Marine Conservation Institute

Pelagic Fish and Seabird Inter-Relationships in the Central Tropical Pacific: Methods and Approaches to Study and Management

Workshop Report by Marine Conservation Institute to NOAA Fisheries Pacific Islands Regional Office

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Contents

1 Executive Summary 6

2 Introduction 10

3 Foraging ranges and links to oceanography 12

3.1 Primary research objective 12

3.1.1 Understand at-sea seabird distribution in relationship to PRIM boundaries and beyond, both within and across seasons. Data can then be linked to oceanographic conditions 12

3.2 Primary methods 13

3.2.1 At-sea surveys 13

3.2.2 Telemetry studies 14

3.3 Recommended approach 15

3.3.1 At-sea surveys 15

3.3.2 Telemetry studies 15

3.4 Supplementary methods 16

3.4.1 Stable isotopes 16

3.4.2 Streamers and ships of opportunity 16

4 Fish distribution and links to oceanography 17

4.1 Primary research objectives 17

4.1.1 Investigate the scale of movement and exchange rate of large predators in the PRIM region 17

4.1.2 Investigate the vertical distribution of subsurface predators 17

4.1.3 Investigate the ontogeny of tuna schools 18

4.2 Secondary research objectives 18

4.2.1 Distribution of forage fish species and what are the links to oceanography 18

4.2.2 Investigate the relationship between tuna distributions and seamounts in the region18

4.3 Primary methods 19

4.3.1 Animal movement 20

4.4 Recommended approach 22

4.5 Supplementary methods 22

4.5.1 Stable isotopes and diet samples 22

4.5.2 Purse seine fishery data 22
5 Diet, inter-annual variability and links to oceanography 23
5.1 Primary research objectives 23
5.1.1 Develop a comprehensive, up-to-date understanding of seabird diets throughout the entire PRIM region 23
5.1.2 Understand the integrated diet structure of both seabirds and subsurface predators 23
5.2 Secondary research objectives 23
5.2.1 Investigate energetics associated with diet and foraging, and how stress influences population trajectories 23
5.3 Primary methods 24
5.3.1 Stable isotopes 24
5.3.2 Stomach samples 24
5.4 Recommended approach 25
5.5 Supplementary methods 25
5.5.1 Historical data 25
5.5.2 Guano cores 26
6 Limiting factors for reproduction 26
6.1 Primary research objectives 26
6.1.1 Determine basic breeding and population metrics across the PRIM region 26
6.1.2 Relate breeding and population metrics to factors that may limit reproduction including on-island predation and prey availability 26
6.2 Primary methods 27
6.2.1 Satellite imagery 27
6.2.2 Long-term population monitoring 28
6.3 Recommended approach 28
6.4 Supplementary methods 28
6.4.1 On-island cameras 28
6.4.2 Radio telemetry 29
7 Subsurface predator facilitated foraging 29
7.1 Primary research objectives 29
7.1.1 Develop an integrated understanding of the movements of seabirds, subsurface predators and fishing vessels with the objective of attempting to correlate fishing success and breeding success 29

7.1.2 Investigate the localized versus population level effects of fishing, and investigate if seabird populations would increase if subsurface predator populations increased 30
7.1.3 Characterize the level of impact of different threats on seabirds, determining the relative effects of each (i.e. land predation versus fishery impacts)..31
7.1.4 Investigate how seabirds may respond to a reduction of subsurface predators 31
7.2 Primary methods 31
7.2.1 At-sea surveys, telemetry and diet studies for integrated data collection.....................31
7.2.2 Comparative studies between regions...32
7.2.3 Fishery data for understanding basic patterns of the interaction over the long-term . 32
7.3 Recommended approach...32
7.4 Supplementary methods 33
7.4.1 Ecosystem modeling 33
8 Conclusion 33
9 Citations 34
10 Appendices...39
10.1 Appendix 1: Research priorities matrix 39
10.2 Appendix 2: Research opportunities matrix 41
10.3 Appendix 3: Workshop Attendees..42

Preface

The Pacific Remote Islands Marine National Monument (Monument) was designated by Presidential Proclamation in January 2009 to preserve the marine environment in these isolated ocean areas. The ecosystems surrounding the islands and atolls within the Monument are believed to be flourishing with healthy coral reefs, large numbers of apex predators and high fish biomass. In order to effectively protect the marine life in these areas, Monument management plans are being prepared by NOAA Fisheries and the Fish and Wildlife Service. However, even as the plans are being developed many important questions remain unanswered. In order for the Monument's managers to develop comprehensive and effective management plans they must review and consolidate data on natural resources, understand and manage for ecological interactions among species (such as seabirds and pelagic fishes), as well as develop a clear picture of current and historical human activities and their impacts.

This report, based on literature reviews and an expert workshop conducted by Marine Conservation Institute on behalf of NOAA Fisheries Pacific Islands Regional Office will help provide managers with insight into the complex inter-relationships of seabirds and pelagic fishes. Preparation of this report entailed a thorough search of literature and other sources to summarize what is known about this relationship in the Central Tropical Pacific Ocean, and summary of a three day workshop held in Honolulu, HI. In addition to the more generalized search for information about seabirds and pelagic fish interactions, specific attention was given to methods that could help managers support research into pelagic fishes, seabirds and their prey.

Terms of Reference

Conduct a workshop on the ecological interactions of seabirds, pelagic fishes and their prey. Coordinate background research and work with Pacific Region scientists to address the following research objectives:

A. Determine foraging ranges of seabirds breeding in the Central Tropical Pacific and their inter-annual and intra-annual variability and associations with oceanographic conditions.
   - Prioritize seabird species to be monitored and selected for the research contract
   - Analyzing POBSP (Pacific Ocean Biological Survey Program) at-sea, seabird distribution data collected in 1960's to augment future data collected efforts
   - Discuss means Obtaining year round data of seabird distributions at sea
   - Developing a pelagic seabird data base for the Central Pacific Ocean

B. Investigate food habits of breeding seabirds in the Central Tropical Pacific and document inter-annual and intra-annual variability and associations with oceanographic conditions.
   - Review and recommend the most effective sampling technology to be used to ascertain prey consumption (i.e., consider fatty acid, stable isotopes, satellite tags, archival info, etc.)

- Review and recommend methods to ascertain diet partitioning and locations of nekton or other prey consumption

C. Determine distributions of pelagic fishes and their inter-annual and intra-annual variability and associations with oceanographic conditions.
   - Assess numbers, distribution and associations with seabirds
   - Develop scope and range of what pelagic species and/or fish biomass to monitor

D. Determine prey availability and distribution for seabirds and document variability and relationships of these measures to oceanographic conditions and regimes.
   - Assess the possibility of measuring tuna biomass feeding at the surface
   - Determine methods to analyze the reproductive performance of seabirds
   - Evaluate and recommend most effective prey sampling techniques

The final product would be a work plan and recommended research methodologies, that when executed, will provide science-based management tools to fulfill the seabird and pelagic fishes protection and fisheries management goals in the PRIM and US Central Pacific Ocean

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1 Executive Summary

In conjunction with the NOAA Pacific Islands Regional Office, Marine Conservation Institute conducted a three-day expert workshop in Honolulu, HI to set a framework for obtaining a better understanding of the dynamic interrelationship between seabirds, pelagic fishes and their shared prey in the Central Tropical Pacific (**CTP**). The workshop focused on five topics identified by NOAA to be important to understanding the seabird-subsurface predator interaction, and how knowledge of these topics are important for managing the Pacific Remote Islands Marine National Monument (**PRIM**). A background document[1] summarizing previous research was circulated prior to the workshop, and participants were asked to identify specific research objectives, methods and a recommended approach for addressing these topics. Below we summarize each of the topics and their associated objectives, methods and approaches.

1. Foraging ranges of breeding seabirds in the CTP and their inter-annual and intra-annual variability and associations with oceanographic conditions.

Workshop participants agreed that there is little information available about the distribution of seabirds in the PRIM region, and that most of these species have not been studied in either the PRIM region or other areas of the world. Obtaining increased knowledge of seabird distribution and ecology and how this relates to oceanographic conditions is critical to seabird management. Data from the study of seabird distributions can further be used to understand temporal variability and if, when, or how they are influenced by oceanographic conditions.

Primary research objective:

1. Understand seasonal variation in at-sea seabird distributions in relation to PRIM boundaries. Link distribution data to oceanographic conditions.

Primary methods: (1) At-sea surveys and (2) telemetry studies.
Supplementary methods: (1) Stable isotopes and (2) streamers and ships of opportunity.

Recommended approach: These two methods should be applied in a coordinated fashion, ideally with studies being conducted simultaneously, as the methods will complement each other. Survey data collected via remote sensing or *in situ* by tracking devices or survey vessels can then be used to statistically determine what oceanographic features are important to seabirds. The recommended telemetry studies focus on red-footed boobies, sooty terns, wedge-tailed shearwaters and red-tailed tropicbirds to span a diversity of foraging strategies.

2. The distribution and behavior of subsurface predators, namely epipelagic fishes, with respect to oceanographic conditions and their relationship with inter-annual and intra-annual variability in seabird populations and breeding performance.

[1] Maxwell, S and L Morgan (2011). Ecological Inter-relationships between Pelagic Fishes and Seabirds in the Central Tropical Pacific. Report to the NOAA Pacific Islands Fisheries Science Center, 43 p.

Despite the abundance of data on tropical tunas, there is relatively little data inside the PRIM region. The behaviors and movements of individual tunas and schools can vary dramatically depending on the combination of oceanographic conditions and body size, indicating the need for specific studies in the CTP. Knowledge of the scale of tuna movements – both horizontally and vertically – and school dynamics in time and space are key elements to understanding how tuna movement and distribution may influence seabird populations.

Primary research objectives:

1. Investigate the scale of movement and exchange rate of large predators, especially pelagic fish in the PRIM region;
2. Describe the vertical distribution of tunas in the PRIM region; and
3. Investigate the ontogeny of tuna schools.

Primary method: (1) Tagging and tracking studies.

Recommended approach: Workshop participants recommended using a combination of conventional, electronic and acoustic tagging so that residence time and general movements could be investigated. They also suggested focusing tracking studies on skipjack tuna (as tag and body size allow) since it is the key species in tuna-seabird interactions and because there is experience and ongoing conventional tagging efforts. Participants highlighted the need for site-specific understanding of animal movements because of biogeographic variation across the vast zones of the PRIM region.

3. Food habits of breeding seabirds in the CTP and their inter-annual and intra-annual variability and associations with oceanographic conditions.

In-depth knowledge of diets and ecological niches occupied by seabirds and subsurface predators is a key element to understanding the nature of seabird-subsurface predator interactions. Studies through time can be used to track changes in environmental conditions, and how seabird-subsurface predator relationships might change in the face of increased fishing pressure and environmental variability.

Primary research objectives:

1. Develop a comprehensive, up-to-date understanding of seabird diet throughout the entire PRIM region; and
2. Understand the overlap between the diets and foraging strategies of both seabirds and subsurface predators.

Primary methods: (1) Stable isotopes and (2) stomach samples.
Supplementary methods: (1) Historical data and (2) guano cores.

Recommended approach: Participants recommended that stomach sampling and isotopic analyses be conducted at each island to investigate diet composition and spatial variation in foraging grounds. They recommended a 'snapshot' of all islands to provide a starting point for future analyses. They highly recommended sampling seabirds and subsurface predators as close together as possible in space and time in order to best investigate resource partitioning.

4. Methods to examine and measure the limiting factors for seabird reproductive performance in the CTP.

Just as we lack data on the distribution of most seabirds, we similarly lack basic data and metrics of breeding success and population trends. Participants suggested that collecting these baseline data is the critical first step to understanding what influences breeding success and populations. On-island predation and at-sea prey availability were identified as the key factors likely to influence seabird reproductive performance, and participants further identified the importance of determining the effect of different on-island and at-sea management measures on reproductive success.

Primary research objectives:

1. Evaluate basic breeding and population metrics from across the PRIM region; and
2. Relate breeding and population metrics to factors that may limit reproduction including on-island predation and at-sea prey availability.

Primary methods: (1) Satellite imagery and (2) long-term population monitoring.
Supplementary methods: (1) On-island cameras and (2) radio telemetry.

Recommended approach: For all of the techniques outlined above, participants strongly advocated that studies be conducted at all possible PRIM islands, and that they be conducted frequently. Because so little is known or understood about the periodicity of breeding in tropical seabirds, it was recommended that long-term monitoring research be conducted year-round, with a reduction possible after several years of data have been gathered and patterns of breeding chronology and performance (if any exist) have been described.

5. Investigating the importance of subsurface predators to tropical seabird foraging in the CTP.

Workshop participants emphasized the need for integrated data collection and increased understanding of seabird-subsurface predator interactions. This included examining the spatial scales over which tuna and fisheries interact with seabirds, evaluating the success of both fisheries and seabirds in relation to tuna distribution, and investigating the influence of oceanographic conditions. The relative impact of different management actions should be further considered. The suggested research objectives are likely outside the range of what may be possible, reflecting the challenge inherent in evaluating whether or not fishing is having an effect on fish and seabirds within the PRIM.

Primary research objectives:

1. Develop an integrated understanding of the movements of seabirds, subsurface predators and fishing vessels with the objective of attempting to correlate fishing success and seabird breeding success;

2. Investigate the local- versus population-level effects of fishing, and investigate whether or not seabird populations would increase if subsurface predator populations increased; and
3. Characterize the level of impact of different threats on seabird populations, determining the relative effects of each (i.e., land predation versus fishery impacts).

Primary methods: (1) At-sea surveys, integrated telemetry and diet studies; (2) comparative studies between regions; and (3) understanding and mapping patterns of fishery landings with seabird distributions over the long-term.
Supplementary methods: (1) Ecosystem modeling.

Recommended approach: Participants recommended that a number of different datasets (i.e., side-scan sonar, survey techniques, diet sampling, and tracking) be employed simultaneously in order to best understand seabird-subsurface predator interactions. They suggested comparing heavily fished areas with areas of less fishing to understand relative fishery impacts on bird populations, and collaborating with regional fishery management organizations (**RFMOs**) such as the Western and Central Pacific Fisheries Commission (**WCPFC**) to use and integrate existing data.

Summary

Workshop participants recognized that baseline data are lacking and that significant resources are required to adequately address this research topic in the Pacific Remote Islands Marine National Monument. Telemetry studies of seabirds and pelagic fishes, and basic survey and population monitoring are important baseline studies on which future work can be built.

2 Introduction

In conjunction with the NOAA Pacific Islands Regional Office, Marine Conservation Institute conducted a three-day workshop in Honolulu, HI on the inter-relationships of seabirds and tunas in the Central Tropical Pacific (**CTP**). We prepared a background document in preparation for the workshop[2] and invited a group of experts in seabirds, fisheries, oceanography and ecology (Appendix 3) to discuss and give insights into how we can better study and understand this complex interaction, and how NOAA, the US Fish and Wildlife Service (**USFWS**) and other research entities can apply our current knowledge, and support future research, to improve management of the Pacific Remote Islands Marine National Monument (**PRIM**).

The topics addressed in this summary stem directly from discussions that occurred during the workshop and topics developed by the managing agencies of this region. The primary questions workshop participants attempted to answer were:

> Is the subsurface predator-facilitated foraging interaction critical to seabirds, and is it necessary to consider when planning management strategies? If we do not have enough information to answer these questions, what are our primary research questions and which methods will provide the most appropriate data to answer these questions?

During the workshop, we discussed five topics identified by NOAA and FWS to be important to understanding the seabird-subsurface predator inter-relationship:

1. Foraging ranges of breeding seabirds in the CTP and their inter-annual and intra-annual variability and associations with oceanographic conditions;
2. Food habits of breeding seabirds in the CTP and their inter-annual and intra-annual variability and associations with oceanographic conditions;
3. The distribution and behavior of subsurface predators, namely epipelagic fishes, with respect to oceanographic conditions and their relationship with inter-annual and intra-annual variability in seabird populations and breeding performance;
4. Methods to examine and measure the limiting factors for seabird reproductive performance in the CTP; and
5. The importance (including methods of studying the importance) of subsurface predators to tropical seabird foraging in the CTP.

At the outset of the meeting, the experts identified a number of key questions they considered important regarding subsurface predator-facilitated foraging interaction with seabirds (Table 1). Over the course of the meeting they determined that there is a lack of baseline data regarding basic bird and epipelagic fish biology and distribution, as well as the nature of the association between seabirds and subsurface predators. Overall, however, the group concluded that a small number of baseline studies would greatly inform management needs. They identified a number

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[2] Maxwell, S and L Morgan (2011) Ecological inter-relationships between pelagic fishes and seabirds in the Central Tropical Pacific. Report to NOAA Fisheries Pacific Islands Regional Office. 42 pgs. **Web link needs to be added.**

of opportunities to combine existing research programs that will both reduce the cost of research to managers and also increase the managers' understanding of the system.

Table 1. Critical challenges to understanding and managing the seabird-subsurface predator interaction in the Central Tropical Pacific.

Seabird-Subsurface Predator Interaction Dynamics
Is seabird foraging success, and particularly subsurface predator-facilitated foraging, a critical factor affecting seabird population dynamics?
What effect do the number of subsurface predator schools and their dispersion have on bird population dynamics?
How does the 'global' subsurface predator abundance affect the 'localized' abundance within seabird foraging ranges via movement and replenishment?
What metrics of seabird and subsurface predator population densities can be developed such that population level responses are strong enough to emerge as signals in this highly variable system?
What are the impacts of commercial fishing on seabird reproductive success? What are the best ways to monitor these interactions?
What were the historic population baselines for both predatory fish and seabirds from the area before fishing and other anthropogenic impacts?
How might foraging strategies of seabirds shift in the absence of large schooling epipelagic fish?
How flexible is seabird foraging, and what other mechanisms may serve to concentrate prey?

Seabird Dynamics
How can we create a method of monitoring seabird responses to prey availability?
What are the environmental predictors for seabird foraging success in the CTP?
What are seabird population trends in the CTP?
To what extent are seasonal seabird residents (e.g. non-breeders) and migrants that breed elsewhere using the marine environment of the PRIM?
What are the geographic ranges of seabird species in the CTP?

Prey Dynamics
What are the dynamics of prey abundance, availability and distribution?
What is the link between shared prey species of seabirds and subsurface predators?

General Questions
How do we include seabird-subsurface predator interactions in an ecosystem-based management

plan?

What kinds of data do we really need and what kind of data can we feasibly get with the available resources?

For most of the discussion topics, participants focused on the need for general 'baseline' or 'snapshot' data at a large spatial scale. They concluded that the continued collection of data at specific sites over multiple years (to show inter-annual variability and responses to oceanographic drivers) was a secondary objective once a solid underlying dataset has been established. Once this snapshot (or baseline) has been established, they emphasized the importance of studying these questions at different spatial and temporal scales to account for inter-annual variability, as well as different scales of animal movement, local and regional fishery impacts, and contrasting at-sea and on-island impacts.

Participants noted that the concept the workshop aimed to investigate was not the influence of the *amount* of food available to seabirds and its potential impact on their populations; it was the *level of availability*. Subsurface predators have an important role in increasing food availability for seabirds by making food available on the water's surface. Participants highlighted that the distinction between the amount and availability of food is critical in interpreting data as well as in formulating studies. While the methods and approaches recommended below are in keeping with a number of key basic seabird and tuna biology questions, the participants identified them within the larger framework of subsurface facilitated foraging, choosing questions whose answers are necessary to identify and quantify key ecological components of this relationship (i.e., population level effects).

3 Foraging ranges and links to oceanography

3.1 Primary research objective

3.1.1 Understand at-sea seabird distribution in relationship to PRIM boundaries and beyond, both within and across seasons. Data can then be linked to oceanographic conditions

The workshop participants uniformly agreed that there is a lack of information on the distribution of seabirds in the PRIM region, as most species have not been studied in the PRIM region, or other areas of the world. Only red-footed boobies, masked boobies, brown boobies and great frigatebirds have been studied via telemetry in the CTP (Young et al 2010b, Young and Shaffer unpublished, Schreiber unpublished). Tracking studies have been conducted in other regions on additional species including red-tailed tropicbirds (Midway Atoll), brown boobies (Eastern Tropical Pacific, ETP), great frigatebirds (Europa Island) and wedge-tailed shearwaters (Seychelles) (Laniawe 2008, Gilardi et al 1992, Weimerskirch et al 2004, Catry et al 2009a). For the remainder of species found in the PRIM (white-tailed tropicbirds, lesser frigatebirds, grey-backed terns, white terns, sooty terns, brown noddies, black noddies, blue-gray noddies and

Christmas shearwaters), no tracking studies have been conducted anywhere in the world, in many cases because the species are too small to carry tags. Any knowledge of their distribution is known from at-sea observations, but these observations cannot be related to a specific colony or breeding stage. There is only one study in the PRIM region (Young et al 2010b, masked and red-footed boobies) that attempts to link seabird distribution to the oceanographic environment to understand both why seabirds choose certain regions, and what other regions might be important under other seasonal or climate scenarios.

Several studies have been conducted in the Eastern Tropical Pacific on the same seabird species occurring in the PRIM that show that birds have a strong association with thermal structure in the ocean (Spear et al 2001, Ballance et al 1997). For example, tropicbirds and boobies are found to be strongly associated with a shallow thermocline (Gould 1983, Ballance et al 1997), while other species such as sooty terns prefer deeper thermoclines (Ballance et al 1997). The thermocline gradient between deep, cold water and surface water is sharpest in warm, equatorial waters, trapping planktonic organisms above the gradient in a more concentrated vertical swath of the water column. This provides feeding opportunities for mid-trophic level prey species, in turn providing feeding opportunities for apex predators like seabirds and tunas (Fiedler et al 1998).

3.2 Primary methods

Workshop participants identified at-sea surveys and satellite tracking as the primary methods for achieving the above objective and to investigate ranges and abundance of birds at sea. They recommended that the two methods be applied in a coordinated fashion, ideally with studies being conducted simultaneously, as one method can be used to complement the weaknesses of the other method. Tracking or survey data can then be used to statistically determine what oceanographic features are important to seabirds through the collection of environmental data, either via remote sensing or *in situ* by tracking devices or survey vessels. There are a variety of models that exist to characterize these relationships (e.g., generalized linear and additive models, maximum entropy, classification and regression trees to name a few, Elith et al 2006) and these models can be the basis for predicting other important habitat regions (i.e., areas not surveyed or not used by tracked individuals that may also be important habitats).

3.2.1 At-sea surveys

At-sea surveys allow for large-scale classification of seabird habitats and assemblages at sea, and were identified by participants as a well-established, high-impact methodology. Because surveys are point-in-time sampling, they can be used to investigate not only general seabird foraging distributions but also how these distributions relate to prey assemblages, other seabird species, and oceanographic variables that are collected *in situ* or remotely, in the case of oceanographic data. Surveys are particularly critical in areas too remote for satellite tracking, and can be used to investigate the distribution of seabirds that are too small to carry transmitters. Currently, approximately 8 of the 16 seabird species that breed in the PRIM region are potentially too small to carry transmitters currently available (Table 2).

At-sea surveys were identified as being a high-cost method, at over $200,000 per study. Newer NOAA vessels cost between $30,000-40,000 per day. Participants noted, however, that if surveys are done under the auspices of the Marine Mammal Protection Act or in conjunction with other government-mandated assessments (e.g., for other protected species or commercial fishes), it is possible to avoid the daily cost, or additional days can be purchased as needed for seabird-related research so that transit time costs are avoided. They noted as well that chartered vessels can easily be fitted with basic oceanographic equipment such as conductivity, temperature and depth (**CTD**) recorders, and chartered vessels might cost less than NOAA vessels. USFWS is also in the process of negotiating retrofitting of the *MV Tiglax,* but this is still several years away.

3.2.2 Telemetry studies

Telemetry was identified as a methodology with high impact because it directly determines foraging distributions of seabirds, and can be used to evaluate how much time animals spend in or out of the PRIM boundaries. Telemetry is a well-established method that is particularly useful for gathering year-round information in a cost-effective manner (Burger and Shaffer 2008), and tag recovery rates for seabirds are exceptionally high (over 95%). Telemetry allows for individuals to be followed, and if enough individuals are tagged, population level assessments can be made.

Participants recommended tracking at a local scale in order to effectively manage birds based on these data, but some islands are not easily accessible by researchers. Tracking studies require that tags be deployed and recovered, meaning that not only must researchers be able to access islands, but they must also be able to reside there for considerable lengths of time (1-2 months) to collect adequate information. This is prohibitively difficult at Jarvis, Baker and Howland Islands, and ship-based surveys may be the only option in the near future. Additionally, though tag technology is rapidly advancing, some of the PRIM seabirds may be too small to be able to carry tracking devices (Table 2). Again, in these instances survey methods are the only option.

Table 2. Likelihood of seabird species being able to carry tracking devices

Large enough for tags	Potentially too small for tags
White-tailed tropicbirds	Brown noddies
Red-tailed tropicbirds	Black noddies
Masked boobies	Blue-gray noddies
Brown boobies	White terns
Red-footed boobies	Sooty terns
Great frigatebirds	
Lesser frigatebirds	
Wedge-tailed shearwaters	

The cost of telemetry studies ranges between $75,000-200,000 per island, not including cost of transport to, and time on, the islands. The cost of tags varies, ranging from less than $100 for a single GPS tag to $800 for tags that include diving data. GPS tags collect highly accurate data (within several meters, Young et al 2010) but can only be used during the breeding season when birds make short trips because of on-board memory constraints. GPS tags cost cost approximately $100 each for larger birds, while smaller models for species such as sooty terns may cost upwards of $700 each. Geolocation tags cost approximately $150 per tag and can be deployed during non-breeding seasons, but the accuracy of the data is considerably lower (approximately 200 km, Shaffer et al 2006). Argos satellite tags must be used for at-sea tag deployments. Argos data are typically accurate to between 1 and 3 km (Burger and Shaffer 2008) and the data are transmitted via satellite, meaning that the tags do not need to be recovered. The cost per tag is at least $1700, and data must be collected via the Argos satellite system at a cost of approximately $100 per month per animal.

3.3 Recommended approach

3.3.1 At-sea surveys

Participants recommended beginning with one survey of each monument region (e.g. Palmyra/Kingman, Howland/Baker, Wake, Jarvis, Johnston) using methods applied in the Hawaiian Islands Cetacean and Ecosystem Assessment Surveys (**PICEAS** 2006). This initial set of 'snapshot' surveys will give a single comprehensive dataset for each island, and along with telemetry studies, will help focus where future studies should occur. Participants recommended subsequently doing surveys back-to-back in three- to four-year cycles in order to maximize the chances of incorporating strong El Niño-Southern Oscillation (**ENSO**) events, and recommended that studies take place in the same months of the year in order to capture inter-annual variability. Participants recommended that all the islands could be surveyed in three separate cruises: one covering Howland and Baker Islands, one covering Johnston Island, Palmyra Atoll, Kingman Reef and Jarvis Island, and one covering Wake Atoll.

3.3.2 Telemetry studies

Participants recommended using a variety of telemetry methods in the beginning of research. This will provide a general sense of where birds are traveling and can help focus at-sea surveys. The tracking of breeding birds was identified as a priority because this is the most important, as well as most spatially limited, life history stage. Participants recommended initially tracking as many bird species as possible at as many islands as possible. Subsequent to initial studies, participants recommended focusing on a subset of species every two-to-five years to get quality life history information over both the breeding and non-breeding seasons, and focusing continued research on individuals or locations to address more specific questions as needed (e.g., foraging site fidelity, etc).

Tracking birds from breeding colonies was recommended because tags can be recovered, thereby reducing study cost and allowing for the use of archival tags such as GPS that have higher quality transmissions. Additionally, when birds are tagged at colonies, the breeding location and status of the bird is known. Tagging of birds during at-sea surveys was also recommended, in order to increase our understanding both of the distribution of non-breeding animals and additional movement patterns, particularly of birds captured far from breeding colonies.

Participants recommended the following species for focused telemetry studies because of their size, diversity in foraging ecology and the extent of background studies conducted:

- *Red-footed boobies:* plunge diver, good accessibility to birds at nesting sites, easy to get diet and isotopes, large enough for tracking devices, well studied (have tracking, reproductive performance, breeding time series at some locations);
- *Sooty terns:* more difficult logistically but abundant and easy to catch; possibility of using archival tags due to small size of birds but archival tags have poor data resolution;
- *Wedge-tailed shearwaters:* flock or solitary forager, diving bird, large enough for tracking devices; and
- *Red-tailed tropicbirds:* large enough for tracking devices, different foraging strategy (solitary foragers).

3.4 Supplementary methods

3.4.1 Stable isotopes

Isotopic data can provide general information on foraging ranges that can also be used to further focus telemetry studies. Nitrogen isotopes highlight the relative pelagic or coastal signature of seabirds using well-established methodologies (Young et al 2010a). These data can be collected via both feather and blood samples: blood plasma reflects recent foraging while feather samples provide a foraging signal since the last molt (Bearhop et al 2001). These data, particularly feather samples, can be easily collected at multiple sites, giving at least a general sense of relative foraging ranges. Cost of the analytical work for this method is relatively low (approximately $50,000 per island), and cost of data collection is very small if paired with other efforts. Participants recommended that these studies only need to be conducted approximately every five or more years.

3.4.2 Streamers and ships of opportunity

Previous studies have attached streamers of different colors to breeding birds from different breeding colonies (King, 1974). The location and streamer colors were then noted by observers deployed on Navy ships as part of the Pacific Ocean Biological Survey Program (**POBSP**) that was designed to understand distribution of birds at sea. Participants suggested that while studies such as this one have been successfully conducted in the past, attaching the streamers can be labor-intensive and therefore costly, and the observations would have to be from the public aboard vessels transiting the area anyway in contrast to the dedicated observers surveying during the POBSP. Additional resources would be required for outreach to vessel owners in order to make them aware of the research program.

4 Fish distribution and links to oceanography

4.1 Primary research objectives

A considerable amount of research has been conducted on the distribution of large pelagic fish species throughout the Pacific Ocean basin. Tuna tend to be abundant where food is concentrated in areas with suitable temperature (Blackburn and Williams 1975, Zagalia et al 2004). This results in two driving oceanographic forces dictating tuna distribution. First, physiological limitations from both temperature and oxygen concentration limit where animals can survive (Sund et al 1981, Andrade & Garcia 1999, Weng et al 2009). As a result, tuna have an even stronger relationship with the physical environment than seabirds because they are more physiologically limited. They must be able to attain high swimming speeds and travel great distances, all the while maintaining body temperatures above ambient temperatures (Sund et al 1981, Andrade and Garcia 1999). Second, the distribution of tuna is driven by oceanographic features that concentrate prey, including fronts, thermoclines and mixed layers, to name a few.

Despite the abundance of information on tropical tuna, data are lacking for the PRIM region. Sibert and Hampton (2003) published one of the only comprehensive studies on the movement of tuna in the PRIM region. Tuna behavior and movement can vary dramatically depending on the combination of oceanographic conditions and body size, and there are marked differences between oceanographic conditions in the Central and Eastern Tropical Pacific (Sund et al 1981).

Workshop participants identified the need to study tuna movement and distribution in the Central Pacific Ocean. These data are critical to understanding the interaction between seabirds and large pelagic fish. They also cautioned that although bird-pelagic fish interactions are likely to occur in relation to skipjack and yellowfin tuna, mahi-mahi should also be considered. Some seabird species are known to forage over mahi-mahi in other areas of the Pacific (Hebshi et al 2008). Additionally, Kitchell et al (1999) modeled an ecosystem shift from yellowfin to mahi-mahi due to a long-term reduction in yellowfin tuna biomass as a result of fishing.

4.1.1 Investigate the scale of movement and exchange rate of large predators in the PRIM region

In order to better understand how fishing may influence the interaction between birds and pelagic subsurface predators, it is necessary to understand the scale of pelagic predator movements across the PRIM boundaries as well as within the CTP. This is a critical issue because it gives insight into whether or not tuna (or other pelagic predators) reside within protected areas long enough to be effectively protected from fishing pressure. This then gives insight into whether or not the interaction between birds and tuna (and other fish) can be similarly protected. Understanding the movements of birds and tuna – and how these movements relate to each other – involves understanding both spatial and temporal boundaries of fish movement.

4.1.2 Investigate the vertical distribution of subsurface predators

For seabirds to engage in subsurface predator-facilitated foraging, predators need to be both present in the region *and* foraging in the surface layer (top few meters). Understanding the vertical behavior and distribution of fish predators, and how these change temporally and with thermocline depth, is thereby a critical component to understanding seabird-subsurface predator interactions. Yellowfin and skipjack tuna, for example, spend much of their time within 50 m of the surface, particularly at night (Holland et al 1990, Schaefer et al 2007) but it is unknown how much of this time is spent close enough to the surface to drive seabird-subsurface predator interactions, and how this dynamic changes temporally (i.e., seasonally, or during El Niño events when the thermocline depth shifts).

4.1.3 Investigate the ontogeny of tuna schools

Similar to understanding the vertical distribution of tuna, understanding how tuna schools build, degrade and maintain cohesiveness, and what forces drive the various ontogenic stages of a fish school are necessary to understand bird-tuna interactions. Is a school of 100 tuna equivalent to a school of 1,000? How long do these schools remain intact? Does the presence of birds influence the length of time a school is intact? Does fishing directly influence school dynamics, either in terms of school dynamics or fish biomass? Participants noted that in their experiences schools often stay together even when being fished, though this may depend on school size; thus, effects on seabird foraging might be variable. They also noted that in the ETP, larger schools tend to break into multiple smaller schools, however when productivity is depressed, schools tend to be larger. This has important implications, given current and projected climate change. Attempts to mathematically model school dynamics have been made in the tuna purse seine fishery (Clark and Mangel 1979) and could be of further help in understanding these dynamics.

4.2 Secondary research objectives

4.2.1 Distribution of forage fish species and what are the links to oceanography

Workshop participants identified two secondary research objectives they considered to be of importance to understanding fish distribution and links to oceanography. They particularly pointed out the lack of information on forage fish species in the region. For example, flying fish have been identified as one of the most important forage species for tuna and birds (Ashmole and Ashmole 1967, Harrison 1990, Roger 1994). Despite this, almost nothing is known about their ecology or distribution, and the 16-19 species of flying fish are often combined together because so little is known about them. Participants identified Jeffery Drazen[3] at the University of Hawaii, Manoa as a potential collaborator for mid-trophic level sampling as he is involved in a number of projects that use pelagic sampling.

4.2.2 Investigate the relationship between tuna distributions and seamounts in the region

Due to their importance in other areas of the world (Morato et al 2010), seamounts (particularly those less than 500 m deep) were also identified as ecosystems of probable importance to tuna in the CTP, and participants suggested that an inventory of seamounts combined with knowledge of tuna distribution would be a first step toward better understanding how these ecosystems may be

[3] http://www.soest.hawaii.edu/oceanography/faculty/drazen.html

influencing tuna and also seabird-subsurface predator interactions. They suggested similar analyses of island wakes.

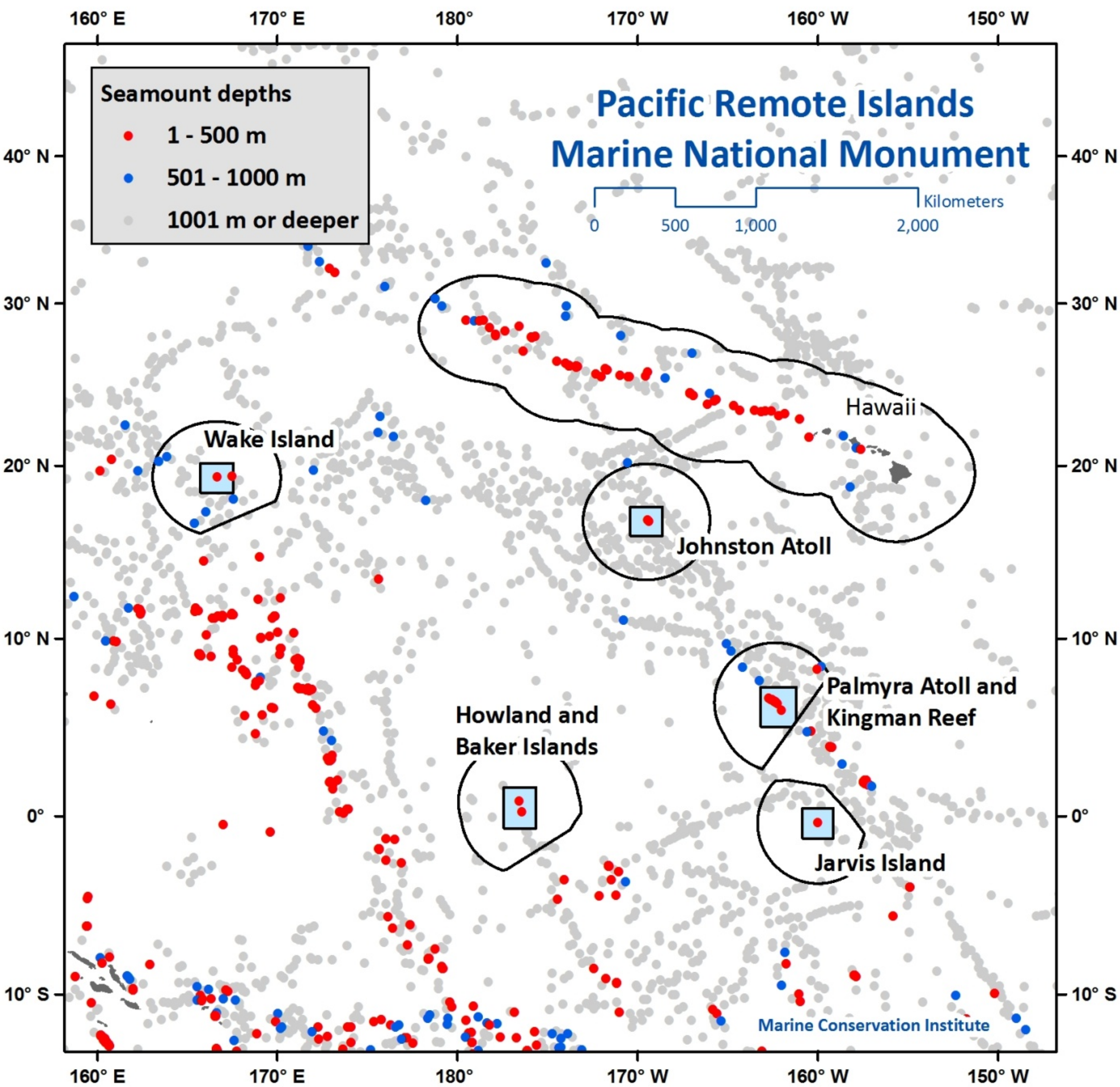

Figure 1. Seamounts in the Pacific Remote Islands Marine National Monument region.

4.3 Primary methods

Participants identified electronic tracking and conventional tagging studies as the primary methods to answer the research questions above, and noted that there is extensive expertise in this arena among some of the participants and all of the region's fishery research organizations.

Tracking and conventional tagging studies give an understanding of the spatial and temporal distribution of animals in relation to protected area boundaries, making it a high impact methodology.

4.3.1 Animal movement

4.3.1.1 *Conventional tagging*

For conventional tagging, scientists insert a dart tag with a plastic barbed head behind the second dorsal fin of the fish. The fish is released and if fishermen find a tagged tuna, they can pass on information about the date and location of the catch. Large campaigns must be organized to inform fishermen about the tagging studies, but conventional tagging is the source for the majority of our understanding on fish movements to date. This data has been applied to a wide range of management questions including defining habitat and home ranges and predicting movements (e.g., Holland et al 2001, Adam and Sibert 2002, Sibert and Hampton 2003). Participants identified the Pacific Tuna Tagging Project[4] (maintained by the Secretariat of the Pacific Community of the Western and Central Pacific Fisheries Commission) as a primary source of information on both conventional and electronic data. Conventional tags are inexpensive (less than $100 including reward to fishermen who recover the tags) but there are drawbacks associated with the method. Conventional tags only give two locations: where the fish was tagged, and where the tag was recovered. This data is fishery-dependent and thus might not represent the entire range over which tuna move (Block et al 1998), however many of the species in the CTP are too small to carry electronic tags, making conventional tagging the primary option.

4.3.1.2 *Electronic tracking studies*

Electronic tagging overcomes some of the drawbacks of conventional tagging. Because electronic tags record locations throughout the deployment, multiple locations are recorded regardless of where the tags were deployed or recollected. If tagged from a fishing boat, there may be a bias toward fishing grounds, but efforts to obtain fishery-independent release locations for any type of tagging are often cost-prohibitive, as conventional fishing gears in high-catch areas provide highly efficient means for tagging.

Satellite telemetry, particularly geolocation archival tags and pop-up satellite archive tags (**PSATs**), have proven to be an effective technology for monitoring the movements of large pelagic fish (Block et al 1998, Schaefer et al 2007, Weng et al 2009, Musyl et al 2011). These tags are attached to the animals, detach automatically on a specified date, pop-up to the surface, and transmit the archived data via the Argos satellite system. Many of these tags record not just location but also vertical behavior and subsurface oceanographic conditions (Block et al 1997). Electronic spaghetti tags were also suggested as a potential methodology and function similar to conventional fish tags but with fishery-independent recovery (Gaertner et al 2004). Similar to conventional tags, the location of tagging is recorded on release, but the final location is recorded when the tag comes off at a programmed interval, instead of when the animal is caught in fishing gear.

[4] http://www.spc.int/tagging/

Though electronic tagging has become a well-established methodology, tracking of pelagic fish is more complex than tracking seabirds or other air-breathing marine animals because fish do not come to the surface to breathe. Most electronic tags rely on archived geolocation data instead of GPS or Argos satellites for locations. Resolution of geolocation data is much lower than Argos or GPS, so determining animal locations is both more difficult and less precise. Tag return rates vary depending on the tag technology, and are often over 40% for pop-up satellite tags (Musyl et al 2011) to near 20% for archival tags (Walli et al 2009).

4.3.1.3 *Residence*

Participants identified acoustic tags as another important method for understanding animal movement and particularly residence. Acoustic tags are attached to animals and rely on a receiver to detect the presence of, and sometimes collect stored data from, the tag when it comes within a given radius of the receiver (Gunn and Block 2001). Receivers may be either at a fixed station or attached to a vessel. Fixed receivers help to determine residence time of animals in a given area, answering one of the primary research questions identified. Vessel-mounted tracking receivers provide movement trajectories, but are limited by crew endurance. Habitat can be described from telemetered depth or transmitted archive data. Passive acoustic techniques, which rely only on the noises naturally made by fish, are also a possibility though this has not been widely applied with tuna (Allen and Demer 2003). Participants identified Reka Domokos[5] at the Pacific Islands Fisheries Science Center as a potential collaborator due to her experience with calibration acoustics.

4.3.1.4 *Costs*

The costs of tags vary widely, but most tagging and tracking studies fall into the high cost category (greater than $200,000). Conventional tags cost less than $100 per tag (including reward money) but a large number of tags are needed, and campaigns to alert fishermen to watch for the tags can be costly. Archival tags are the cheapest of the electronic tags at $200-900 per tag, but the return rate of tags can be low (sometimes less than 10%, though sometimes up to 53%, Brill and Lutcavage 2001, Schaefer et al 2007) and depends on animals being caught in fisheries and the tags being returned to researchers. Pop-up tags archive data and then transmit it via the Argos system. They cost considerably more than regular archival tags ($4000 per tag) but they also record temperature and depth, and data are transmitted using the Argos satellite system, eliminating the need for tag recovery. Data collected from pop-up tags, however, are only accurate to within 100 km (Teo et al 2004). Electronic spaghetti tags also transmit data by the Argos system but they cost $2,000 per tag and only give two locations. Acoustic tags cost on the order of $100 each. To create an array of acoustic receivers can cost around $25,000 (plus maintenance through time), and require that the animal be within approximately 0.5 nm of the receiver in order to be recorded (Gunn and Block 2001).

[5] Pacific Islands Fisheries Science Center, http://www.pifsc.noaa.gov/eod/eod_staff.php

4.4 Recommended approach

Workshop participants recommended using a combination of conventional, electronic and acoustic tagging so that both residence time and general movements could be investigated. They also suggested focusing electronic tagging studies particularly on skipjack tuna if possible, since it is one of the key species in tuna-seabird interactions and because there is so little data on the fine-scale movement of this species due to its small body size. Participants highlighted the need for site-specific understanding of animal movements, because of biogeographic variation across the vast zones in the PRIM region. Given logistical restraints of the PRIM islands, however, participants suggested that studies could be conducted in Hawaii as a model for Johnston and Wake Islands, and islands in the Republic of Kiribati and Palmyra Atoll as proxies for Jarvis, Howland and Baker Islands. For conventional tags, a critical restraint is the need for commercial fisheries to release and recover tags, and must be considered in choosing study sites.

4.5 Supplementary methods

4.5.1 Stable isotopes and diet samples

Similar to the research described above for seabirds, stable isotopes can be used to infer general fish distribution. Nitrogen isotopes can highlight the relative pelagic or coastal signature of fish (Young et al 2010a) and is a well-established methodology. Red and white axial muscles give short-term signals while otoliths can be used to determine signatures over the span of years (Hobson 1999, Buchheister and Latour 2010). Some data already exist from Palmyra Atoll (Young et al 2010a). Stable isotopes are relatively inexpensive, on the order of $10,000 per study to analyze samples. Similarly, diet samples can be used to evaluate distribution of animals if the distribution of the prey base is known. Samples for both stable isotopes and diet can be obtained from fish markets assuming the catch location can be obtained. This should be possible because most tuna can be traced back to their catch location as tuna are placed in different holds as they are caught. Both data types need to be studied in a site-specific manner, and sample collection needs to be repeated at two-to-five year intervals.

4.5.2 Purse seine fishery data

Fishery-dependent data has been the basis for much of our knowledge to date and continues to be an important source of information on the distribution of tuna (Zagalia et al 2004). Workshop participants recommended a focused analysis of these data to understand tuna distribution and exploitation dynamics in the relevant areas. They further recommended better coordination between National Marine Fisheries Service fishery scientists and seabird scientists in the USFWS to make the best use of fishery data.

5 Diet, inter-annual variability and links to oceanography

5.1 Primary research objectives

5.1.1 Develop a comprehensive, up-to-date understanding of seabird diets throughout the entire PRIM region

Only two studies have been conducted on seabird diet in the PRIM region. Ashmole and Ashmole (1967) described the diets of over a dozen species of seabirds on Christmas Island using stomach samples. Using stable isotopes, Young and colleagues (2010a) characterized the diets of all 10 species of seabirds and subsurface predators (yellowfin tuna, wahoo and flying squid) surrounding Palmyra Atoll. Workshop participants highlighted that these studies, while a start, are not sufficient. The Ashmoles' study occurred over 40 years ago and the other is of limited spatial scope (Young et al 2010a). In order to adequately inform current management strategies or objectives over the scale of the PRIM, more research over the entire region is needed. Participants recommended that the first steps must be developing a 'snapshot' understanding of seabird diet across the scope of the entire PRIM region, and then focusing studies on specific life stages, species and islands in order to better understand inter-annual variability.

5.1.2 Understand the integrated diet structure of both seabirds and subsurface predators

Participants further recommended that to understand the interaction between seabirds and tuna, it is essential to investigate the integrated foraging and diet structure of the different species, a critical component in determining the nature of the interaction (competitive, mutualistic, etc). A number of studies have successfully investigated the foraging niches associated with seabird and subsurface predator species, largely using isotopic techniques (Cherel et al 2008, Young et al 2010a), satellite tracking studies (Young et al 2010b, Weimerskirch et al 2009) and diet studies (Harrison et al 1984, Ashmole and Ashmole 1967, Catry et al 2009b). These studies have largely shown that different bird species occupy independent foraging niches, and that they also occupy different niches from subsurface predators isotopically, spatially, behaviorally and in regard to the species and size of species. Despite the success of these techniques, however, they have not been applied in all of the geographic regions of the PRIM, and marked differences in foraging strategies between the same species in different regions have been documented within the Pacific Ocean (e.g., booby species on Palmyra Atoll versus elsewhere, Young et al 2010b, Weimerskirch et al 2009). A larger-scale understanding of the differentiation or overlap between diets is also critical to predict how this relationship would change in the face of increased fishing pressure and environmental variability.

5.2 Secondary research objectives

5.2.1 Investigate energetics associated with diet and foraging, and how stress influences population trajectories

Energetic studies were identified as another important area of research because they allow for the synthesis of a number of data types such as diet and tracking, creating large-scale understanding of foraging ecology. Tracking data combined with energetic requirement estimates (gathered through techniques such as doubly-labeled water) can be used to measure energy expenditure, and can be related to behavior and movement (Shaffer 2010). Movement and energy expenditure can also be integrated with energy gained from diet and prey items (Duffy and Jackson 1986), and vulnerabilities can be predicted based on changes in either oceanographic conditions or fish distribution due to fishing pressure. Workshop participants highlighted that energetics data already exist for sooty terns (Flint and Nagy 1984) and red-footed boobies (Ballance 1995) in the PRIM region, as well as for other species in other locations such as white-tailed tropicbirds (Pennycuick et al 1990, Ellis and Gabrielsen 2002).

5.3 Primary methods

5.3.1 Stable isotopes

Isotopic analyses were considered to be moderately informative for management because they provide general diet and foraging characteristics such as trophic level (Bearhop et al 2001). Stable nitrogen isotopes increase with the trophic level consumed by the predator, giving an indication of the general diet of individual species (Young et al 2010a). Different tissues integrate stable isotopes over different time periods, meaning that inferences on trophic level and foraging can be made across multiple time scales. For example, blood plasma indicates foraging structure over shorter time scales (i.e., days), while feathers indicate structure over the time period since the last molt (Bearhop et al 2001). Stable isotopes are particularly useful for considering resource partitioning across entire multi-species seabird colonies, as has been done on Palmyra Atoll (Young et al 2010a) and Europa Island in the Indian Ocean (Cherel et al 2008). Data can also be easily compared to subsurface predators to create a complete picture of resource partitioning among all top predators in the system, as was done on Palmyra Atoll (Young et al 2010a). Stable isotope analysis is relatively inexpensive, ranging around $10 per sample, and samples from an entire island can be processed for on the order of $10,000. The major drawback of the technique is that individual prey species cannot be determined.

5.3.2 Stomach samples

Collecting diet samples of partially digested food directly from birds is one of the most frequently used and straightforward methods of diet analysis that has been used for many decades (Duffy and Jackson 1986). Collection without lethal sampling usually requires the regurgitation of food. Many birds 'spontaneously regurgitate' when handled, and stomach lavage can be used in instances when this is not the case.

Workshop participants identified stomach samples as a moderately expensive ($75,000-200,000 per study), but a method for which standards have been established (Duffy & Jackson 1986). There are, however, a number of potential drawbacks. First, stomach sampling can be time- and labor-intensive, requiring the handling of a large number of birds. Second, achieving adequate sample sizes to accurately represent the diet of a population can be difficult (Duffy and Jackson 1986). Third, diet sample analysis may require expertise in prey species taxonomy, which is increasingly difficult to come by with the decrease in scientists entering the field of taxonomy.

Workshop participants noted that there are very few individuals with the expertise, such as Bill Walker[6] has, to process stomach content samples.

Additionally, a number of biases exist with stomach sampling. Samples are usually collected on land, meaning that some prey items may have been fully digested (particularly those ingested earliest in the trip), while others are in varying states of digestion. Many species, such as bony fish and squid have bones (i.e., otoliths or beaks) that are not easily digested and will remain intact for months, but some species, particularly crustaceans, can be fully digested in relatively short amounts of time and may not appear in diet samples, though in reality they may make up considerable volumes (Duffy and Jackson 1986). Seabirds may choose different prey to feed to chicks versus what they consume for themselves. Regardless, diet samples are a powerful, well-established method and are the only way to determine prey to the species level for seabirds.

5.4 Recommended approach

Participants recommended that both stomach sampling and isotopic analyses be conducted at a local level in order to investigate the spatial variation in diet, and that a 'snapshot' of all islands was a good starting point for future analyses. They highly recommended that for all studies, sampling of both seabirds and subsurface predators be conducted as close together as possible in space and time in order to most accurately evaluate resource partitioning. For isotopic data, they recommended analyzing data from Palmyra Atoll on a yearly basis because it is easily accessible. Sampling intervals of every five years is appropriate for the other islands. For stomach sampling, they recommended sampling all islands every two-to-three years due to expense and time involved with processing samples, but they did recommend sampling over a range of seasons to elucidate variability. They highlighted that collection of samples is simple and straightforward, particularly the collection of feather samples; thus sample collection can easily be piggybacked on other studies to save costs. Collection of samples (diet and/or feathers) by observers when birds land onboard vessels was identified as an additional opportunity for data collection.

For stomach samples, participants recommended identifying prey to both the species and the life history stage because diets are likely to be similar between species, and this level of specificity will be necessary in order to adequately characterize resource partitioning. One option identified for determining prey-to-species level is genetic fingerprinting. The Barcode of Life[7] database is currently free to use as long as the prey species being searched is already contained in the database. Participants further suggested determining the energy density of diet samples so that these data could also be used in energetic studies (see above).

5.5 Supplementary methods

5.5.1 Historical data

Participants suggested the possibility of including a number of historical sources of data in studying diet as well. Museum collections house bird samples, and feather samples could be used

[6] Bill Walker, NOAA National Marine Mammal Laboratory, Seattle WA
[7] http://www.barcodeoflife.org/

to compare stable isotopes of current and historical populations. Participants warned that due to the long time scale, it can be difficult to decipher changes in diet in comparison to background changes in oceanic isotopic structure, but it is possible. Lisa Ballance and her student Ignacio Vilchis are attempting this work currently, and other studies have previously been conducted on animals such as living and extinct bears, as well as marbled murrelets (Hilderbrand et al 1996, Becker and Beissinger 2006, Norris et al 2007). There are strong cautions in using historical samples for isotopic analysis, however, because isotopic signatures of both consumers and prey can change over time, and the burning of fossil fuels has depleted carbon isotopes in comparison to the background isotope levels through time (Bond and Jones 2009).

5.5.2 Guano cores

Guano cores were also suggested as a source of diet information because fish otoliths may have been preserved in the cores. This method has a number of potential biases (e.g., invertebrate samples may not be preserved as well) but may provide interesting data. This method has never been attempted.

6 Limiting factors for reproduction

6.1 Primary research objectives

6.1.1 Determine basic breeding and population metrics across the PRIM region

Before being able to fully characterize impacts on seabird reproductive success, workshop participants cited a lack of baseline knowledge. Just as we lack data on the distribution of the majority of seabirds, we similarly lack data on basic metrics of breeding success, and population metrics that are important for determining short and long-term trends in population levels. For example, in most cases we know close to nothing about the seasonality of breeding, inter-annual variability of breeding, or general breeding success. In addition, we know little about the environmental drivers of the observed variability; some tropical birds have asynchronous breeding cycles, and breed throughout the entire year though with seasonal peaks (Ashmole and Ashmole 1967). Collecting these baseline numbers is the critical first step to understanding what influences changes in breeding success and populations.

6.1.2 Relate breeding and population metrics to factors that may limit reproduction including on-island predation and prey availability

Workshop participants identified predation and prey availability as the factors limiting seabird reproduction in the PRIM region. Introduced species such as rats and domestic cats can eat eggs, chicks and occasionally adult birds, greatly influencing breeding success on islands (Rauzon 2008). Rats still exist on Wake Atoll (Rauzon 2008), and eradication is awaiting confirmation on Palmyra Atoll (USFWS 2011). Recently introduced yellow crazy ants (*Anoplolepis gracilipes*) are abundant on a portion of Johnston Island. They may subdue or kill animals by spraying them with formic acid, possibly reducing breeding success of some species (Jaquemet et al 2005).

Prey availability is likely influenced by oceanographic conditions as well as subsurface predators, thus potentially linking reproductive success to fishing impacts. Still, few studies have linked environmental patterns with breeding success in the PRIM region, and those that have highlighted negative influences, such as the total breeding failure in the Central Pacific during the 1983 El Niño (Schreiber and Schreiber 1984). This is further complicated by the fact that remote sensing imagery shows only productivity and not prey distribution or density, data that are difficult and expensive to collect.

In one set of studies conducted off the Great Barrier Reef in Australia, researchers found that changes in oceanographic conditions over different timescales influenced seabirds in different ways (Dunlop et al 2002, Peck et al 2004, Erwin and Congdon 2007, Devney et al 2010). By following birds from the pre-laying and nest excavation season all the way through to the end of the breeding season, they were able to link oceanographic conditions to breeding success at time scales of only a few days. They further considered chick growth rates and physiological capacity to regulate growth when food shortages occurred on long and short time scales to understand how chicks are able to adapt to the variable oceanographic environment parents forage in. These studies highlight the importance and feasibility of the integration and interaction of oceanography, prey, physiology and reproductive success. Participants suggested that studies such as these be conducted in the PRIM region. In addition to oceanographic variability, they thought that links to fishing impacts should be similarly considered. They considered, however, that direct links to fishing impacts are likely to be more difficult to determine and may require increased baseline information, as well as an appropriately tailored study design. Workshop participants stressed the importance of designing research studies and management actions such that on-land versus at-sea impacts can be distinguished if possible.

6.2 Primary methods

Workshop participants recommended a number of methods for gathering data on breeding effort and population dynamics to investigate factors affecting breeding success. Below we highlight the methods that were suggested by participants to be the most useful.

6.2.1 Satellite imagery

Satellite imagery was recommended as a potential high-impact, low-cost (less than $75,000) method of determining baseline breeding metrics such as timing of breeding, number of breeding pairs, etc. Imagery from satellites such as Quickbird give up to 0.5m resolution in some places and cost only $400 per image, with most islands fitting on a single image. The use of satellite imagery has previously been used to determine the presence or absence of birds, relative to true abundance (see review in Gottschalk et al 2005). The data need to be ground-truthed and will only work in areas where vegetative cover is low enough to make accurate counts, where nests or birds contrast with the surrounding environment (i.e., dark nests on white sand background), and for bird species that do not nest directly in or under vegetation. This technique has worked well for Weddell seals and Adélie and King penguins due to the contrast between animals and the ice background (Schwaller et al 1989, Guinet et al 2005, LaRue et al 2011), and has recently been used to enumerate ground-nesting boobies (Hughes et al 2011).

6.2.2 Long-term population monitoring

Despite the cost of setting up and maintaining a long-term research camp (minimally $100,000 per year), workshop participants highlighted that there was no technological replacement for the data gained from this kind of well-established method. Long-term population monitoring can evaluate changes in number, survival and productivity of populations, and allow multi-year comparisons of nest and fledging success. Banding individual birds allows for long-term diet sample collection and the ability to detect changes in the environment that lead to changes in the population (Ainley et al 1994, Hatch et al 1994). Additionally, because many tropical seabirds in the PRIM region have very little breeding synchrony or seasonality, long-term population monitoring allows for data to be collected even in the most anomalous of years, giving insight into the nuances of breeding variability that cannot be gathered using other methods. Such long-term monitoring was conducted as part of the Pacific Ocean Biological Survey Program (POBSP) from 1963 to 1969 but has not been conducted since (King 1974). Additionally, some of the data are not consistent over space and time and, in some instances, have not been published or made available in digital format. Participants additionally noted that currently Pacific Rim Conservation[8] is being contracted to monitor twelve species of seabirds on Wake Atoll three-to-four times a year, and that monitoring occurred on Wake from the 1970's through to 2006, with some data published (Rauzon et al 2008).

6.3 Recommended approach

For all of the techniques outlined above, participants strongly advocated that studies be conducted at all possible PRIM islands, and that they be conducted frequently. Because so little is known or understood about the periodicity of breeding in tropical seabirds, it was recommended that long-term monitoring research be conducted year-round, with a reduction possible after several years of data have been gathered and breeding patterns (if any exist) have been determined. Participants also suggested that tracking individual birds through time on at least one island was an important component to determining breeding success, a study design that requires bird banding and frequent population monitoring. This requires three-to-four people dedicated to the study, and is currently feasible only at Wake Atoll, Johnston Island and Palmyra Atoll, though additional resources (both financial and on-island) above what is currently available would be necessary.

6.4 Supplementary methods

6.4.1 On-island cameras

In the absence of funds for long-term population monitoring, or for islands where frequent visitation or long-term residence is not possible, participants suggested a number of potential methods that rely on remote monitoring. On-island cameras, similar to the Turtle Cam developed by SeeMore Wildlife Systems[9] and used on East Island of French Frigate Shoals in the Northwestern Hawaiian Islands to monitor green turtles, can take video and/or images at a

[8] http://pacificrimconservation.com/
[9] http://www.seemorewildlife.com/

designated frequency and transmit the images via satellite for remote monitoring of bird density and presence of individuals (if individual nests can be determined). Cameras have been used to successfully monitor auklet populations in Alaska and African penguins in South Africa (Piatt et al 1990, Sherley et al 2010). It was suggested that such a camera could be mounted on the day beacon on Howland Island, for example.

6.4.2 Radio telemetry

Radio telemetry can be used to determine the arrival and departure times of individual birds and these data can be used to investigate breeding success, incubation length, foraging trip length and breeding season cycle (Bradley et al 2004). Participants recommended tracking at least 20 breeding pairs using a listening station. Additionally, wireless acoustic monitoring systems (WAM, also known as song monitors) can be used to investigate the presence of bird species, onset of breeding activity, and breeding phenology (i.e., courtship, chick hatching, etc.), as well as the relative abundance through time[10]. Data are collected by solar-powered, lunchbox-sized sensors that last for years, and are transmitted through radio, wireless or satellite networks. Software is readily available to automatically process the data. WAM systems are currently deployed at over 15 locations, including Palmyra Atoll where it is being used to monitor the success of conservation efforts there. Each monitoring box costs about $50, though data transmission costs can be highly variable depending on the amount of data that needs to be transmitted and the means of transmission (i.e., satellite, radio, cell tower).

7 Subsurface predator facilitated foraging

7.1 Primary research objectives

This section of the workshop incorporated the key questions that ultimately need to be answered to effectively manage seabird and pelagic fish populations and to maintain a healthy interaction between the two. Participants emphasized that seabird reproduction may be limited by factors other than food availability (e.g., land predation, breeding habitat) and that intervention may not be required. It was suggested that more research needs to be conducted to evaluate if there is a need for management intervention related to subsurface predators and seabird foraging. The research objectives identified by the participants were admittedly farther-reaching than may be possible, but the goal was to understand the level of knowledge needed for managers to know if fishing is having an effect on fish and seabirds in the PRIM.

7.1.1 Develop an integrated understanding of the movements of seabirds, subsurface predators and fishing vessels with the objective of attempting to correlate fishing success and breeding success

Participants identified the need for an integrated understanding of all the components outlined in the previous sections, and they particularly highlighted the need for an integrated understanding of the associated movements of seabirds, subsurface predators and fishing vessels, as well as the

[10] Contact Matthew McKown at University of California Santa Cruz for information

oceanographic drivers behind these movements. In order to create effective regulations, participants noted that there is a need to understand the success of both fisheries and seabirds in relation to subsurface predator distribution and abundance. They suggested research to understand the distribution of tuna schools based on environmental drivers, as well as the patchiness and persistence of these schools, and how birds and fishing boats follow these patterns (i.e., residence time over schools, etc.). They also noted that we must consider how oceanographic productivity drives these interactions, including what the time lag may be between increases in productivity and when subsurface predators, seabirds and fisherman are able to detect foraging/fishing grounds. To relate breeding success to fishing efforts, participants suggested that it may be possible to follow individual fishing fleets, modeling them similarly to satellite-tracked animal populations. It may then be possible to link fishing efforts to changes in bird behavior and breeding metrics and also to investigate how tuna numbers translate to foraging and breeding success by seabirds.

7.1.2 Investigate the localized versus population level effects of fishing, and investigate if seabird populations would increase if subsurface predator populations increased

Similar to other research objectives under other topics, participants again underscored the need to understand effects of fishing at different spatial scales, this time in relationship to fishing impacts. They hypothesized that there might be a marked difference between localized and population (i.e., large-scale) fishing effects, and answering this question is critical to understand what influence different management strategies might have on seabird populations. For example, they highlighted the importance of knowing what influence fishing has on seabird foraging and relating this to the size of the PRIM. This relates to fish and seabird movements in that if tuna movements are relatively restricted (i.e., at the spatial scale of the individual island protected areas, 50nm^2 boxes), fishing restrictions inside the PRIM boundaries are likely to positively influence seabird populations. On the other hand, if tuna movements are variable and widespread, fishing restrictions at the scale of the island protected areas are not likely to have a discernible effect. This knowledge can guide managers seeking to implement ecosystem-based management in terms of the scope of management measures that need to be considered. Knowledge of the ranges of foraging seabirds and the energetic costs associated with varied foraging ranges will further inform management.

Participants further highlighted a study by Hampton and colleagues (1995) to illustrate this point. In a Food and Agriculture Organization-published study, scientists studied the impact of industrial purse seine fleets on pole-and-line and artisanal catches around Kiribati. Using correlation analyses, they found that at large spatial and temporal scales (e.g., 300-600 km, months), catches of both groups were similar, but at small spatial and time scales (<60 km, weeks), the industrial purse seine fisheries had a negative impact on small-scale fisheries, indicating possible localized effects, although this relationship varied over time, particularly in association with ENSO events. Using tagging data, they also found a modest negative effect at the 1x1 degree scale (approximately 60 nm resolution). Participants suggested similar analyses be conducted to investigate the effects of purse seine fishing on tuna abundance and near-island fishing success using the additional data from more recent years.

7.1.3 Characterize the level of impact of different threats on seabirds, determining the relative effects of each (i.e. land predation versus fishery impacts)

Again, as in the breeding success section, participants highlighted the importance of understanding the impacts of fishing versus other impacts such as on-island predation. They stressed the importance of being able to evaluate the relative influences of each of these impacts in order to guide appropriate management actions and regulations, particularly with regard to fishing. Lisa Ballance highlighted the example of Clipperton Island, where feral pigs were suppressing brown booby populations until the pigs were eradicated in the 1950's (Pitman et al 2005). Despite continued heavy fishing for yellowfin tuna in the region, masked booby populations drastically increased from 500 brown and 150 masked boobies to 25,000 brown and 125,000 masked boobies after the removal of the pigs. With the grounding of vessels containing rats around the year 2000, the populations of a number of seabird species began to decline again due to rat predation. Participants suggested that all threats to seabird populations need to be addressed and that it is important to be able to distinguish at-sea from land-based threats and remain vigilant to introduced species that might compete with, or prey upon, seabirds.

7.1.4 Investigate how seabirds may respond to a reduction of subsurface predators

Participants identified understanding the ecosystem-level reaction to a reduction in subsurface predators as a key element in being able to manage seabird populations. This would lend insight into whether or not management intervention is necessary to maintain this interaction, and which management objectives, if any, should be prioritized over others. For example, participants suggested it was important to have some knowledge of how the prey base would respond if subsurface predator abundance was reduced, and how this would likely influence seabirds. They stated it was also important to understand how flexible seabird foraging strategies are (i.e., what foraging strategy might they use if subsurface predator-facilitated foraging was greatly reduced), and what other mechanisms might concentrate prey for seabirds with either reduced abundance of subsurface predators, or the reduction of some and the ecologically-mediated increase of others (e.g., mahi-mahi, Kitchell et al 1999).

7.2 Primary methods

7.2.1 At-sea surveys, telemetry and diet studies for integrated data collection

In keeping with the integrated approach to answer this question, participants recommended that a number of different datasets be collected simultaneously in order to best understand the seabird-subsurface predator interactions. They recommended the collection of data using a number of well-established methods at a single feeding event including:

- Side-scanning sonar and underwater drop-cameras to investigate school dynamics, composition and abundance
- Survey techniques to determine seabird abundance

- Diet sampling to investigate tuna and seabird diet from the same feeding event (may require lethal sampling of seabirds as well as tuna)
- Tracking birds captured at the feeding event (would require the use of Argos tags and, thus, larger birds; see above)

Survey-based work such as this was identified as a high cost (more than $200,000 per survey), high-impact method but participants considered there to be few, if any, technological or other alternatives to direct field observations of the interactions as they occur.

7.2.2 Comparative studies between regions

Participants considered the idea of an experimental design that might allow better understanding of fishing impacts on seabird populations. The idea included the 'fishing down' of tuna populations in one region, and comparing this to an un-fished region. In the end, this was not considered to be politically, logistically, or possibly even scientifically feasible. They recommended instead comparing seabird populations at already existing heavily-fished versus not heavily-fished areas to investigate the response of seabird populations. This would require high-resolution and detailed fishery data, as well as monitoring of seabird populations over the chosen time frame.

7.2.3 Fishery data for understanding basic patterns of the interaction over the long-term

Participants recommended collaboration with regional fishery management organizations (**RFMOs**) such as the Western and Central Pacific Fisheries Commission (**WCPFC**) to accomplish a number of the above goals. They suggested that such collaboration would allow for the most efficient integration of fishery statistics with bird distribution and breeding success, and help both NOAA and WCPFC gain a better understanding of the ecosystem in a larger context. Participants also highlighted the importance of having fine-scale fishery data in order to answer the above questions, but stressed that obtaining these data might be difficult given issues of confidentiality.

7.3 Recommended approach

Participants recommended the use of at-sea surveys on a time-scale of approximately every five years for general cruises, and recommended that this integrated work be part of the cruises identified in the previous sections. They also suggested that it may be possible to piggyback this work on efforts by the International Sustainable Seafood Foundation (**ISSF**)[11] which conducts cruises in most ocean basins. The main focus of these cruises is to reduce bycatch in purse seine fishing, but this research involving tuna-seabird interactions may be of interest to them as well.

To compare heavily- versus lightly-fished regions, participants suggested a number of potential comparative areas including:

- Tuvalu (high fishing) versus Christmas Island (low fishing)
- Heavily fished regions of Kiribati (high) versus Palmyra Atoll (low)

[11] http://iss-foundation.org/

- Hawaiian Islands (high) versus Wake Atoll or Johnston Island (low)
- Jarvis Island (high) versus Howland and Baker Islands (low)

They also suggested looking at the newly-formed high seas 'donut holes' in the Western Central Pacific that are now off limits to fishing.

Participants recommended drafting a white paper of relevant questions in studying the seabird-subsurface predator interactions, to discuss at the scientific and technical meetings of the WCPFC. They suggested that this white paper might include simple maps of bird distributions to begin the conversation based simply on spatial overlap between PRIM species and fishery distribution. Workshop participants suggested that by highlighting the breeding distributions of birds of interest to PRIM management, we could identify a small spatial and temporal footprint necessary to do the appropriate analyses, reducing the size of the 'ask' from the RFMOs such as WCPFC. If data associated with breeding birds does not explain the patterns we are trying to investigate, the data region can be expanded to include other areas and stages (i.e., non-breeding, pelagic stages). Participants also noted that it might be possible to obtain finer-scale data by going directly to individual boat owners.

7.4 Supplementary methods

7.4.1 Ecosystem modeling

Participants identified ecosystem modeling as an additional method that could be used to look at the ecosystem-level impacts of subsurface predator-facilitated foraging, and what perturbations to the abundance of these species or changes in the oceanographic conditions may mean for seabirds and the larger ecosystem. They highlighted a number of models and previous studies as successful examples of ecosystem modeling. Patrick Lehodey (2001) created a spatial environmental population model (**SEPODYM**) that was applied to evaluate the response of tuna species to environmental variables such as sea surface temperature, oceanic currents and primary productivity using a coupled physical-biogeochemical model (Lehodey et al 2003). Ecosim models can similarly be used to look at large-scale ecosystem responses such as trophic dynamics, as has been done in the Central Pacific (Cox et al 2002) and elsewhere in the world.

8 Conclusion

Over the course of the three-day workshop, participants were able to: identify key research questions, suggest appropriate methods and experiments, and clarify a path for managers to attempt to understand the complex interaction between seabirds and subsurface predators. The lack of baseline information available for the region is a significant obstacle to understanding this interaction, and thus almost any research on seabirds will benefit managers. There is no doubt that teasing out the extent of ecosystem-level impacts of fishing on seabirds, if any exist, will be difficult, and will require a significant financial commitment and the talents of many diverse scientists and research programs. The managers of the PRIM are in a unique position of being able to foster this ecosystem research. Participants noted many times over the course of the workshop the importance of the topic, both scientifically and in terms of management, and many also expressed their enjoyment at having the opportunity to interact with scientists in other fields with which they rarely come into direct contact. In a workshop evaluation form, the respondents all agreed that we had met the objectives of the workshop, and strongly agreed that the workshop would benefit their future work. We hope this document will aid in developing a relevant research program and guide future management objectives and decisions.

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10 Appendices

10.1 Appendix 1: Research priorities matrix

Workshop participants were asked to rank potential methods that could be used to research topics and objectives identified relevant to various components of seabird-subsurface predator interactions. They were asked to choose and rank three methods for each topic, ranking most appropriate or impactful method as a three (3).

Participant	1	2	3	4	5	6	7	8	9	10	11	12	13	14	Sum
Seabird Distribution															
Tracking studies of key species	3	3	2	3	3	3	3	3	3	2	3	3		3	37
At-sea surveys			3	2	2		2	2	2	3	2	2		2	22
Isotopes		2	2	1	1	1	1								8
Using ships of opportunity to sight streamers on breeding birds															0
Integrate fishery statistics with bird distribution, breeding, etc; involve RFMOs	2	1							1		1	1	1		7
Synthetic studies of existing bird data to link with oceanography through remote sensing														1	1
School dynamics						2		1					3		6
Comparative study: high vs. low predator abundance	1									1			2		4
Fish Distribution															
Examination of fishery landings data		2		3	3				2	2			3	1	16
Analyze existing data for Near Island Catch Competition			3			3	3	3							12
Electronic spaghetti tags			2			2	2	2	1						9
Pop-up tags							1					1			2
Implanted archival tags															0
Acoustic tags			1												1
Double tags	2	1		1	2					3					9
Skipjack tagging studies						1					2	2		3	8
Mahi mahi stock assessment								1			1			2	4
Oceanographic proxies for tuna distribution		3		2					3			3	2		13
Mid-trophic/micronekton sampling (nets primarily but acoustic in the future)	1										3				4
Survey fish distribution at-sea using 'bird piles'	3				1										4
Diet samples for tuna from canneries (known locations)															0
Ecosim modeling (Martell et al)															0
Seabird diet															
Simultaneous seabird and pelagic fish diet sampling (purse seine boat or ISSF)	2		1	3	3	3	3	3	3			3	3		27
Stomach samples from birds on island		1	3					2	1	2	2	1	1	3	16

Participant	1	2	3	4	5	6	7	8	9	10	11	12	13	14	Sum
Fatty acids															0
Stable isotopes	1		2	1			2	1	2	3	3	2	2		19
DNA analysis using seabird excreta														2	2
Guano deposits														1	1
Studies on forage fish species	3	3			2	2	1								11
Historical isotope samples to look at changes in diet through time															0
Diet analysis from skipjacks at Canneries		2		2		1				1	1				7
Reproductive performance															
Satellite imagery (breeding and abundance)		1	3	2	2	3		3		3	3	3			23
On-island cameras (breeding and abundance)		2		3	3		1		3				1		13
Remote-control drones (breeding and abundance)						2				2					4
Radio telemetry for foraging effort	1							2	2			2	2	3	12
Mass gain studies for foraging effort						1						1			2
Satellite tracking for foraging effort	2				1		2			1	2			2	10
Long-term seabird monitoring programs at Wake, Johnston, Palmyra	3	3	2	1			3	1	1		1		1	1	17
Long-term behavior & reproductive performance on individuals															0

10.2 Appendix 2: Research opportunities matrix

	High	Mid	Low	Global	Regional	Local	High	Mid	Low	Low	Mid	High	Single	Rare	Occasional	Frequent
Study or Method	Directly informs mgmt	Informs mgmt with some inter-pretation	Baseline knowledge	Knowledge at other sites sufficient	Knowledge in the CPO sufficient	Requires site-specific knowledge	Simple, established methods	Established methods but complex studies	New, less established method	< $75k	$75-200k	> $200k	Only one study needed	Need to repeat every 5+ years	Need to repeat every 2-5 years	Need to repeat every year
Seabird distribution methods																
Satellite tracking studies of key species	1					1	1				1				1	
At-sea surveys	1					1	1					1		1		
Isotopes		1				1	1			1				1		
Fish distribution methods																
Electronic spaghetti tags	1					1		1				1			1	
Pop-up tags	1					1		1				1			1	
Implanted archival tags	1					1		1				1			1	
Acoustic tags	1					1		1				1			1	
Double tags	1					1		1				1			1	
Skipjack tagging studies	1					1		1				1			1	
Seabird diet																
Simultaneous seabird / fish diet sampling	1				1				1		1		1			
Stomach samples from birds on island	1					1	1				1				1	
Stable isotopes		1				1	1			1				1		
Reproductive performance																
Satellite imagery (breeding, abundance)	1					1			1	1						1
Long-term seabird monitoring programs	1					1		1				1				

10.3 Appendix 3: Workshop Attendees

Name	Title	Representing
David Ainley	Senior Marine Wildlife Ecologist	Last Ocean/ HT Harvey
Lisa Ballance	Seabird ecologist director protected resource division	NMFS, SWFSC
Chris Boggs	Fishery Biologist	NOAA Fisheries
Eric Breuer	Oceanographer	NMFS/PIFSC
Paul Dalzell	Senior Scientist	WPRFMC
David Duffy	Professor	UH PCSU
Beth Flint	Wildlife Biologist	USFWS

Name	Title	Representing
Aaron Hebshi	Navy Biologist	UH
Heidi Hirsh	Natural Resources Manager	NOAA-NMFS
Kim Holland	Researcher	HIMB
James Hong	Intern	Monuments FWS
David Hyrenbach	Professor	HPU
Alvin Katekaru	Assistant Regional Administrator	NMFS PIRO
Shelly Magier (*Note taker*)	Intern	Marine Conservation Institute
Sara Maxwell (*Facilitator*)	Postdoctoral Fellow	Marine Conservation Institute
Lance Morgan (*Facilitator*)	Vice-President for Science	Marine Conservation Institute
Maura Naughton	Regional Seabird Biologist	USFWS-migratory Birds
Katie Nichols (*Note taker*)	Resource Manager	NMFS monuments
Patricia Pinto da Silva	Lead Monument Program	NOAA-NMFS
Dan Polhemus	Program Manager	USFWS
Kim Rivera	Coordinator	NOAA-NMFS
Scott Schaffer	Assistant Professor	SJSU
Michael Seki	PIFSC Department Director	NMFS/PIFSC
Noriko Shoji	Science Operations	PIFSC
Mike Tosatto	Regional Administrator	NOAA-NMFS
Susan White	Project Leader	Monuments FWS
Hillary Young	Research Biologist	Stanford University
Lindsey Young	Wildlife Biologist	Pacific Rim Conservation
Kevin Weng	Project Manager	UH-PFRP