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**ACOUSTIC ACTIVITY AS A LOW COST AND SCALABLE INDEX OF SEABIRD  
COLONY SIZE:  
AN EXAMPLE WITH FORSTER'S TERNS (*S. FORSTERII*)**

A thesis submitted in partial satisfaction  
of the requirements for the degree of

MASTER OF ARTS

in

ECOLOGY AND EVOLUTIONARY BIOLOGY

by

**Abraham L. Borker**

September 2012

The thesis of Abraham L. Borker  
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## ABSTRACT

# **ACOUSTIC ACTIVITY AS A LOW COST AND SCALABLE INDEX OF SEABIRD COLONY SIZE: AN EXAMPLE WITH FORSTER'S TERNS (*S. FORSTERII*)**

by

**ABRAHAM L. BORKER**

Although wildlife conservation actions have increased globally in both number and complexity, the dearth of scalable, cost-effective monitoring hampers effective intervention to understand conservation efficacy. Automated sensors and computer aided analysis have expanded the tools available for conservation monitoring. For threatened and elusive seabirds, acoustic monitoring presents a cost-effective, scalable alternative to traditional monitoring methods that are limited by remote or inaccessible locations requiring skilled field personnel. A key assumption in monitoring population trends acoustically is that measures of acoustic activity are correlated with the relative nesting abundance of seabirds at colony sites. Here we tested the efficacy of acoustic activity as an index of seabird nesting abundance at colonies. Sensors recorded ambient noise at Forster's Tern (*Sterna forsteri*) breeding colonies in San Francisco Bay for two breeding seasons. We used an automated method (spectrogram cross-correlation) to detect and count tern advertisement calls from recordings. We calculated mean seasonal call rate and compared it to the mean

active nest count at colonies. Our results show that acoustic activity was a reliable index of colony size among breeding sites and an accurate index of change in colony size between years (adj.  $R^2=0.94$ ,  $n=5$ ,  $p<.01$ ). Acoustic activity was a strong enough index to detect population differences anticipated by effective conservation actions. Acoustic activity was a more precise index when comparing within sites between years, than among different sites, likely due to differences in the sound environments of the small islands. Quantifying the relationship between acoustic activity and relative abundance is a fundamental step in designing effective and scalable acoustic monitoring programs to monitor the effectiveness of conservation actions for seabirds and other vocalizing wildlife.

## **Acknowledgements**

First and foremost I would like to thank my academic advisors, Donald Croll, Bernie Tershy and Matthew McKown for their continued support and mentoring roles. This manuscript would not exist today if not for their intellectual and logistical support. Collaboration with Josh Ackerman and Collin Eagles-Smith (USGS) enabled us to compare acoustic activity with bonafide measures of colony abundance. Such reliable measures of abundance from tern colonies are credited to incredible diligence of Dena Spatz, USGS crew leader in 2009 and 2010. Costly field work was supported in part by The American Museum of Natural History (Frank M. Chapman Fellowship), the Sigma Xi Scientific Research Society (GIAR), Friends of the Long Marine Lab, Conservation, Research, and Education Opportunities (CREO), and the Packard Foundation Marine Birds Initiative. I'd like to thank all those who gave me advice in writing and analysis, particularly thesis committee member Chris Wilmers, and Pete Raimondi, as well as aforementioned collaborators. I am grateful for financial support from the Coastal Conservation Action Lab and an NSF Graduate Research Fellowship while conducting this research.

I dedicate this thesis to the memory of Guy Baldassarre, a great friend and professor from SUNY-ESF, who set a gold standard for science, teaching and mentorship.

Lastly, my greatest thanks are reserved for my loving parents Carol Cohen and Joseph Borker who gave me the preparation and chance to pursue my passions in conservation biology and ornithology wherever they take me.

## **Introduction**

Conservation is hindered when decisions are made solely from anecdotal evidence rather than empirical data (Sutherland et al. 2004). Unfortunately, inadequate quantitative monitoring of outcomes is widespread in conservation projects (Cook, Hockings, and Carter 2010), particularly when data are costly or challenging to collect. In the absence of empirical data, conservation actions that are ineffective, inefficient, or even detrimental to conservation goals can continue undetected (Pullin & Knight 2001; Ferraro & Pattanayak 2006). Historically, empirical evidence-based conservation has not been valued by the conservation community or incentivized by conservation funders (Pullin 2004). This is changing (Stewart et al. 2005), but the cost and difficulty of effective monitoring remains a significant obstacle. Integrating monitoring and evaluation into conservation activities brings new challenges of scale and complexity in the face of limited resources. Intensive monitoring efforts can decrease an organization's available resources for conservation actions (McDonald-Madden et al. 2010) and remove funds from conservation action. Conversely, less intensive monitoring efforts yield data with limited statistical power and value (Legg & Nagy 2006), and can lead to a significant waste of limited conservation funding.

Therefore, cost-effective and reliable tools for measuring change in biological communities are needed. Automated sensor technologies offer one such tool, and their use has increased in recent years (Karanth & Nichols 1998; Freitag et al. 2001; Sherley et al. 2010). Automated sensors are advantageous because they can increase



the spatial and temporal scale of wildlife surveys, lower the cost of sampling, and decrease inter-observer and temporal biases in data collection (Brandes 2008; Blumstein et al. 2011). Furthermore, sensors reduce bias due to human presence and the sometimes detrimental effects of intensive monitoring activities on conservation outcomes (Carey 2009).

Passive acoustic sensors are a potentially powerful tool for monitoring sound-producing wildlife (Acevedo & Villanueva-Rivera 2006; Brandes 2008; MacSwiney G. et al. 2008; Dorcas et al. 2009). Acoustic monitoring programs have been established to detect the presence of rare species (Fitzpatrick et al. 2005; Wade et al. 2006; Grava et al. 2008), monitor activity patterns (Mckown et al. 2008) and estimate population densities (Barlow & Taylor 2005; Dawson & Efford 2009; Celis-Murillo et al. 2009; Thompson et al. 2010).

Seabirds are particularly promising candidates for automated acoustic monitoring. Twenty-eight percent of seabirds are currently listed as threatened (Croxall et al. 2012), and nearly all seabirds produce detectable sounds at their breeding colonies. Forty-five percent of island threatened seabirds primarily vocalize at night, and nest in cryptic, inaccessible burrow sites (M.M., unpublished data) – a challenge to traditional survey methods. Seabird breeding colonies often are located on remote islands that are logistically difficult and expensive to visit. Additionally, seabird colonies are sensitive to human disturbance that can lead to temporary egg neglect, increased rates of egg and chick depredation, reduced chick provisioning rates, or

abandonment of offspring (Carey 2009). This combination of isolation, elusiveness, and sensitivity to disturbance leads to less effective monitoring resulting in a poor understanding of the efficacy of conservation actions.

Acoustic sensors take advantage of seabird acoustic communication at breeding sites. A number of studies have monitored acoustic activity by seabirds to quantify patterns of colony attendance (McKown et al. 2008), examine large-scale seabird responses to island restoration (Buxton & Jones 2012), and to detect elusive species at remote colonies (Wood et al. 2002). A key assumption of these acoustic studies is that changes in vocal activity at breeding colonies are correlated with changes in the relative abundance of individuals. However, daily rates of acoustic activity in seabird colonies can be highly variable (Buxton & Jones 2012), and are influenced by weather (Piatt et al. 1990), co-occurring species, non-breeder activity, and other factors independent of breeding bird abundance. The acoustic activity of any given breeding pair is influenced by phenology, which may be inconsistent across a colony. Thus, a daily measure of acoustic activity may not fully reflect the nesting abundance at that moment in time (e.g. vocally active breeding pairs that have not laid eggs or already hatched chicks). However, at the seasonal scale, the mean of acoustic activity may reflect nesting abundance, even if there are some temporal mismatches at smaller scales. Whereas counts of acoustic call activity have been used as an index of seabird breeding abundance, few studies have measured acoustic activity throughout the breeding season.

Here we test the hypothesis that inter-annual and inter-colony differences in Forster's Tern (*Sterna forsterii*) nesting abundance are correlated with their acoustic calling activity. We measured acoustic calling rates while simultaneously conducting weekly nest counts at tern colonies that varied in size across two breeding seasons. We evaluated the effectiveness of acoustic indices for estimating relative nest abundance and their ability to detect changes in relative abundance among colonies and between years. Specifically, we tested the use of acoustic activity as a scalable, low-cost index of the relative abundance of seabird nests between years and among colonies to evaluate whether large population changes associated with conservation outcomes can be effectively monitored using acoustic activity.

## **Methods**

### **Study Species, Site, and Design**

Forster's Tern (*Sterna forsteri*) is a small tern (~150g) that breeds at inland marshes and lakes, and estuaries throughout North America (McNicholl et al. 2001). In San Francisco Bay, terns nest predominately on small (<1ha) islands within former shallow salt ponds delineated by levies (Strong et al. 2004). Terns arrive at their breeding colonies in late May and remain through August. Colony nest abundance is highly variable both annually and among breeding colony sites. Forster's Terns have at least nine distinct adult vocalizations and four chick vocalizations (Hall, 1998).

We selected islands for this study that represented a range of colony sizes, and were also easily accessible (Ackerman et al. 2009; Bluso-Demers et al. 2010). We considered colonies acoustically independent if they were at least 250m apart.

## **Nest Monitoring**

We visited colonies weekly from nest initiation (May) until the last chicks fledged (August) in the 2009 and 2010 breeding seasons. At each colony visit, we found all newly initiated nests and marked them with a uniquely numbered anodized aluminum tag, and continued to monitor previously found nests for nest fate. For each nest, we floated each egg in the clutch to estimate incubation stage (Ackerman & Eagles-Smith 2010) and determined whether the nest was depredated, abandoned, or still active. A nest was considered “active” from the time the first egg was laid to when the chicks fledged or the nest failed. Initiation date was estimated based on the assumption that terns lay one egg per day and then began incubation on the day the last egg is laid. A nest was considered “inactive” after all eggs hatched, the nest was abandoned, or depredated. The total number of nests per site did not incorporate varied nest survival, therefore we calculated the number of active nests each day, and report the average number of active nests per day in addition to the total nest abundance. We excluded daily active nest counts for days when the sensor was not recording to account for differences in sensor uptime. The seasonal mean numbers of active nests ranged from 0.3 to 44.1 active nests per day and were correlated with total nest abundance ( $r^2=0.88$ ,  $p<0.01$ ,  $n=12$ ).

## Acoustic Sampling

At each colony we collected ambient acoustic recordings using an Automated Recording Unit (ARU) (Cornell Lab of Ornithology, Ithaca, NY) or SongMeter SM2 (Wildlife Acoustics, Concord, MA). Sensors were deployed within 35m of the field-assessed “center” of the colony, and were positioned at the same location each year. In 2009, ARU microphones were attached to a 1m high t-post. In 2010, three of the ARU sensors were replaced with SongMeters (SM2's), and microphones were placed closer to the ground (0.2m).

Both sensor types recorded with omni-directional microphones (ARU Sensitivity:  $-35\pm 4$ dB, SM2 Sensitivity:  $-36\pm 4$ dB, same Frequency Response: 20Hz-20kHz, and S:N Ratio:  $> 62$ dB) ARUs recorded at a sampling rate of 24,000Hz whereas SM2s recorded at 22,050Hz. Both of these recording rates encompassed the range of dominant tern vocalization frequencies (2.3 kHz – 5.5 kHz) (Hall 1998). SongMeters had longer battery life (over six weeks compared to four weeks for ARUs). All sensors recorded ambient acoustic activity at the study site during a one minute time period that occurred every 10 minutes throughout the day (i.e., we recorded 144, 60 second recordings per day).

We tested for differences in sensor types to detect tern calls. Hardware changes (ARU vs. SM2) had a very slight, but significant effect (ARU's had a 1.3% higher rate of detections per unit time) on call detection when tested on a simultaneous recording (Analysis of co-variance,  $F_{(df=2088)}=103700$ ,  $p= <.01$ ). This slight advantage of the

ARU could be due to the higher microphone placement (1m versus 0.2m for the SM2).

### **Automated Acoustic Analysis**

We used computer software (eXtensible BioAcoustic Tool - XBAT, <http://www.xbat.org>) to automate call detection. XBAT uses a pattern matching algorithm known as spectrogram cross correlation to find calls similar to a search template (Mellinger & Clark 2000; Goyette et al. 2011) (Figure 3). We used calls detected with XBAT to quantify acoustic activity rates at each colony in an efficient and replicable manner.

Our analysis focused on the advertisement, “kerr” call of Forster’s Terns as it is used for communication between mated individuals and chicks (Hall 1998). Search templates were chosen and designed using the “Detect – Data Template” tool in XBAT. A clip of an advertisement call with high signal to noise ratio was chosen as an exemplar for the search template. The template focused on the relatively stereotypic declining tonal frequency sweep of the call (with a peak frequency between 3.0-3.5kHz), as this helped differentiate the call from other sounds in the environment (Hall 1998). Call detections were exported to calculate calls per unit time, and to make statistical comparisons using the MATLAB and R computing platforms (The MathWorks 2010; R Development Core Team 2011). We calculated the seasonal mean rate of calls per minute for all breeding sites and seasons.

*Data subsets analyzed*

Because high wind levels in the afternoon and evening typical in San Francisco Bay masked acoustic activity by terns, we restricted our analysis to a subset of morning samples between 00:00 and 12:00. Samples were binned by hour (6, 1-minute files recorded per hour).

### *Evaluating performance of call detection*

To analyze the effectiveness of automated detectors, a human observer identified the first ten “kerr” calls in >25 randomly selected minutes of recordings from each site. We then compared these known “correct” call detections to the results obtained from automated analysis with XBAT to measure the rates of false detections (Type I errors/Accuracy) and missed calls (Type II errors/Sensitivity) across colony sites and years made by the software. Variation in detector sensitivity and accuracy from each site and year was compared with a two way analysis of variance (ANOVA).

## **Index of Acoustic Activity**

### **Acoustic activity and nest abundance among colonies**

We used a linear mixed model to test whether nest abundance (or random variation in sites and years) explained differences in the seasonal mean of acoustic activity among colonies. We included site and year as non-nested random factors (Systat 13). We used Restricted Maximum Likelihood to estimate model parameters, and ANOVA Type III estimation to test the variance components effects of the fixed effect (nest abundance) and random factors (site and year).

To test the precision of acoustic activity as an index of abundance, we used leave-one-out cross validation (LOOCV). LOOCV reported the mean error in predicting nest abundance for each of the twelve measurements of call rate if each had been left out of the initial model building. We report the mean absolute value of the prediction error.

### **Acoustic activity and nest abundance between years**

We compared changes in call rates at 5 breeding colonies to changes in mean and total nest abundance between the 2009 and 2010 breeding seasons with linear regression. This paired design explicitly accounted for potential site effects on acoustic activity, testing the ability of acoustic sensors to detect changes in abundance between years at the same sites. Once again we used LOOCV to measure prediction error in change in nest abundance for observations of change in call rate.

## **Results**

Acoustic sensors sampled 4,984 hours in 2009 (n=5 colonies) and 7,836 hours in 2010 (n=7 colonies). In total there were 1,302 sensor days, or an average of 86 days of acoustic sampling per colony. Over 3,800 continuous hours of acoustic data was archived (953 GB) at the end of both seasons. We found and monitored 725 tern nests during 2009 and 2010, and colony size ranged from 15 to 111 total nests per colony site. The maximum number of simultaneously active nests in a colony was 77. Mean nest abundance explained most of the variation in acoustic activity among sites (88%) and between years (94%).



## Performance of Call Detection

Overall, spectrogram cross correlation identified 1,370,071 sounds as “kerr” calls.

Mean hourly calling activity reached a maximum of 99.2 calls/minute and averaged 10.8 calls/minute. A randomly selected subset of recordings from each site was used to investigate detector accuracy and sensitivity for each site in each year.

On average, the automatic detector accurately classified  $77.3 \pm 4.7\%$  (95% CI) of calls across sites and years (measured as the percentage of sounds detected that were correctly classified as tern advertisement calls by the software). We found no significant influence of colony site or year on accuracy, but there was weak evidence of an interaction of colony site and year (Two-way ANOVA, Site:  $F(4,9)=1.26$ ,  $p=0.29$ ,  $\beta_{(\delta=0.1)}=0.41$ ; Year:  $F(1,9)=1.83$ ,  $p=0.18$ ,  $\beta_{(\delta=0.1)}=0.9$ ; Site\*Year:  $F(4,9)=2.28$ ,  $p=0.06$ ,  $\beta_{(\delta=0.1)}=0.36$ ).

Automatic detector sensitivity (the percentage of sounds the software detected compared to all tern advertisement calls available for detection on the recording) was  $53.6 \pm 7.3\%$  (95% CI). We found a significant influence of colony site and its interaction with year on detector sensitivity (Two-way ANOVA, Site:  $F(4,9)=7.19$ ,  $p<0.01^*$ ; Year:  $F(1,9)=0.08$ ,  $p=0.77$ ,  $\beta_{(\delta=0.1)}=0.87$ ; Site\*Year:  $F(4,9)=3.22$ ,  $p=0.04^*$ ). Differences in sites explained 10.2% of the variation in detector sensitivity.

## Acoustic activity and nest abundance among colonies

Within each breeding season, mean acoustic activity (calls/minute) varied significantly among sites in each year (2009,  $F(6,91)=5.65$ ,  $p<0.01$ ; 2010,  $F(4,60) =$

5.76,  $p < 0.01$ ). We found a strong positive correlation between the mean rate of acoustic activity (calls/minute) and the mean number of active nests among sites. A linear mixed model tested for the effect of the season's mean nest abundance on mean call rate, with site and year as random factors. Mean nest abundance explained 88% ( $F(1,3)=58.9$ ,  $p < 0.01$ ) of the variance in the mean calls/minute, whereas sites and year contributed only 6% and 4% of the variation in mean calls/minute (Site: $F(6,3)=4.3$ ,  $p=0.13$ ; Year: $F(1,3)=2.7$ ,  $p=0.20$ ). Using leave one out cross validation, the model predicted nest abundance with a mean magnitude of error of  $\pm 5.1$  mean active nests.

Similarly, the season's total nest abundance explained most of the variation in mean call rate when used as an alternative to the mean nest abundance. Total nest abundance explained 61% of the variation in mean call rate ( $F(1,3)=31.4$ ,  $p=0.01$ ), with site and year contributing 26% and 7% (Site: $F(6,3)=2.3$ ,  $p=0.27$ ; Year: $F(1,3)=3.6$ ,  $p=0.16$ ). LOOCV predicted abundance with a mean magnitude of error of  $\pm 21.6$  total nests.

### **Acoustic activity and nest abundance between years**

At the five colonies where two breeding seasons of data were obtained, we compared changes in nest abundance to changes in call rate (Figure 2). Change in the mean active nest abundance explained 94% of the variation in changes in mean calls per minute ( $df=3$ , adj.  $R^2=0.94$ ,  $p < 0.01$ ). Using LOOCV to estimate prediction error for

future observations of call rate the mean magnitude of error was a change of  $\pm 4.7$  mean active nests.

Similarly, the change in total nest abundance between years explained 88% of the variation in change in mean call rate when used as an alternative in the change in mean nest abundance (df=3, adj.  $R^2=0.88$ ,  $p=0.01$ ). Using LOOCV to estimate prediction error for future observations of call rate the mean magnitude of error was a change of  $\pm 17.7$  total nests.

## **Discussion**

We found tern acoustic activity was strongly correlated with nesting abundance among colony sites, and the change in nest abundance between years. Collectively, this demonstrates that acoustic activity can be used as a reliable tool for monitoring colonial seabird relative abundance. As acoustic sensors are increasingly applied to conservation monitoring (Brandes 2008; Blumstein et al. 2011; Buxton & Jones 2012), our study strengthens the case for employing automated acoustic monitoring as a scalable tool for monitoring conservation outcomes and rapid abundance assessment among breeding sites. Rather than calibrate acoustic indices for every species and environment to estimate population sizes directly, we advocate the use of acoustic activity to measure relative differences in populations across breeding sites and over time.

### **Acoustic activity and nest abundance among colonies**

Acoustic call activity was correlated with nest abundance among colony sites. The mean number of active nests explained 88% of the variation in the mean acoustic activity. As an index, mean calls per minute was an accurate predictor of nest abundance, with a mean prediction error of  $\pm 5.1$  mean active nests (LOOCV). Additionally, the total number of nests during a breeding season at a colony site also was correlated with mean acoustic activity, with a mean prediction error of  $\pm 21.6$  total nests. This provides sufficient ability to detect even moderate differences in colony abundance expected from effective conservation actions. The relationship between nest abundance and call rate was not significantly influenced by year, suggesting that acoustic call activity indexes colony abundance similarly among years. This provides the opportunity to use vocal activity to examine changes in colony size over time.

### **Acoustic activity and nest abundance between years**

To monitor the efficacy of conservation outcomes, biologists need scalable tools to describe populations pre- and post-intervention. We found that changes in acoustic activity closely reflected year to year changes in mean active nest abundance at five sites (Adj.  $R^2=0.94$ ). These changes in acoustic activity between years could be used to predict changes in colony size within  $\pm 4.7$  mean active nests (LOOCV). Similarly, the change in the total number of nests at a colony site between years also was correlated with the change in acoustic activity between years (Adj.  $R^2=0.88$ ), with a mean prediction error of  $\pm 17.7$  nests. Despite a low sample size, these results,

particularly the high proportion of variance explained, suggests that acoustic activity is a powerful index of seabird nest abundance over time.

### **Performance of call detection**

Spectrogram cross-correlation provided relatively consistent, if not finely accurate results. Detector accuracy was not significantly influenced by colony site or year, remaining near 77%. By contrast, detector sensitivity differed by colony site. Large changes in detector accuracy and sensitivity could bias measurements of acoustic call activity. Differences among sites accounted for more variation in accuracy and sensitivity than year or their interaction, suggesting that error rates were relatively constant across the two years compared to across sites. These results suggest caution when making spatial comparisons without assessing differences in detector sensitivity and accuracy across sites. More thorough evaluation of environmental influences on automated call detection among colony sites is encouraged.

### **Improving Acoustic Monitoring Methods**

With any monitoring program, a host of factors can cause variability in the detection of wildlife and cause variation in abundance indices (Anderson 2001; Pollock et al. 2002; Alldredge et al. 2007). In traditional seabird monitoring, few studies explicitly account for temporal biases in availability and detection associated with human observers (Steinkamp et al. 2003). Common sources of error include differences in phenology, vegetation cover (Walsh et al. 1995), the presence of other species (Piatt et al. 1990), meteorological conditions (Bourgeois et al. 2008), bird behavior (Harding et al. 2005), or the behavior of human observers (Spear et al. 2004).

Acoustic indices are subject to these same sources of error as traditional abundance indices and potentially prone to some new biases relying exclusively on acoustic signals compared to methods incorporating visual detection. However, automated acoustic monitoring has the advantage of sampling over a large spatial area simultaneously during long sampling time periods, and, importantly, using scalable and comparable methods that eliminate differences in observer ability.

Acoustic monitoring approaches are not without limitations. We did find some significant differences in detection sensitivity among colony sites. Individual colony sound environments vary in local microclimate and disturbance patterns, having the potential to affect acoustic indices (similar problems are found with traditional surveys). Thus, it appears that these local effects (weather, habitat factors, co-occurring species, etc.) on acoustic and traditional monitoring results are important, and understanding these effects can further improve the potential utility of acoustic monitoring for seabird abundance at larger scales.

Despite these limitations, acoustic activity was an effective index of nesting abundance among colony sites ( $\pm 5.6$  mean active nests) and between years ( $\pm 4.7$  change in mean active nests). Acoustic call activity is more useful for comparing changes in abundance at the same site among years, rather than estimating actual population sizes for comparisons among different breeding colonies. Given that effective conservation actions should trigger large changes in abundance, we believe automated acoustic monitoring can effectively measure the relative changes in seabird

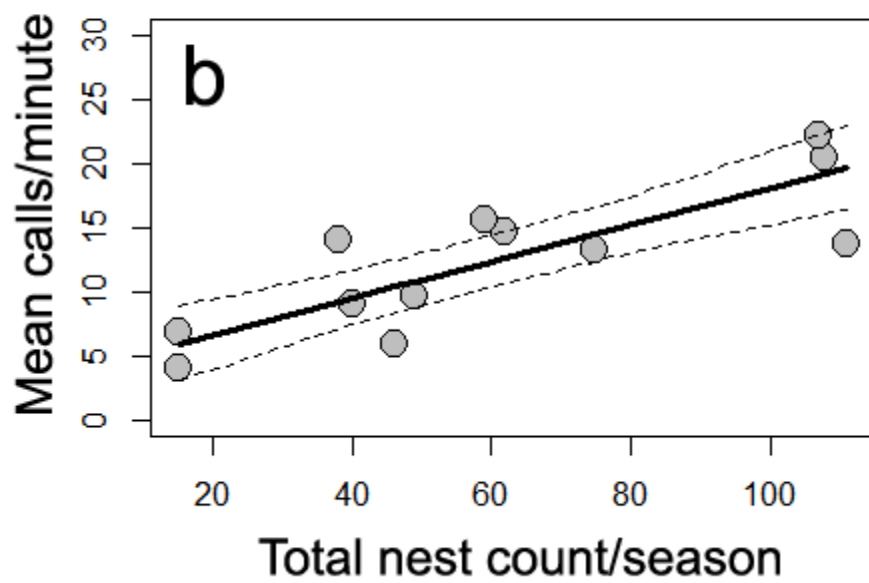
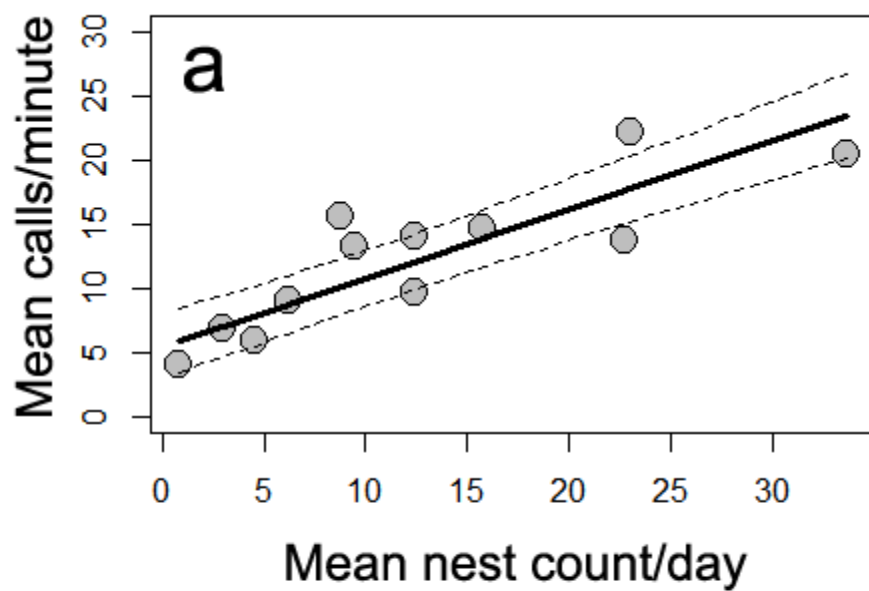
abundance caused by conservation actions in remote areas, and can do so at larger temporal and spatial scales than previously possible with traditional survey methods.

In summary, our results suggest that automated acoustic sensors present a low-cost and scalable tool for monitoring colonial seabirds. Patterns in acoustic vocal activity represent important biological information, and provide estimates of population metrics at a fraction of the cost of traditional methods. This is especially true for seabirds that breed in remote and challenging monitoring environments or have challenging life history traits, such as nocturnal attendance and nesting in burrows and crevices. In the future, the cost of automated acoustic sensors and analysis are likely to decrease (Brandes 2008; Porter et al. 2009), leading to turn-key acoustic monitoring solutions that managers and conservationists can implement easily.

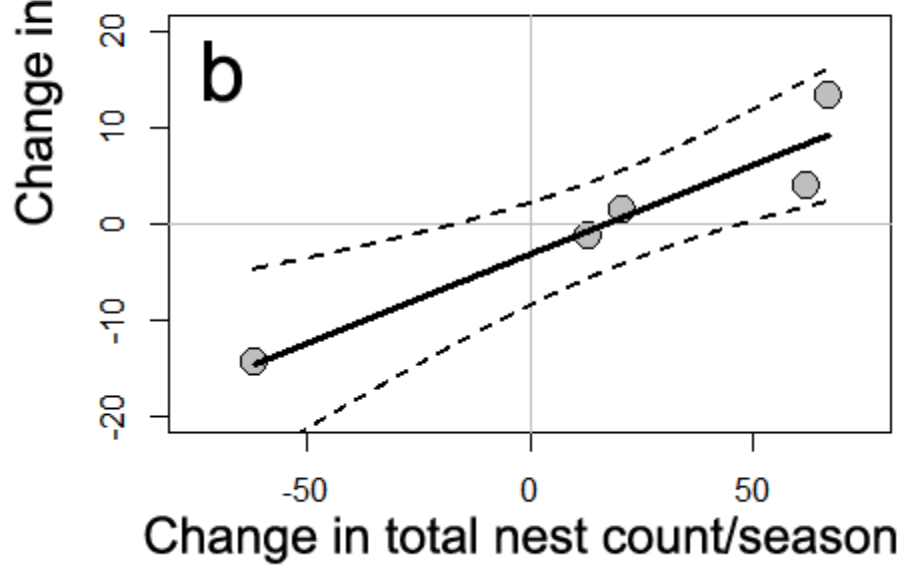
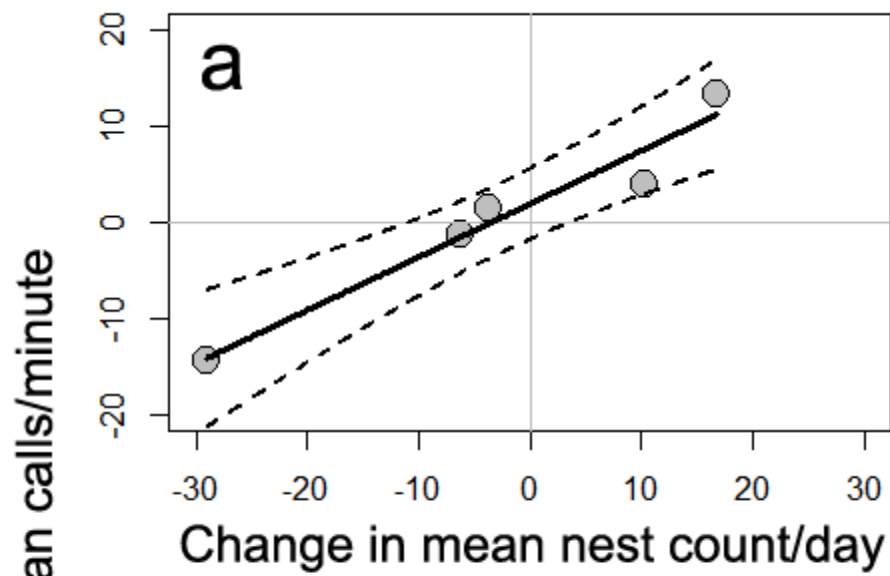
Testing and improving the efficacy of these new monitoring approaches will allow managers and conservation scientists to measure both human impacts on populations and the outcomes of conservation actions on seabird populations at increasing scales.

**Figure 1.** Seasonal mean of acoustic call activity (calls per minute) and (a) mean nest abundance and (b) total nest abundance during the 2009 & 2010 breeding seasons of Forster's Terns at colonies in San Francisco Bay. Black line is best fit from a linear mixed model incorporating nest abundance with site and year as random factors. The mean number of active nests each day explained 88% of the variation in mean nest abundance or 61% of the variation in total nest abundance. Dashed lines are 95% confidence intervals around the slope.

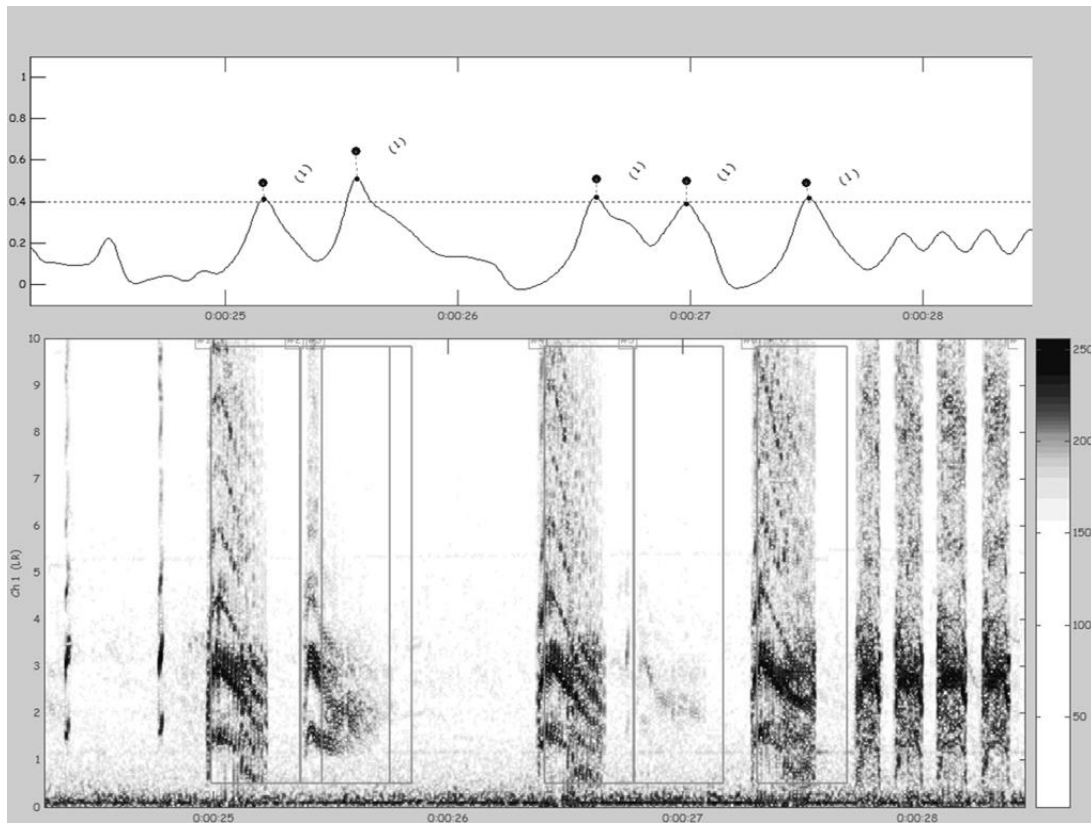




**Figure 2.** Change in the seasonal mean of acoustic call activity (calls per minute) and (a) mean nest abundance and (b) total nest abundance between 2009 and 2010 at five Forster's Tern colonies in South San Francisco Bay. Black line is linear best fit line with the change in call rate explaining 94% (df=3, adj.  $R^2=0.94$ ,  $p<.01$ ) of the variation in changes of mean nest abundance or 88% (df=3, adj.  $R^2=0.88$ ,  $p=0.01$ ) of the variation in changes of total nest abundance. Dashed lines are 95% confidence intervals around the slope.



**Figure 3.** The spectrogram cross correlation process visualized with call detections within gray rectangles when correlation with a search template crossed a user defined 0.4 threshold.



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