

**State of California  
Natural Resources Agency  
Department of Fish and Wildlife  
Wildlife Branch**

**Long-term Analysis of California Least Tern Data**

**By**

**R.L. Lewison and D.H. Deutschman**

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**Nongame Wildlife Program, 2014-02**

# **Final Report**

To

State of California  
Department of Fish and Wildlife  
South Coast Region  
3883 Ruffin Road  
San Diego, CA 92123

## **Long-term Analysis of California Least Tern Data**

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State of California  
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Department of Fish and Wildlife

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### ABSTRACT

Substantial resources have been used to monitor the California least tern (*Sternula antillarum browni*; LETE) since it was listed as endangered in 1970. This report contains a suite of analyses designed to address two tasks: (1) identify population trends and drivers of those trends and (2) evaluate current monitoring and management practices. We focused our analysis on 24 sites (index sites) that have been consistently monitored from 1990 to 2013. These index sites account for 99.2% of nests monitored during this time period. We evaluated trends in population size and per capita productivity metrics including eggs, hatches, and fledglings. In this report, we define per capita rates as the number per nest although the results would be similar if we used numbers per breeding pair since breeding pairs and nests are highly correlated.

Quadratic regression models provide strong evidence of the recent decline in the number of breeding pairs statewide. The number of fledges per nest also has declined significantly across the state. There was no detectable trend in eggs or number of hatched eggs per nest. These measures of productivity were not significantly related to colony size or latitude with one notable exception. The number of fledglings per pair increases significantly with latitude. In other words, fledglings per pair is higher in the north than the south.

We evaluated whether changes in productivity were density dependent. We found almost no evidence of density dependence. Potential density dependence was observed in only 3 models (out of 72) and these results were weak and erratic. We also considered whether there was any evidence that total mortality or recorded predation exhibited density dependence. The spotty data available exhibited no clear evidence of density dependent predation in egg or chick/fledge mortality as a function of breeding pairs. From both analyses, we conclude that there is no strong and consistent evidence of density dependence.

Abiotic drivers are environmental fluctuations that are often driven by broad scale processes like El Niño (ENSO) or the Pacific decadal oscillation (PDO). We explored the relationship between fledges per nest and these large-scale oceanographic processes. We found the ENSO was modestly and positively correlated with fledges per nest.

We used stable isotope analyses from egg membranes and albumen from salvaged eggs. We determined the relative contribution of expected prey sources from the stable isotope signatures of LETE diet items including rockfish, squid, saury, anchovy, perch, topsmelt, staghorn sculpin, goby, blue mud shrimp, yellow shore crab and krill. Krill, saury, rockfish and topsmelt were found to comprise the largest proportional contribution to LETE diet in all years. We found evidence of differences in diet proportions among years and we did find some suggestive correlations between upwelling, ENSO, PDO and the observed percent of krill, topsmelt and saury in the LETE diet, although these relationships are still not well resolved.

We used LETE banding data compiled by the Bird Banding Lab from 1955-2011 to try and evaluate age-dependent survival rates, age-structure, and movement rates. Banding data included 60,490 records but only 577 (0.95%) captures of known age birds. We used joint live encounters and dead recoveries to model survival, recapture, and recovery probabilities of LETE. There were no significant differences in vital rates through time or across areas. The lack of significant findings is explained entirely by the lack of data. Although banding levels have been high, recapture effort has been extremely low.

Conceptual models are an important part of the adaptive management process and serve to strengthen the process by articulating and documenting the current understanding of how the system works. We constructed two conceptual models using a participatory, inclusive process that included a comprehensive review of existing literature, reports, and expert opinion to capture best-available science and knowledge. To ensure that these models would be accessible to people who had not participated in model construction, we created a complete narrative (i.e. translational document) that provides the justification and rationale for the model structure and components.

There is a clear need for standardized data collection into a searchable database. The current effort by the California Department of Fish and Wildlife (CDFW) to improve and standardize data recording (datasheet) and reporting (central database) will improve the accuracy and consistency of estimates of nests and breeding pairs. In the past, the ratio of effort directed to data collection and to data analysis was skewed (i.e. there was tremendous effort to collect data and relatively little effort dedicated to data analysis).

The comprehensive synthesis and rigorous evaluation of the data contained in this report is an important piece of the adaptive management feedback cycle and one that has been largely overlooked for the duration of the statewide LETE monitoring program. Based on our analyses, we recommend:

- Adopting the new data collection and reporting protocol deployed by CDFW in 2013;
- Decreasing emphasis on number of eggs per nest;
- Increased emphasis on fledgling monitoring using the improved chick classification method;
- Improved vital rate monitoring through a well-designed and coordinated recapture effort;
- Exploring new methods of colony monitoring like video or pellet and isotope analyses; and
- Rebalancing the effort directed to data collection and analysis to include more frequent comprehensive analyses.

<sup>1</sup>Lewison, R.L. and D.H. Deutschman. 2014. Long-term analysis of California least tern data. California Department of Fish and Wildlife, Wildlife Management, Nongame Wildlife Unit Report, 2014-02. Sacramento, CA 29pp + App.

## INTRODUCTION

Since the California least tern (*Sternula antillarum browni*; LETE) was listed as endangered in 1970, there has been considerable effort to recover the population (1). The number of breeding pairs has gone from just 624 in 1973 to approximately 5000 in 2013 (CDFW 2014). Although this shows significant progress towards recovery of the species, the increase in breeding pairs meets only one of the three recovery targets specified by US Fish and Wildlife Service (2). Additionally, while the number of breeding pairs has increased substantially, reproductive output has been reported to be decreasing (3).

Despite nearly 40 years of continuous data collection on LETE, there have been very few comprehensive analyses of collected monitoring data. Yet, comprehensive and robust data analyses are needed to identify population patterns, explore population dynamic processes, evaluate management efficacy, and direct future monitoring and management efforts.

This effort was designed to address the need for robust and comprehensive data analysis of the long-term LETE monitoring data. The current analyses were designed to address two primary tasks: **identify population trends and drivers of those trends** and **evaluate current monitoring and management practices**. This report is organized according to this task/subtask structure:

### **Task 1. Analyze existing LETE data to identify population drivers**

- a) Conduct trend analyses on existing colony data to identify patterns in and potential drivers of population parameters over time
- b) Quantitative exploration of abiotic and biotic variables that influence reproductive output.
  - i. Identify the relative influence of density-independent food limitation on annual reproduction metrics.
  - ii. Evaluate annual shifts in forage consumption and links to reproductive output.
  - iii. Consolidate, integrate and analyze available banding data.
- c) Map changes in statewide colony sizes over time.
- d) Develop a conceptual model that builds on Task 1 analyses and current literature to inform adaptive management of LETE.

### **Task 2. Evaluating the current monitoring protocols and colony management**

- a) Quantitatively evaluate reliability/bias in the different colony metrics (# of fledglings, nesting pairs, etc.).
- b) Develop recommendations for modification of monitoring and data collection protocols as well as potential changes to the LETE recovery plan and identify critical needs for research going forward.

## METHODS, RESULTS, AND DISCUSSION

### Task 1a. Identifying population trends and potential drivers

#### Data filtering

The first step in trend analyses is data filtering or data cleaning. In a standard trend analysis, an analyst may look for outliers, atypical data points that may not represent the pattern of the whole. In the LETE context, the issue is largely one of identifying which nesting colonies have received the most consistent sampling effort for the longest period of time. Using the CDFW meta-data, we constructed a sampling grid (Figure 1) to map where and for what years LETE data had been collected. This sampling grid denotes sampling effort by site and decade. There are a few larger sites (e.g. Camp Pendleton) that are comprised of multiple subsites. For this analysis, these are treated as a single site for two reasons. First, subsite reporting was inconsistent so data often had to be pooled to the larger unit. Second, the larger site reflected a relevant physical and management unit delineation. We used this grid to identify both the sites and the time period for the trend analysis.

Temporally, we focused our attention on 1990-2013. We identified this as the time period where the population dynamics and the associated drivers were not clearly characterized or understood, e.g., previous research quantified the population response of the population in the time period following its classification as a listed species under the Endangered Species Act (4). With this time designation, we then turned our attention to identifying which monitoring sites were appropriate for trend analyses. This site filtering step is important. If the goal is to detect trends over time, the analysis needs to compare sites that were consistently monitored over the time period. An analogy for this comes from the business world when calculating same-store sales. By comparing same-store sales, a company is demonstrating that sales data from a fixed set of stores (i.e., excludes new stores or stores which have closed), the trend analysis avoids comparing data among years that are fundamentally incomparable. The same-store sales designation is important because it reflects a true change in sales rather than an increase or decrease in the number stores. Similarly, the designation of index LETE sites creates a comparison of population changes that reflect a true change in population dynamics rather than an increase or a decrease in the number of monitored colonies. It is important to clarify that sites that were not identified as index sites may be critical to LETE population recovery. In contrast to interior (*S. a. athalassos*) and eastern (*S. a. antillarum*) least tern colonies which can move in response to newly created or removed nesting habitats (from storms or floods), California LETE colonies are restricted to existing sites, and all potential habitat is likely necessary to support population viability.

During 1990-2013, 49 sites were monitored for at least 1 year. Many sites have been monitored continuously for this period (24 years, 1990-2013 inclusive). Others have been monitored for only a year or two. We divided the data into two groups. First, we identified sites which had been monitored continuously (or nearly so) for the past 24 years (average = 23.6 years); these sites were identified as major, or index, sites. The remaining sites were monitored an average of 4.8 years out of 24. These sites were not considered in the trend analyses, but were used when calculating state totals. The index sites we identified account for 82.6% of the monitoring records (566/685 site-years). More importantly, they accounted for 99.2% of nests monitored during this 24-year period. The proportion of nests included in this group varied from year to year but never

fell below 98.7%. Dividing the data this way allowed us to analyze the long-term trends from a consistent set of sites. This simplifies and strengthens the analysis but insures little to no loss of information.

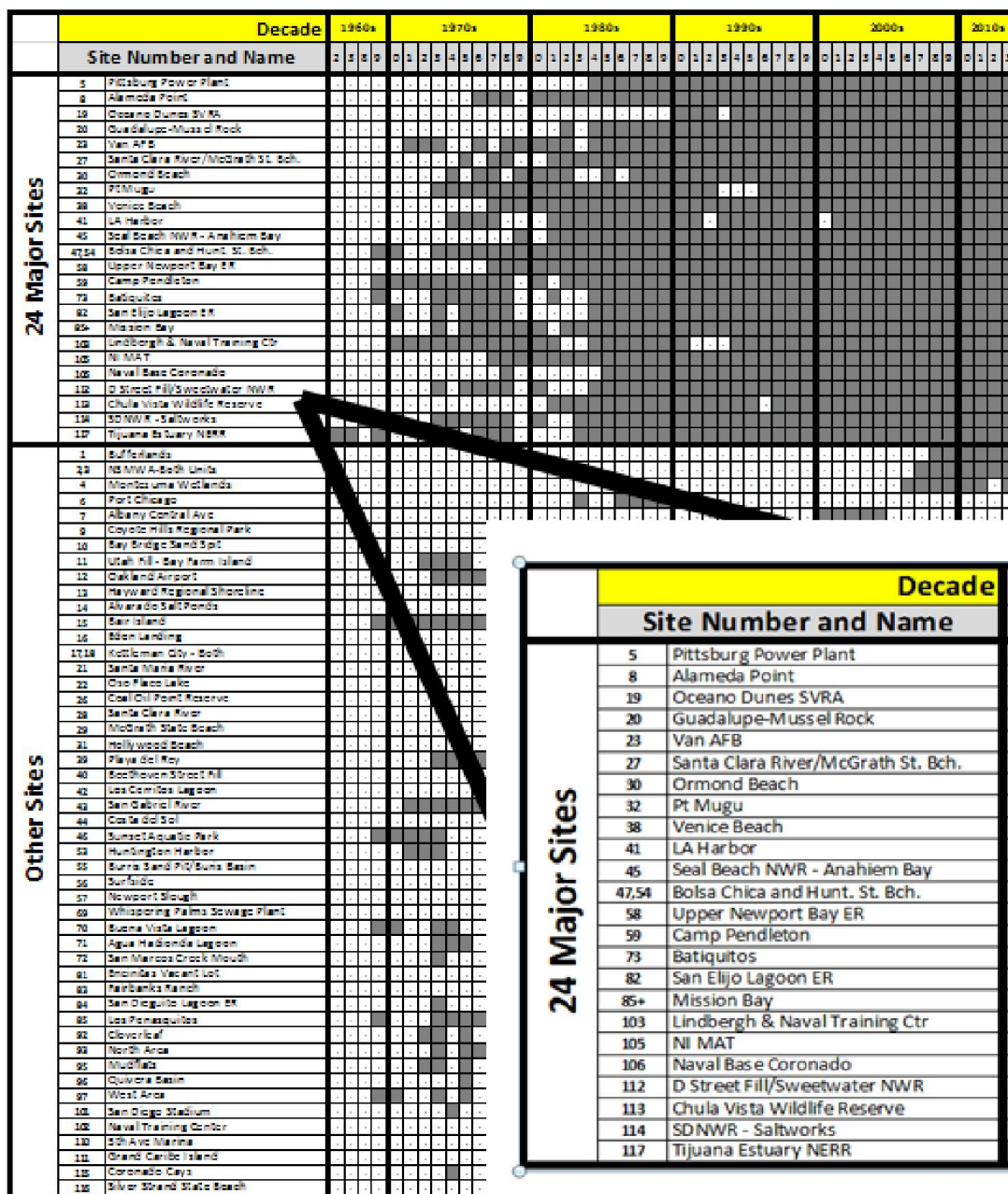


Figure 1. Sampling grid to determine the appropriate sites to use in an analysis of the long-term population trends. This filtering process is important to identify sites where a long-term trend *could* be detected should it exist. See Appendix I for full table.

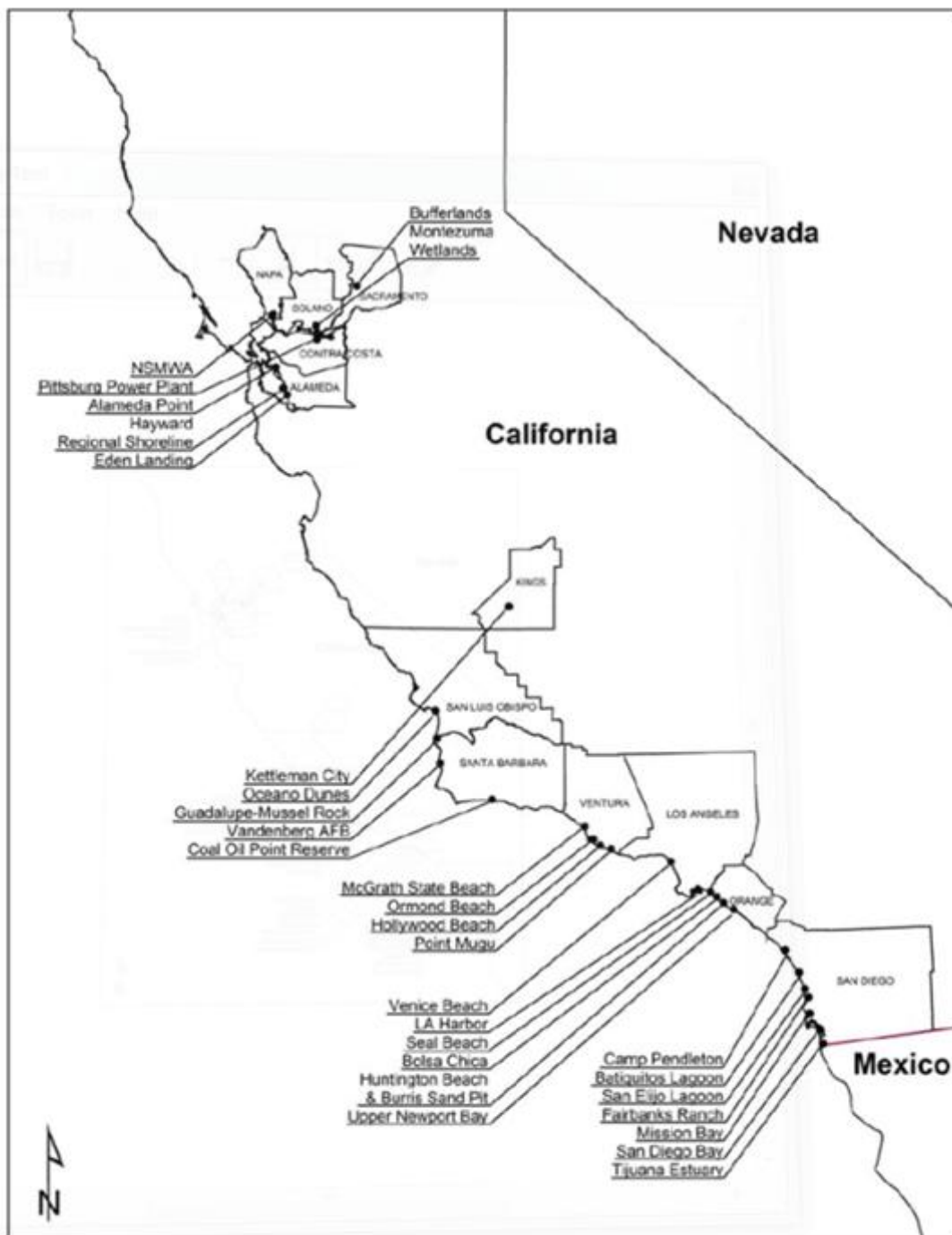
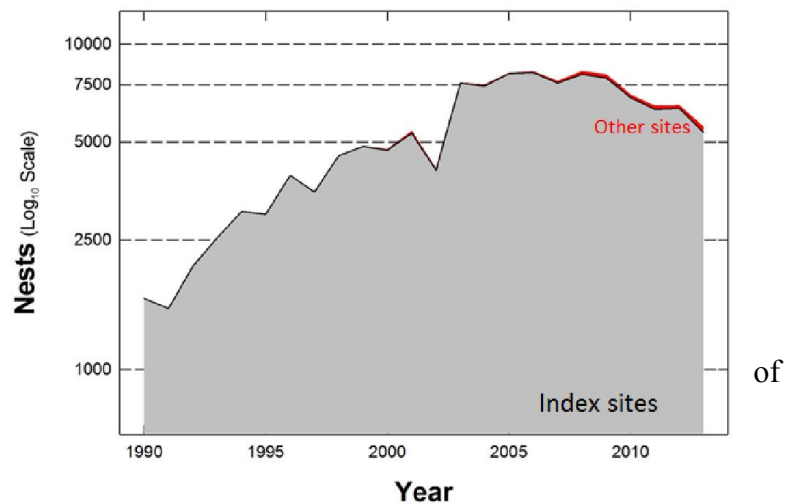


Figure 2. Sampling sites identified as index sites for the trend analyses. The designation was based on sample frequency and consistency from 1990-2013. This group of sites represents both large and small colonies across the range.



Figure 3. A graphical representation of the number of nests ( $\log_{10}$  scale) between 1990-2013 in sites identified as index sites versus other sites. This designation reflects the relative frequency and constancy of sample effort.

We can also confirm the assertion that our index sites capture population performance and output graphically, looking at the percentage of nests that derive from the index sites versus what we are referring to as the non-index, or other, sites. In Figure 3, we see nests on a log scale between 1990 and 2013 from index sites which represent 99% the nests versus the other sites, which represent 1%. While the index site designation may seem unnecessary given the enormous disparity in nest numbers between index sites and other sites, this data filtering is important in the context of trend analysis for the other derived population parameters, e.g., eggs, hatches and fledges.



#### **Population trends: changes at the state level**

With this comparable dataset, we then analyzed the data using linear and non-linear regression to fit trend lines through data to ask whether there were any statistically significant trends in state-wide colony output between 1990 -2013. We calculated these trend lines for the number of nests, as well as the number of eggs, hatched chicks and fledges, with each of the last three measurements represented as per capita. There has been some discussion within the LETE community about whether per capita statistics should be calculated per breeding pair or per nest. Statistically, these are the same. Statewide, nests and breeding pairs are nearly identical ( $r = 0.97$ ,  $R^2 = 95\%$ ). Furthermore, correlations at individual sites average  $r = 0.96$ . Although there may be fluctuations at a given site in a single year, these small-scale fluctuations do not change broad scale trends. In this report, we define per capita rates as the number per nest. For each response variable, we considered line fit (as represented by  $r$  or  $R^2$ ), and whether the trend was significant. We calculated these trend lines for both 1990-2013 and a more current time period, 2000-2013.

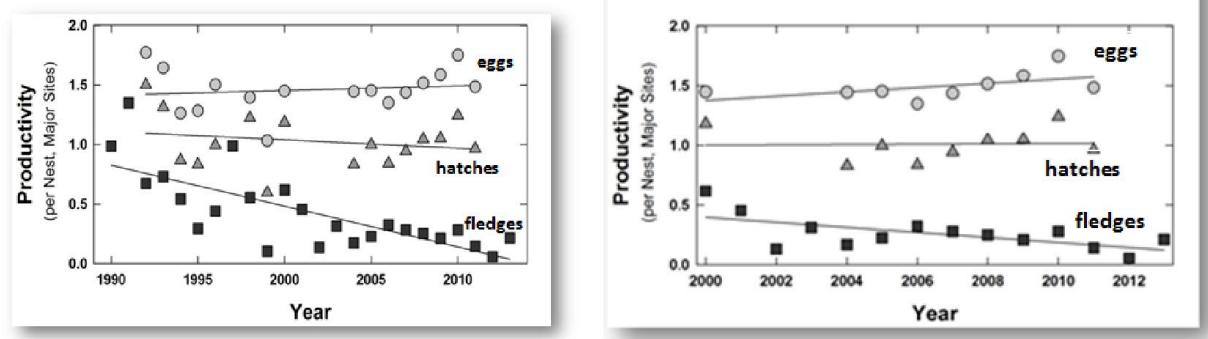
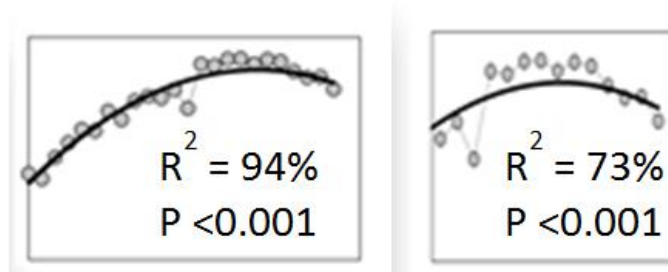


Figure 4. Fitted trend lines of the number of eggs, hatches and fledges per nest for all index sites from 1990-2013 (left) and 2000-2013 (right).

Two population parameters were found to have a significant, detectable trend: breeding pairs, nests and fledge per pair. Breeding pairs showed a significant decline since ~2007 ( $p < 0.001$ ) and best-fit models using long-term (1990 to present) and short-term (2000 to present) data provide strong evidence of the recent decline in the number of breeding pairs.

Figure 5. Quadratic models best fits the number of nests from 1990-2013 (left) and 2000-2013 (right). Both trend lines demonstrate a significant decline in recent years.



The number of fledges per nest also has declined significantly across the state ( $\text{Fledge} = 0.826 - 0.034 \times \text{Year}$ ,  $r = -0.75$ ;  $p < 0.001$ ). There was no detectable trend in eggs per nest (i.e. clutch size,  $\text{Eggs} = 1.413 + 0.004 \times \text{Year}$ ,  $r = 0.14$ ;  $p = 0.607$ ) or number of hatched eggs per nest ( $\text{Hatch} = 1.109 - 0.119 \times \text{Year}$ ,  $r = -0.20$ ;  $p = 0.448$ ).

From these analyses, we conclude that:

- The number of breeding pairs and nests have declined significantly since ~2007 ( $p < 0.001$ );
- Eggs per nest, i.e. clutch size, has remained constant across the state both over the last 20 years and the last 10 years;
- The number of hatched eggs exhibit some year to year variability, but no statistical trend over the time period; and
- The number fledged has been extremely variable over the time period and has declined significantly across the state.

### **Population trends: identifying covariates**

Based on the conceptual model (Task 1d) and existing knowledge on LETS population drivers, we explored two colony covariates to consider whether these variables influence the observed trends.

#### *Colony size and latitude*

We asked whether the detected trends were linked to the size (as measured by the number of pairs or nests present) or latitude of the colony, defined by the existing latitudinal range of colony distribution (see Figure 2). We found that all trends are non-significant as a function of colony size or latitude for both 1990-2013 and 2000-2013 *with the exception of fledglings per pair and latitude* (Figure 6) which increases significantly with latitude. To ensure that the detected relationship was not driven solely by the upper right most data point (the most northerly colony, Alameda), we calculated the relationship both with and without Alameda. The relationship between fledges per pair and latitude was significant whether Alameda was included or excluded from the analysis ( $r \sim 0.70$ ;  $p < 0.01$ ) suggesting that the latitude relationship on fledges per pair is real and robust.

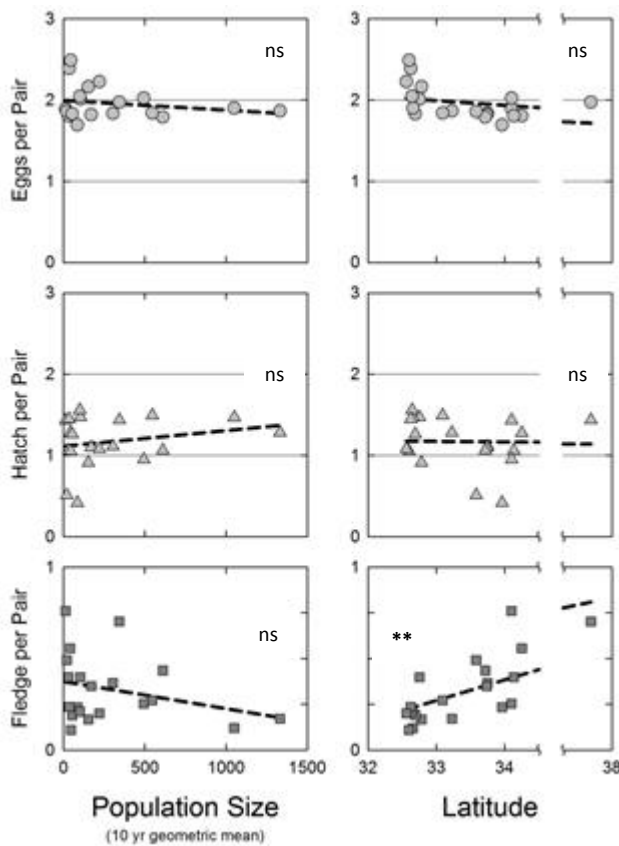


Figure 6. Changes in egg/pair, hatch/pair and fledge/pair as a function of colony size (left) and latitude of the colony (right). ns = not significant, \*\* =  $p < 0.01$

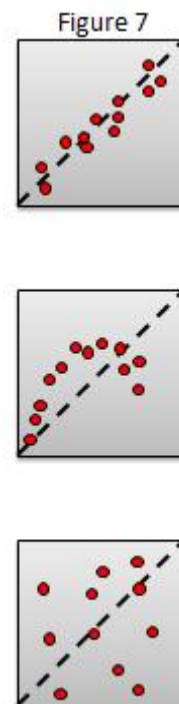
From these analyses, we find that:

- There are no detectable or significant relationships between colony size and latitude for eggs per pair or hatches per pair; and
- Per capita fledges were found to have a significant positive relationship with latitude (fledges per pair increases with latitude), but is not significantly related to colony size. The relationship between per capita fledges was significant even when Alameda (the highest latitude colony) is excluded from the analyses.

## Task 1b. Quantitative exploration of biotic and abiotic variables that influence reproductive output

### Biotic drivers: density dependence

Density dependence has been proposed to serve as a biotic driver that may influence LETA population dynamics. Density dependence is a process by which vital rates (survival/mortality, fecundity) of the population and its growth rate are dependent on the density of the population (5). Intraspecific competition within a population caused by limited space or food resources is a common mechanism of density dependence. If a population is exhibiting density dependence, we would expect to observe a drop in one or more vital rates, i.e., growth, survivorship, fecundity, recruitment, as a population increases. Predation can have a similar negative density-dependent effect, i.e., we observe an increase in predation, and a decrease in survival, as a population increases. A population experiencing density dependence would exhibit a response between population size (x axis) and vital rate (y axis) that resembles the concave pattern seen in the middle graph in Figure 7. Compare that concave response where a vital rate declines as a function of increasing population size to a vital rate that is independent of population size (top graph) or exhibits an erratic response irrespective of population size (bottom graph).



While density dependence is an intuitively basic concept, measuring density dependence in a population is challenging in non-experimental or wild populations (7). To quantify whether LETE populations exhibited evidence of density dependence based on intraspecific competition, we graphed the annual number of eggs, hatches, and fledges as a function of breeding pairs to identify whether at the state or colony level we detected the expected concave relationship. On these graphs we also overlay several recruitment lines. The recruitment lines identify the ratio between the reproductive measure of interest and number of breeding pairs, e.g. 4:1, 3:1, 2:1, 4:3, 1:1. These lines help identify whether there is a clear pattern in reproductive output by capturing the patterns in the ratio of each output parameter to breeding pairs. These relationships are shown in Figure 8. As Figure 8 demonstrates, at the state level, there is no evidence of density dependence, illustrated by the lack of the expected concave curve in any of the measures of reproductive output. We also see that there is a clear pattern of reproductive output for eggs, with egg production closely following a 2:1 relationship, meaning that two eggs are produced for every one pair.

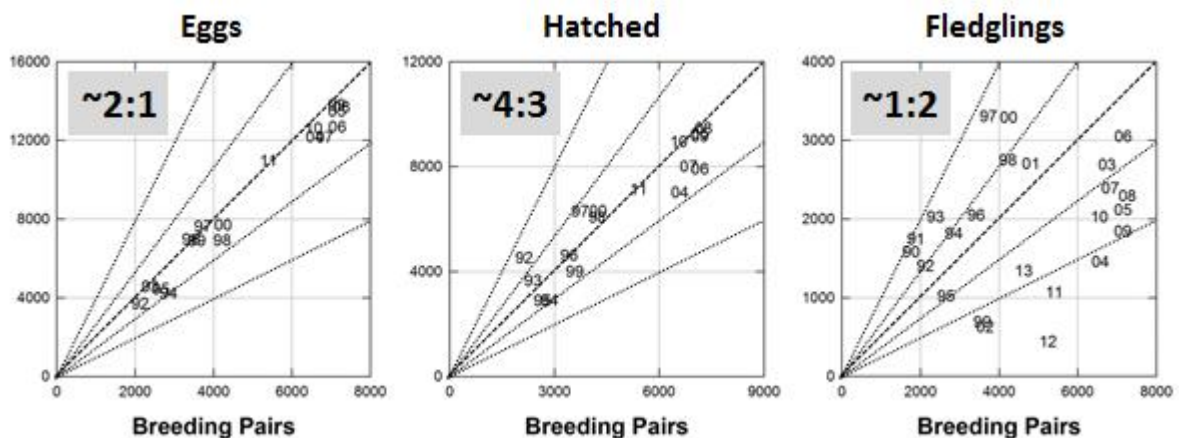


Figure 8. Exploration of state-wide data to determine whether colonies exhibited the expected concave pattern of density dependence. Each data point represents an annual measure of eggs, hatches or fledges. The ratios in the gray box represent the average numerical calculation of output per breeding pair to which each graph is scaled.

For hatches, there is somewhat more variability among years, with years above and below the 2:1 line, with an average of approximately 1.3 hatches per breeding pair. The relationship between fledges and breeding pair typifies the erratic relationship shown in Figure 7 and there is no clear pattern in fledge per pair among years.

To consider whether there was evidence of density dependence at the colony level, we took an analytical approach and fit quadratic models (which capture the concave relationship expected in a population exhibiting density dependence) to the number of eggs, hatches, and fledges per nest and per breeding pair for all of the index sites. Using this analytical output, we investigated any site that had a significant relationship significant at  $p < 0.10$  for a reproductive measure per nest and per breeding pair (see Appendix 2) which would signify a fit of the concave curve to the observed reproductive output. Significant fits of the quadratic terms were only found in 7 of the 72 models evaluated. In four of these, the relationship was concave-up which would indicate a population that has a positive density dependent relationship, i.e. reproductive output increases as breeding pairs increase.

We found three colonies that exhibited the expected concave-down curve relationships, which indicates density dependence. However, these relationships were very weak or demonstrated extremely inconsistent variability among consecutive years (Appendix 2). These weak and erratic relationships confirm the initial assertion that density dependence is not an important biotic driver of LETA reproductive output at the state or colony level.

We also considered whether there was any evidence that total mortality or recorded predation (a constituent of total mortality that is recorded separately in some sites) exhibited density dependence. Data on all types of mortality are recorded or reported inconsistently to the CDFW and as a result there is limited data on predation and non-predation mortality. Predation can have a similar negative density-dependent effect whereby predation increase (and survival decreases) as a function of population size. Unlike the colony data on reproductive output, predation data are not readily accessible. Although many colonies have predation data that are collected by colony monitors, U.S. Department of Agriculture Wildlife Services or other predator control contractors, these data have not been integrated into a common data format or archive, nor have these data been collected or collated into a searchable database. As such, the ability to evaluate whether predation changes as a function of breeding pair or nests is limited at this time. We took advantage of a compilation of predation data that Nancy Ferguson at the U.S. Fish and Wildlife Service had completed to review the relationship between predation-related mortality and number of breeding pairs. Because of the uncertainty associated with classifying a mortality event as predation, we also evaluated the relationship between total mortality (predation plus other mortality sources) and breeding pairs. We fit regression lines to predation and mortality data for eggs and chicks/fledges combined (Figure 9).

As we saw with the reproductive measures, the data available exhibited no clear evidence of density dependence predation in egg or chick/fledge mortality as a function of breeding pairs. Rather, these data suggest a site-specific effect of predation with some sites exhibiting lower predation at higher densities, some showing higher predation at both high and low densities, and some show higher predation at higher densities.

From these analyses, we conclude that:

- There is no evidence of density dependence on reproductive output at the population or colony level; and
- We also found no evidence of density dependent predation or total mortality although the non-centralized management and storage of predation data present challenges to a comprehensive treatment of this question.

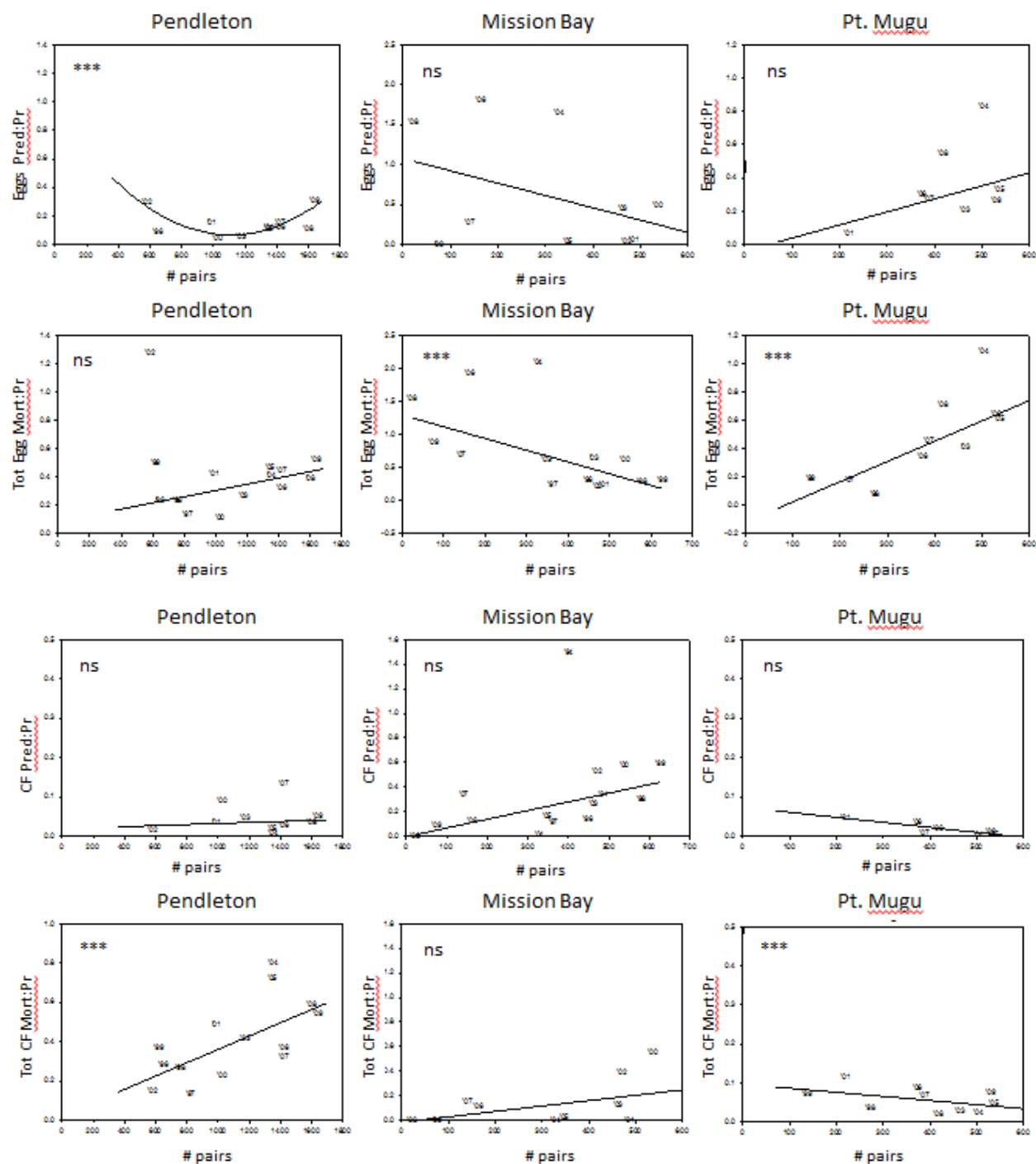


Figure 9. The existing colony predation data exhibited no clear evidence of density dependence in eggs or chicks/fledges (CF) predation or total mortality, as illustrated by three example colonies. Rather, these data suggest a site-specific effect of predation. ns = non-significant, \* and \*\*\* represent the  $p < 0.05$  and  $p < 0.001$  respectively



### Abiotic drivers: environmental variability and changes in prey base

Abiotic drivers are factors that derive from environmental fluctuation or variability. Unlike biotic drivers which vary as a function of inter or intra-specific interactions, environmental fluctuations are driven by local, regional or global climatic, atmospheric or other natural disturbances.

Abiotic drivers have been identified as factors that influence LETE population dynamics (4).

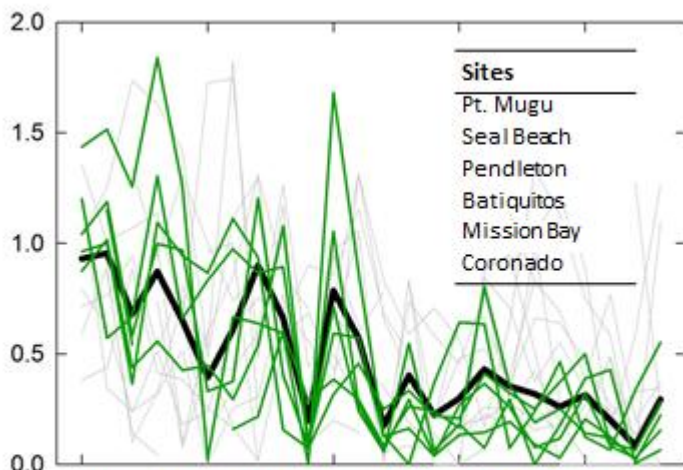


Figure 10. The observed trend in fledges per nest shown as the state average (in bold) and across six spatially distinct colonies (listed, in green)

One of the patterns we observed that highlighted the need to explore abiotic factors as a potentially important driver of LETE population dynamics came from exploration of the pattern of fledges per nest across sites. Because fledges per nest were identified as one of the significant declining trends over times, we asked how congruent this decline was among different sites. A high degree of similarity in the observed trends among geographically separate and or disparate colonies (large vs. small)

across the range suggests there maybe be larger forces beyond site-specific processes influencing colony dynamics.

What we found as we looked across sites was that many sites tracked the state-wide average of fledges per nest in a comparable manner. Another potential explanation of the declining fledges links the declines to the challenges associated with field logistics, i.e. difficulty identifying or locating fledges as the birds become larger and more mobile in colonies with more breeding pairs. If this were to be the case, we might expect highly variable patterns in reported fledge values among sites. However, this pattern of extreme variability did not occur. While there could be other explanations for the observed congruence, one explanation is that these distinct sites are experiencing similar environmental variability.

#### Large-scale environmental variability

We first considered two large-scale sources of environmental variability, the Pacific Decadal Oscillation (PDO) and El Niño–Southern Oscillation (ENSO). Both PDO and ENSO have been documented to influence conditions on the coast of California and have been linked to fluctuations in LETE foraging or reproductive output (Robinette 2004). The PDO is a long-lived pattern of Pacific climate variability, characterized by monthly sea surface temperature variability. ENSO is a bi-phasic oscillating pattern (El Niño – La Niña). In El Niño year, warm ocean water temperatures develop off the Pacific coast of South America and influence the physical and biological oceanographic conditions throughout the Pacific.

Over the past 24 years, ENSO and PDO indices have been positively correlated ( $r = 0.73$ ) although the two environmental forces differ in temporal scale and spatial extent. Temporally, PDO "events" persist for 20-to-30 years, while typical ENSO events persist for 6 to 18 months. Spatially, the climatic fingerprints of the PDO are most visible in the North Pacific/North American sector, while the opposite is true for ENSO. Potentially as a function of the different temporal signatures, we found the ENSO (MEI index) more strongly correlated with fledges per nest ( $r = 0.55$ ,  $p = 0.005$ ) than the PDO.

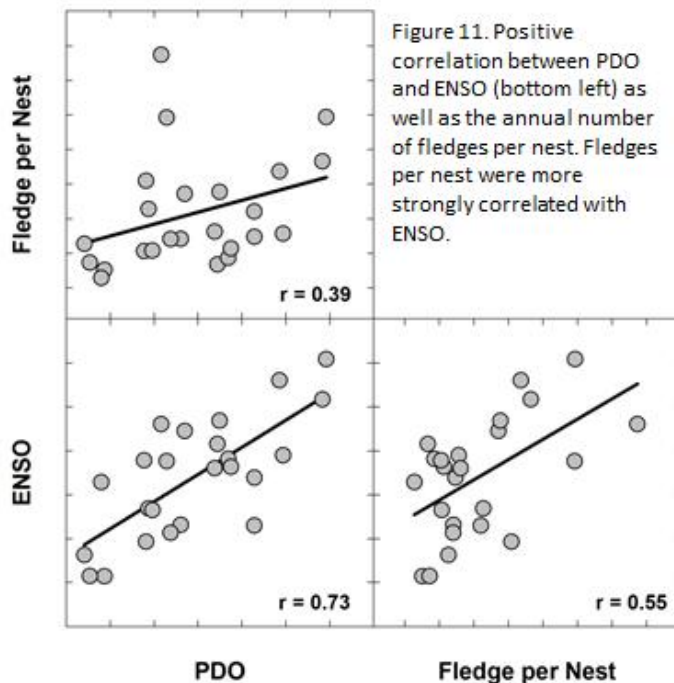


Figure 11. Positive correlation between PDO and ENSO (bottom left) as well as the annual number of fledges per nest. Fledges per nest were more strongly correlated with ENSO.

### Changes in prey base

The observed correlation between ENSO and fledges per nest is interesting but alone is insufficient in pointing to the importance of environmental variability as a driver of LETE population dynamics. We continued to evaluate the potential influence of environmental variables on LETE population dynamics by considering finer scale environmental variability and the potential influence that both large and small scale environmental variability may have on the LETE forage base.

LETE diet has received fairly limited attention in the recent published

literature but published and grey literature has documented LETE diet at particular colonies (see Appendix 3 for annotated list). This diet characterization comes largely from dropped fish records although more recently, direct diet characterization methods have been implemented such as otolith or scale analysis in fecal pellets (See Appendix 3). We opted to use another direct method to characterize diet - stable isotope analyses. Isotopes are atoms with the same number of protons and electrons but differing numbers of neutrons, e.g. carbon can be found as  $^{13}\text{C}$  or  $^{12}\text{C}$  and by looking at the ratio of the heavier to the lighter (more common) form we can characterize an animal's diet. Stable isotope analysis of salvaged samples such as feathers (8), blood (9) and eggs (10) can be used to track foraging patterns with the time scale varying among tissue types. Isotopic ratios of nitrogen ( $^{15}\text{N}/^{14}\text{N}$ , expressed as  $\Delta 15\text{N}$ ) and carbon ( $^{13}\text{C}/^{12}\text{C}$ ,  $\Delta 13\text{C}$ ) have become the most commonly used when characterizing feeding patterns for many types of seabirds. Measurements of  $\Delta 15\text{N}$  have been shown to represent a consumer's trophic level based on enrichment of nitrogen compared to the prey base (11). Measurements of  $\Delta 13\text{C}$  translates into a general understanding of foraging location of consumers based on an inshore/offshore gradient of carbon: the more negative carbon values represent offshore foraging locations (11).



Building on the work initiated by J. Fournier (SDSU), we used egg membranes and albumen from salvaged eggs collected by permitted individuals to conduct stable isotope analyses on breeding females. Egg tissue has been demonstrated to capture the diet signature of roughly two weeks, a similar time period captured by blood tissue. We used the documented relationships and tested methodologies that govern stable isotope research, summarized as “you are what (and where) you eat”, to consider how changes in female diet during egg formation change as a function of environmental variability and whether any observed shifts in diet related to reproductive activity or output.

For this analysis we used salvaged eggs samples from six sites, with substantial sample sizes (> 15) from each site from 2003-2008 (with the exception of CB in 2008, Table 2). For two sites, Camp Pendleton (CP) and Coronado (NB), we had samples from 2003-2012.

	CB	NI	TJ	SB	CP	NB
2003					X	X
2004	X	X			X	X
2005		X				X
2006	X	X	X	X		X
2007	X	X	X	X	X	X
2008	X (2)	X	X	X	X	X
2009					X	X
2010					X	X
2011					X	X
2012					X	X

Table 2. The years and sampling sites used for the stable isotope analyses. CB = Central San Diego Bay, NI = North Island, TJ = Tijuana Estuary, SB = South San Diego Bay, CP = Camp Pendleton, NB = NABO/Coronado. We had 20 samples from each sample site with the exception of CB in 2008.

To interpret the isotopic signatures of the shell tissue, we identified the stable isotope signatures of all recorded LETE diet items either by directly analyzing the forage item or using published isotopic values. This included rockfish, squid, saury, anchovy, perch, topsmelt, staghorn sculpin, goby, blue mud shrimp, yellow shore crab and krill. We analyzed and considered multiple sub-species and age classes (juvenile, adult) within each species group, e.g. *Sebastes* spp.

A large proportion of seabird stable isotope studies use egg membrane, transparent protein membranes that lie between the eggshell and egg white (12). In the process of analyzing the hundreds of data samples, we determined that LETE egg membrane was not a robust tissue type for isotope analysis. This determination was supported by the inconsistent isotopic signatures obtained from duplicate runs of the same sample, primarily for carbon. This was further supported by the lack of congruency between albumen and membrane, two tissue types that should have a high degree of correlation (13). The lack of consistent data from LETE egg membrane may be explained by the thinness of the LETE membrane as compared to other terns and seabirds. Membrane thinness may result in carbon leaching, in which the carbon signal in the membrane is affected by the carbon from the egg shell, or may lead to poor tissue isolation. Irrespective of the cause, we derived a conversion factor based on the observed relationship between albumen and membrane to correct for this effect and convert the membrane carbon values.

Considering all samples from all sites, we used MixSIAR GUI (14), a Bayesian based mixing model, to determine the relative contribution of expected prey sources to stable isotope signatures in LETE egg membrane. MixSIAR determines the relative contribution among different potential prey items. Krill, saury, rockfish and topsmelt were found to comprise the largest proportional contribution to LETE diet in all years. Using this data we ran a general additive model to identify whether the observed diet variability is explained by annual or site differences.

We found evidence of differences in diet proportions among years, most notably large diet shifts in 2005 and 2006 (Table 3). Significant annual variability appears to be largely driven by annual differences in the proportion of krill and saury. However, in addition to annual differences in prey proportions, we also found significant variability in the proportional composition of diet among sites, driven largely by differences in samples taken from South San Diego Bay and Tijuana Estuary where rockfish was a more dominant contribution to diet and krill was not detected.

Table 3. Results from a general additive model to determine whether the changes in diet proportions are explained by annual or site differences for the four dominant prey types.

Krill											
Source	SSQ	df	MSQ	F-Ratio	p-Value	Factor	Level	Mean	SE	N	
YEAR	0.613	9	0.068	3.32	0.014	YEAR	2,003	0.457	0.11	2	
SITE\$	0.757	5	0.151	7.378	0.001		2,004	0.55	0.076	4	
Error	0.369	18	0.021				2,005	0.09	0.108	2	
							2,006	0.193	0.065	5	
							2,007	0.522	0.058	6	
							2,008	0.488	0.058	6	
							2,009	0.359	0.11	2	
							2,010	0.454	0.11	2	
							2,011	0.44	0.11	2	
							2,012	0.393	0.11	2	
						Factor	Level	Mean	SE	N	
						SITES	CB	0.305	0.081	4	
							CP	0.607	0.053	8	
							NB	0.615	0.045	10	
							NI	0.449	0.073	5	
							SB	0.023	0.094	3	
							TJ	0.369	0.094	3	

Saury											
Source	SSQ	df	MSQ	F-Ratio	p-Value	Factor	Level	Mean	SE	N	
YEAR	0.434	9	0.048	3.635	0.01	YEAR	2,003	0.135	0.089	2	
SITE\$	0.25	5	0.05	3.766	0.016		2,004	0.135	0.061	4	
Error	0.239	18	0.013				2,005	0.491	0.087	2	
							2,006	0.388	0.052	5	
							2,007	0.142	0.047	6	
							2,008	0.095	0.047	6	
							2,009	0.165	0.089	2	
							2,010	0.159	0.089	2	
							2,011	0.151	0.089	2	
							2,012	0.147	0.089	2	
						Factor	Level	Mean	SE	N	
						SITES	CB	0.306	0.065	4	
							CP	0.092	0.042	8	
							NB	0.107	0.036	10	
							NI	0.346	0.059	5	
							SB	0.117	0.076	3	
							TJ	0.236	0.076	3	

Topsmelt											
Source	SSQ	df	MSQ	F-Ratio	p-Value	Factor	Level	Mean	SE	N	
YEAR	0.078	9	0.009	1.39	0.263	YEAR	2,003	0.199	0.061	2	
SITE\$	0.097	5	0.019	3.126	0.033		2,004	0.117	0.042	4	
Error	0.112	18	0.006				2,005	0.108	0.06	2	
							2,006	0.133	0.036	5	
							2,007	0.078	0.032	6	
							2,008	0.186	0.032	6	
							2,009	0.25	0.061	2	
							2,010	0.166	0.061	2	
							2,011	0.191	0.061	2	
							2,012	0.243	0.061	2	
						Factor	Level	Mean	SE	N	
						SITES	CB	0.234	0.045	4	
							CP	0.25	0.029	8	
							NB	0.211	0.025	10	
							NI	0.158	0.04	5	
							SB	0.05	0.052	3	
							TJ	0.099	0.052	3	

RockFish											
Source	SSQ	df	MSQ	F-Ratio	p-Value	Factor	Level	Mean	SE	N	
YEAR	0.012	9	0.001	0.052	1	YEAR	2,003	0.162	0.123	2	
SITE\$	0.998	5	0.2	7.848	<.001		2,004	0.157	0.084	4	
Error	0.458	18	0.025				2,005	0.197	0.121	2	
							2,006	0.142	0.073	5	
							2,007	0.201	0.065	6	
							2,008	0.173	0.065	6	
							2,009	0.168	0.123	2	
							2,010	0.166	0.123	2	
							2,011	0.165	0.123	2	
							2,012	0.165	0.123	2	
						Factor	Level	Mean	SE	N	
						SITES	CB	0.049	0.091	4	
							CP	0.013	0.059	8	
							NB	0.024	0.05	10	
							NI	0.025	0.081	5	
							SB	0.677	0.105	3	
							TJ	0.229	0.105	3	

Pearson correlation		
	CP	Coronado
<b>Krill</b>	0.23	0.14
<b>Saury</b>	-0.41	0.03
<b>Topsmelt</b>	-0.21	-0.38
<b>RockFish</b>	-0.43	0.05

Table 4. Correlations between diet proportions and per capita fledges at Camp Pendleton and Coronado

Does this switch in proportional composition translate into a change in reproductive activity or output? The longest time series we have in both colony output and isotope data is for Camp Pendleton and Coronado. As a first step to answer this question, we calculated Pearson correlation between per capita fledges and the proportions of primary diet items for these two sites with the longest data time series (Table 4). The patterns between the two sites are variable but there appears to be some relationship between krill and topsmelt, where krill is positively related to fledge output and topsmelt is negatively related. That said, the relationships are weak

and there is considerable variability unexplained by these two variables. Given the temporal gap between egg formation and fledge production, further exploration of the relationship between diet and other reproductive activity and output measures are needed.

We also explored what environmental shifts may contribute to the observed switch in the LETE diet among years. We considered large-scale environmental variability (PDO and ENSO) as well as a more local measure of environmental variability, the upwelling index. Upwelling describes a process by which nutrient rich water from depth is circulated to the surface and is measured at many stations along the California coast. For this analysis, we selected the 33N 119W station in the Southern California Bight as a location that likely represents coastal conditions for LETE colonies for which we had isotope samples. We used the upwelling anomaly index from April-August, the time period that the birds are present on the colonies (Table 5).

This upwelling pattern may contribute to the observed shift in proportional diet in 2005 and 2006, although there are smaller detectable shifts in the upwelling index in other years as well. Given the temporal scope of the isotope data from egg tissue, which reflects the diet proportion of breeding females during egg formation, it may be more appropriate to consider upwelling within a more narrow time period.































Year	Apr-Aug Upwell	ENSO	PDO
2003	 0.93	 0.25	 1.02
2004	 -1.09	 0.31	 0.57
2005	 -0.82	 0.60	 1.06
2006	 -1.05	 0.10	 0.28
2007	 -0.09	 -0.16	 0.18
2008	 -0.66	 -0.52	 -1.39
2009	 -0.90	 0.39	 -0.81
2010	 -0.02	 -0.12	 -0.12
2011	 -0.04	 -0.70	 -0.96
2012	 0.35	 0.48	 -1.15

Table 5. Three indices of local and large-scale environmental variability: upwelling anomaly index from April to August, El Nino Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO). The yellow shading denotes the two years when we detected the largest shift in diet.

We did find some suggestive correlations between upwelling, ENSO, PDO and the observed percent of krill, topsmelt and saury in the LETE diet, although these relationships are still not resolved (Table 6). Upwelling exhibited a moderate positive correlation with krill and topsmelt, but a negative correlation with saury; ENSO and PDO had the opposite correlations with krill and topsmelt and saury, respectively. ENSO and PDO had positive correlations with saury.

Index	% of diet Krill	% of diet Topsmelt	% of diet Saury
Upwelling	0.49	0.56	-0.52
ENSO	-0.43	-0.34	0.41
PDO	-0.50	-0.56	0.53

Table 6. Pearson correlations between fine and large scale environmental variability and diet proportions. This relationship is still unresolved.

From these analyses, we conclude that:

- There are broad patterns that suggest congruency in population processes among spatially distinct colonies. These congruent patterns may reflect the role of large or local environmental factors;
- Adult female LETE diet can be characterized using stable isotope analyses despite some unique features of LETE egg structure;
- Adult female LETE diet during the period immediately prior to egg laying was primarily comprised of four items: krill, topsmelt, saury and rockfish. Diet composition varies among years and sites;
- There is weak evidence that the observed shifts in breeding female diet is related to changes in reproductive output and activity. However, additional analyses are required to more fully explore this relationship; and
- There is some evidence that observed diet shifts are linked to changing environmental conditions.

### **Estimates of vital rates:**

At the heart of LETE population dynamics and trends in population growth are vital rates, i.e., survival and reproductive parameters. For LETE, and for many species of conservation concern, data of vital rates are limited. The key questions of interest with banding data include:

- Have survival rates (or capture probabilities) changed over time?
- Are there spatial/regional differences in survival rates?
- How much **banding and subsequent recapture effort** do we need to do to be able to make robust rate calculations?

Massey and Atwood (15) estimated survival rates and population age structure of LETE for the time period from 1983-1989 at Venice Beach, California. Survival varied by age class, ranging from 0.81 for younger breeders (2-3 year olds) to 0.92 for older birds (4 or older). Survival to breeding (return rate) for hatchlings was estimated to be 0.16 over the study period. Age-specific survival rates for adult birds appeared to remain constant from ages 4-9 (range 0.87-0.92), while survival rates for 10- and 12-year-old birds were 0.76 and 0.60, respectively. Age structure profiles for breeding LETE were dominated by 3-year-old birds, with 80% of birds between 2-7

years old. The oldest banded bird in the study was 13 years old. Since this study was conducted at only one known LETE colony in California over 20 years ago, re-evaluation of vital rates is warranted in light of additional data collected from banded birds in the last 20 years.

We used LETE banding data compiled by the Bird Banding Lab from 1955-2011 to more comprehensively evaluate age-dependent survival rates, age-structure, and movement rates. Banding data included 60,490 records of LETE originally banded in California and 662 recaptures or resightings. Of these resightings, 577 were of known-age birds. We removed all birds banded in the northern-most sites (SF Bay area) because there has been no targeted recapture effort in this area. We also removed 11 encounters (four in Mexico, five in San Diego County, and two from L.A. County) from the data because they were isolated encounters that were not part of a larger capture effort. We have no information about sampling effort for these incidental data. As a result, they could bias the results. This left 59,004 banded birds and 555 encounters in the database.

We used joint live encounters and dead recoveries (16) to model survival, recapture, and recovery probabilities of LETE over the past 56 years. We modeled survival probabilities as a function of age class (0, 1, 2, and 3+), decade (1955-1969, 1970-1979, 1980-1989, 1990-1999, 2000-2011), area (San Diego County and all others), and additive combinations of the three. We modeled recapture probabilities as a function of age class (1, 2, and 3+), area (San Diego County and all others), capture effort (0 or 1), as well as additive combinations and interactions of the three. Capture effort was set to 1 for 1981-1985, 1991, and 2008-2011 for San Diego County and for 1969-1989 for all other sites. Effort was set to 0 for all other year and area combinations since there was no effort to recapture animals in these locations/years. We modeled recovery probabilities as a function of two age classes (0 and 1+). We ran all combinations of models and used AIC for model selection (17).

We generated age-structure profiles for both live, breeding birds and dead birds, and generated separate profiles for records collected after 2000 to determine if age-structure had shifted as the population grew. Finally, we calculated the distance between banding and encounter locations for all birds that were recaptured or resighted at least once. We divided these distances by the number of years between subsequent encounters to get an apparent average distance travelled per year.

Results showed no significant differences in survival probabilities for the 1, 2, and 3+ age classes, between decades, or between areas (San Diego County and all other colonies). Survival rates for chicks were very low (1.1-16.9%), though given that recovery and recapture rates for 0, 1, and 2-year-old birds were nearly 0, survival rates for these three age classes likely are partially confounded, with estimates for chicks biased low, and estimates for 1 and 2-year-olds biased high. Survival rates for adult (age 3+) birds ranged from 91.4%-94.8% (SE range = 0.013-0.030). Capture probabilities were not different between the two areas, and was estimated to be ~13% (95% CI = 9-18%) for years with targeted capture efforts. Recovery of dead birds was much higher for birds > 1-year old ( $r = 13\%$ ) compared to chicks ( $r = 0.05\%$ ). This is likely due to dead chicks not being collected and reported in the database.

The age profile for all banded birds captured, resighted, or found dead was dominated by 3-year-old birds, with the majority of birds (68%) ranging from 3-10 years old. The oldest banded bird was 23 years old, and average age of all birds was 7.35 years (SD = 4.51). The age profile of live birds captured between 1969 and 2011 (excluding birds found dead) was dominated by 3-year-olds as well, with an average age of 7.85 years (SD = 4.02). Live birds captured after 2000 were older (though not significantly) than all live birds captured (8.39 years, SD = 4.11,  $t = 1.84$ ,  $p = 0.067$ ). The age profile for banded birds that were found dead was much younger than for live birds. Average age for all dead birds was 5.84 years (SD = 5.50) and was dominated by hatch year birds (Age 0). Dead birds found after 2000 were only slightly significantly older than all dead birds found (7.34 years, SD = 5.73,  $t = 2.00$ ,  $p = 0.047$ ).

Movements of LETE ranged from 0-4830 km for banded birds captured, resighted, or found dead between 1941 and 2011. Four birds moved distances near to or greater than 1000 km (range = 936 – 4830 km). All were banded as chicks and found dead ( $n = 3$ ) or in unknown condition ( $n = 1$ ) less than a year later in various locations (Baja, Mexico, Guatemala, and New Jersey, USA). These records were considered as outliers in the dataset. Excluding these long-distance movements, average distance moved by all birds encountered at the colonies (live and dead) was 56.9 km. Apparent average distance moved per year (total distance divided by number of years between encounters) for these birds was 19.0 km/year. Birds encountered live moved an average of 31.2 km total, or 5.9 km/year, compared to 53.2 km, or 16.3 km/year for birds found dead. Hatch-year (Age 0) and 1 year old birds moved an average of 19.9 km (live) and 26.0 km (dead).

From these analyses, we conclude that:

- We have developed a robust analytical structure with which banding data can be analyzed;
- The lack of significant findings is explained entirely by lack of data. Although banding levels have been high, recapture effort has been extremely low (<0.01% of all banded birds have been recaptured);
- There have only been 2 primary recapture efforts (late 1980's [ $\approx 150$ ] and 2008-2010 [396]) and these have occurred in two colony locations. A carefully designed (ideally state-wide coordinated) recapture/resighting effort is required;
- As little data as we have on adult survival, we have even less data on birds < 3 years old (of the recaptures, 68% are  $\geq 3$  yo). There are some efforts underway to address this gap in age class information (e.g. geolocator deployments - T. Ryan 2014, pers. comm.). More off-colony efforts will be required to generate estimates of fledge to < 3 year old survival rates. A centralized database of banded birds that die during the season is also needed to capitalize on the extensive banding efforts and generate robust estimates of young of year survival; and
- We found no clear pattern of inter-colony movement within or among seasons, but this conclusion should be considered tentative given the limitations of the data.

### **Task 1c. Mapping changes in colonies over time: exploring the population network**

Given the spatial distribution of LETE regionally and across the state, one hypothesis has been that colonies are part of an integrated population network in which birds returning to the breeding area (breeders and non-breeders) may move among colonies. Anecdotally, neighboring colonies have reported observing inversely related abundance patterns, i.e., Colony A has a high density of breeding birds whereas an adjacent Colony B has a low density of breeding birds. This

paired or spatially correlated patterning of distribution is important to explore as it may help explain variability in colony reproductive activity and output among years.

We tested this hypothesis analytically rather than visually mapping colony changes as originally planned, because we felt a map would be challenging to interpret. Furthermore, a graphical representation of colony size over time would do little to formally test the hypothesis that colony activity and output demonstrate detectable spatial patterning.

We evaluated this hypothesis of spatial linkages two ways. First we looked at correlations among known paired, or neighboring colonies, namely LA Harbor: Venice Beach, Pt. Mugu: Hollywood, Bolsa Chica: Huntington. We found no evidence of coupled distribution patterns across the

different reproductive measures. Although neighboring or paired sites show uncoupled change, we did find evidence of correlated changes across sites throughout the state, shown in Figure 12. Given the geographical distance among the correlated sites, this pattern may suggest a common environmental driver for LETE population dynamics.

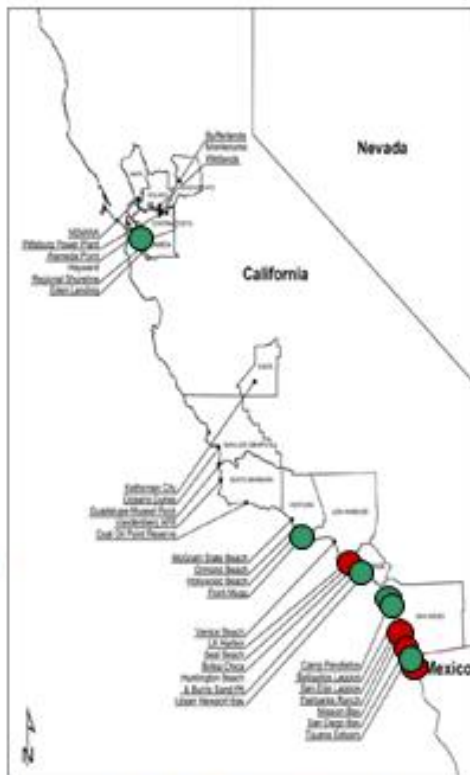


Figure 12. Sites that exhibit correlated (green) and Uncorrelated (red) patterns of change over time

We also considered the question of a spatial population network by employing another analytical method using measures of distance, similarity and dissimilarity to assess whether changes among LETE colonies reflected a linked population network. We used Bray Curtis dissimilarity, Euclidean distance on standardized data, Spearman rank correlation on raw data. This approach is also used to evaluate genetic differences by distance and, as is done with genetic data, we ran Mantel tests to assess reproductive measures as a function of geographic distance (See isolation by distance web service at [ibdws.sdsu.edu](http://ibdws.sdsu.edu) for more information). Based on the results from these three tests, we found no evidence that the number or pattern of nests or breeding pairs varied as a function of distance to neighboring populations at this scale.

These two analyses suggest that there is no evidence of paired or correlated colony performance among neighboring colonies. This finding does not negate the importance of having a network of colonies, with some sites occupied and others unoccupied in any one year. Rather, these results suggests that nesting activity is not correlated as a function of distance to other sites and that neighboring colonies do not function as a colony complex, rather they are influenced by site-specific conditions. This conclusion is supported based on the resolution of the available data.

From these analyses, we conclude that:

- There is little empirical evidence for the colony complex concept, where neighboring sites have linked activity or output;
- Colony metrics were not correlated as a function of distance to other sites; and
- There is evidence of congruent colony metrics among sites across a relatively large spatial area which may suggest common environmental drivers influence colony performance and output.

#### **Task 1d. Conceptual model: models to inform research and adaptive management of California least terns**

Conceptual models are an important part of the adaptive management process and serve to strengthen the process by articulating and documenting the current understanding of how the system works. Whether by a formal model building process or an entirely informal integration of experiential knowledge, the explicit action of recording and documenting the assumptions that guide management and monitoring activity is fundamental to the evolutionary process of learning that serves as the basis for successful adaptive management.

We constructed two conceptual models using a participatory, inclusive process that included a comprehensive review of existing literature, reports, and expert opinion to capture best-available-science and knowledge. These models serve to expedite the learning process that is vital in the adaptive management process by defining the boundaries of the system of interest and providing a foundation from which to generate a focused and effective plan for monitoring and management. Models were constructed and reviewed by numerous LETE experts, including members of the LETE Species Advisory Group and attendees of the 2013 Annual LETE meeting (January 13, 2013).

The first model (Model 1, Figure 13) represents a process-based, system dynamics model. This model aims to capture all the elements that influence LETE population dynamics and as such, the model has many elements and components. The second model (Model 2, Figure 14) is focused on management actions, specifically on manageable elements in the LETE system. Given this more narrow focus, Model 2 has fewer elements and components.

To ensure that these models would be accessible to people who had not participated in model construction or who were not present at the many meetings where these models were formally presented and discussed, we have compiled a complete narrative (i.e. translational document) that provides the justification, rationale for the model structure and components (see Appendix 4). This document also captures all the scientific sources that were used in model construction.



### How can these models be used?

Conceptual models are living documents that require continual evaluation of the current knowledge and best-available science. These models need to be updated to reflect current understanding of the system and allow reassessment of critical uncertainties and management priorities. These models can be used to prioritize research, i.e. which uncertain model elements are most critical to address, to help focus management action and monitoring activity. Each year or at a designated interval, the SAG or another expert team will need to review and update the models to account for new knowledge and information.

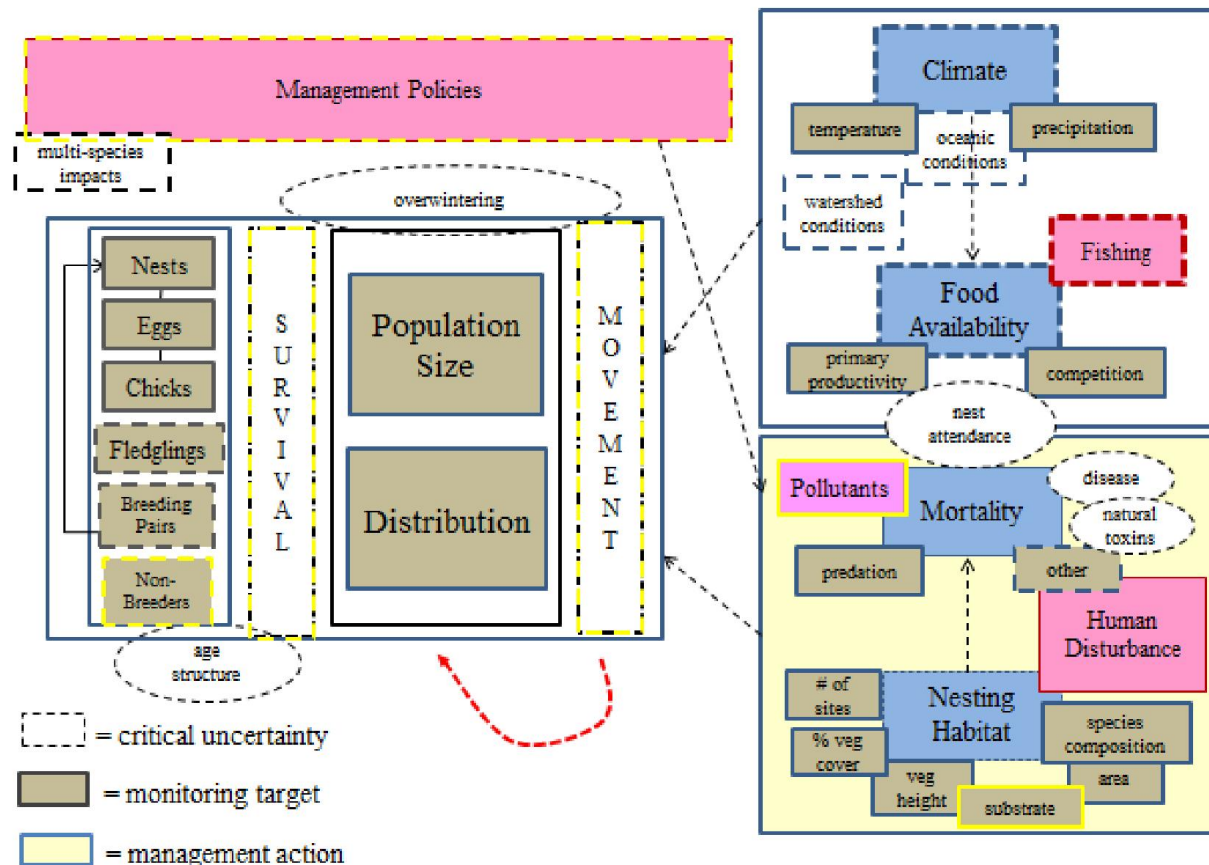


Figure 13. A process-based model of LETS system dynamics designed to comprehensively capture the different elements and factors that influence LETS population dynamics. Items outlined in yellow were added after an open review process prior to the January 2013 LETS meeting.

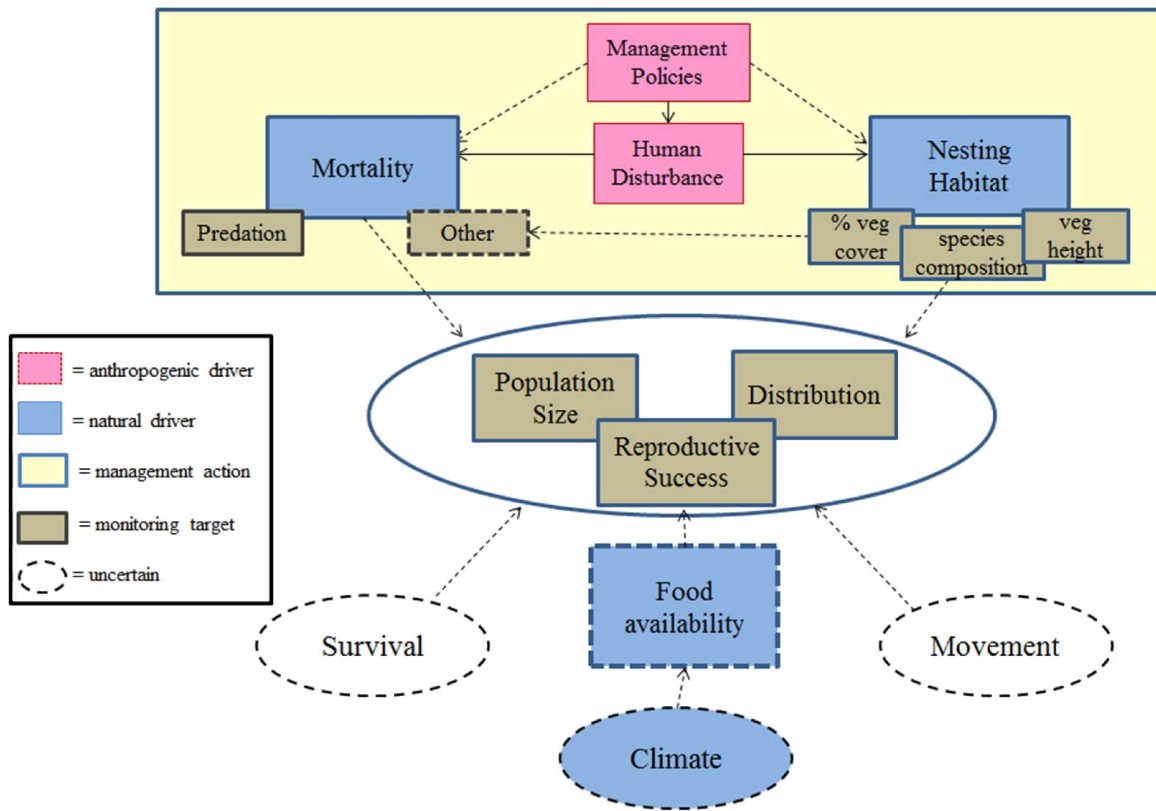


Figure 14. A conceptual model of the LETE system dynamics focused specifically on the elements that can be managed.

## **Task 2. Evaluating the current monitoring protocols and colony management**

To meet or exceed the recovery goals for LETE, a more coordinated, adaptive, statewide monitoring and management approach that can be used across nesting colonies and management jurisdictions will be required. This should not be confused with a “one size fits all” approach which given the diverse management structure, personnel type, and funding levels across LETE colonies and the organizations that management them would not be possible. Rather, the aim should be to ensure that each site is using their resources effectively to collect a minimum, common suite of colony attributes and measurements.

There is a clear need for standardized data collection into a searchable database. The lack of such a database limits the ability to analyze the data that the colony monitors work so hard to collect. In this effort, we made use of all metrics that were reported to CDFW but for many colonies, these data represent a fraction of the data that are actually collected. Likewise, predation data, although reports exist in hardcopy form, must be included in a central database. Without that, the ability to monitor trends in predation pressure or predator control efficacy is limited.

The current effort by CDFW to create a common database for all colonies is promising. This database creation is an important step in addressing many of the limitations in the existing data. The new effort to improve and standardize data recording (datasheet) and reporting (central database) will improve the accuracy and consistency of estimates of nests and breeding pairs. The improved database will allow the statistical estimation of changes in breeding initiation and nesting activity throughout the breeding season and a sequential data record from each colony will obviate the need to pick an arbitrary date for breeding pair estimation. Moving forward, the new database will also provide information on the relationship between nest attendance and colony performance and the parameters needed to characterize the relative impact of predation and other disturbances. Some colony monitoring teams have also been measuring more fine-scale information such as growth rates of chicks over time at their colonies. These data are critical to understanding the factors that influence colony performance and, to date, have not been included in a robust, comprehensive analysis framework. A detailed record of the mortality of banded individuals, which are needed to improve survivorship estimates, may also be collected by many monitoring teams but are not reported to CDFW.

A central finding of this analysis effort is that the current ratio of effort directed to data collection and to data analysis is skewed, i.e. there has been a tremendous effort at data collection and relatively little effort dedicated to data analysis. There is no question that consistent, well-executed, and standardized data collection at index sites (which can change over time as colonies monitoring changes) is essential to tracking the population trajectory of LETE. However, without periodic, robust and comprehensive data analyses, it is virtually impossible to use these monitoring data to inform statewide LETE management and to support the monitoring and management process.

## CONCLUSION

The comprehensive synthesis and rigorous evaluation of the data contained in this report is an important piece of the adaptive management feedback cycle and one that has been largely overlooked for the duration of the statewide LETE monitoring program. We recommend the following modifications of monitoring, data collection protocols and data analyses and have identified the following critical needs for LETE research and the LETE recovery plan going forward:

- The new data collection and reporting protocol deployed by CDFW in 2013 is an important development in that it provides the standardization that is needed in documenting population change over time and potential drivers of that change. Predation and mortality data and predator control data must be included in this central database. Without that, the ability to monitor trends in predation pressure, the relative importance of predation relative to other threats or pressures on the colonies or the efficacy of predator control is limited.,
- The number of eggs per nest has exhibited no significant change since 1990. If this is low-cost data to collect, continued collection of this parameter is reasonable. However, if collection of these data uses substantial resources, colonies should consider recording this data for a representative subsample within the colony and re-allocating these resources to other data collection needs. This is particularly relevant for the large colonies which, even with an easy to collect data type, may expend substantial personnel resources to obtain a metric that has varied very little over time;
- The number of fledges per nest or the estimate of total fledglings is a critical and highly variable metric. Much of this variability stems from the inherent challenges of censusing and monitoring a mobile and sometimes cryptic age class. An improved and standard chick classification method (as discussed by K. Miner at 2014 LETE meeting) can help reduce uncertainty in this metric as can range-wide use of the same fledge calculation method. At large colonies, fledge monitoring should be reduced to index areas or subsites (subsampling) rather than attempting to monitoring the entire colony. Having a single monitoring team deployed to record this particular metric statewide may be worth considering. This could be linked to the recapture efforts (see next comment);
- Improved vital rate monitoring is essential to track population growth. Banding data paired with well-designed, coordinated and representative recapture efforts are needed to improve vital rate estimates. Without this approach, there will be little return on investment from banding data. The sampling design needs to be guided by very clear objectives (i.e., How precise do survival or movement estimates need to be? For what ages? Do these rates vary spatially or through time?) to ensure there is adequate power to answer the identified questions;
- Although we found no evidence of density dependence in the dataset, the relative importance of other drivers of population change remain uncertain. It is likely these differ among sites, e.g., at some sites predation may be extremely important whereas at others

human disturbance may be a key driving force. Without an electronic database into which standardized data fields are inputted, a detailed analysis of the relative importance of these site-specific drivers will not be possible;

- New methods of colony monitoring warrant attention. Continued development of direct diet monitoring from pellet and isotope analyses is needed to determine the potential influence of changes in diet or foraging locations on colony performance. Video monitoring is also a new method of colony monitoring that should be explored immediately, particularly at sites with an existing fence line. The use of infrared micro-video cameras to observe focal nests can provide data that no other monitoring method can duplicate including data on predation rates, correct identification of predators, observations of anti-predator behavior, and nest attendance; and
- One of the central findings from this analysis effort is that the current ratio of effort directed to data collection and to data analysis is skewed, i.e. there has been a tremendous effort at data collection and relatively little effort dedicated to data analysis. Synthesis and comprehensive analysis of the methods, data, and our conceptual model of LETE population dynamics should occur regularly. These periodic reviews are often strongest when they are performed by external experts. The timing will depend on the quantity and quality of new data as well as the status of LETE populations. We expect that the information on the nature and causes of LETE population change should be re-assessed in 3 to 5 years based on the data in this report and some of the current or new initiatives.

## Appendix 1

### Exploring colony-specific density dependence

To consider whether there was evidence of density dependence at the colony level, we took an analytical approach and fit quadratic models (which capture the concave relationship expected in a population exhibiting density dependence) to the number of eggs, hatches, and fledges per nest and per breeding pair for all of the index sites (Tables 1-3). Using this analytical output, we investigated any site that had a significant relationship at  $p < 0.10$  for a reproductive measure per nest and per breeding pair.

	Site	Per Nest				Per Breeding Pair			
		Coef ( $10^{-3}$ )	SE ( $10^{-3}$ )	t	p-value	Coef ( $10^{-3}$ )	SE ( $10^{-3}$ )	t	p-value
Eggs	5_Pitt_Power	-17.49	17.55	-1.00	0.343	-51.29	23.21	-2.21	0.052
	8_Alam_Pt	2.45	0.88	2.80	0.014	0.89	0.95	0.94	0.365
	19_Oceano_Dune	5.10	6.75	0.76	0.471	16.22	10.45	1.55	0.159
	20_Guad_Mussel	3.85	9.17	0.42	0.682	9.69	4.77	2.03	0.065
	23_Van_AFB	-56.11	35.67	-1.57	0.144	-37.80	45.15	-0.84	0.420
	27_SCLAR_McG	2.63	6.79	0.39	0.705	-4.99	6.52	-0.76	0.460
	30_Ormond	11.17	24.16	0.46	0.658	5.09	26.40	0.19	0.853
	32_Pt_Mugu	-1.04	0.56	-1.84	0.103	-1.25	0.86	-1.45	0.180
	38_Ven_Bch	-0.52	0.21	-2.53	0.025	2.03	1.39	1.46	0.168
	41_LA_Harb *	<b>0.30</b>	<b>0.06</b>	<b>4.75</b>	<b>0.000</b>	<b>0.22</b>	<b>0.07</b>	<b>2.99</b>	<b>0.011</b>
	45_Seal_Bch_NWR	3.15	2.60	1.21	0.249	4.17	3.34	1.25	0.236
	47_54_BC_Hunt	1.76	1.25	1.41	0.181	1.77	1.42	1.25	0.233
	58_Up_NewPrt	-36.79	61.06	-0.60	0.608	40.42	47.15	0.86	0.482
	59_CP	1.34	0.43	3.11	0.008	0.02	0.35	0.06	0.955
	73_Bati	-0.68	0.39	-1.74	0.105	-1.22	0.50	-2.45	0.028
	82_San_Elijo	-324.21	180.84	-1.79	0.101	-186.84	94.83	-1.97	0.075
	85.5_Mission_Bay	-0.03	0.80	-0.03	0.976	-0.41	0.99	-0.42	0.684
	102_103_Lind_NTC	-1.11	1.25	-0.89	0.394	-2.96	2.02	-1.47	0.171
	105_NI_MAT *	<b>-3.54</b>	<b>1.04</b>	<b>-3.39</b>	<b>0.005</b>	<b>-4.68</b>	<b>1.57</b>	<b>-2.98</b>	<b>0.011</b>
	47_54_BC_Hunt	0.04	0.12	0.36	0.728	0.12	0.12	1.06	0.307
	112_D_St	1.35	2.42	0.56	0.586	-6.41	3.22	-1.99	0.068
	113_CV	-6.08	3.56	-1.71	0.122	-9.93	10.29	-0.97	0.360
	114_Saltworks	-1.09	2.34	-0.46	0.649	-0.19	8.67	-0.02	0.982
	117_TJ	6.35	2.43	2.61	0.021	1.58	2.49	0.63	0.536

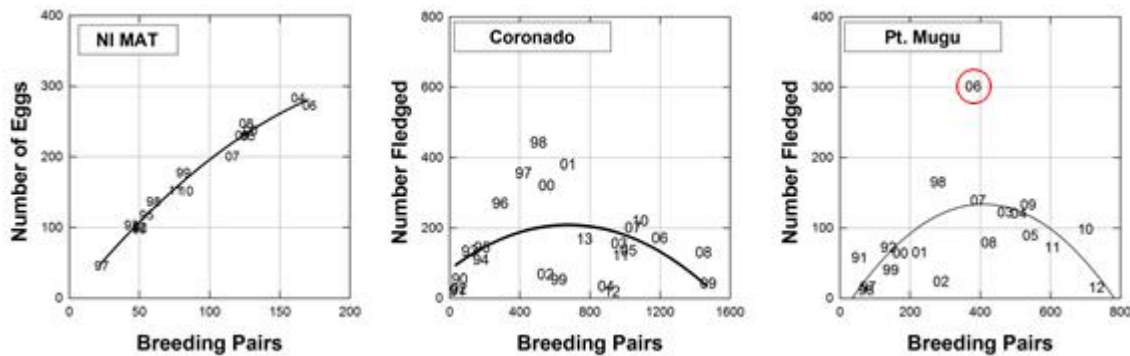
Table 1. Fit of the quadratic model to the relationship of eggs per nest and breeding pair at the index sites to consider evidence of density dependence at the colony level. Sites that had a significant fit with the quadratic model are shown in **bold**.

The site specific analysis confirmed what was found at the state level – there is no clear evidence of density dependence at the colony level. Significant fits of the quadratic terms were only found in 7 of the 72 models evaluated. In four of these, the relationship was concave-up which would indicate a population that has a positive density dependent relationship, i.e. reproductive output increases as breeding pairs increase.

Site	Per Nest				Per Breeding Pair			
	Coef ( $10^{-3}$ )	SE ( $10^{-3}$ )	t	p-value	Coef ( $10^{-3}$ )	SE ( $10^{-3}$ )	t	p-value
5_Pitt_Power	-51.33	115.24	-0.45	0.675	41.63	99.43	0.42	0.693
8_Alam_Pt	1.50	1.04	1.44	0.173	-1.30	1.82	-0.71	0.487
19_Oceano_Dune	3.01	9.45	0.32	0.757	5.76	8.22	0.70	0.502
20_Guad_Mussel	-0.62	7.56	-0.08	0.936	1.54	5.61	0.27	0.788
23_Van_AFB	-58.42	27.82	-2.10	0.065	-61.90	36.22	-1.71	0.122
27_SLAR_McG	11.74	9.29	1.26	0.242	5.75	6.75	0.85	0.419
30_Ormond	-16.36	14.60	-1.12	0.305	-25.88	11.11	-2.33	0.059
32_Pt_Mugu	-0.54	1.72	-0.32	0.760	0.33	1.43	0.23	0.822
38_Ven_Bch	-2.24	1.49	-1.50	0.156	-3.79	4.15	-0.91	0.377
41_LA_Harb *	<b>0.89</b>	<b>0.13</b>	<b>6.69</b>	<b>0.000</b>	<b>0.95</b>	<b>0.16</b>	<b>5.81</b>	<b>0.000</b>
45_Seal_Bch_NWR	-8.30	20.41	-0.41	0.694	-6.75	18.85	-0.36	0.728
47_54_BC_Hunt	0.73	2.02	0.36	0.722	0.24	2.37	0.10	0.921
58_Up_NewPrt	-33.53	68.76	-0.49	0.674	52.97	47.28	1.12	0.379
59_CP	1.23	0.64	1.92	0.076	0.32	0.63	0.51	0.622
73_Bati	-0.56	0.61	-0.92	0.373	-1.11	0.71	-1.56	0.141
82_San_Elijo	-25.52	45.95	-0.56	0.591	-24.00	20.45	-1.17	0.268
85.5_Mission_Bay	-0.19	1.51	-0.13	0.900	1.57	1.28	1.23	0.239
102_103_Lind_NTC	-0.80	1.88	-0.43	0.677	-2.65	2.88	-0.92	0.377
105_NI_MAT	-18.73	17.97	-1.04	0.316	-13.02	20.27	-0.64	0.532
106_Coronado	-0.08	0.19	-0.42	0.682	0.02	0.21	0.08	0.938
112_D_St	4.94	3.69	1.34	0.204	-3.37	4.60	-0.73	0.477
113_CV	6.57	6.21	1.06	0.318	6.71	11.37	0.59	0.570
114_Saltworks	-3.34	8.34	-0.40	0.695	-7.50	15.28	-0.49	0.631
117_TJ	0.57	1.07	0.53	0.603	-1.13	2.34	-0.48	0.638

Table 2. Fit of the quadratic model to the relationship of hatches per nest and breeding pair at the index sites to consider evidence of density dependence at the colony level. Sites that had a significant fit with the quadratic model are shown in **bold**.

We found concave-down relationships between breeding pairs at three colonies: eggs at North Island, fledges at Pt. Mugu and fledges at Coronado. However, these relationships were very weak as seen in Figure 1A below (left graph), or were extremely inconsistent among consecutive years (center and right graph). These weak and erratic relationships confirm the initial assertion that density dependence is not an important biotic driver of LETE populations at the state or colony level.



	Site	Per Nest				Per Breeding Pair			
		Coef (10 <sup>-3</sup> )	SE (10 <sup>-3</sup> )	t	p-value	Coef (10 <sup>-3</sup> )	SE (10 <sup>-3</sup> )	t	p-value
Fledglings	5_Pitt_Power	35.17	33.78	1.04	0.310	95.36	37.29	2.56	0.018
	8_Alam_Pt	0.36	1.17	0.31	0.761	-2.13	2.02	-1.06	0.303
	19_Oceano_Dune	-8.08	6.36	-1.27	0.219	0.33	10.14	0.03	0.974
	20_Guad_Mussel	-4.20	2.91	-1.44	0.165	5.17	4.53	1.14	0.266
	23_Van_AFB	-1.41	3.36	-0.42	0.680	-3.28	6.98	-0.47	0.645
	27_SCLAR_McG	5.13	4.75	1.08	0.298	5.16	4.71	1.10	0.287
	30_Ormond	6.87	8.42	0.82	0.425	3.31	7.32	0.45	0.656
	32_Pt_Mugu *	<b>-0.94</b>	<b>0.34</b>	<b>-2.72</b>	<b>0.018</b>	<b>-0.96</b>	<b>0.33</b>	<b>-2.90</b>	<b>0.010</b>
	38_Ven_Bch	-0.66	0.27	-2.40	0.026	-0.20	0.92	-0.22	0.829
	41_LA_Harb	0.09	0.14	0.63	0.537	0.04	0.17	0.26	0.798
	45_Seal_Bch_NWR	-4.39	5.44	-0.81	0.429	-3.08	5.09	-0.61	0.551
	47_54_BC_Hunt	-1.26	0.87	-1.46	0.161	-1.20	0.90	-1.33	0.197
	58_Up_NewPrt	0.73	3.42	0.21	0.833	2.55	5.15	0.50	0.626
	59_CP	0.32	0.30	1.07	0.297	-0.18	0.36	-0.51	0.618
	73_Bati	-0.36	0.52	-0.69	0.501	-0.52	0.51	-1.02	0.319
	82_San_Elijo *	<b>43.71</b>	<b>17.34</b>	<b>2.52</b>	<b>0.021</b>	<b>18.90</b>	<b>6.72</b>	<b>2.81</b>	<b>0.011</b>
	85.5_Mission_Bay	0.01	0.78	0.01	0.993	0.43	0.95	0.46	0.652
	102_103_Lind_NTC	-0.61	3.52	-0.17	0.863	-1.89	4.03	-0.47	0.643
	105_NI_MAT	-2.26	1.57	-1.44	0.165	-2.39	1.78	-1.34	0.194
	106_Coronado *	<b>-0.21</b>	<b>0.10</b>	<b>-2.04</b>	<b>0.055</b>	<b>-0.28</b>	<b>0.13</b>	<b>-2.15</b>	<b>0.043</b>
	112_D_St	-0.66	1.61	-0.41	0.686	-1.74	1.53	-1.14	0.269
	113_CV *	<b>7.99</b>	<b>2.73</b>	<b>2.93</b>	<b>0.009</b>	<b>6.60</b>	<b>3.51</b>	<b>1.88</b>	<b>0.076</b>
	114_Saltworks	0.56	1.53	0.36	0.720	0.10	2.49	0.04	0.967
	117_TJ	-0.30	0.32	-0.95	0.352	-0.74	0.55	-1.36	0.189

Table 3. Fit of the quadratic model to the relationship of fledges per nest and breeding pair at the index sites to consider evidence of density dependence at the colony level. Sites that had a significant fit with the quadratic model are shown in **bold**.



## Appendix 2

### Annotated list of LETE diet studies. Sources are listed in parenthesis.

(Kelly, MS thesis)

TABLE 1					
COMPARISON OF FOOD EATEN BY LEAST TERNS WITH FISH LEFT UNEATEN AT VENICE BEACH AND HUNTINGTON BEACH BREEDING COLONIES, 1980					
	% of fish observed eaten <sup>a</sup>				% of fish left uneaten on breeding colonies (N = 400)
	Courtship feedings (N = 130)	Small chick feedings (N = 107)	Large chick feedings (N = 392)	Total all feedings (N = 629)	
Northern anchovy/silversides (spp.)	71	55	68	67	70
Unknown/miscellaneous slim-bodied spp. <sup>b</sup>	24	45	27	29	8
Surfperches (spp.)	4	—	3	3	9
Unknown/miscellaneous deep-bodied spp.	2	—	2	1	13

<sup>a</sup> Dates of observation: courtship feedings (15 May–25 May); small chick feedings (1–10 Jun.); large chick feedings (15 Jun.–25 Jul.).

<sup>b</sup> In columns referring to % fish observed eaten, this category includes mostly (>75%) unknown food items seen too poorly for specific identification. Northern anchovy and silversides (spp.) probably comprised a major portion of the unknown, slim-bodied fish observed to be eaten.

(Atwood & Kelly 1984)

**Venice/Huntington Beach:** Northern anchovy was the dominant prey species in nine samples, silversides (especially topmelt and jacksmelt) in seven, and deepbody or slough anchovies in two. This conclusion is consistent with an analysis of 11 stomach contents obtained from adult and juvenile Least Terns found dead in southern California (Kelly, unpubl.).

**Various sites:** For example, terns at **Venice Beach** foraged primarily in nearshore ocean waters (Atwood and Minsky 1983) where schools of juvenile northern anchovy occurred (Fitch and Lavenberg 1971), and this species comprised up to 70% of the fish left uneaten at this colony. By contrast, terns breeding at **Anaheim Bay** fished mainly in shallow saltmarsh channels adjacent to the colony, where Klingbeil et al. (1975) found topmelt and California killifish (*Fundzhs parvipinnis*) to be common but northern anchovy and surfperches to be rare or absent during the summer months. Topmelt and California killifish combined represented 82% of the fish dropped at Anaheim Bay in 1981, while northern anchovy and surfperches comprised only 7% of the sample. Samples of fish dropped at colonies located at **Bolsa Chica** and **Batiquitos Lagoon**, where terns similarly foraged mainly in tidal estuaries, were also dominated by topmelt and California killifish rather than northern anchovy. Deepbody (*Anchoa compressa*) and slough anchovies (*A. delicatissima*), more southerly in distribution than the northern anchovy (Miller and Lea 1972) were the most abundant species dropped on colonies at the southern limit of the study area, but were rare or absent from sites farther north (Table 3).

(Baird 1997)

**San Diego Bay:** Prey were also identified from fecal pellets collected from the colony next to nests and at least-tern-only roosting sites. In these analyses, we looked at otoliths, which pass through the digestive system intact and which are species-specific, as well as other diagnostic body parts. Prey were mainly **bay anchovies**, *Anchoa delicatissima*, and **silverside smelt**, *Atherinops*. No killifish, a common eelgrass species, were taken, and the herring/sardine, opaleye and goby groups were only taken occasionally. All fish were of age-class 1 or first year fish (age 0), that is, juvenile or larval fish. Our visual observations corroborate, in both species composition and size class, the fecal analyses that we concurrently conducted. However, when dropped fish were collected and measured, neither the species composition nor the size class was similar to what we observed or found the terns eating via direct observation or fecal analysis. Our data disagree with other studies which use dropped fish as indicators of species and size class of prey.

(Collins 2011)

**Seal Beach:** In previous studies, California Least Terns nesting at NAVWPNSTA Seal Beach appeared to forage extensively within the **Anaheim Bay system where killifish** (10-19%) and **atherinid fishes, particularly topsmelt**, formed major components (49-60%) of their diet (Atwood and Kelly 1984, Horn and Dahdul 2000). **Topsmelt** were again important in the diet of California Least Terns at NAVWPNSTA Seal Beach in 2008 and 2010. The **northern anchovy** (*Engraulis mordax*) occurs widely in coastal waters and is a major dietary component of California Least Terns at other colonies (Atwood and Kelly 1984, Keane 1988) but was a much less important component (3.6%) at NAVWPNSTA Seal Beach in 1980-1981 (Atwood and Kelly 1984) and in 1996-1998 (Horn and Dahdul 2000). **Killifish and atherinids** appear to provide a dependable prey base for California Least Terns at NAVWPNSTA Seal Beach. They may, as suggested earlier for 2010, buffer these terns, and the growth of their chicks, from the impact of the year to year variations in northern anchovy availability experienced at other colonies where they comprise the principal prey item. However, northern anchovies are calorically dense prey and may be important, even in small numbers, for optimal growth of California Least Tern chicks. The sparse data for 2008-2010 did not include any anchovies but the small sample size of dropped fish recovered in these years precludes any detailed conclusions.

(Elliott et al 2007)

**Alameda Point:** **Silversides** (family Atherinopsidae) were the most abundant prey items found for all years except 1987 and 1992 (Fig. 5). The principle silverside species identified were **Jacksmelt** (*Atherinopsis californiensis*) and **Topsmelt** (*Atherinops affinis*), **Northern Anchovy** (*Engraulis mordax*, family Engraulididae) was the next most numerous prey species collected, making up the majority of collections in 1987 and 1992. **Pacific Herring** (*Clupea harengus*, family Clupeidae) and surfperch species (family Embiotocidae) were also abundant in collection. A small increase in anchovy abundance can have a considerable impact on breeding success; using the equation generated in the Results, increasing Northern Anchovy from 1% to 5% of the dropped fish can result in a breeding success increase from 0.16 to 0.67 fledglings per breeding pair. The Northern Anchovy contains more lipids and energy content than Topsmelt (Dahdul and Horn 2003), which may contribute to improved breeding success in Least Terns.

(Massey et al 1974)

**San Diego:** Adults at **Sunset Aquatic** feed on three species mainly: *Engraulis mordax*, **northern anchovy**; *Cymatogaster aggregata*, **shiner perch**; and *Atherinops*, **topsmelt**. Fish sizes ranged from 4-9 cm. in length and 2cm depth. At Santa Margarita Lagoon the terns feed heavily on the anchovy, *Anchoa compressa*, and the **killifish**, *Fundulus parvipinnis*, as well as northern anchovy, and *A. affinis*.

(TetraTech 2006)

Chick provisioning studies in Alameda area consisted of direct observations, analysis of fish parts from chick feces, and collections of fish dropped on the colony by the terns. Fish brought by adults to their young were mainly slenderbodied forms between about 30 and 80 mm in total length (1.2 to 3.1 inches). Adults generally presented smaller fish to newly hatched chicks than to older chicks. Fish accepted by newly hatched chicks averaged about 25 mm (1 inch) smaller than those accepted by fully-feathered chicks. Chicks occasionally dropped offered fish, and the dropped fish tended to be larger than accepted fish. Considering this size bias, the species composition of collections of dropped fish matched what is known about the tern diet at Alameda. **Fishes of the silverside family (mainly topsmelt and jacksmelt) always dominated, followed by anchovy and herrings.** In most of the deep-water areas, **the numerically dominant fishes were anchovy, jacksmelt, and sometimes sardine**, with modal size classes approaching or exceeding the upper size limit for least terns. The one exception to this pattern was that **post-larval anchovies**, which sometimes form a substantial portion of the tern diet, were often available over the entire Bay during the summer. **Topsmelt, jacksmelt, and grunion** (the native marine silversides), which have been important to the terns in every year dating back to 1981 (when dropped fish were first collected) breed throughout the tern nesting season, and their young were found in highest abundance along beaches and in protected, lagoon-like habitats. The sample included 63 **Atherinopsids (silversides)**, 1 **Clupeid (herrings and sardines)**, 34 **Engraulids (anchovies)**, and 18 **Gobiids (gobies)**. **Atherinopsids** made up most of the dropped fish collected in 2005 and in the other years of this study (Table 7 and Figure 24). **Engraulids, Clupeids, Salmonids, and Embiotocids** made up most of the other dropped prey in 2005; these families were also important in dropped prey collections from 1981 to 2004 (Figure 24).

(Robinette presentation at 2011 Tern Meeting)

**Northern anchovy and silverside smelt** generally compose the majority of the least tern diet but there are years when **Pacific saury** (off-shore species) are present in the diet at a higher proportion...and this is generally when least tern reproductive success is low. Recently there has been an increase in **YOY rockfish** at Vandenberg and Venice (2010 was a good year for rockfish production). An interesting species that turned up at Oceano Dunes was **freshwater bass**. Dropped fish are OK but not a great indicator of diet. Adult attendance could be used as an indicator- of how far adults are traveling to forage.

(From Robinette presentation at 2013 Tern meeting)

**On shore:** N Anchovy, Silverside Smelt, Rockfish (shortbelly?); **Off shore:** Saury, Sardine; **Other:** Killifish / mosquito fish , Fish larva, True smelt, Goby, Sculpin, Greenling, Cabezon, Squid, Surfperch, Pipefish, Krill.

## Appendix 3

### Documentation for California Least Tern Conceptual models

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Photo Credit: USFWS ([http://www.fws.gov/sacramento/ES\\_Kids/CA-Least-Tern/es\\_kids\\_ca-least-tern.htm](http://www.fws.gov/sacramento/ES_Kids/CA-Least-Tern/es_kids_ca-least-tern.htm))

#### Background

California least terns (LETE) were listed as endangered in 1970. Since then, the population has increased from just 624 breeding pairs in 1973 to approximately 6500 pairs in 2010 (Marschalek 2011). Although this shows significant progress towards the recovery of the species, the increase in breeding pairs meets only one of the three recovery targets specified by US Fish and Wildlife (USFWS). Despite an increase in the number of breeding pairs, another important recovery criteria, the number of young fledged per breeding pair, remains low and appears to be declining (Schuetz 2011).

Breeding surveys of LETE have been ongoing since the late 1960s, with the number of breeding pairs and nest success documented for each colony (Marschalek 2011). Despite these long-term efforts, wide variation in management and monitoring methodologies still exist among sites. Likewise, numerous attempts to standardize data collection protocols and documentation across sites and years (Obst and Johnson 1992; Caffrey 1994, 1995, 1998) have been unsuccessful. Challenges still remain in accurately estimating key population parameters (e.g., number of breeding pairs and fledgling success) and identifying key drivers and uncertainties of California least tern population dynamics.

Given the long-term management and monitoring of this species and the extensive expertise of the LETE community, LETEs were an ideal candidate for conceptual model development. **For this species, a conceptual model is particularly useful to help identify and prioritize critical uncertainties.** The model building process also can clarify relationships among the elements that drive LETE population dynamics and identify gaps in knowledge that may be hampering effective management. This is particularly relevant now given recent fluctuations in LETE dynamics within and across sites, with the number of breeding pairs plateauing and even falling in some cases, and breeding success at very low levels.

## Management Goals

Recovery criteria for LETS were established by the USFWS in 1980 in accordance with the federal Endangered Species Act. These were proposed as the de facto management goals for this conceptual model. The USFWS criteria are:

- At least 1,200 breeding pairs in at least 20 of 23 management areas
- Each management area must have at least 20 breeding pairs
- Each management area must have a 3-year mean reproductive rate of at least 1.0 young fledged per breeding pair

There was general consensus in the working group that these criteria need to be updated, and understood by the group that the USFWS are working on this process as part of the LETS 5-year review. Thus, the group decided to adopt a very broad and general management goal that would be guided by the revised USFWS criteria as soon as those are released. In the meantime, the group agreed to use X and Y as proxy for the USFWS established values for population size, and number of colonies:

**“Maintain a population size X with distribution Y within a functioning coastal ecosystem”** where distribution refers to the number of LETS breeding colonies. This management goal incorporated the additional consideration of a larger ecosystem approach by including the phrase “within a functioning coastal ecosystem”, which refers to the importance of the upland and watershed links to the coastal LETS nesting and foraging sites. The group also felt that reproductive or fledging success rates was an important monitoring component but may be less useful as a management goal given the uncertainty associated with measuring or estimating this parameter. This overarching goal is applicable to LETS colonies statewide, with the recognition that specific sites may require a more focused management goal.

## Model Development

The group reviewed and developed two models. **Model A** is a process-based model that presents a comprehensive view of the factors and variables that influence LETS population dynamics. As such, it is more complex. The species variables represent (**population size, distribution, and reproductive success**), namely (**nests, eggs, chicks, fledglings, and breeding pairs**). **Survival and movement** are shown to directly influence population size and distribution, with **age structure** and **overwintering** behavior shown as other influential elements. While it seems intuitive that LETS survival and movement would influence overall population dynamics, there are very little data on survival and movement of adult birds, both among colonies and at winter feeding grounds. The natural drivers in this model are **climate, food availability, mortality and nesting habitat**, with additional components added to more explicitly describe these natural drivers. **Management policies** are shown to have a direct influence on **nesting habitat** and **mortality**. Pollutants, disease, and natural toxins are included as additional human disturbances that influence mortality and can be linked to management policies. This model also considers multi-species impacts as an element that is driven by management policies.

**Model B** was designed to focus on management actions. In this model, the three species variables (**population size, distribution, and reproductive success**) grouped together at the

center of the model. As with Model A, **survival** and **movement** are also included as elements that influence the species variables and are shown as dashed circles, indicating the high degree of uncertainty associated with these elements. Three arrows depict the direct influence of the natural drivers of **mortality**, **nesting habitat**, and **food availability** on these variables. **Food availability** is largely driven by **climatic conditions** (though fisheries may have an impact – see Model B) making it more difficult to manage this natural driver. **Management policies** are an overarching component of the system that guides the management targets, including control of **mortality** (largely through active and passive predator control), **human disturbance** and **nesting habitat**.

## Model Elements

Here we provide more focused discussion on model elements. These include the three species variables (**population size**, **distribution**, and **reproductive success**), two anthropogenic threats (**management policies and human disturbance**), and four natural drivers (**nesting habitat**, **mortality**, **food availability**, and **climate**) that influence these variables.

### Species Variables

- ***Population size***: Population size (whether represented by the individual components as in Model A or an aggregate in Model B) relates directly to the model's stated goal of maintaining a breeding population of a specific size. The population recovery target will be determined by the regulatory agencies (USFWS). A range of 5,000-10,000 breeding pairs was used as an interim value by the group, and is comparable to long-term data records on breeding pairs (Figure 7; Marschalek, unpublished data). Though age-specific survival rates have been estimated for LETÉ, they are outdated and suffer from sample size and other limitations (Massey et al. 1992; Collins et al. 1998). Knowledge of LETÉ overwintering ecology is another key uncertainty related to population size.
- ***Distribution***: The distribution of LETÉ colonies is a key variable identified in the management goal of the model. Distribution refers to the spatial pattern of nesting colonies and the need to maintain a number of large and productive colonies to support population persistence (these could be referred to as “source” colonies) and provide buffers (including the creation of new sites) for colonies should conditions at an existing colony deteriorate (“sink” colonies). Though management of birds at each site is important, it also is important to realize that some colonies may “blink” on and off, and a site that is unoccupied in one year may become re-occupied as conditions change. Given the ability of the birds to move among colonies, nesting areas may act as a network of sites that together support the regional population, although the number of sites necessary to sustain the population in perpetuity is unknown. Movements of LETÉ have a direct influence on their distribution and have been shown to serve as a key factor that influences population viability by the group (Lott). Though some research has been done regarding turnover rates, site fidelity, and movement of LETÉ among sites (Burger 1984; Collins et al. 1998), relatively little is known about movement rates and population structure of LETÉ in California.
- ***Reproductive success***: Reproductive success is typically measured as the number of fledglings produced per breeding pair and is directly related to overall population growth. Monitoring of reproductive success has been identified in previous reports as being important for determining

species status (Winchell et al. 2008), though there is a high degree of uncertainty associated with fledging estimates. There are a number of different methods used to estimate fledgling success, number of fledglings, and number of breeding pairs, and, to date, there is no consensus as to which method (if any) is most accurate. Schuetz (2011) found that fledgling success appeared to decline at colonies larger than 1000 pairs. These empirical data suggest that larger colony (population) size does not always equal greater reproductive output, although it is clear that large colonies are still critical to population recovery. In more recent analyses (Lewison and Deutschman 2014), we did not find support for this relationship.

### **Natural Drivers**

- *Nesting habitat*: Several features of LETE nesting habitat, including percent vegetation cover, vegetation height, nesting area, species composition (native vs. non-native), and the number of sites have been studied relative to the amount of nesting that occurs (Winchell et al. 2008). However, the degree to which vegetation composition and structure impact nest fate relative to predation pressure or other factors is largely unknown. Distance from nesting sites to foraging grounds has also been proposed as an important element of nesting habitat. It may be that colonies closer to foraging areas or to areas of high forage abundance have higher reproductive success, possibly due to higher nest attendance by adult birds.
- *Mortality*: The model divides mortality into two components, predation and “other.” Observed or suspected predation accounted for only 27% of total mortality of LETE in 2010 (Marschalek 2011), and other causes of mortality (disease, natural toxins, pollutants, nest abandonment, etc.) are largely not understood. There is little information on LETE predator population dynamics, including how human disturbance (e.g., trash and supplemental food availability) influences predator presence and populations.
- *Food availability*: Food availability refers to the availability of LETE prey. The model includes factors that likely influence this availability, such as changes in primary productivity, ocean conditions, and competition with other species and commercial/recreational fishing as part of this element. Foraging behavior, availability of primary forage fish, and factors that influence this availability are poorly understood, though studies are in progress to better understand LETE foraging and diet (e.g., Robinette et al. in prep).
- *Climate*: Climate parameters such as temperature and precipitation as well as oceanic conditions, climate change, and sea level rise may influence LETE. Climate change may be a potential threat to LETE, particularly the impacts of sea level rise and associated loss of nesting habitat and changes in prey abundance. The influences of changes in climate on LETE ecology and population dynamics are highly uncertain.

### **Anthropogenic Threats**

- *Management policies*: Policies set by regulatory agencies are key drivers of LETE monitoring and management and directly or indirectly impact species variables identified above. Examples include predator control measures, colony monitoring, and site preparation. The impact of these policies and management actions (site preparation, predator control, etc.) are tracked to some extent (e.g., the number of nests) but are typically not linked to overall performance of a colony (e.g. nest fate).

- Human Disturbance: Both direct (trampling, colony disturbance, watercraft, shoreline construction, lighting, noise, etc.) and indirect (increased predator presence, overwater construction, etc.) human disturbance can impact LETÉ colonies. Management actions have helped (fencing, signage, etc.), but enforcement issues remain a problem in certain areas (Fancher 1992; USFWS 2006). Contaminants such as mercury, selenium, and organochlorides also are included in this element but, based on existing data, are not considered to present a substantial threat to LETÉ; published research shows contaminant levels are generally lower in LETÉ than other seabirds (Boardman 1988; Collins 1992; Hothem and Zador 1995; Hothem and Powell 2000). Eutrophication of foraging areas is a potential threat that may impact the forage base of LETÉ (Smith et al. 1999), though this relationship is not well understood. Likewise, the impact of recreational and commercial fishing on the LETÉ forage base is not well understood.

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## Narrative for: California Least Tern Conceptual Model

Goals:		
Management	Maintain population size X with distribution Y within a functioning coastal ecosystem Z	
Monitoring	<i>Continue to monitor number of breeding adults and fledgling success at all colonies annually and measure responses in these variables to management actions (not directly discussed by group)</i>	
Anthropogenic Threats:		
Management Policies	<ul style="list-style-type: none"><li>Direct impacts on mortality through predator control measures</li><li>Indirect and perhaps direct impacts on mortality through monitoring efforts</li><li>Direct impacts on nesting habitat through site prep and maintenance activities</li><li>Overwater construction and other management of human activities near nesting sites</li><li>None of these relationships have been quantified, thus are represented with dashed arrows</li></ul>	Shwiff et al. 2005; Ryan et al. 2010
Human Disturbance	<ul style="list-style-type: none"><li>Direct: colony visits, watercraft, lighting, noise, shoreline construction</li><li>Indirect: dogs, increased predator presence, overwater construction, sea level rise</li><li>Thought to be the primary culprits in the initial decline of LETE</li><li>Management improvements (i.e., fencing, signage, etc.) have helped</li><li>Enforcement issues remain a problem in certain areas</li></ul>	Chambers 1908; Edwards 1918; Massey 1974; Atwood et al. 1977; Fancher 1992; USFWS 5-year review 2006; Nightengale and Simenstad 2001
Commercial & Recreational Fishing	<ul style="list-style-type: none"><li>Impact generally not well understood</li><li>Cury et al. (2011) - 1/3 of the maximum prey biomass (small fish and krill) needed to prevent reduced and more variable productivity in seabirds. Not clear where current prey abundance is in relation to this threshold</li><li>Competition with commercial/recreational fisheries could be problematic</li></ul>	Cury et al. 2011
Pollutants	<ul style="list-style-type: none"><li>Contaminant studies of LETE have found moderate concentrations of mercury, selenium, organochlorines</li></ul>	Boardman 1988; Collins 1992;

	<ul style="list-style-type: none"> <li>but these were lower relative to other seabirds</li> <li>Zeeman et al. (2008) found organochlorine levels (DDT, PCBs, etc.) to be lower than studies from the 1980s and 1990s</li> <li>Threshold levels thought to impact behavior and reproductive success are still uncertain and not well understood</li> <li>Periodic monitoring of contaminant levels in blood/eggs likely is warranted</li> <li>Eutrophication of foraging areas may impact forage base</li> </ul>	Hothem and Zador 1995; Hothem and Powell 2000; Smith et al. 1999; Zeeman et al. 2008
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Natural Drivers:		
Nesting Habitat	<ul style="list-style-type: none"> <li>Site fidelity of LETE is generally high though variable (43-78% in LA County)</li> <li>Movement between colonies is rare, and generally &lt; 15km</li> <li>LETE can successfully nest in highly disturbed areas (airports, active beaches) on a variety of substrates (rooftops, dredge spoil)</li> <li>Second-wave nesters tend to be 2yo nesting for the first time or older re-nesters who experienced nest failures</li> <li>A 3-year study at Venice Beach found that terns preferred and were more successful in areas with &lt; 30% veg cover</li> <li>Number and acreage/size of nesting sites</li> <li>Species composition (invasive vs. native) may also be important for LETE nesting habitat quality</li> <li>The degree to which vegetation composition and structure impact Species Variables (pop size, distribution, repro success) is largely unknown</li> </ul>	Altman and Gano 1984; Atwood and Massey 1988; Massey and Atwood 1981; Ryan et al. 2010
Mortality	<ul style="list-style-type: none"> <li>Predation accounted for only ~27% of total mortality of LETE in 2010</li> <li>Generally unclear what accounts directly for other mortality (disease, toxins, decreased nest attendance due to longer foraging trips, other abandonment)</li> <li>American crows, gull-billed terns, common ravens and coyotes account for most predation on LETE</li> <li>Akcakaya et al showed that simulated reduction of predation improved population viability only when vital rates (survival and fecundity) were low</li> <li>Economic analysis of predator removal efforts</li> </ul>	Annual Reports; Akcakaya et al. 2003; Shwiff et al. 2005

	showed an 8.1% increase in productivity for a 25% increase in funding, and an investment of >\$1.04 million over 7 years led to roughly a tripling of nesting pairs	
Food Availability	<ul style="list-style-type: none"> <li>• Generally not well understood, though studies are in progress to better understand tern foraging and diet (e.g., Robinette et al.)</li> <li>• Previous studies have shown that anchovies and topsmelt are important components of LETE diets</li> <li>• Decreased availability of forage fish may be negatively impacting reproductive success (see Figure 8). This may be the result of changes in productivity in coastal zone (climate/oceanic conditions)</li> <li>• Impact of intra- and interspecific competition for food (including commercial and recreational fishing) is not well understood</li> <li>• LETE generally forage in shallow waters &lt; 2mi offshore</li> </ul>	Atwood and Minsky 1983; Atwood and Kelly 1984; Birkhead 1985 (book); Keane 2004
Climate	<ul style="list-style-type: none"> <li>• Influence largely unknown</li> <li>• Extreme precipitation and weather events can lead to nest failure</li> <li>• Larger-scale processes are impacting ocean productivity and subsequently LETE food availability</li> <li>• Sea level rise due to climate change will impact LETE populations as well</li> </ul>	Chavez et al. 2003; Cury et al. 2011

Species Variables:		
Population Size	<ul style="list-style-type: none"> <li>• No reliable estimates are available on historical numbers of California least terns, but they once were abundant and well-distributed along the southern California coast.</li> <li>• Given the large increase in population size from the 1960s to present and the current downturn in size, carrying capacity for LETE likely falls somewhere between 5,000-10,000 breeding pairs (expert opinion – based on range of Fig 2 in Marschalek 2011)</li> </ul>	USFWS 1985 revised recovery plan; Marschalek 2011
Distribution	<ul style="list-style-type: none"> <li>• Nesting range in California has always been widely discontinuous, ranging as far north as San Francisco Bay and south to southern Baja California, Mexico</li> </ul>	USFWS 1985 revised recovery plan

	<ul style="list-style-type: none"> <li>• Unknown how many sites are necessary to sustain population over the long term</li> </ul>	
Reproduction	<ul style="list-style-type: none"> <li>• Although breeding pairs have increased 578% from 1988-2009, productivity has declined inconsistently, ranging from ~0.23-0.95 fledglings/pair statewide (Fig 7)</li> <li>• Winchell et al. (2008) identify reproductive success as a key monitoring target due to the delayed response to reproductive problems in the population.</li> <li>• Keane et al (2011) found no statistically significant trends in reproductive variables other than a decrease in clutch size.</li> <li>• Understanding of factors driving reproductive success is critical for management and conservation of LETE</li> <li>• Need robust methods to estimate fledgling success, number of nests, etc.</li> <li>• Lack (1968) suggests that low breeding success in any given year may not endanger populations of long-lived species</li> <li>• Akcakaya model illustrates sensitivity of the model to vital rate parameters indicating they are critical uncertainties that need to be addressed</li> </ul>	<p>Annual Reports; Lack 1968 (book); Akcakaya et al. 2003; Massey 1989; Bailey and Servello 2008; Winchell et al. 2008; Keane et al. 2010; Schuetz 2011</p>
Survival	<ul style="list-style-type: none"> <li>• Massey et al. estimated age-specific survival rates for LETE at Venice Beach (0.16 hatch, 0.81-0.92 adult), but productivity was significantly higher than the rest of the state population</li> <li>• Collins et al. estimated similar rates, though sample size and resighting rates were problematic</li> <li>• Further banding studies are necessary to obtain accurate estimates of age structure and survival rates for LETE throughout their range</li> <li>• Akcakaya model illustrates sensitivity of the model to vital rate parameters indicating they are critical uncertainties that need to be addressed</li> </ul>	<p>Massey et al. 1992; Collins et al. 1998; Akcakaya et al. 2003; Bailey and Servello 2008</p>
Movement	<ul style="list-style-type: none"> <li>• Burger et al. estimated turnover rates between 0.16-0.30, suggesting LETE do not move long distances and exhibit high site fidelity</li> <li>• Collins et al. (1998) found LETE from Camp Pendleton in Huntington Beach and Batiquitos Lagoon</li> <li>• Further study is necessary to determine movement rates and population structure through LETE range</li> <li>• Overwintering behavior of LETE is poorly understood and should be studied further</li> </ul>	<p>Burger 1984; Collins et al. 1998; Patton et al. (ongoing)</p>

### Key Literature for: California Least Tern Conceptual Model

References	Annotation
Akcakaya et al. 2003. <i>Metapopulation dynamics of the CA least tern</i>	Metapopulation model included age-structure, annual variation in survival and fecundity, and regional (ENSO) and local (predation) catastrophes. Model predicted low risk of substantial decline over 50 years. Recommended replicating Massey et al. (1992) study to get better vital rate estimates.
Bailey and Servello 2008. <i>Chick survival, fledgling residency and evaluation of methods for estimating fledgling success in least terns</i>	Authors banded chicks to better understand chick survival and fledgling residency time. 21-d chick survival rates ranged from 0.14 to 0.74. Dugger et. al. (2000) reported chick survival of 0.43 to 0.62. Fledgling residence time (days on colony after initial fledge) ranged from 15-30 days.
Burger 1984. <i>Colony stability in least terns</i>	Annual turnover rates varied from 0.16-0.30 (mean = 0.22; SD = 0.05), which is low to intermediate compared to other coastal nesting seabirds. Turnover was calculated by site, not individuals (colony color band, not individual ID bands).
Collins et al. 1998. <i>Banding of adult LETE at MCB Camp Pendleton between 1987-1997</i>	Resighting rates were not necessarily reflective of actual adult return rates but of search efficiency. Resighting at other colonies was likely underreported due to lower effort in other areas. Pendleton birds were found in Huntington Beach and Bataquitos Lagoon. Most valuable observations were seen before and after nesting season, not during. Mean mate retention was ~54% and adult survival ranged from 0.76-0.93.
Danhardt and Becker 2011. <i>Herring and sprat abundance indices predict chick growth and reproductive performance of common terns breeding in the Wadden Sea</i>	North Sea herring recruitment and sprat abundance in the Wadden Sea explained the largest part of common tern breeding success from 1981-2009.
Elliot et al. 2007. <i>Breeding biology and status of the LETE at Alameda Point, SFB, CA</i>	Found that breeding success declined from the mid-1990s to 2004, similar to statewide and regional (N&S) trends (Figures 9 & 10; Lu 2009). Also studied diet by observing fish dropped at the colony and found that breeding success was significantly and positively correlated ( $r = 0.55$ ) with proportion of anchovy dropped.
Keane 2006. <i>Experiment to protect least terns during an oil spill at the Port of LA nesting area</i>	Author tested whether or not terns would use stocked backyard pools as alternate foraging sources in the case of preferred foraging grounds being contaminated. They found that some LETE were able to successfully obtain fish from pools, and larger, murkier (algae filled) pools were preferred.

Marschalek 2011. <i>LETE breeding survey 2010 season</i>	An alternate index of population size (max number of active nests) and a new fledgling estimator (total chicks – dead chicks) were discussed. Both seem to map similarly to current indices used.
Massey et al. 1992. <i>Demography of a LETE colony including effects of the 1982-1983 El Nino</i>	Return rate of banded hatchlings, young breeders, and older breeders was 0.16, 0.81, and 0.92, resp. and much lower in ENSO years (0.03-0.82). Lifetime productivity was estimated to be 1.49 with a breeding life of 9.63 years. Productivity at Venice colony was significantly higher than the rest of the state (> 1.0 fl/pr in all but 2 years vs. never > 0.9 in the rest of the state), suggesting results may not be applicable to entire population. Age profile of LETE showed that peak breeding age was 3 years and 80% of birds were 2-7.

References	Annotation
Ryan et al. 2010. <i>Venice Beach least tern colony habitat improvement and restoration study 2006-2009</i>	Authors created a 20x20m grid across the colony and used 3 treatments: 1) no manipulation, 2) less than 30% veg cover, and 3) removal of all veg to at least 5% cover. Authors found that nests were less likely to succeed if they were placed within 20 m of the enclosure fence, in grids with fewer than 5 other nests (<125 nests/ha), more than 5 m from their nearest neighbor and more than 70 m from the center of the colony. Additionally, terns were more likely to be predated in areas with less than 5% vegetation cover, and prefer to nest, and are most successful, in areas with 20-40% vegetation cover. They found that the best vegetation management technique was to reduce vegetation to less than 30% cover, but even this was not as successful as areas that are naturally between 5-30% vegetation cover.
Schuetz 2011. <i>Reproductive declines in an endangered seabird: cause for concern or signs of conservation success?</i>	Though breeding pairs increased substantially from 1988-2009, both clutch size and productivity declined. Other than latitude, site characteristics had little bearing on either clutch size or reproduction. Causes of variation remain poorly understood and may reflect 1) reduced food availability, 2) increased density-dependent competition, or 3) age-dependent reproduction reflective of a young population.
Shwiff et al. 2005. <i>Ex post economic analysis of reproduction monitoring and predator removal variables associated with protection of LETE</i>	Predator removal and monitoring hours showed significant impacts on adults and fledglings, though predator removal efforts showed a negative relationship with predator removal (suggesting they are hard to protect from predators). A 25% increase in funding yields an 8.1% increase in productivity, or an investment of >\$1.04 million over 7 years led to roughly a tripling of nesting pairs.

<p>USFWS 2006. <i>LETE 5-year review</i></p>	<p>Gross number of pairs is nearly 6 times the recovery goal, but no other goal had been met. Thirty of 40 known nesting sites in CA have more than 20 breeding pairs, and numbers are not uniformly distributed across sites. Reproductive rates have been considerably lower than those recommended (0.23-0.36), which suggests recovery goal of 1.0 fl/pr is not necessary. Recommended revisiting and revising recovery plan and continuing current monitoring and management programs.</p>
<p>Zeeman et al. 2008. <i>Characterizing exposure and potential impacts of contaminants on seabirds nesting at SSDB</i></p>	<p>Results of eggshell analyses indicate that eggshell thicknesses for failed eggs of black skimmer, Caspian terns, elegant terns, and perhaps California least terns, collected in 2005, were lower than normal, as compared with thicknesses measured in eggs collected before 1945. Concentrations of organochlorines (DDT, DDE, etc.) were lower in least tern eggs compared with concentrations observed in the 1980s and 1990s. Although numerous elements were detected in seabird eggs and forage fish, none were present in eggs at concentrations of concern.</p>

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