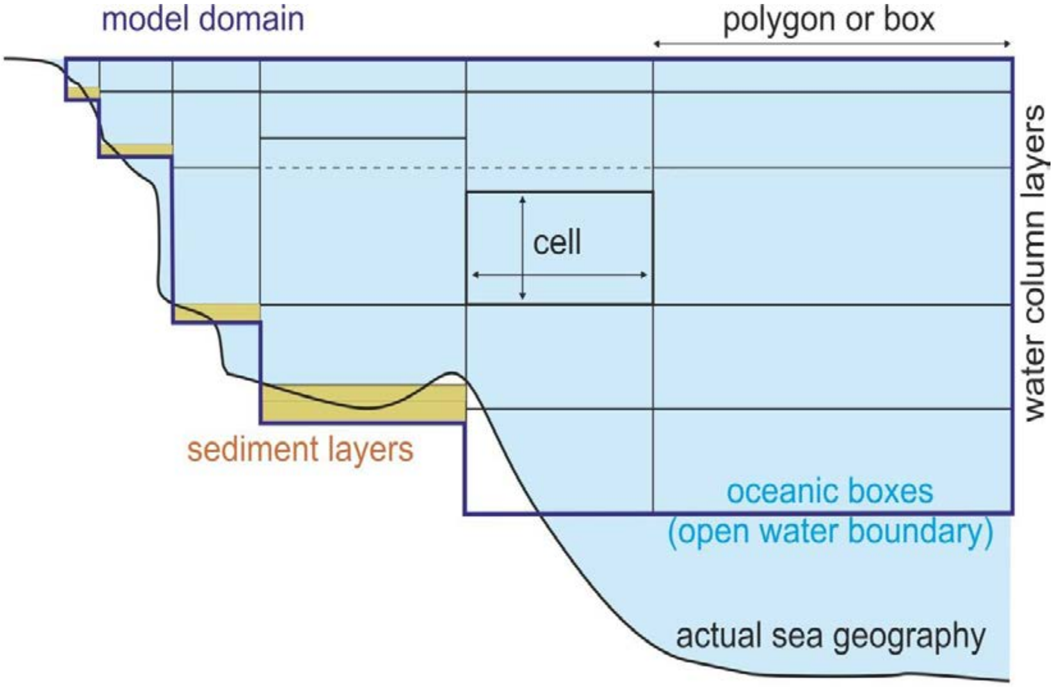


Figure 3-- Schematic overview of model geometry with model boundaries in polygons and vertical water column layers.

General discussion points

Base of drawing boundaries:

DAR fishery reporting zones are based on the commercial data and are the only available data for bottomfish fishery; therefore, it may make sense to use them to set the boundaries in the deeper water layers. The deeper boxes are predominantly drawn as continuation of the shallow boxes. With the help of Thomas Oliver (CREP), we will do a hierarchical cluster analysis using satellite-derived oceanographic data: Chlorophyll-a as a proxy for productivity, photosynthethically active radiation (PAR) a proxy for turbidity (K490), and sea surface temperature to determine whether offshore boundaries should be changed. If they are close to

DAR fishery reporting zones, they will be lined up with those fishery zones. POST WORKSHOP: Results from these cluster analyses are appended in color maps (Appendix 1), and Mariska made some small adjustments (indicated below each cluster map) when existing boundaries did not line up very well with clusters.

For the shallow spatial areas (boxes), commercial reef fish fishery data are thought to greatly underestimate the actual catch values since recreational fishery is a prominent activity in the MHI, and nighttime fishery is not well captured. Therefore, drawing up the spatial boundaries with DAR fishery reporting zones seems less relevant for the shallow zone, and keeping it based on the biological characteristics seems more ecologically accurate. Moreover, DAR does not implement management regulations based on the reporting zones. However, when boundary lines are close to each other, they should be lined up (shared) to facilitate the catch and effort estimates per Atlantis polygon. The relevant scale is dependent on the management, the audience and the end-user of the model. Based on the questions posed previously, the model geometry can address management questions at the currently proposed scale.

Another point made was that boxes should be aligned with enforcement capabilities – e.g. shorelines that are not accessible will have no enforcement. Atlantis has the option to quantify enforcement and can include 0% enforcement (which then assumes fishing is occurring) in boxes that are difficult to access or completely inaccessible.

Higher vs lower spatial resolution

There are three compelling reasons to keep boxes to a slightly lower spatial resolution: (1) creating more boxes and faces (sides of each box) increases uncertainty, (2) data limitation is likely to be the constraining factor to the number of boxes we can have supported by data, and (3) as currently envisioned, Atlantis is not configured to directly support site-based management, and should be used as a strategic tool. Two core datasets are represented well – the CREP sectors and the DAR fishery reporting zones - which are a little less coarse than the sectors. From a fisheries management perspective, it is not clear what is required for PIRO as they are operating more on a case-by-case basis and highly involved with stock assessments, however, there are guiding documents for EBFM with a focus on cumulative effects of management interventions given climate impacts. There was also a discussion on how this MHI model can be used to inform potential future island-scale models with higher spatial resolution.

Adaptability of Atlantis model outcomes

Management scenarios will change over time, which will require re-running the model. At present, climate change is a hot topic but model output can be used to evaluate the priority of driver impacts (climate vs LBSP) that could drive research questions and funding in the future. Unfortunately, the Atlantis model framework does not currently have a user-friendly interface and due to complexity will likely always require direct technical expertise. Therefore, there is a need for long-term commitment from management agencies and the PIFSC to operationalize and institutionalize ecosystem models into the management process.

Island specific maps

Oahu

Where possible, the DAR fishery reporting zones and CREP sectors should be tweaked to align at Kaena point. Along the Ewa coastline, boxes should reflect highly vs lightly populated areas, not just ecological characteristics. Decision to split at Barber's Point – given the sewage outflow pipe – for the nearshore boxes.

Maui

The nearshore area along the north coast should have an extra box in the 'dip,' as the reef fronting that urbanized area is very different from the reefs to the east and west.

Penguin Bank and Molokai

Keep as is.

Lanai

Keep two sectors given that it is of low management interest, but shift the break to obtain a west box and a box wrapping the north, east, and south sides of the island.

POST WORKSHOP: Based on mesophotic data I added Kaho'olawe Island.

Big Island

Move the northern break a little bit further to the right to coincide with the northern tip. On the Kona coast, shift the break a little southward so that the nearshore and offshore breaks match the bathymetry contour.

Kauai and Niihau

Add an extra break in the nearshore SE box of Kauai. Niihau is fine as is.

Goal 3: Functional Group Identification

Spinner dolphins could be included as they are currently managed under the U.S. Endangered Species Act (ESA) and the Marine Mammal Protection Act. Their management issues are relevant to the MHI. Biomass numbers for spinner dolphins are available, diet data are more limited (scattering-layer fish, squid, and shrimp), so it was determined to use proxies from other locations for unknowns. Consensus was reached to include them and their target food in the mesopelagic scatterlayer, if that falls within our model domain. POST WORKSHOP: Following up with references sent by Frank Parrish on diet and foraging behavior, it appears that the mesopelagic boundary layer migrates up to shallow (<100 m) depth, so we will include the dolphins and their prey. Following up with Erin Oleson, bottlenose dolphins are opportunistic feeders and often steal prey from hooks, such as bottomfish, and their forage area includes a large part of the insular system, so we decided to include them as well.

Anecdotally, it was mentioned that Big Island fishermen think that there is a relation between spinner dolphins and opelu (mackerel scad) and akule (big-eye scad). Tourist activities, focused in the nearshore, can drive spinner dolphins away from these areas. This maintains the fishermen's catch of opelu and akule.

We decided to include green turtles (very abundant) and hawksbills turtles (rare) since they also fall under the ESA. The prior assumption was that the ecological impacts of hawksbill turtles is so low that they could be justifiably excluded. However, by including hawksbills, it offers an opportunity to assess area specific effects on this species. Their abundance is low so their variability will not have a big impact on the energy flow through the ecosystem in the model. As with the spinner dolphins, if data are absent, we can use other locations for proxies.

We had a discussion of the inclusion of yellow tangs and other reef fishes targeted by aquarium trade collectors. However, the aquarium trade is location specific and there is a lot of information available, so it was not deemed a priority to include in this model.

The abundance and presence of mesophotic reef fishes – anthias, *Naso hexanthus* – will come from the recent baited remote underwater video stations (BRUVS) data, we must ensure there is a good representation across life history types. POST WORKSHOP: Mariska has followed up on this item and identified experts in mesophotic coral ecosystem (MCE) biota and will discuss data availability.

For management purposes, bottomfish are considered as one group (deep-7), with uku being the dominant species for the non-deep 7 (97% of landings of bottomfish that are not part of the deep 7: 6 snapper species and one grouper). Uku is a growing management concern because this species is targeted when the deep 7 are not available. Data are limited on the life history of the deep 7, so splitting them into smaller groups is not viable. However, based on different diet, fishery (night-day time), the fact that Opakapaka and Onaga are both a substantive component of the catch, and Opakapaka has life history data available and a unique shallow nursery grounds (making them more exposed to LBSP pressure), we decided to separate them into 3 groups: (1) Opakapaka and Kalekale snappers (night-time fishery) and Lehi (similar diet); (2) Onaga, Ehu, Gindai, and the grouper Hapu'upu'u (day-time fishery), and (3) Uku.

The shallow forage fish (akule and opelu) also led to some discussion. Aerial spawner surveys indicate the abundance of akule is seasonally different from opelu. Schools are spatially distinct although they are ecologically quite similar. Both are short lived (2-3 years), and both are commercially sought so fishers switch between targeting one then the other. Because of their similar ecological roles and management regulations do not make a distinction between the two, we decided to group them.

For the elasmobranchs group, we decided to separate out the plankton-feeding manta rays from sharks as manta rays are petitioned to be listed under the ESA by the Defender of Wildlife (Nov. 2015) and this ray is quite important for tourism. Since sting rays have a similar diet (large macro-heterortrophs, urchins) to reef sharks, we decided to group them together.

Myctophids are a large part of the energy flow on the slope and important for the pelagic species but they can migrate inshore up the slope where dolphins feed on them. Although there are no good estimates of myctophid biomass, which is an important information gap, we decided to include them as one of the pelagic coastal community groups.

For cephalopods, we will include octopus (shallow water) and squid (deep).

Depending on the species/groups, invertebrates can be grouped as reef associated, mesophotic, or subphotic. For example, shrimp (heterocarpus) is an important catch target and only occurs in the deeper boxes. Crustaceans will be separated out by depth:

1. Large crabs, lobsters, and shrimp (deep trap caught – heterocarpus – a pulse fishery)
2. The remaining species are split by reef associated, mesophotic, or subphotic or based on diet depending on data availability.

Opihi, a culturally important species, is only present in the intertidal zone and therefore not included in the model.

The boring and burrowing infauna will be impacted differently by ocean acidification; therefore, we will separate out the boring species and include the burrowing species with the worms.

The discussion in the grouping of coral species resulted in separating them based on the 5 dominant genera/structure: *Porites* massive, *Porites* branching, *Montipora* & *Leptosperis*, *Pocillopora*, and *Leptastrea*. Fungia, or other free standing genera, and acroporids are sparse in the MHI, so it was assumed it would probably be permissible to ignore these genera. The selected five groups have their own group specific growth strategies and thermal and ocean acidification sensitivities. POST WORKSHOP: Since *Leptoseris* is prevalent in the mesophotic zone and has different growth rates, I decided to make it a separate group and since *Leptastrea* is not very dominant, I deleted that species as a group.

Black corals are a fishery interest. Although there is a moratorium on gold corals, the black coral fishery is open; however, only one fisher is operating in this fishery at present. There is only one known fish association (hawkfish), so black coral beds are of little ecological and fishery interest and are therefore not included.

The primary producers should be separated in calcareous and fleshy macroalgae. *Halimedia* beds are prevalent at greater depths (e.g. in the ‘Au’Au Channel) and provide structure. Moreover, the calcareous algae play a different role in carbonate systems than fleshy macroalgae. Separating them would provide an opportunity to investigate different future carbonate scenarios on *Halimeda* beds which are relevant to sand production. Due to a data deficiency, we decided not to separate out invasive macroalgae.

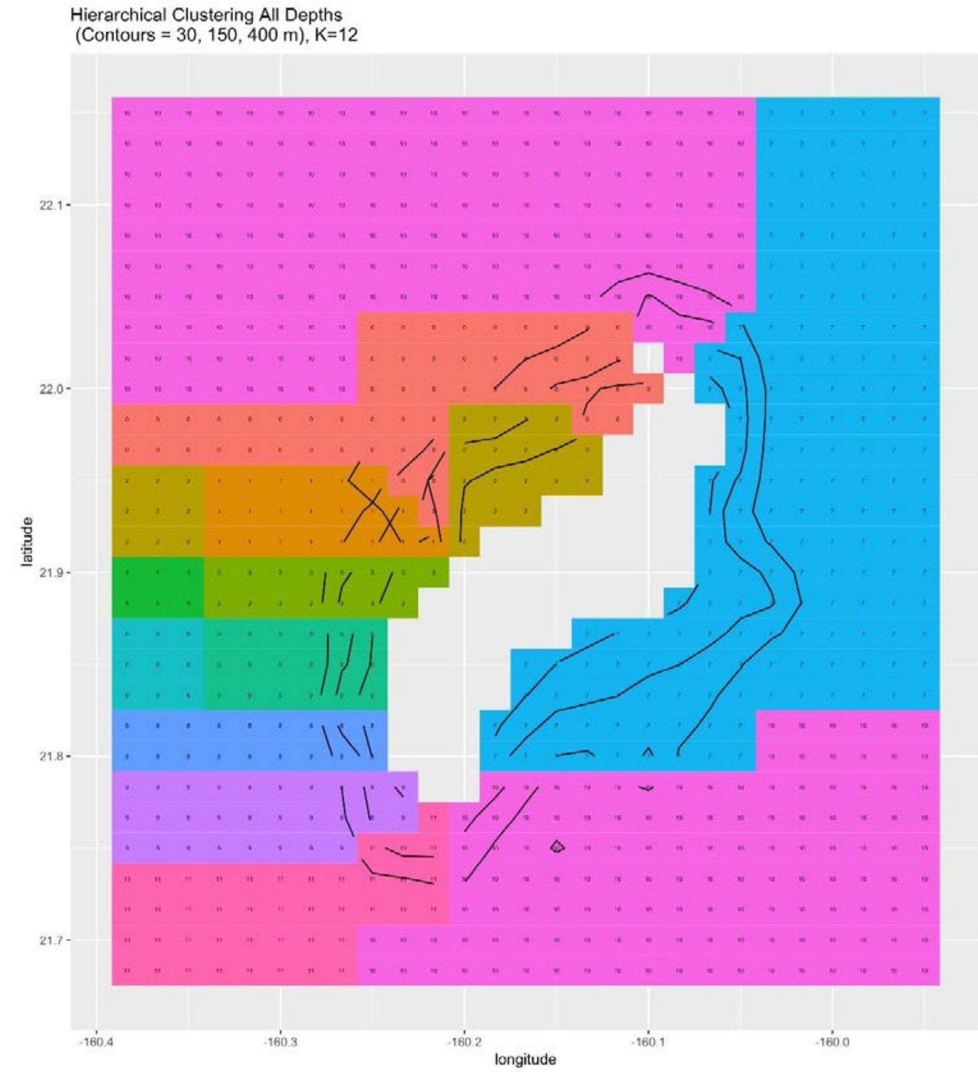
Calcareous and non-calcareous plankton will be treated separately in the model, although presently we do not know if there are sufficient data available to realistically do so. It would be useful for someone to investigate that issue.

Finally, we decided to change the group name 'Pelagic invertebrates' to 'Coastal pelagics' to be more inclusive. POST WORKSHOP: many roving piscivores (e.g. jacks, sharks) are prevalent in all depth zone so I included tem in the "Coastal pelagics" group.

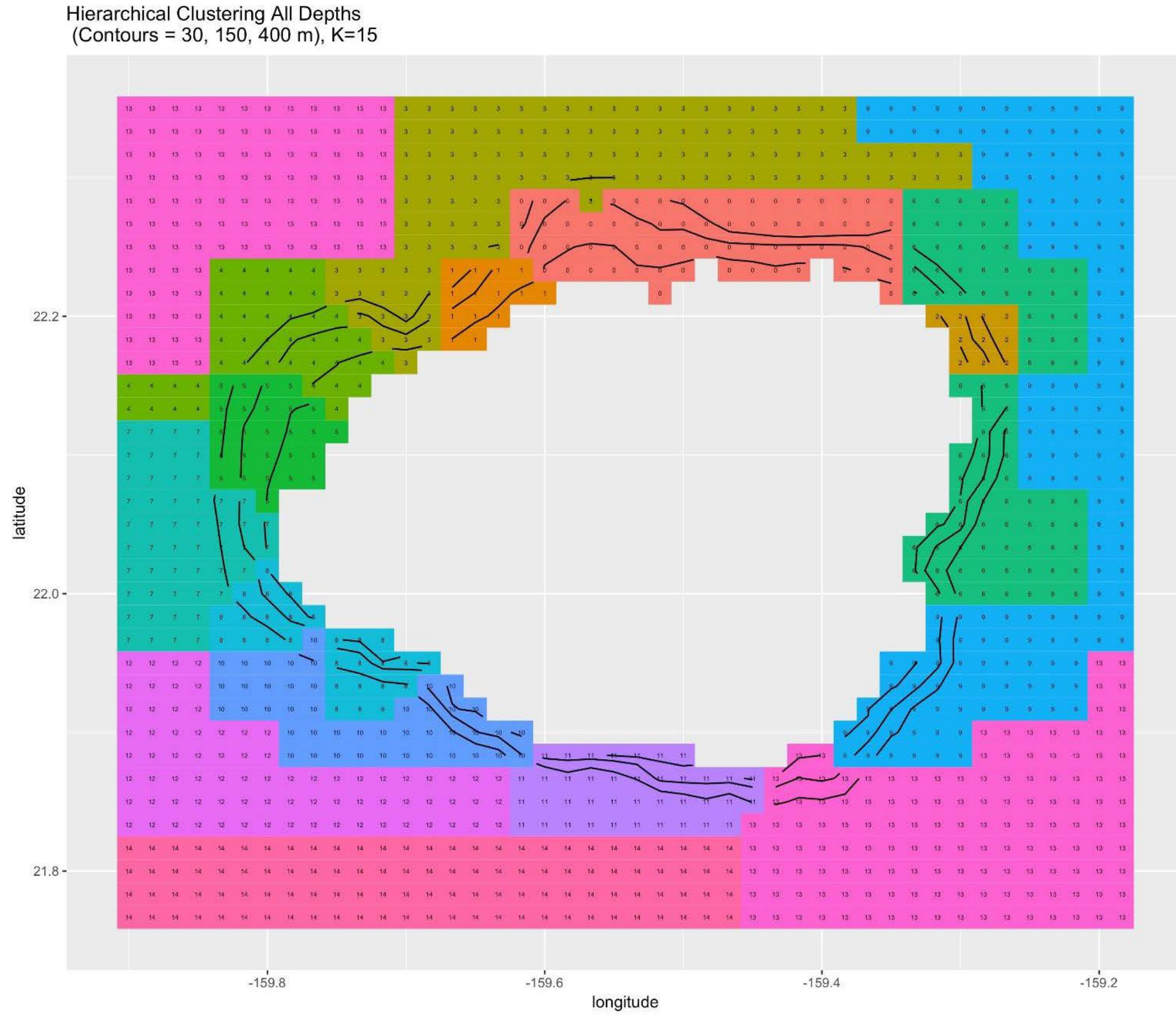
At 3 pm, we ended the workshop. Mariska sent out a draft workshop report to ascertain that everybody's comments and suggestions are properly included and that everybody is still OK with the questions, model geometry (Appendix 1), and functional groups (updated list in Appendix 2). After a review period of 2 weeks, she incorporated the suggested changes in this final version.

Appendix 1. Cluster analysis of off-shore model areas and updated maps of modeled areas

Results of cluster analysis per island. Clusters are represented by colors and numbers, K in the legend indicates the number of clusters searched. Tom used a K between 1 and 50, I picked out the maps that showed clusters that made ecological sense by also comparing them with those we had that were drawn as a continuation of the shallow boxes that were based on habitat and fish biomass and based on the fisher reporting zones, keeping it on the reporting zone boundaries if the oceanographic distinction was close.



Based on these clusters, we left the current spatial geometry.



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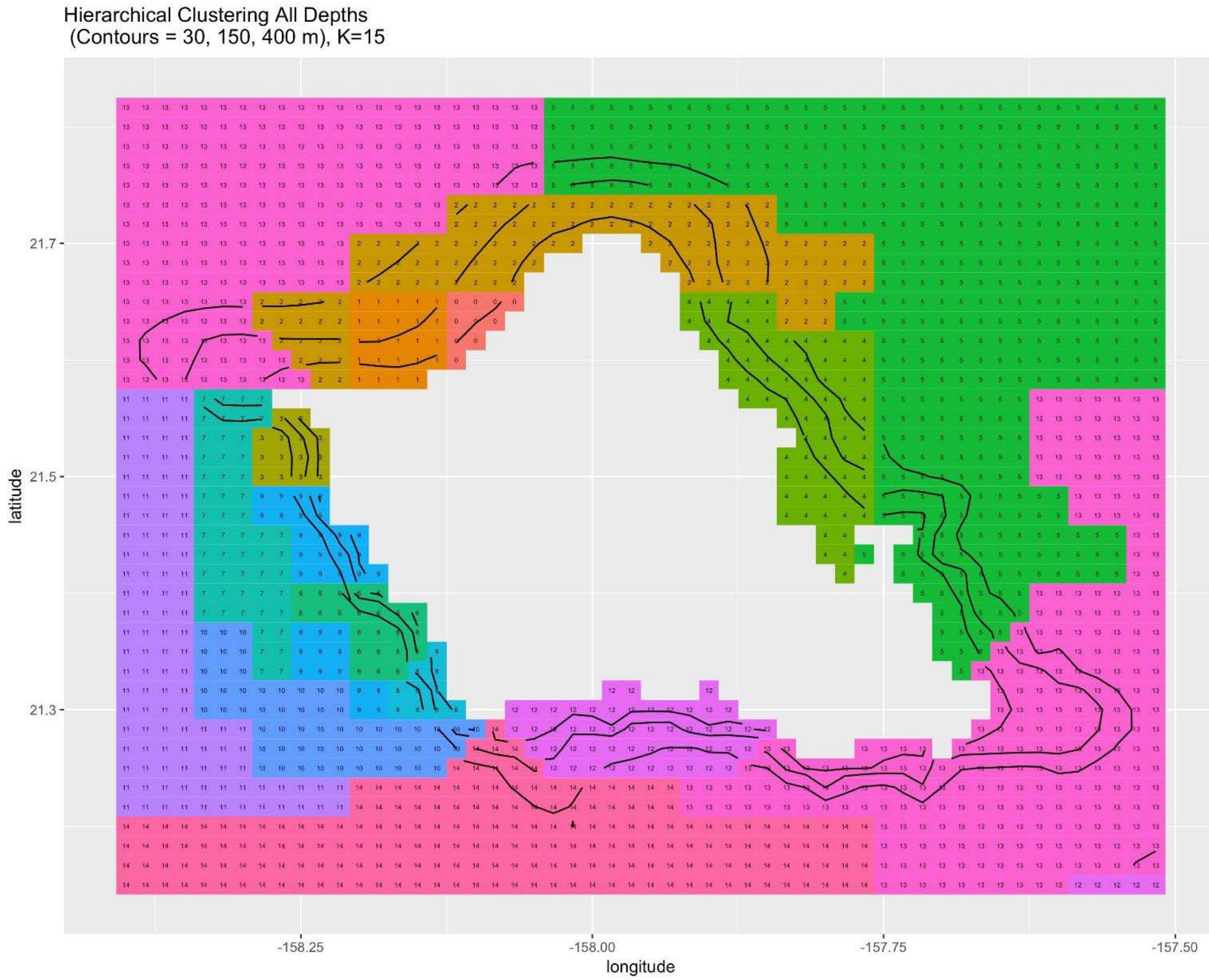
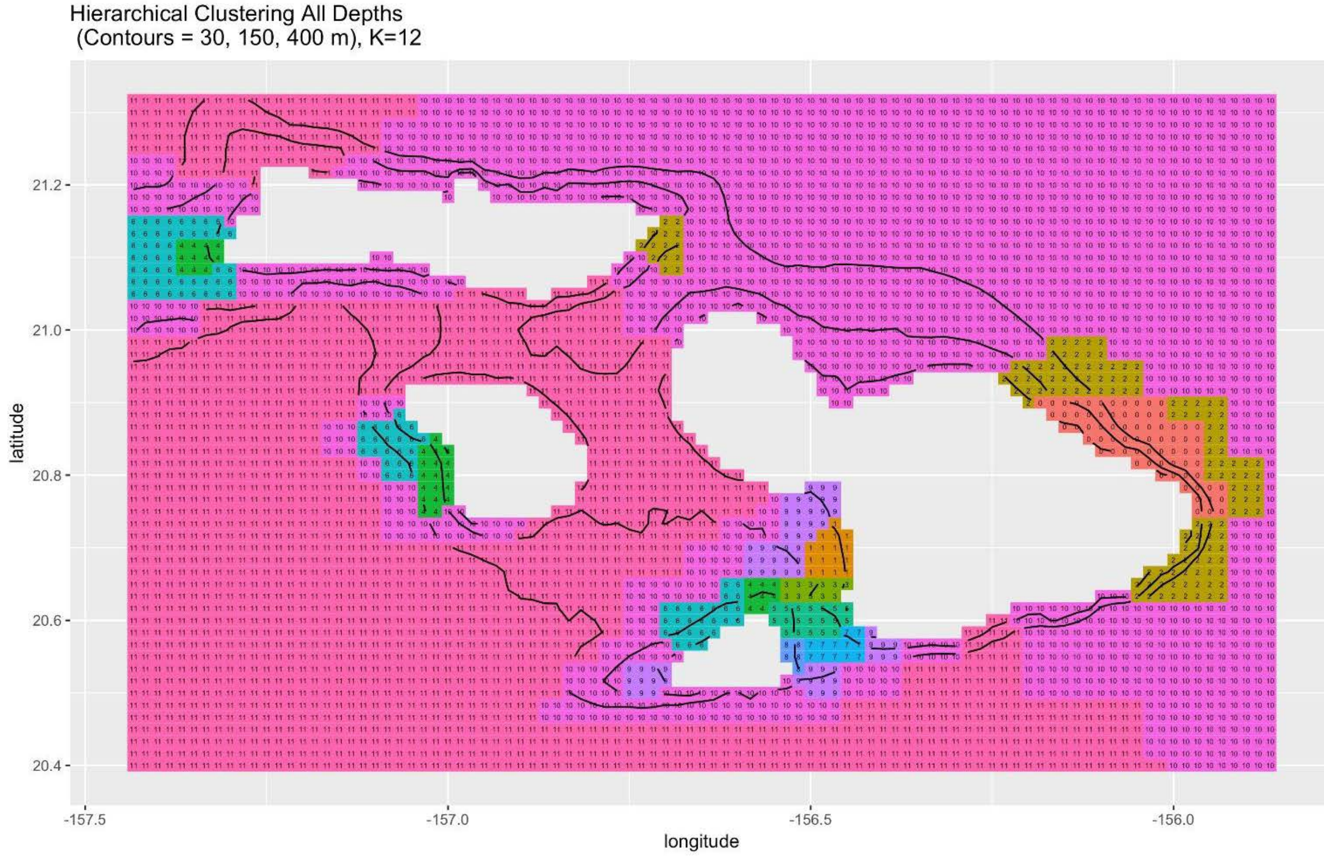
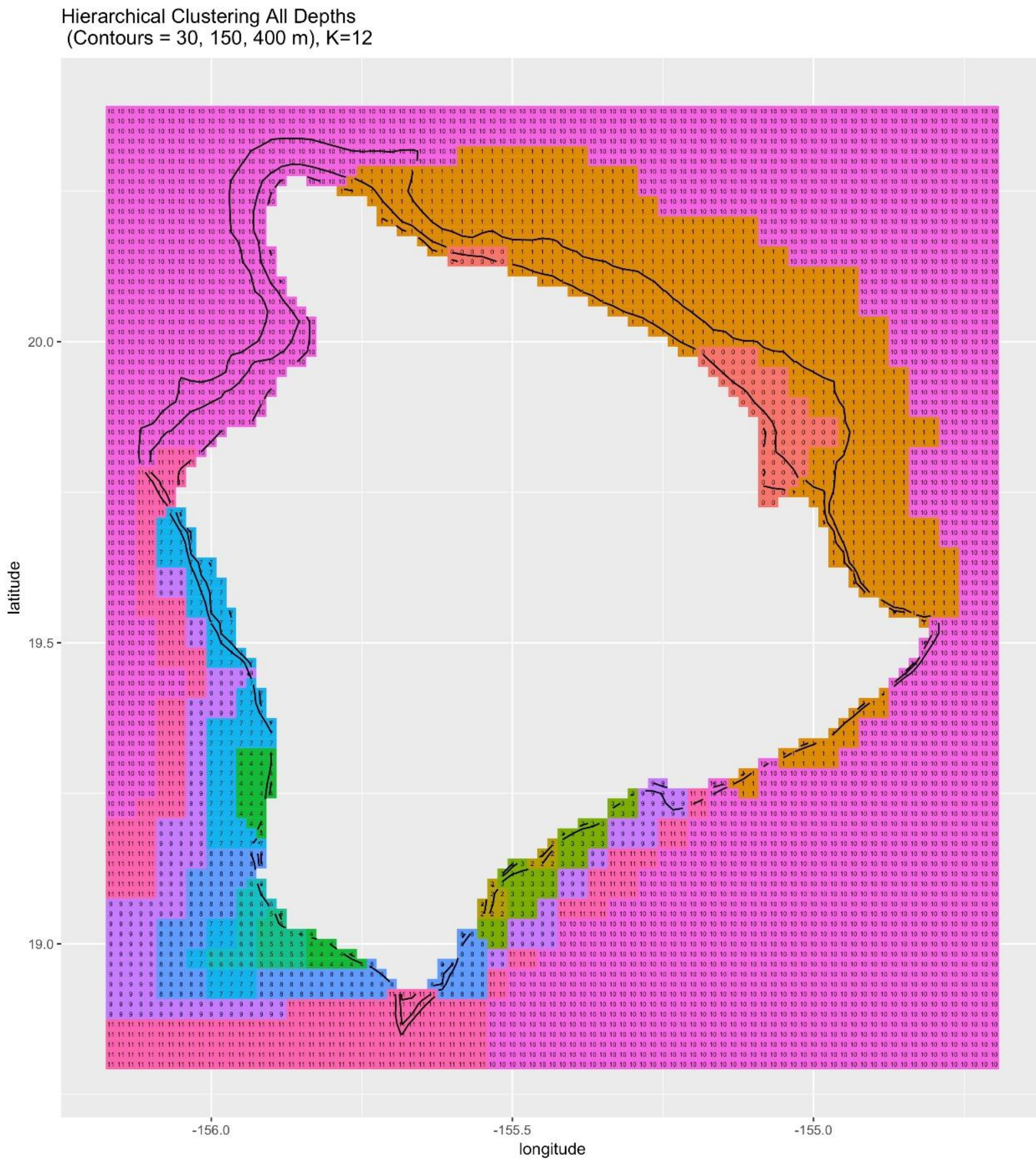


Based on these clusters, I extended the northeast box to go around the corner to the west to line up with the brown and green cluster separation which also coincided with a fishery reporting boundary. I did this for all depth layers. I also extended the 30-150 m and 150-400 m layers north to the southern tip of Kaneohe Bay (dark and light green). I did not do this for the 0-30 m as the habitat clearly changed at the present boundary just south of this outcrop.

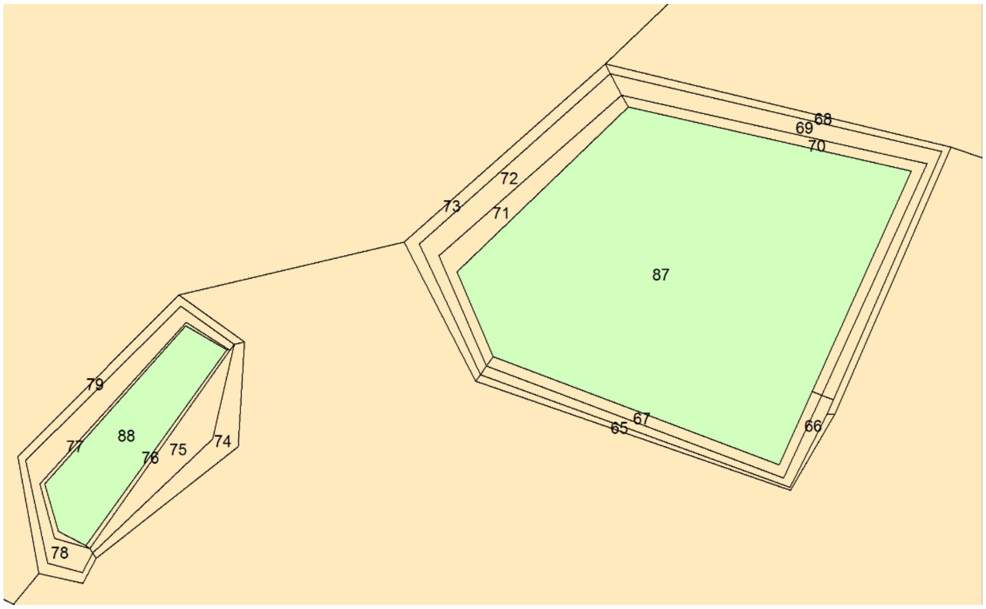


Based on these clusters, I added a polygon in the southwest (Kihei coast) to separate purple and pink and merged the two 30-150 m polygons south of Molokai and north of Lanai (both pink in this map above). I did not merge northeast Maui as that area has extensive *Leptoseris* beds and is clearly different from the other two (now one). I also decided to include Kaho'olawe with northeast and southwest 0–30 m polygons and north, east, and southwest 30-150 m polygons.

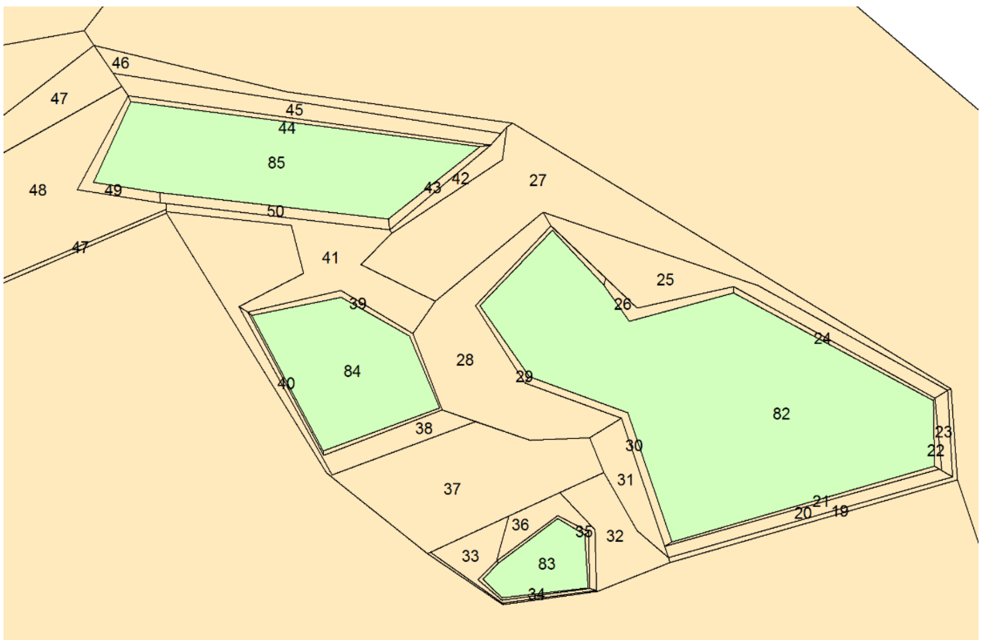


Based on these clusters, I moved the 150-400 m division at the north tip to the right to line up with the cluster separation between pink and orange/brown.

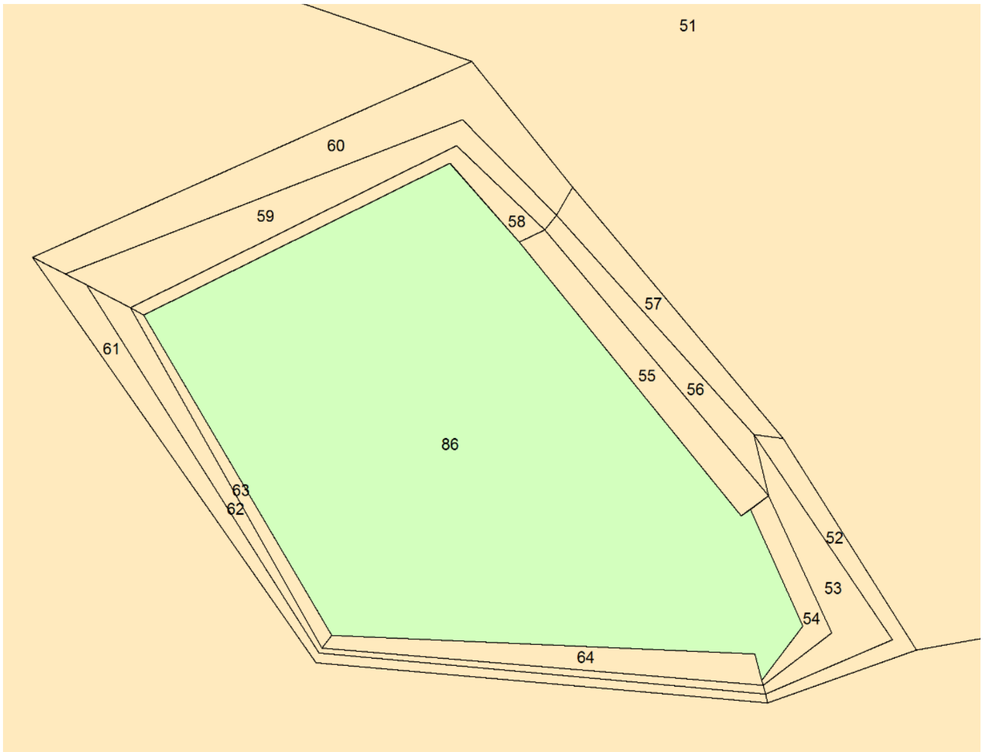
Final geometry maps showing Atlantis boxes around each island in the Main Hawaiian Islands



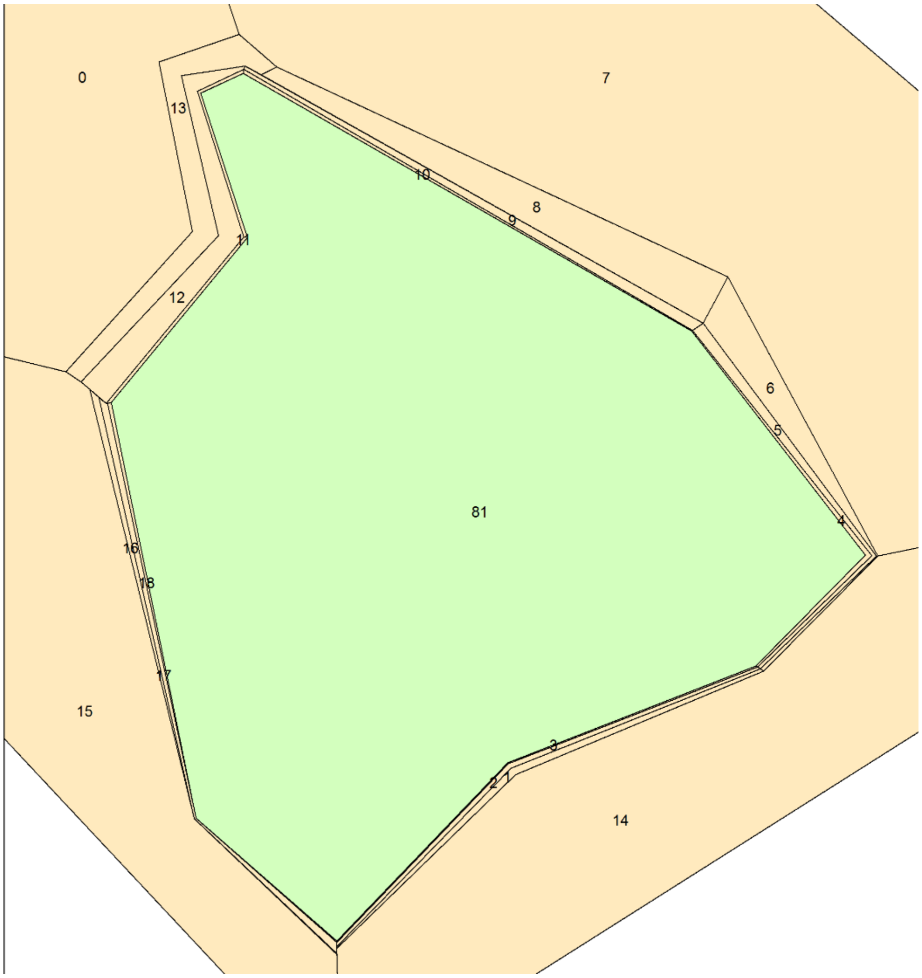
Niihau and Kauai



Molokai, Lanai, Kaho'olawe and Maui



Oahu



Big Island

Appendix 2. Updated list of functional groups

Category	# of groups	Functional group name (with examples of main families/species)
Marine mammals	1 2 3	Monk seals Spinner dolphins Bottlenose dolphins
Sea turtles	4 5	Green sea turtle Hawksbill turtles
Reef fish	6 7 8 9 10 11 12 13 14	Corallivores (butterflyfishes) Herbivore browsers (chubs, unicornfish) Herbivore grazers (surgeonfish) Parrotfishes Benthic carnivores (snappers, goatfish, squirrelfish) Large planktivores (unicornfish, soldierfish) Small planktivores (sergeants, chromisses, cardinalfish) Other reef fish Benthic piscivores (groupers, eels, scorpionfish)
Mesophotic fish	15 16	Benthic carnivores (wrasse, goatfish, flounder, perch) Planktivores (anthias, flame wrasse, triggerfish)
Bottomfish	17 18 19	Opakapaka, Kaleakale, Lehi Onaga, Ehu, Hapu'upu'u, Gindai Uku
Subphotic fish	20 21 22	Piscivores (eels, scorpionfish, dogfish), Benthic carnivores (flounder, beard fish, orange rakefish), Planktivores (Spikefish, boarfish, armorhead)
Shallow prey fish	23	Mackerel scad, bigeye scad
Coastal pelagics	24 25 26 27 28	Roving piscivores (jacks, barracudas) Sharks & Rays (reef & pelagic sharks, sting rays) Manta ray Mesopelagic scatter layer (myctophids) Squid
Macrobenthos	29 30 31 32 33	Large crabs, lobster, heterocarpus Carnivorous macrobenthos Detritivorous macrobenthos Urchins Octopus
Infaunal meiobenthos	34 35 36	Polychaeta & burrowing inverts Boring inverts Crustaceans
Filter feeders	37 38	Sponges , tunicates, octocoral,gorgonians,zoanthids Bivalves, clams, oysters
Structural benthic	39	*Porites* massive

species	40 41 42 43 44	*Porites* branching *Montipora* *Pocillopora* *Leptoseris* CCA
Primary producers	45 46 47 48 49	Macroalgae fleshy Macroalgae calcareous Turf algae Large phytoplankton (diatoms, Trichodesmium, dinos)) Small phytoplankton (cyanos, picoeukaryotes)
Zooplankton	50 51 52 53 54	Micro zooplankton (ciliates, protozoa, nano flagellates) Herbivorous zooplankton (copepods) Carnivorous zooplankton (euphausiids, chaetognaths) Epipelagic mollusks (heteropods, pteropods) Gelatinous zooplankton (salps, jellies, ctenophores)
Nutrient cyclers	55 56 57 58 59	Pelagic bacteria, Bentic bacteria, Labile detritus, Refractory detritus Carrion detritus,