Distribution and Abundance of Harbor Seals in Cook Inlet, Alaska. Task I: Aerial Surveys of Seals Ashore, 2003-2007

FINAL REPORT

By
Peter L. Boveng, Josh M. London, Robert A. Montgomery and Jay M. Ver Hoef
National Marine Mammal Laboratory
Alaska Fisheries Science Center
7600 Sand Point Way NE
Seattle, WA 98115

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U.S. Department of Interior
Bureau of Ocean Energy Management
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Environmental Studies Section
3801 Centerpoint Drive, Suite 500
Anchorage, AK 99503-5823

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PROJECT ORGANIZATION

Peter Boveng; NMFS, Seattle, Washington:
Principal Investigator, survey observer, and report author

Josh London; NMFS, Seattle, Washington:
Co-Principal Investigator, database administrator and report author

Michael Simpkins; NMFS, Seattle, Washington (currently Woods Hole, Massachusetts):
Co-Principal Investigator and survey observer

Robert Montgomery; NMFS, Seattle, Washington:
GIS Specialist, survey observer and report author

Jay Ver Hoef, NMFS, Seattle, Washington:
Statistician

Shawn Dahle, John Jansen, Jennifer DeGroot; NMFS, Seattle, Washington:
Survey observers

Oriana Badajos; Kachemak Bay Research Reserve, Homer, Alaska:
Survey observer

ABSTRACT

The National Marine Mammal Laboratory (NMML) conducted 152 aerial surveys in Cook Inlet, Alaska from 2003-2005 to understand the seasonal abundance and distribution of harbor seals (*Phoca vitulina richardii*). Surveys were flown in August, October, April and June to coincide with breeding and pupping (June), molting (August) and non-breeding periods (October and April). The effects of seasonal and environmental variables (covariates) on the numbers of harbor seals hauled out during surveys were assessed using a generalized linear model. The final fitted model of harbor seal counts provided a measure the magnitude of seasonal changes in harbor seals hauled out in the study area. The adjusted counts and standard errors of harbor seals in the study area for each season were 2,635 (257) for April; 7,111 (313) for June; 8,301 (292) for August; and 2,407 (454) for October. Kachemak Bay and Kamishak Bay were two regions with consistently high numbers of seals ashore across all seasons. Additional areas with relatively high numbers in some seasons were the mouth of Iliamna Bay, Augustine Island, Redoubt Bay and the sandbars north and south of Kalgin Island. In general, areas with high numbers of seals in June also had large numbers of pups. The results presented in this report provide a solid foundation for understanding the seasonal distribution and abundance of seals ashore and can aid planning agencies in reducing, avoiding, or responding to impacts from human activities. Analysis of data from satellite-linked geo-location and dive-recorder tags, obtained in Task III of this study, will complement these results by providing measures of habitat use at sea. Haul-out time lines, also obtained from satellite tags, will allow estimation of the total abundance of harbor seals in Cook Inlet, in contrast to the abundance ashore that we estimated from the aerial surveys alone.

KEY WORDS: harbor seal, *Phoca vitulina*, haul-out, abundance, aerial survey, Cook Inlet

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INTRODUCTION

There are five subspecies of harbor seals (*Phoca vitulina*) (Bonner 1972) found exclusively in the Northern Hemisphere (Scheffer and Slipp 1944). *Phoca vitulina richardii* inhabit the western coast of North America and are the most abundant subspecies, a large number of which reside in Alaskan waters where the population numbers close to 150,000. Harbor seals occupy a broad range in Alaska from approximately 130°W to 172°E (over 3,500 km east to west) and from 61°N to 51°S (over 1,000 km north to south). The Cook Inlet region of Alaska is located in the western Gulf of Alaska (Fig. 1) and supports a large abundance of harbor seals year round. The National Marine Fisheries Service and the Alaska Native Harbor Seal Commission recognize 12 stocks of harbor seals in Alaska. The seals in Cook Inlet are represented by a stock that ranges from Cook Inlet through the north side of Shelikof Strait and towards the Shumigan Islands. This study focuses on harbor seals within the Cook Inlet region.

Harbor seals are marine mammals that haul out on land (Pitcher and McAllister 1981, Thompson 1989) to rest, molt, play (Renouf and Lawson 1986) and escape aquatic predation (Watts 1992). Additionally, immersion in water is energetically expensive (Watts 1992) and periodic exposure to sunlight aids skin health (Feltz and Fay 1966).

Harbor seals haul out throughout the year (Thompson 1989) on reefs, sandy beaches, rocks, mudflats, ice and even man-made structures (Pitcher and McAllister 1981, Schneider and Payne 1983, Stewart 1984, Calambokidis et al. 1990, Nickel 2003). Harbor seals' haul-out behavior varies seasonally (Härkönen et al. 1999, Huber et al. 2001, Simpkins et al. 2003). The seals are primarily aquatic throughout the winter months, and spend more time on land during the summer months (Allen et al. 1984, Härkönen 1987, Huber et al. 2001). Their haul-out abundance peaks during the pupping season (Grellier et al. 1996) and the annual molt (Jeffries 1986, Thompson et al. 1989, Watts 1996). Following the molt there is a rapid decline in the number of seals hauled out on land (Sullivan 1980, Thompson et al. 1989, Thompson and Harwood 1990, Mathews and Kelly 1996, Frost et al. 2001, Boveng et al. 2003, Ver Hoef and Frost 2003).

In recent decades, the abundance of harbor seals has declined at several Alaska locations. For example, counts of harbor seals at Tugidak Island declined 85% between 1976 and 1988 (Pitcher 1990) and counts in Prince William Sound suggest population declines of approximately 63%

between 1984 and 1997 (Frost et al. 1999). The significance and causes of these declines are unknown, but there is concern about the present and future status of Alaska harbor seal populations. Because of the proximity of the declining populations to Cook Inlet, and the particularly high oil and gas activity within Cook Inlet, it is important to assess the potential impacts of oil and gas activities on harbor seals within Cook Inlet.

Reliable estimates of harbor seal abundance are needed to develop sound plans for conservation, management, and response to environmental impacts. The most feasible approach to estimating regional abundance is to use aircraft to count seals when they are hauled out of the water and visible. Understanding the timing of haul-out behavior, therefore, is of critical importance to survey design. There are two seasonal peaks in the numbers of harbor seals hauled out in Alaska, one during May - June associated with pupping, and the other during July - September associated with molting (Ashwell-Erickson et al. 1986, Jemison and Kelly 2001). Harbor seals spend 60 percent of the time in the water in May and 40 percent in July. This compares with 68-75 percent of time in the water from September to April (Frost et al. 2001). In Alaska, aerial surveys have generally been conducted during the molting period when the number of seals hauled out is thought to be highest and the weather conditions are likely to be favorable for flying. Patterns of abundance at other times of year are not well known except at a few selected sites, such as Tugidak Island, where long-term, land-based studies have been conducted.

Although harbor seals are not typically wide-ranging, marked seasonal changes in abundance and distribution are commonplace (e.g., Brown and Mate 1983, Bayer 1985, Jeffries 1986, Thompson 1989). These changes are due to regional movements and behavior changes in response to complex interactions between the seals' annual life history cycle and variation in prey abundance and distribution. The details of these complex interactions may be difficult to determine, but the resulting patterns in the abundance and distribution of the seals at key times of the year are possible to assess by appropriate aerial survey techniques.

This study used aerial surveys to provide information about the numbers and distribution of harbor seals found at haul-out sites in Cook Inlet and the seasonal variability at key times in the seals' annual cycle. Other than this study, surveys in Cook Inlet have been conducted infrequently (e.g., every 5 years and only during July/August). To provide a more comprehensive picture for assessment of potential risks to harbor seals from human activities in Cook Inlet, we conducted surveys during pupping (June), molting (August) as well as in other seasons when seals are not as constrained by major life history events (October and April).

Figure 1. Map of Alaska highlighting the Cook Inlet region**.**

OBJECTIVES

This project's main objectives were to:

1. assess the abundance and distribution of harbor seals throughout Cook Inlet,

2. identify and document the harbor seal haul-out sites that are most important for the key life history events of pupping (June) and molting (August), and
3. compare the pupping and molting situations to other seasons when these important life history events do not constrain the seals' behavior.

Hypothesis 1: The relative abundance of harbor seals among the haul-out sites in Cook Inlet changes seasonally, probably reflecting differences among sites in their suitability for rearing young and molting, and their proximity to local prey aggregations.

Hypothesis 2: The numbers of seals ashore in seasons other than pupping and molting are lower but less variable over the period of a survey (about 2 weeks) than the numbers ashore during June and August when certain age and sex classes are subject to strong and rapidly changing life history constraints.

METHODS

Study area

Physical description

Cook Inlet is a large tidal estuary that extends 350 km northeastward from the Gulf of Alaska continental shelf. The Inlet is widest at its mouth (129 km), and is geographically divided into the upper and lower portions by a narrow constriction between the East and West Forelands, only 20 km across. Except for a few deep troughs, Cook Inlet is shallow and averages 60 m (200 ft) in depth (Muench et al. 1978). There are two large bays, Kamishak and Kachemak, located on the west and east coasts, respectively, in southern Cook Inlet. Cook Inlet has a predominately north to south orientation with the mouth draining into the Gulf of Alaska via the Shelikof Strait, and the Kennedy and Stevenson entrances (Muench et al. 1978). Cook Inlet is an extremely important watershed and is the outflow of Mt. McKinley, portions of the Chugach Mountains and the Aleutian mountain range. It has an area of approximately 20,000 km^2 (8,000 miles^2) with 1,350 km (840 miles) of coastline (Rugh 2000).

Large salt marshes and mud flats are a dominant coastal feature along Cook Inlet, although sand and gravel beaches, and rocky shores are also quite common. Second only to the Bay of Fundy in Nova Scotia, Cook Inlet has some of the largest tides in the world ranging up to 36 vertical feet (Desplanque and Bray 1985). Currents of greater than 12 knots are not uncommon.

Although not geographically discrete, the southeastern side of Cook Inlet is oceanographically and biologically distinct from the rest of the Inlet, leading it to be classified as a separate ecoregion (Piatt and Springer 2007). In general, there is a persistent upwelling of cold, nutrient-rich waters entering the southeastern side of the inlet (Kennedy Entrance), causing extremely high rates of primary and secondary production. In contrast, relatively fresh, turbid, and therefore less productive, waters from the upper inlet move southward along the west side and leave the inlet through Shelikof Strait (Burbank 1977, Larrance et al. 1977, Muench et al. 1978, Drew and Piatt 2002).

Human Use

Cook Inlet activities include tourism, commercial fishing, oil and gas development, and shipping traffic. Anchorage is Alaska’s largest city (280,000 people) and is situated at the head of Cook Inlet between the Turnagain and Knik Arms. Another 52,000 people live on the Kenai Peninsula on the eastern side of the inlet. The western side is remote and uninhabited, with the exception of the village of Tyonek in the northern inlet and the occasional fishing lodge or homestead. Tourism peaks each summer with over one million people visiting Cook Inlet for fishing, hiking, wildlife viewing, or other recreational opportunities. Cook Inlet represents one of the most productive fisheries in Alaska, in which five species of salmon, herring, scallops, halibut, and several other species of bottom fish are harvested. From May through September, there are about 500 to 900 commercial fishing vessels operating in Cook Inlet (CIRCAC 2006). The Cook Inlet basin contains large oil and gas deposits including several offshore fields. There are currently 16 offshore oil production platforms operating in Cook Inlet. The oil is refined in Nikiski (near Kenai) and shipped to Alaskan markets (CIRCAC 2000). With over 700 deep draft vessels arriving in ports each year, Cook Inlet has low to moderate levels of vessel traffic when compared to other large North American ports. Many of the vessels are container ships (47%), but a high proportion of the traffic is gas or liquid petroleum tank ships (29%) (CIRCAC 2006).

Study Area and Scope

The harbor seal research was performed exclusively in central and lower Cook Inlet (Fig. 2). The northern boundary was at the Forelands near Nikiski, with the southern boundary at the Barren Islands. This study, based on aerial surveys of harbor seals, is part of a greater investigation of harbor seal distribution and ecology in Cook Inlet. The scope was originally limited to aerial surveys (Task I), but, with additional funding, was expanded to include deployment of time-lapse cameras at selected haul-out locations (Task II) and satellite telemetry of seal movement, behavior, and habitat use (Task III). Task I and Task II focus on understanding the behavior, distribution and abundance of seals ashore. Task III addresses questions related to the time seals spend away from shore and also provides a higher resolution dataset for examining the relationship between seals and their environment. While the methods, results and discussion presented in this report focus on the aerial surveys, it is important to recognize that a much more complete understanding of harbor seals in Cook Inlet will result from combining results from all three studies. This synthesis of results will be presented in the Task III Final Report.

Figure 2. The study area in central and lower Cook Inlet. Aerial survey units, encompassing all harbor seal haul-out habitat (except occasional haul-out sites on sea ice or man-made structures) are outlined.

Aerial Surveys

Aerial surveys have been the primary means for estimating the abundance of harbor seals throughout Alaska (Jeffries 1986, Withrow and Loughlin 1997, Hill and DeMaster 1998, Frost et al. 1999, Adkison et al. 2003, Boveng et al. 2003). Aerial surveys were conducted in Cook Inlet during the months of June, August and October of 2003, April, June, August and October of 2004 and April, June, August and October of 2005. The study area was divided into two routes, north and south. Each of the study areas could be surveyed by one aircraft per day. A variety of aircraft were used throughout the study including Cessna L-19, Cessna 185, AC-680 and AC-690. Surveys were generally flown at altitudes of 150 – 275 m (500-900 ft).

Surveys were flown during the period comprising two hours before and two hours after low tide. During the first 1 – 2 days of each survey period, the entire coastline was surveyed to identify all harbor seal haul-out locations. When a seal haul-out site was identified, the position was marked with a GPS unit (Garmin® 76, 76S, or 295). A site where at least one seal was found to be hauled out on at least one day constituted a haul-out site and was included in the analysis. Each haul-out site was then revisited on each successive day of the survey, weather permitting.

When harbor seals were observed, the haul-outs were photographed to encompass all seals within the image. Haul-out sites with <10 seals were frequently counted visually without photographs. Digital photographs were taken with a Nikon® D1X camera and 70-210 mm lens. The August survey of 2003 was flown with a 35 mm Nikon SLR (model 8008 or N90S) camera and a 70-210 mm lens. In this case, the film was developed and digitally scanned at high resolution. Additionally, weather conditions were recorded at regular intervals. Any disturbance to seals was also recorded for reporting under Marine Mammal Protection Act scientific permit number 782-1767, which authorized this work.

When large seal groups were encountered, several overlapping pictures typically were taken. In the lab these pictures were pieced together and counted in a photographic editing program (ACDSee™ and Adobe® Photoshop® CS). Each seal was digitally marked with a dot and tallied. Only animals counted on land (i.e., not floating or submerged) were included in the analysis. Those seals observed in the water directly adjacent to haul-out sites were not included in the count because they are part of the population that would be recorded as not hauled out in telemetry-based estimates of the fraction in the water (Task III). All observations where the count was compromised, through disturbance or low picture quality, were excluded from analysis. Pups, which could be visually identified in the June surveys, were also eliminated from the analysis of overall abundance.

Geographic Survey Units

A system of survey units has been developed by the National Marine Mammal Laboratory for coastal Alaska to divide all available harbor seal haul-out habitat into distinct units (Fig. 3). These were generated in ArcMap™ 9.0 (ESRI©, Redlands, CA). The first step in this procedure was to isolate all intertidal habitats where harbor seals could potentially haul-out. In estuaries, the intertidal range commonly presents the only suitable haul-out habitat for harbor seals (Thompson et al. 1997). We defined the intertidal range to include all areas between the extreme high tide line (+4 m) and the extreme low tide line (-2 m). The coastline data provided by the Alaska Department of Natural Resources includes coastal features, offshore islands and intertidal rocks. However, these data do not include all areas potentially exposed at low tide. Therefore, bathymetry data were used to isolate intertidal habitats. High quality bathymetry data were used to create low tide contour intervals (-2 m) in areas, such as Cook Inlet, with large tidal changes.

This complete coastline data was then merged with a large river dataset also provided by the Alaska Department of Natural Resources. These data included areas of river deltas which are potential harbor seal haul-outs, even though they may be above the extreme high tide line. Finally, all of the historic harbor seal haul-out locations from previous aerial surveys were incorporated into the dataset. These points were buffered with a 1 km radius and merged with the previous layers. This complete file was then buffered to include the tracks of the survey aircraft, so that each photograph taken by observers fell within the boundary of a polygon. The merged polygon feature was buffered by an additional 1 km on each side and then dissolved, leaving a single continuous shapefile.

To divide this buffered shapefile into units for recording and analyzing survey data, we first created a fishnet grid at a resolution of 1 km over the entire state of Alaska. We clipped this fishnet to the buffered shapefile so that only the available haul-out area was gridded. We added a field to the table of the gridded shapefile called “cluster” to represent the aggregation ID. Then using the edit function in ArcMap we aggregated individual grid cells into larger clusters. The intention of this aggregation process was to generate clusters, or survey units, that were small enough to survey without significant changes in weather and tidal conditions, but large enough to avoid variations in counts from day-to-day differences in haul-out site preferences of local groups of seals. This editing process resulted in 57 units within lower and central Cook Inlet. These final polygon survey units were then named using a standardized letter-number grid (Fig. 3) that the National Marine Mammal Laboratory has applied to the entire range of harbor seals throughout Alaska.

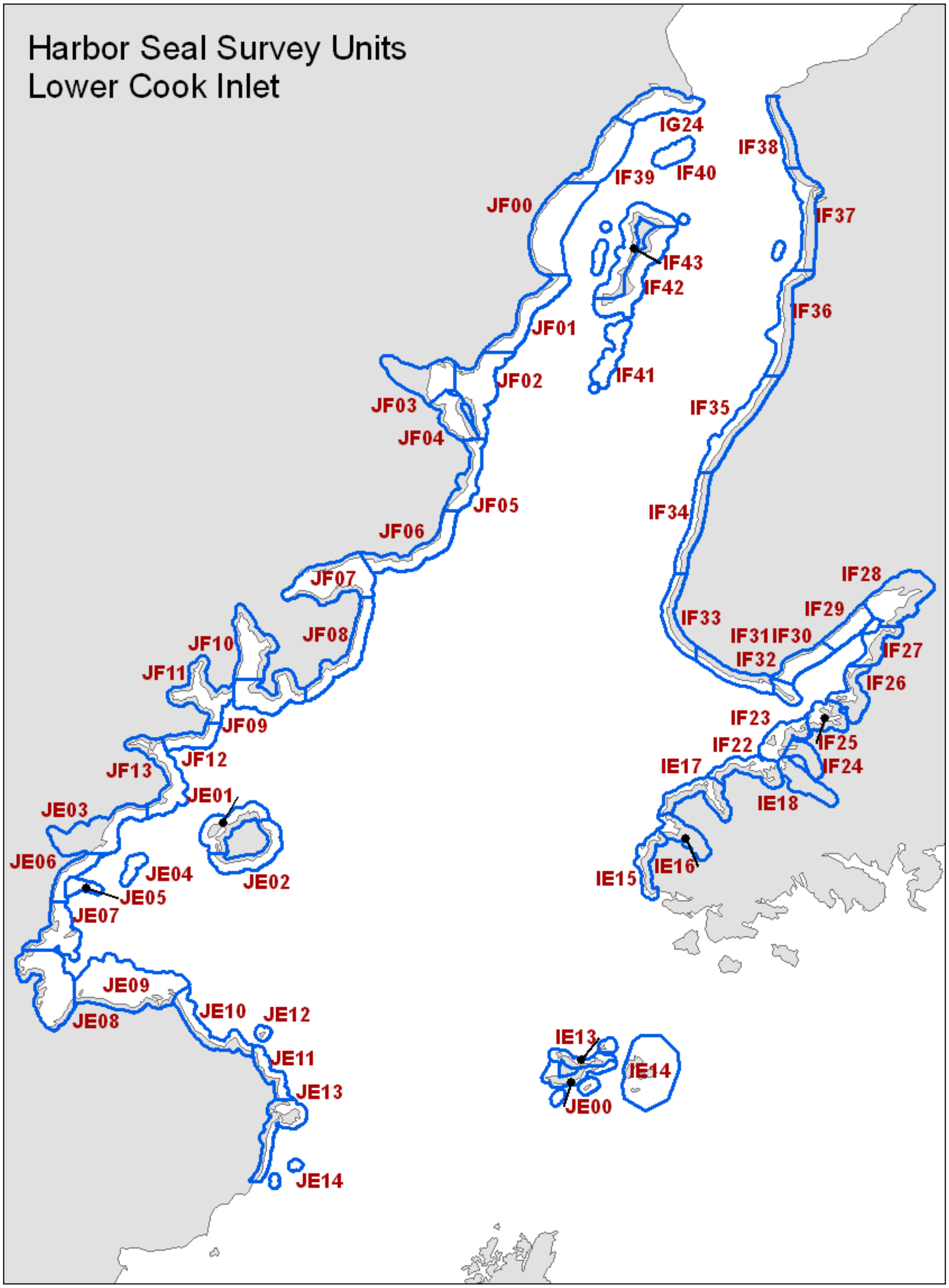

Figure 3. Unique survey units identified in the central and lower regions of Cook Inlet, Alaska.

Assigning Counts to Survey Units

All counts of harbor seals were geo-referenced to either the position of a known haul-out location or a position derived from the digital photo timestamp and the GPS track log. A spatial-join was performed to assign all counts to a survey unit. The survey track and observer recordings were used to determine survey effort. When a survey unit was covered, but no photos were taken and no visual counts recorded, the count for that survey unit was recorded as zero. If all of the known haul-out sites within a survey unit could not be surveyed on a given day or a survey unit without known sites was not surveyed satisfactorily, the count was recorded as 'NULL'. Counts were then summed within survey units for each survey day and these aggregated counts formed the basis for all analyses.

Statistical Analysis of Factors Affecting Seal Haul-out Behavior

Harbor seals are well known to be highly variable in their haul-out patterns. The numbers of seals on shore typically fluctuate with the seasons, time of day, tide height, weather, and other—often unseen—factors. Although it is possible to reduce the variability in counts from some of these factors by survey design (e.g., restricting surveys to a particular time of year), it is not feasible to use survey design to control for many factors at once. For example, low tides occur only at certain times of the day that are not optimal for hauling out during some seasons. Therefore, it is preferable to reduce variability in survey counts and population estimates by statistical adjustments to account for variability in conditions when the surveys were conducted. Although the following description of statistical methods for adjusting counts may be complex in notation for some readers, the purpose is simply to use a regression framework to obtain counts that reflect a consistent and standardized set of survey conditions. The adjusted counts are more comparable than raw or simple averages of counts that do not explicitly consider the variation in survey conditions.

We modeled the effects of environmental variables (covariates) on the numbers of harbor seals hauled out during surveys using a method similar to that used by Frost *et al.* (1999), Boveng *et al.* (2003), and Ver Hoef and Frost (2003), which is based on a generalized linear model (McCullagh and Nelder 1989). We assumed an overdispersed Poisson distribution (Ver Hoef and Boveng 2007) for the count, denoted Y_{ijkl}, from the ith site and the lth flight in the jth season of the *k*th year. While it is possible to write down an exact distribution for overdispersed Poisson models (Efron 1986), estimation often proceeds from the first two moments and estimating equations (Lee and Nelder 2000). This formulation has the advantage of leaving parameters in a natural, interpretable state and allows standard model diagnostics without a loss of efficient fitting algorithms. Properties of an overdispersed Poisson regression are the expectation,

$$E(Y_{ijkl}) = \mu_{ijkl}, \tag{1}$$

and variance that is a scalar multiple of the expectation (mean),

$$\mathrm{var}(Y_{ijkl}) = \phi\mu_{ijkl}. \tag{2}$$

Because we used Poisson regression, we allowed the mean in Equations (1) and (2) to be a function of covariates,

$$\mu_{ijkl} = \exp(\mathbf{x}'_{ijkl}\boldsymbol{\beta}), \tag{3}$$

where $\mathbf{x}_{ijkl}$ is a vector of measured covariates for the *l*th flight of the *i*th site in season *j* of year *k*, and $\boldsymbol{\beta}$ is a vector of parameters. We fit the following model

$$\begin{aligned}\mathbf{x}'_{ijkl}\boldsymbol{\beta} = {} & (\theta\alpha)_{ij} + \alpha_j + \psi_k + (\alpha\psi)_{jk} + \eta_1(\mathrm{hour})_{ijkl} + \eta_2(\mathrm{hour})^2_{ijkl} + \eta_3(\mathrm{hour})^3_{ijkl} + \eta_4(\mathrm{hour})^4_{ijkl} + \\ & (\eta\alpha)_{1j}(\mathrm{hour})_{ijkl} + (\eta\alpha)_{2j}(\mathrm{hour})^2_{ijkl} + (\eta\alpha)_{3j}(\mathrm{hour})^3_{ijkl} + (\eta\alpha)_{4j}(\mathrm{hour})^4_{ijkl} + \\ & \tau_1(\mathrm{tide})_{ijkl} + \tau_2(\mathrm{tide})^2_{ijkl} + (\tau\alpha)_{1j}(\mathrm{tide})_{ijkl} + (\tau\alpha)_{2j}(\mathrm{tide})^2_{ijkl},\end{aligned} \tag{4}$$

where $(\theta\alpha)_{ij}$ is a separate intercept for the *i*th site in the *j*th season, α_j is a season effect, ψ_j is a year effect, $(\alpha\psi)_{jk}$ is an interaction between year and season, $(\mathrm{hour})_{ijkl}$ is the hour of day for the *ijkl*th observation with $\eta_1 - \eta_4$ as regression coefficients and $(\eta\alpha)_{1j} - (\eta\alpha)_{4j}$ are interaction regression coefficients for seasonal effects, and $(\mathrm{tide})_{ijkl}$ is the absolute tide height (in meters) for the *ijkl*th observation with $\tau_1 - \tau_4$ regression coefficients and $(\tau\alpha)_{1j} - (\tau\alpha)_{4j}$

are interaction regression coefficients for seasonal effects. All of the parameters $[\{(\theta\tau)_{ij}\},\{\alpha_j\},\ldots\{(\tau\alpha)_{2j}\}]$ are contained in the vector $\boldsymbol{\beta}$. For the overdispersed Poisson model, estimation of the regression parameters $\boldsymbol{\beta}$ remains unchanged from the standard Poisson regression. The overdispersion parameter is estimated by,

$$\hat{\phi} = \frac{1}{\text{rows}(\mathbf{X}) - \text{rank}(\mathbf{X})} \sum_{i=1}^{S} \sum_{j=1}^{4} \sum_{k=1}^{3} \sum_{l=1}^{n_{ijk}} \frac{(y_{ijkl} - \hat{\mu}_{ijkl})^2}{\hat{\mu}_{ijkl}}, \tag{5}$$

where $\hat{\mu}_{ijkl} = \exp(\mathbf{x}'_{ijkl}\hat{\boldsymbol{\beta}})$, with $\hat{\boldsymbol{\beta}}$ being the coefficients estimated from Poisson regression, $\mathbf{X}$ is the design matrix containing rows $\mathbf{x}'_{ijkl}$, S is the number of sites, and n_{ijk} is the number of flights for the *i*th site in *j*th season of the *k*th year. All estimation used PROC GLIMMIX in SAS Version 9.1.

Adjusting Counts to Standardized Covariate Conditions

The fixed effects estimates $\hat{\boldsymbol{\beta}}$ were modeled on the log scale. Seasonal abundance estimates or the predicted effects of covariates were all determined through linear combinations of the parameters in $\hat{\boldsymbol{\beta}}$; we denote any such linear combination as $\mathbf{L}\hat{\boldsymbol{\beta}}$, which is on the log scale. The adjusted estimates back on the original scale of the data are

$$\hat{\mathbf{a}} = \exp(\mathbf{L}\hat{\boldsymbol{\beta}}). \tag{6}$$

Let $\hat{\mathbf{C}}$ be the estimated covariance matrix for the parameter vector $\hat{\boldsymbol{\beta}}$, which includes the effect of overdispersion. The details on obtaining the estimated covariance matrix are beyond the scope of this report, but we followed the pseudo-likelihood method of Wolfinger and O'Connell (1993) and implemented it in SAS PROC GLIMMIX version 9.1. The covariance matrix of $\mathbf{L}\hat{\boldsymbol{\beta}}$ is $\text{cov}(\mathbf{L}\hat{\boldsymbol{\beta}}) = \mathbf{L}\hat{\mathbf{C}}\mathbf{L}'$. We left the effects of covariates on the log scale. We back transformed site-specific abundance estimates to the original scale of the data to get adjusted estimates (Equation (6)). Using the delta method (Dorfman 1938), the approximate variance of total abundance estimates is,

$$\mathrm{var}(\mathbf{1}'\hat{\mathbf{a}}) \cong \hat{\mathbf{a}}'\mathbf{L}\hat{\mathbf{C}}\mathbf{L}'\hat{\mathbf{C}}\hat{\mathbf{a}}.$$

In Equation (6), we had a separate **L** for each season, and hence a separate $\hat{\mathbf{a}}$ for each season provided estimates and standard errors. More details are given in Ver Hoef and Boveng (2007).

Model Selection

P-values for explanatory variables were based on the Type III hypothesis test as in SAS (Littell et al. 1996). We examined *p*-values for all interaction terms. Following Ver Hoef *et al. (2001)*, interactions with $p > 0.15$ were removed one at a time, starting with the least significant variable. This step-wise regression continued until the final model structure included all interactions with $p < 0.15$. If an interaction was not significant, each lower level effect was also eliminated using $p < 0.15$; however no effects were removed if they were contained in an interaction effect that was kept in the model. Final statistical significance was based on $p < 0.05$. Note that pseudo-likelihood does not use a true likelihood so it was not possible to use Akaike's Information Criterion (AIC). Therefore, we used the traditional approach of stepwise selection of fixed effects based on *p*-values.

Seasonal Differences

Aerial surveys were scheduled to coincide with seasonal changes in life history factors believed to impact the behavior and ecology of harbor seals. June corresponds with the timing of peak pupping and August with peak molting. During October and April, seals are not influenced by those major life history events. To evaluate how the abundance of harbor seals on shore changes from season to season, a standardized difference parameter was developed. The standardized difference is the difference in estimates between subsequent seasons divided by the difference in standard errors. This value is similar to a t-test in that larger values represent more significant changes. When the subsequent counts are lower, the standard difference parameter will be negative. Increases are represented by a positive standard difference.

Identification of Pupping Locales

Pup counts were analyzed for the June surveys in 2003, 2004 and 2005. Pups were identified in the photographs by relative size and proximity to an adult seal (putative mother). Pup counts were summarized by survey unit. An average total pup count and average pup ratio (pup:non-pup) were calculated across the years, giving equal weight to each year. These values were then included in our GIS to identify survey units important for pupping.

RESULTS

A total of 152 aerial survey flights were completed between June 2003 and October 2005. Complete surveys, each comprising approximately one week of daily survey flights, of the lower and central Cook Inlet were conducted in October (n=3), April (n=2), June (n=3) and August (n=3). Of the 57 identified survey units within central and lower Cook Inlet, harbor seal haul-out locations were identified in 46 (Fig. 4). Of those 46 units, 29 had seals present in all four seasons (months).

We created four seasonal models from the global model given by Equation (4). We adjusted counts for each site for each season to a standardized set of covariate conditions, representing a tide height of 0 m at noon for each season in 2005. Estimates of abundance on shore and standardized difference were calculated for each month and for each survey unit (Table 1). The final fitted model of harbor seal counts provided evidence of seasonal changes in harbor seals hauled out in the study area (Table 2). Note, the only factor removed from the initial model was the interaction term $tide^2{*}season$. The seasonal effects were most notable when examining the tide-height and hour-of-day factors (Figs. 5-6). Date within season was not included as a factor because there was no evidence of an effect.

The adjusted counts and standard errors for each season (Fig. 7) were 2,635 (257.15) for April; 7,111 (313.44) for June; 8,301 (292.39) for August; and 2,407 (454.11) for October. Seasonal differences in the distribution and abundance of seals on shore are shown in Figures 8-11 as adjusted counts and in Figures 12-15 as standardized difference from the previous season. The results show there was a seasonal component to both the overall abundance and the distribution of seals ashore within Cook Inlet. In general, while there were fewer seals ashore in October and April, the seals were more evenly distributed across the study area. The strong influence of breeding and molting in June and August appeared to concentrate seals in certain areas. Upper Kachemak Bay, Kamishak Bay, Augustine Island, the mouth of Iliamna Bay, and the sandbars near Kalgin Island were key areas for harbor seals during those months. Some of these areas exhibited potentially important seasonal dynamics. The Upper Kachemak Bay region and the Kamishak Bay area were consistently two of the highest concentrations of seals across all seasons. The SE side of Augustine Island was only used in high concentrations during the molt in August, but the NW side was used consistently throughout the year. The standardized difference between counts in June and counts in August also reflected the importance of this site for molting. Seals were more dense on the western side of the Cook Inlet compared to the east, with the exception of Kachemak Bay, which had the highest densities of all.

The analysis of pup counts (Figs. 16-17) showed that some areas are particularly important for the production of pups in June. Areas important for pupping and breeding can also be identified from the analysis of standardized differences in seals ashore between April and June (Fig. 12). The areas of strong increase (red and orange units) correspond with high pup counts. In general, the average number of pups in a given survey unit is related to the total number of seals. Areas with large numbers of seals also have large numbers of pups. However, there are a few locations identified in this analysis with smaller numbers of pups, but high ratios of pups to non-pups. These areas may be important locations for females as they seek habitats away from large concentrations of seals to give birth and wean their pups. The north side of the Barren Islands, the region in Kachemak Bay across from Homer and the coastline of Redoubt Bay are examples of areas with typically lower numbers of seals but with high pup ratios in June.

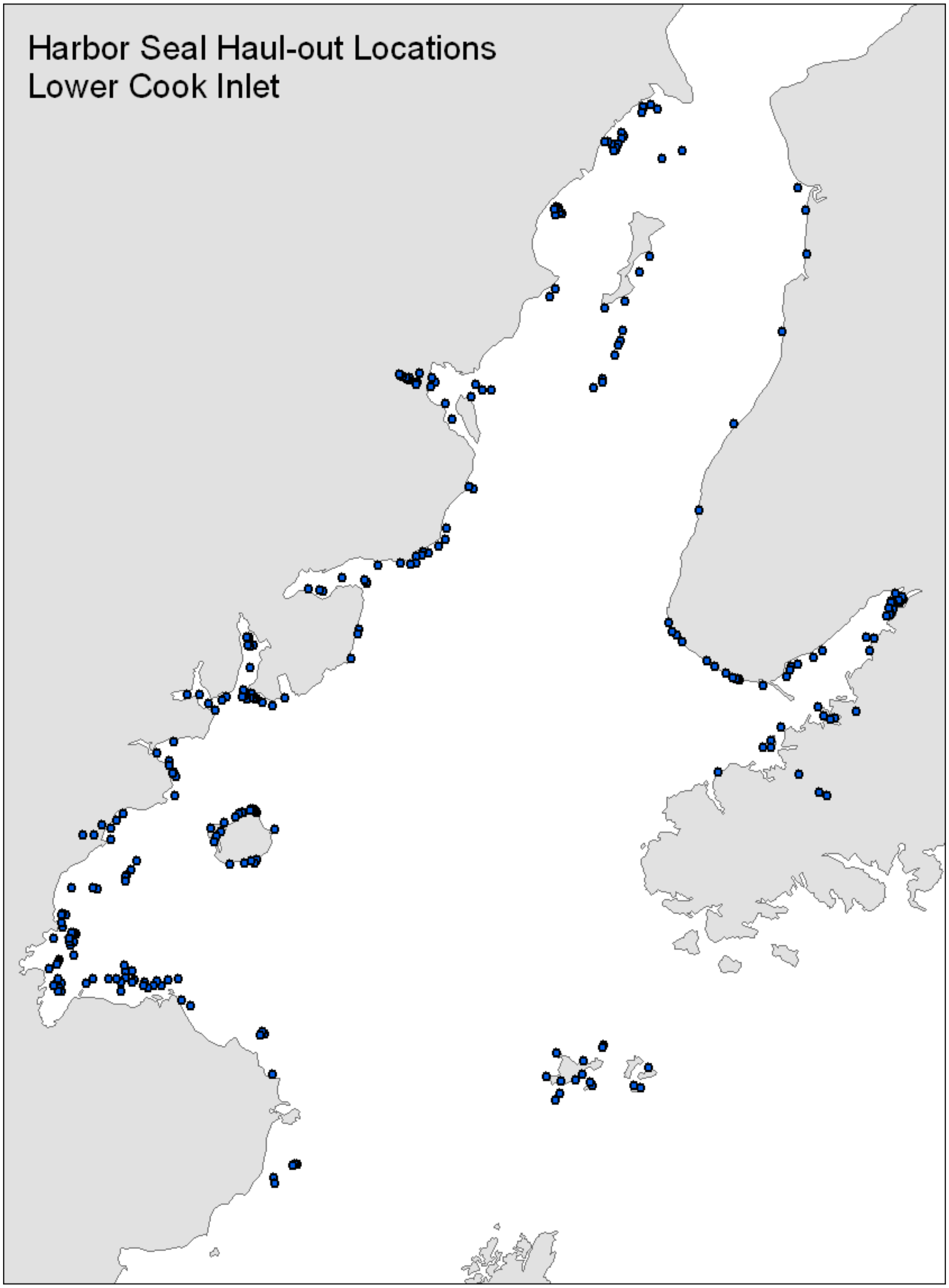

Figure 4. Unique survey units identified in the central and lower regions of Cook Inlet, Alaska.

Table 1. Estimates of adjusted counts for hauled out harbor seals in each survey polygon in April, June, August and October.

POLYID	APRIL		JUNE		AUGUST		OCTOBER	
	Estimate	SE	Estimate	SE	Estimate	SE	Estimate	SE
IE13	119.71	27.98	50.99	12.11	75.08	27.20	4.24	4.60
IE14			8.55	8.74				
IE18	1.81	2.48	1.48	2.11	7.44	4.23		
IF22					0.19	0.99	0.32	1.72
IF23	40.16	11.97	27.97	9.47	51.00	13.98		
IF25	8.12	5.03	30.22	6.59	10.77	4.83	4.039	2.92
IF26	25.45	8.74			10.11	4.98		
IF27	52.61	13.25	100.90	11.82	29.44	8.91	67.90	12.42
IF28	420.43	52.20	1527.20	65.30	105.75	23.41	2176.52	120.61
IF30	15.47	6.57	16.00	4.53	12.17	4.94	11.81	5.92
IF32	62.11	13.89	22.55	5.47	62.95	15.61	22.52	7.72
IF33	143.16	22.85	33.30	6.72	45.31	11.79	6.58	4.59
IF34	2.51	2.79			0.53	1.40		
IF37							0.63	1.50
IF39			688.80	34.66	68.29	12.91	390.88	35.54
IF40			240.02	20.56	0.25	0.65	139.79	18.07
IF41	286.94	36.93	272.65	22.23	248.27	38.74	122.07	17.16
IF42			0.11	0.58	0.35	0.93	0.63	1.67
IG24			4.78	2.66			193.53	24.26
JE00	21.76	11.51	73.76	14.57	50.46	22.35	27.71	10.64

POLYID	APRIL		JUNE		AUGUST		OCTOBER	
	Estimate	SE	Estimate	SE	Estimate	SE	Estimate	SE
JE01	357.99	48.63	396.48	31.28	282.95	49.93	366.99	28.24
JE02	14.71	7.40	488.26	35.48	30.84	9.90	43.63	9.10
JE03	1.42	2.68	1.71	1.66	0.41	0.97	9.44	4.59
JE04	147.09	27.59	74.61	11.94	90.26	20.92	122.57	15.95
JE05	38.92	12.64	85.45	12.80	17.77	7.03	138.23	17.10
JE07	35.22	12.56	236.77	21.89	3.80	2.91	197.62	21.38
JE08	13.19	7.64	363.66	27.49	79.28	19.35	247.82	24.55
JE09	80.58	19.71	852.29	51.75	237.13	51.48	675.99	46.71
JE10			0.11	0.42			0.09	0.47
JE11							0.20	0.62
JE12	132.52	26.88	820.76	47.92	236.27	55.67	495.37	38.46
JE14	134.52	25.62	567.23	40.05	452.03	106.87	402.83	33.65
JF00	4.72	3.68	50.79	8.73	6.20	3.35	121.29	18.64
JF01	4.58	3.57			9.39	4.72	14.41	5.40
JF02	1.70	2.20	74.29	10.65	10.13	4.40	72.38	12.49
JF03	17.48	7.17	59.91	9.53	22.19	6.91	274.52	26.65
JF04	3.64	3.19	0.05	0.29			0.48	1.03
JF05			0.55	0.92	5.24	3.17	0.25	0.75
JF06			0.88	1.17	0.19	0.58	2.87	2.50
JF07	164.60	28.49	182.65	19.46	86.69	17.24	4.48	3.10
JF08	34.12	10.08	5.03	2.50	20.22	7.20	88.32	15.03
JF09	230.046	35.61	849.13	43.65	102.21	19.80	350.07	27.89
JF10	38.22	12.49	92.80	12.76	16.79	7.32	184.32	20.09

POLYID	APRIL		JUNE		AUGUST		OCTOBER	
	Estimate	SE	Estimate	SE	Estimate	SE	Estimate	SE
JF11	25.23	9.09	67.14	10.90	3.69	3.22	103.73	14.64
JF12					0.20	0.76	0.29	0.90
JF13	5.30	4.09	41.39	8.23	3.27	2.86	19.50	7.30

Table 2. Type III tests of fixed effects.

EFFECT	Num DF	Den DF	F-value	Pr > F
Season	3	2005	2.30	0.0753
SiteID*Season	150	2005	70.15	<.0001
Year	2	2005	18.91	<.0001
Year*Season	5	2005	7.52	<.0001
HourOfDay^{1}	1	2005	7.63	0.0058
HourOfDay^{2}	1	2005	18.69	<.0001
HourOfDay^{3}	1	2005	1.86	0.1728
HourOfDay^{4}	1	2005	20.07	<.0001
HourOfDay^{1}*Season	3	2005	5.73	0.0007
HourOfDay^{2}*Season	3	2005	7.12	<.0001
HourOfDay^{3}*Season	3	2005	4.80	0.0025
HourOfDay^{4}*Season	3	2005	8.05	<.0001
TideHeight	1	2005	0.74	0.3892
TideHeight^{2}	1	2005	16.34	<.0001
TideHeight*Season	3	2005	2.47	0.0602
Overdispersion Parameter: 28.1630				

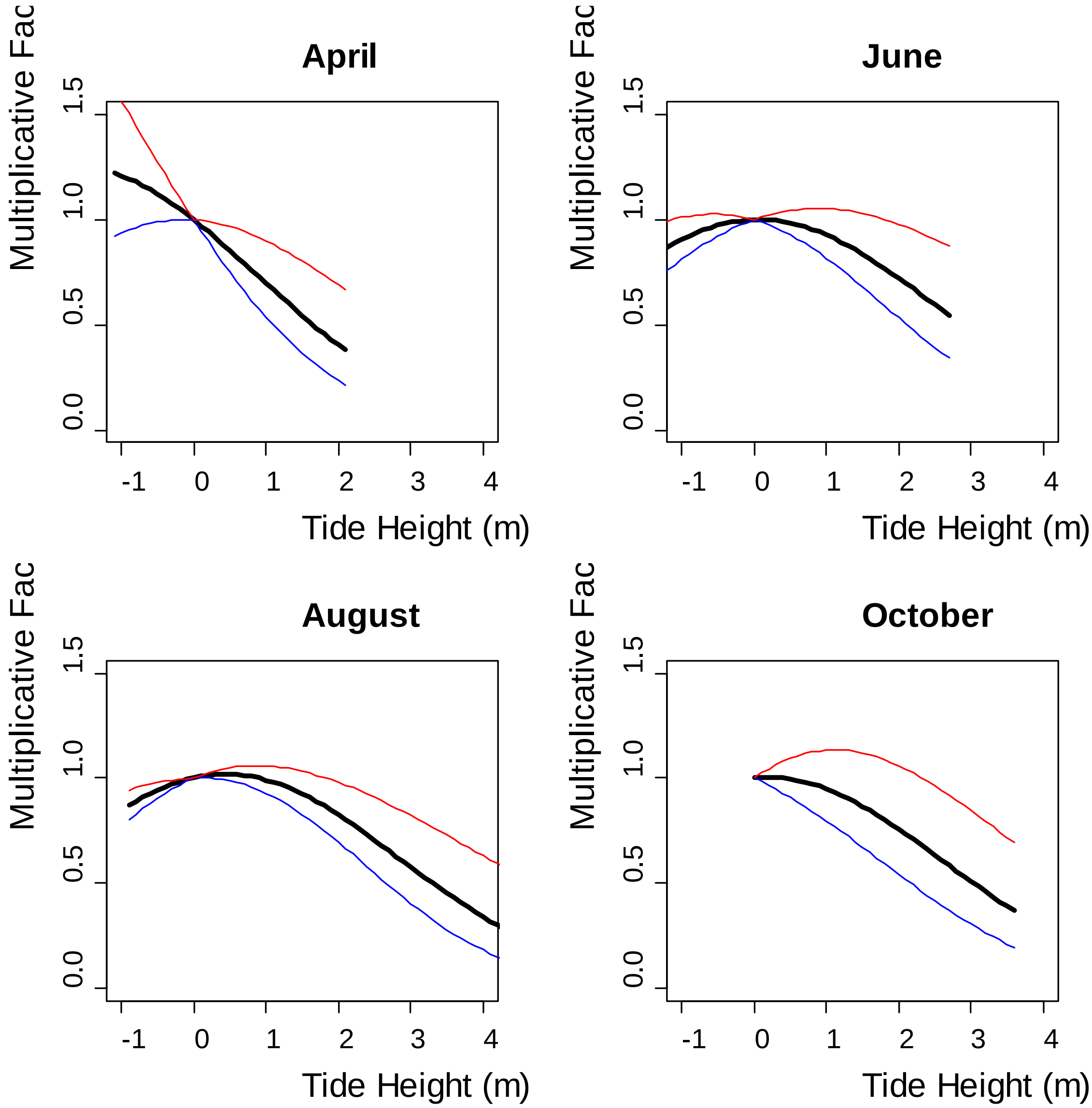

Figure 5. Results showing the different effects of tide-height on the survey counts across the four survey periods.

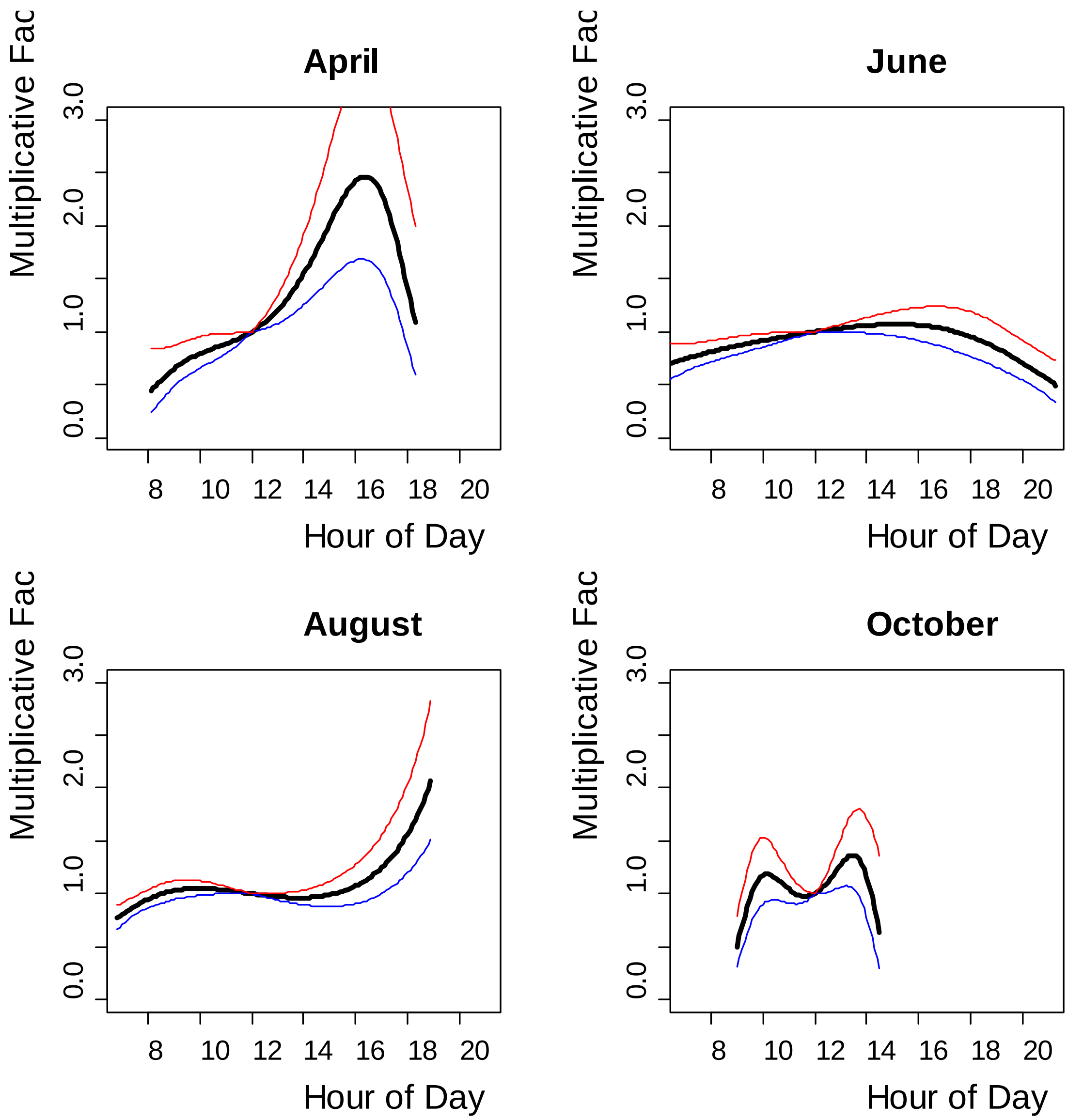

Figure 6. Results showing the different effects of hour of day on the survey counts across the four survey periods.

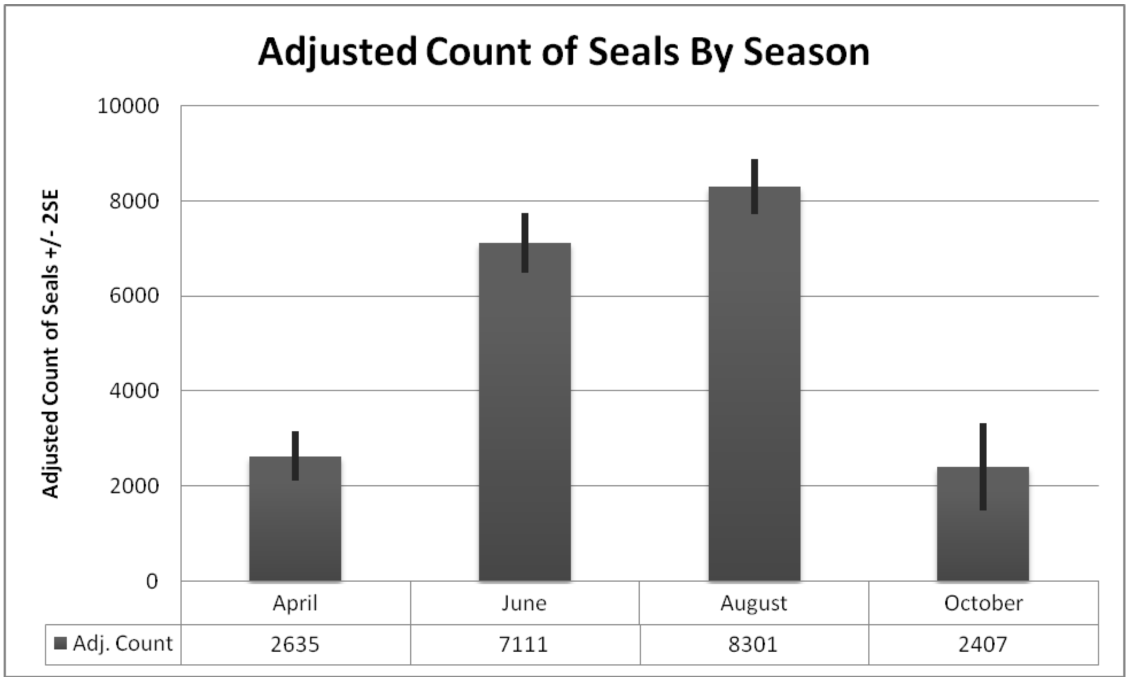

Figure 7. Adjusted counts of harbor seals hauled out in Cook Inlet by season. Error bars indicate two standard errors.

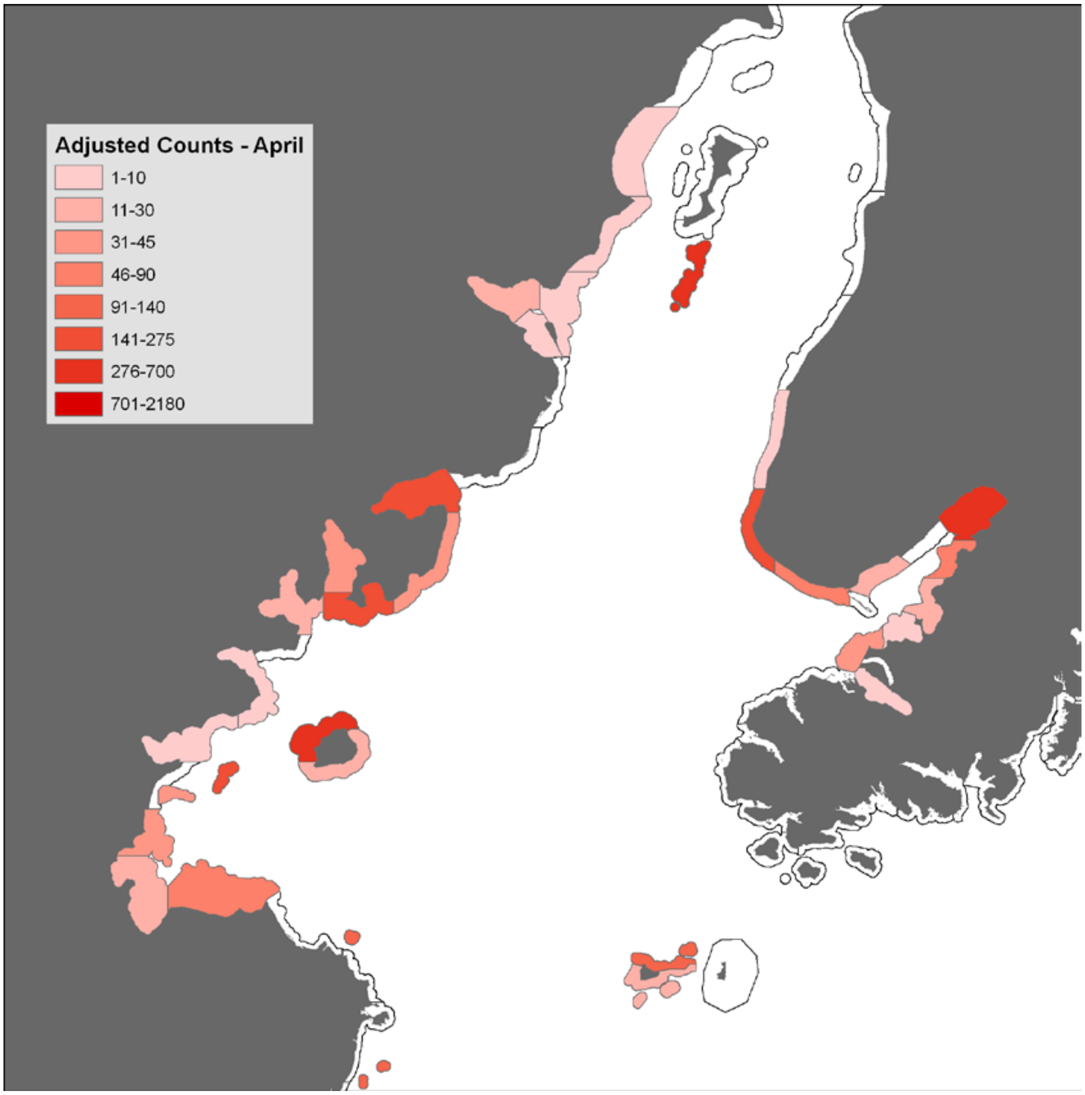

Figure 8. Adjusted counts of hauled out harbor seals by polygon in April.

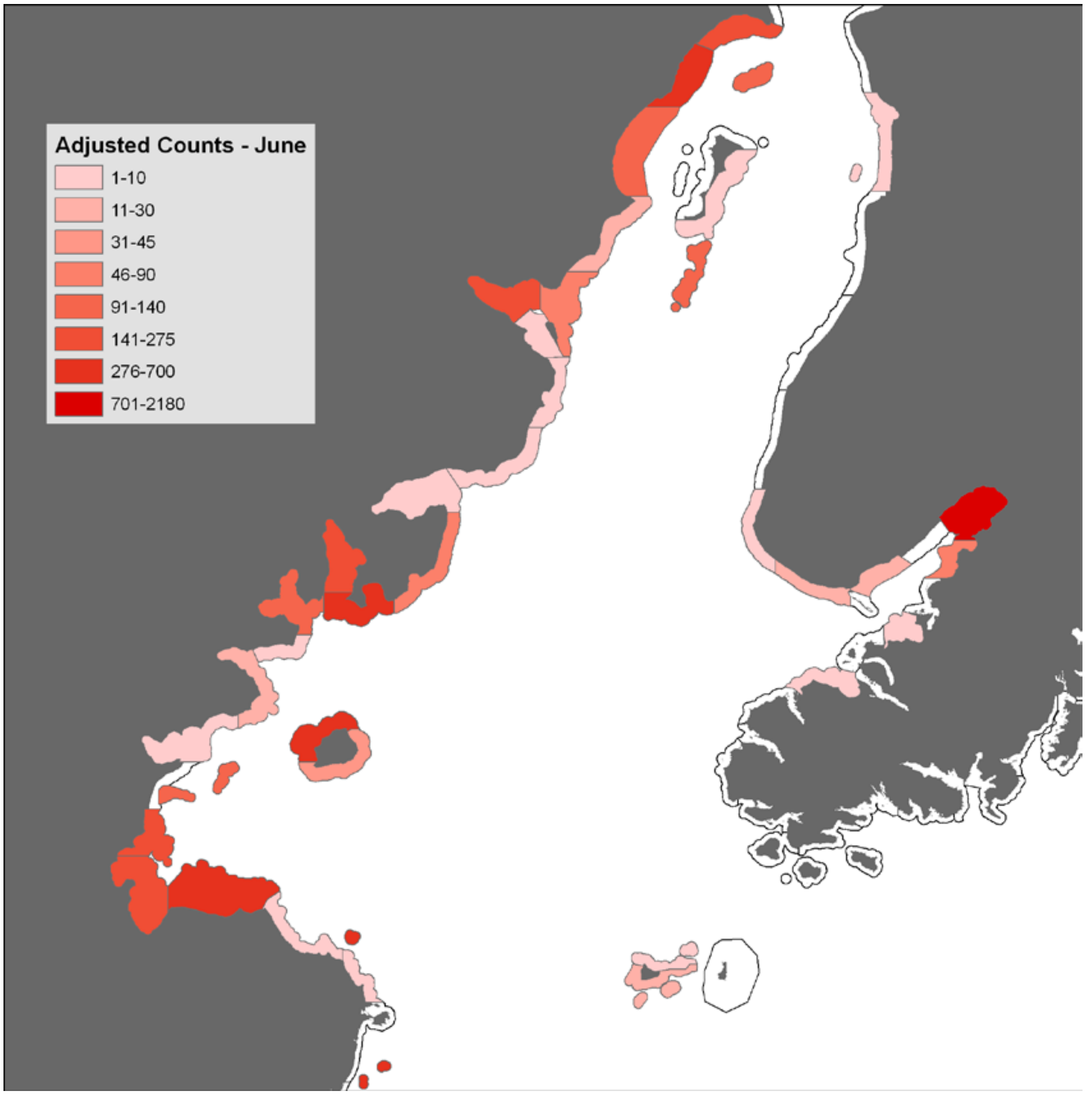

Figure 9. Adjusted counts of hauled out harbor seals by polygon in June.

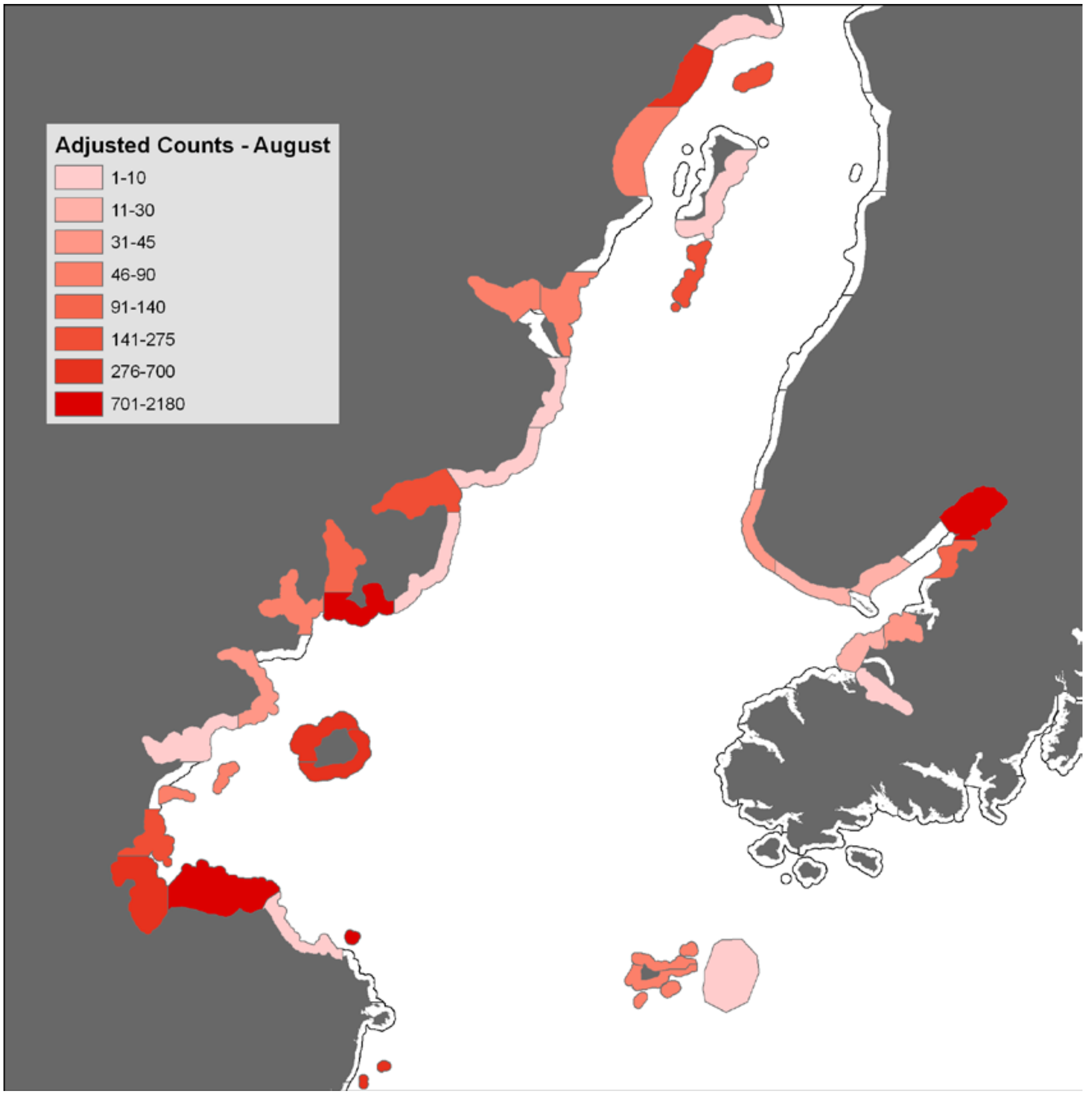

Figure 10. Adjusted counts of hauled out harbor seals by polygon in August.

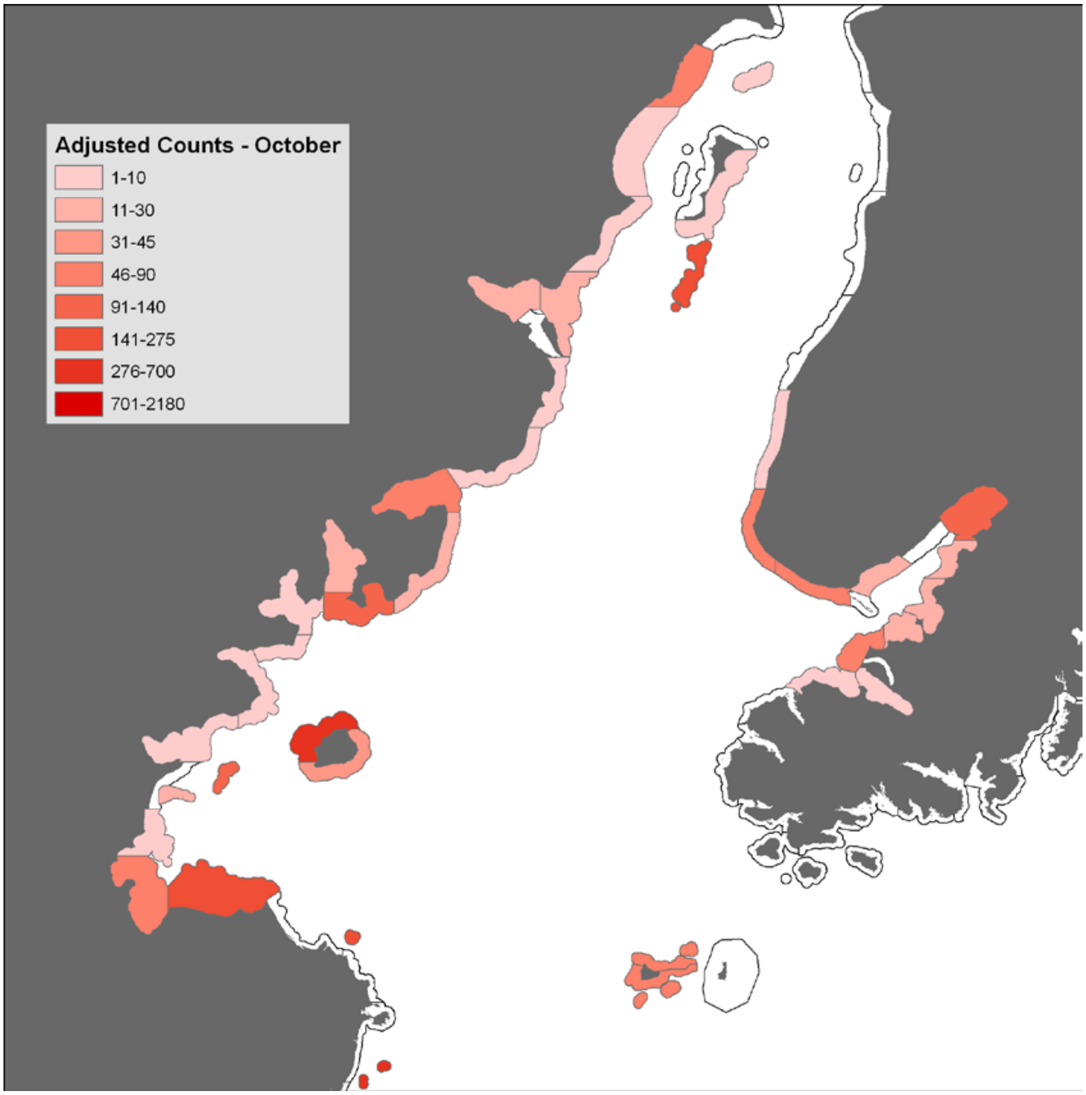

Figure 11. Adjusted counts of hauled out harbor seals by polygon in October.

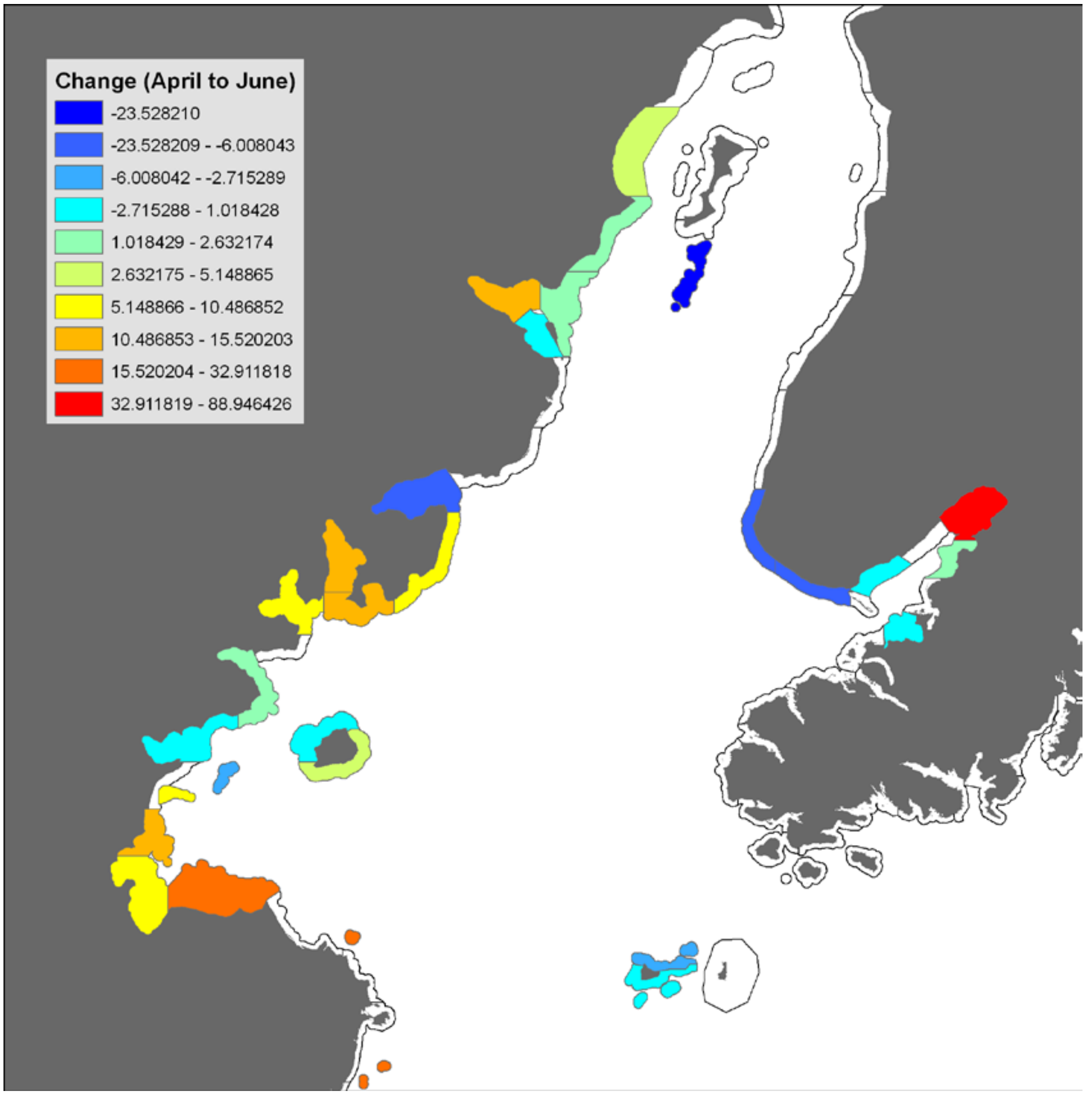

Figure 12. Standardized difference representing change in harbor seal counts from April to June.

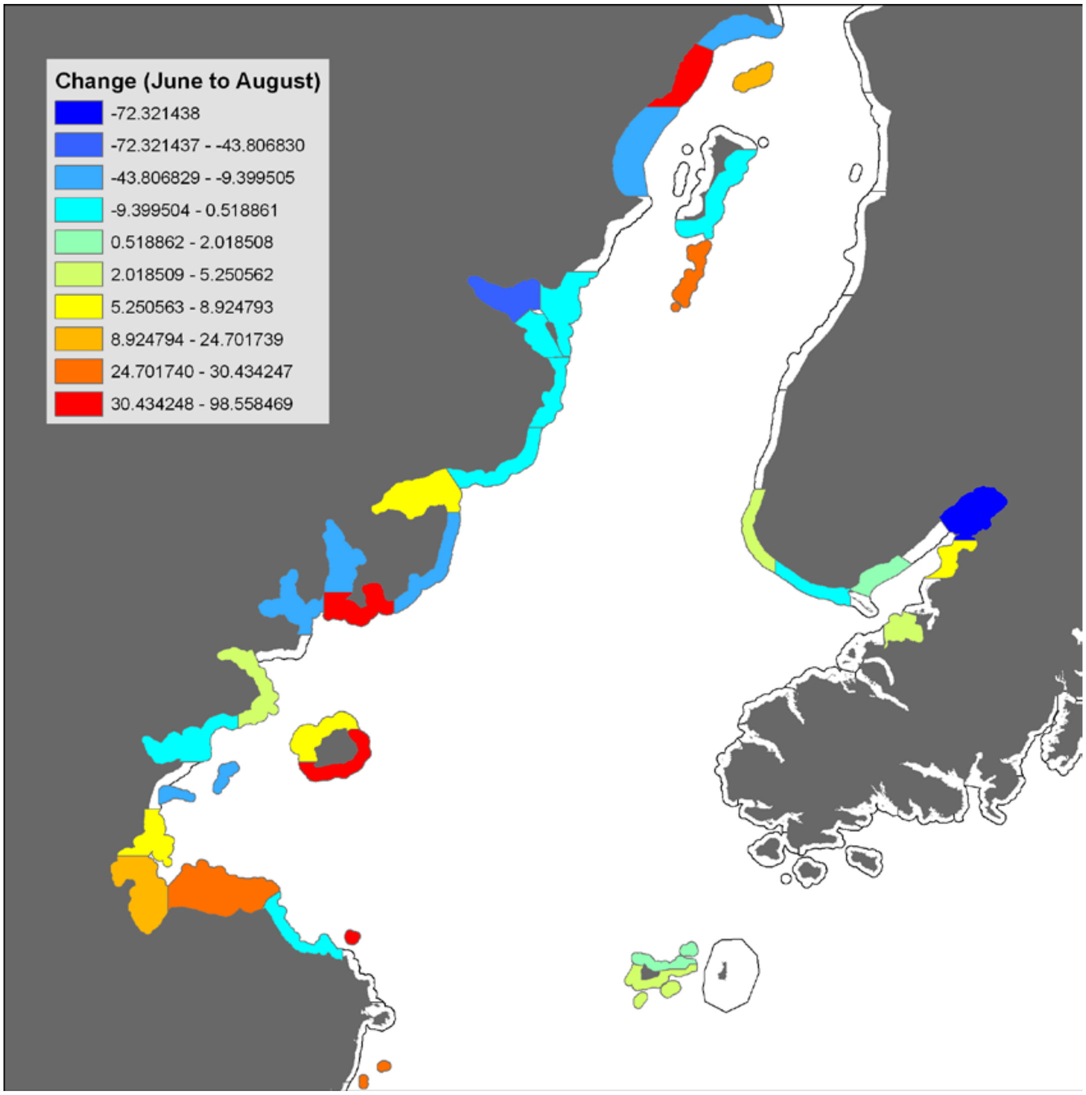

Figure 13. Standardized difference representing change in harbor seal counts from June to August.

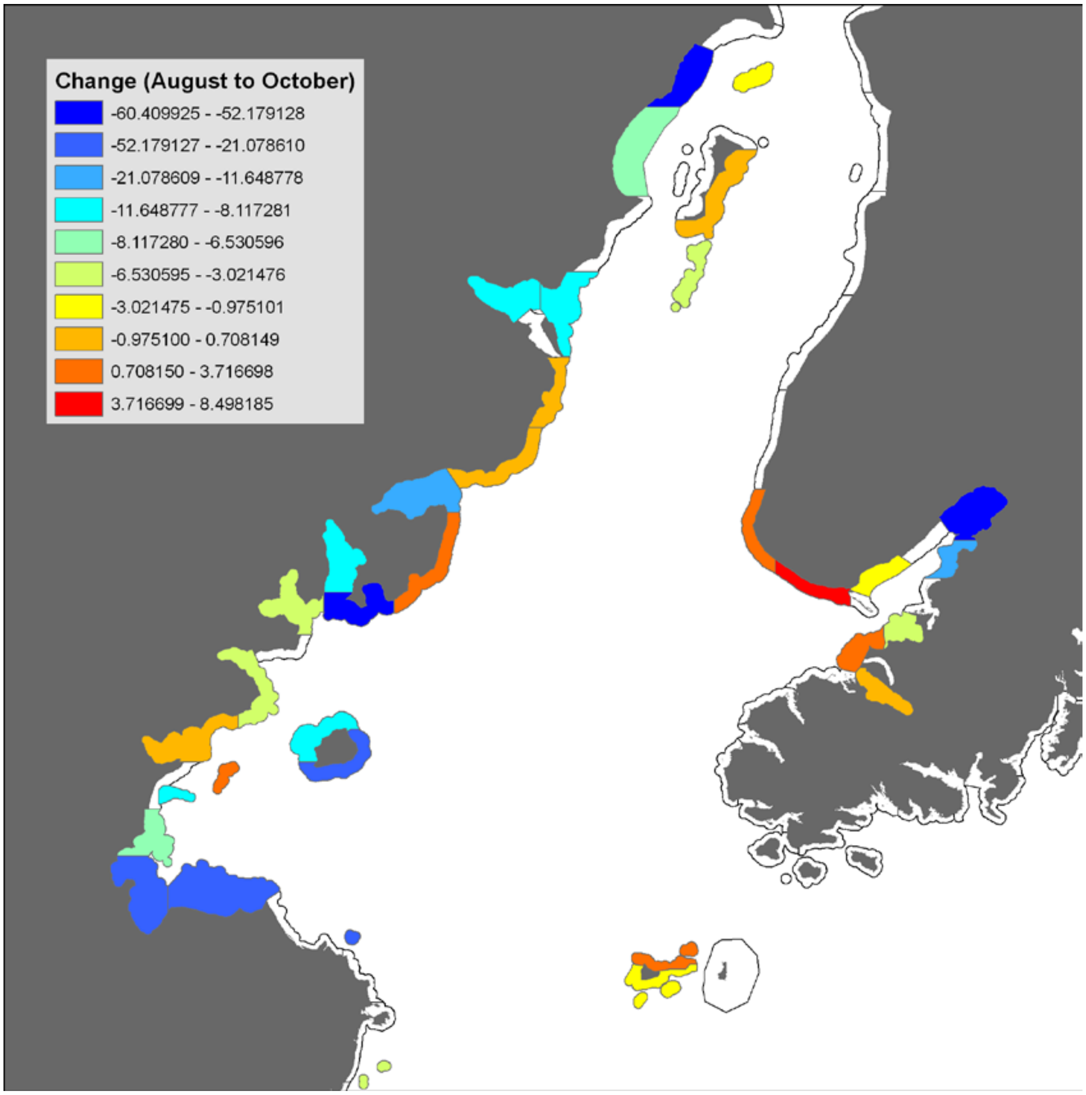

Figure 14. Standardized difference representing change in harbor seal counts from August to October.

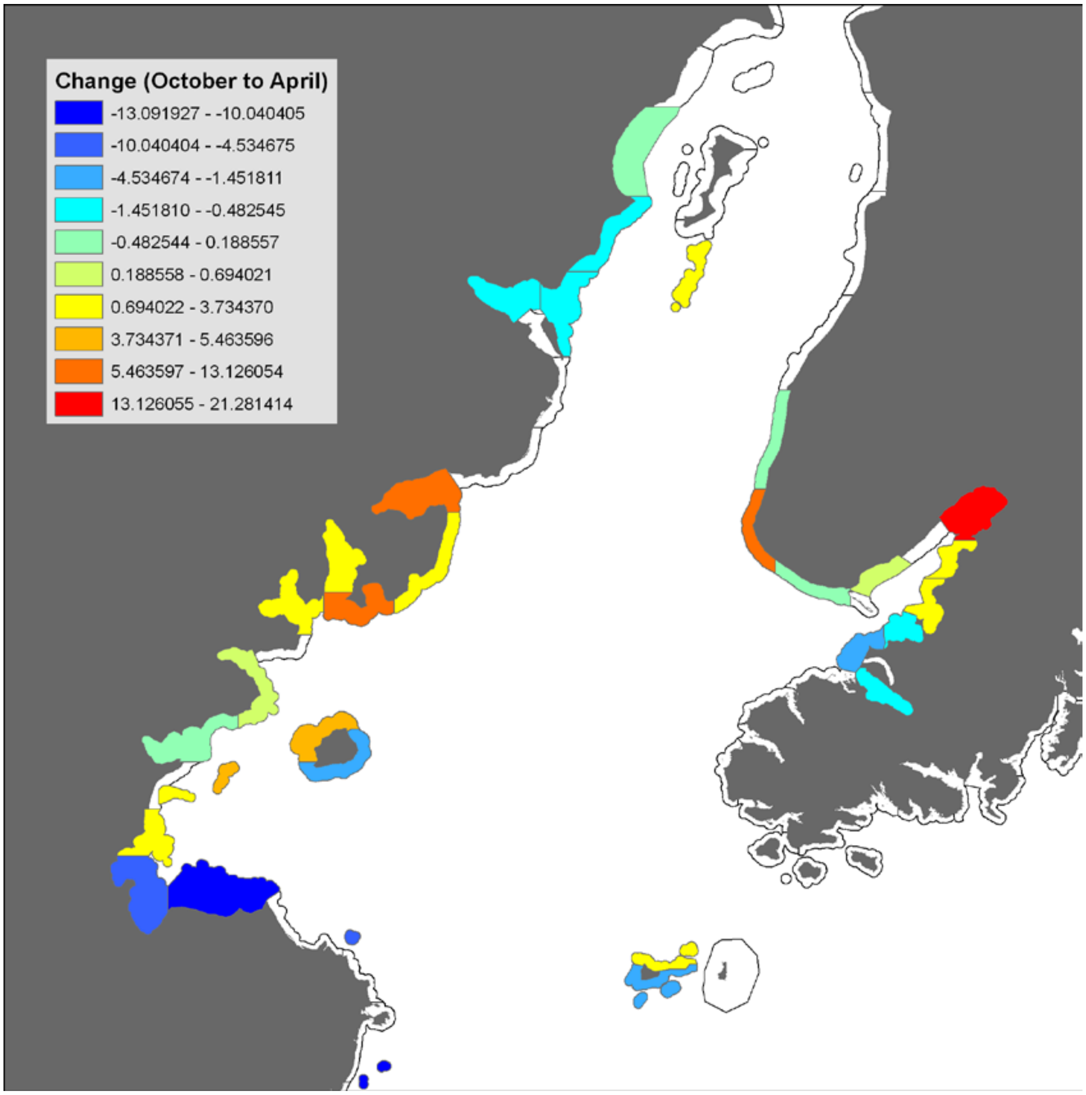

Figure 15. Standardized difference representing change in harbor seal counts from October to April.

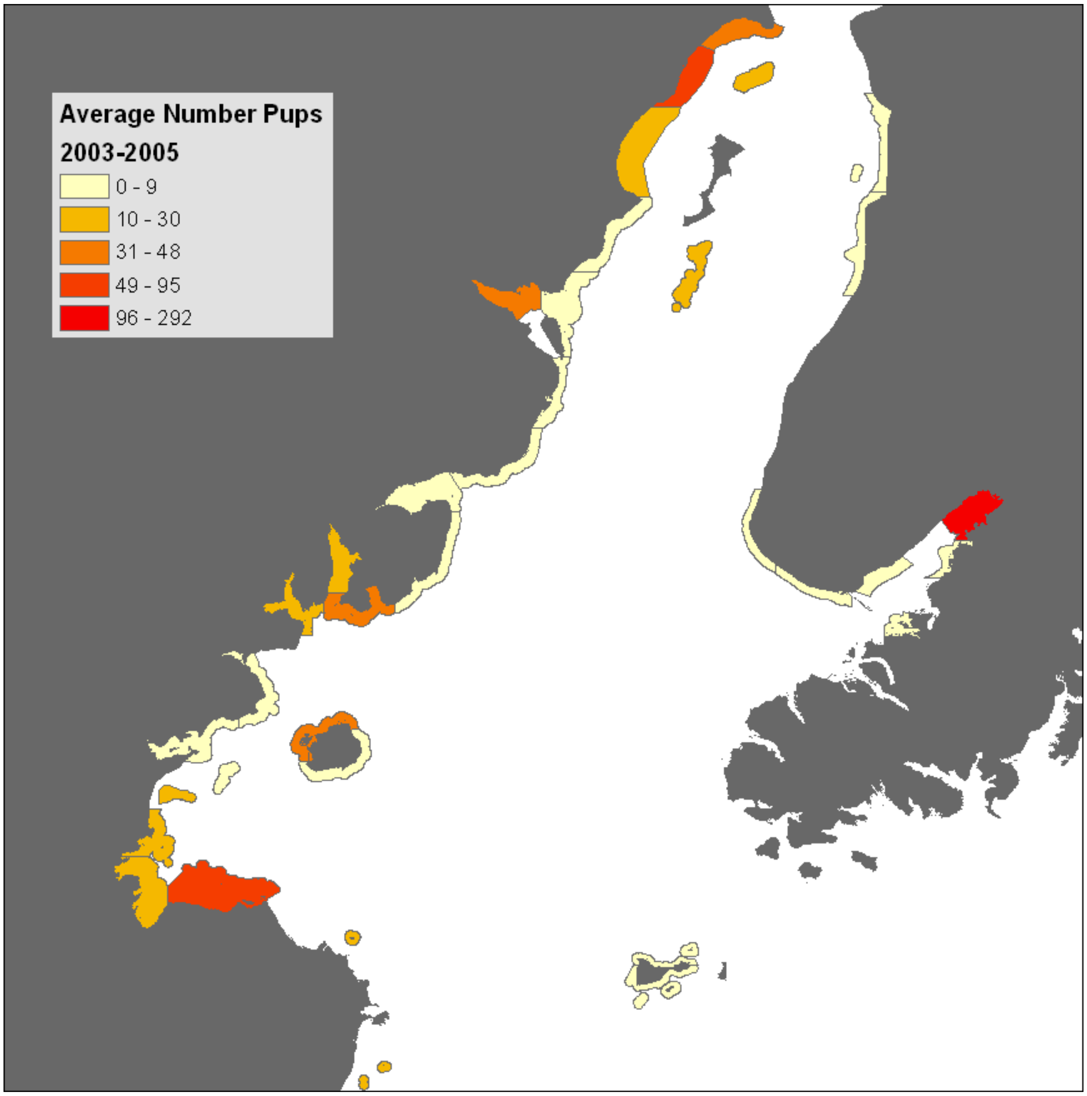

Figure 16. Average number of harbor seal pups in June. Counts are summarized by survey unit from 2003-2005.

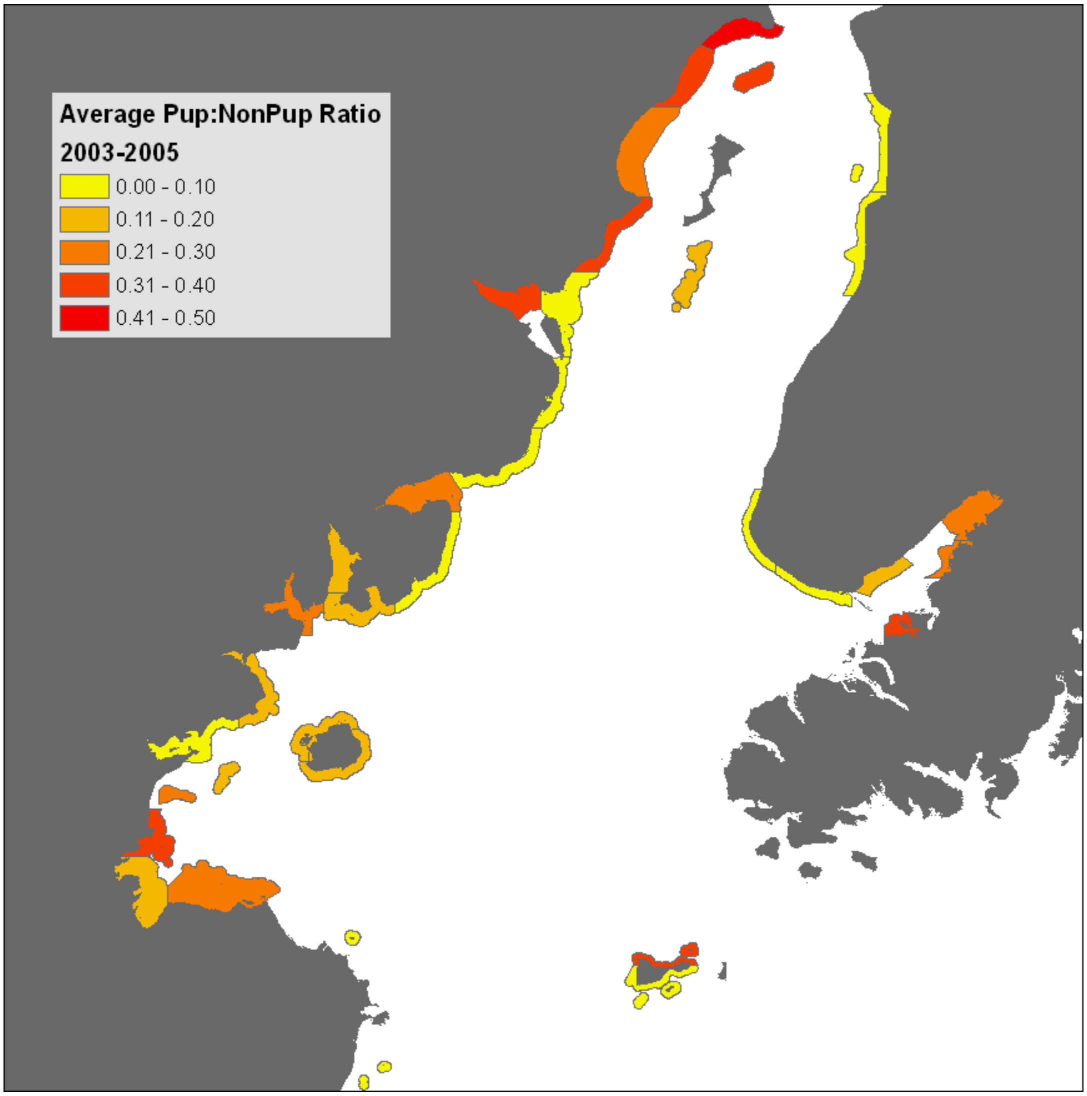

Figure 17. Average ratio of harbor seal pups to non-pups. Counts are summarized by survey unit from 2003-2005.

DISCUSSION

Hypothesis 1*: The relative abundance of harbor seals among the haul-out sites in Cook Inlet changes seasonally, probably reflecting differences among sites in their suitability for rearing young and molting, and their proximity to local prey aggregations.*

The survey results were strongly consistent with the concept that the abundance and distribution of harbor seals on shore in Cook Inlet change seasonally. Season was an important component of the fitted model and the estimates of seasonal abundance reflected this. The results showing increased counts in June and August were expected and are similar to patterns seen in other studies. The results also indicated seals are more concentrated during the pupping and molting periods of June and August compared to the late fall and spring when they are more dispersed. While the numbers of seals may vary with season, some sites were identified to consistently represent large portions of the harbor seal population in Cook Inlet. Upper Kachemak Bay, the mouth of Iliamna Bay, Kamishak Bay and the sandbars south and north of Kalgin Island had relatively high counts regardless of season and the counts in these areas were especially high in August.

Augustine Island provides an example of how seals may be responding to environmental variables across seasons. Seals consistently use the northwest side of the island across all seasons. The prevailing winds in Cook Inlet are typically from the southeast, so the use of the lee side by harbor seals is not unexpected. In August, there is a notable increase in the number of seals using the southeast side of the island. This may reflect a response to reduced winds in the late summer, making the relatively large southern beaches more suitable for prolonged haul-out bouts by molting seals. The distribution of pup numbers and pup ratios also reflects a preference for haul-out locations protected from prevailing winds.

Montgomery *et al.* (2007) conducted a spatial regression analysis using the 2003 and 2004 harbor seal counts (from this study) to examine the relationships between harbor seal abundance and environmental variables related to haul-out locations. They found harbor seals in Cook Inlet preferred to haul-out near available prey and were less likely to choose haul-out sites in close proximity to human development and disturbance. They also showed seals tended to haul-out on rock substrates near deep water (20 m). These relationships between harbor seal abundance and environmental covariates were consistent across each of the survey seasons (October, April, June and August). However, proximity to anadramous fish spawning streams was shown to vary between seasons. In April, more seals were counted ashore at sites near steelhead spawning streams, while, in June, sites near chinook spawning streams were higher. In August, higher counts were found at sites closer to pink salmon spawning streams. In October, distance to anadramous fish spawning streams was not a significant factor. Distance to deeper water (60 m) was significant and may reflect a change in foraging focus from returning salmon to more offshore prey species.

Hypothesis 2*: The numbers of seals ashore in seasons other than pupping and molting are lower but less variable over the period of a survey (about 2 weeks) than the numbers ashore during June and August when certain age and sex classes are subject to strong and rapidly changing life history constraints.*

We were able to confirm the first part of this hypothesis. There are fewer harbor seals on shore outside of the pupping and molting seasons. Estimated abundance on shore for April (2,635) and October (2,407) was approximately one-third the estimates for June (7,111) and August (8,301). To examine and test for seasonal effects, we created a single model for counts of seals ashore. Therefore, the variability aspect of this hypothesis cannot be addressed directly with the methods and results presented in this report. Some initial analysis with separate models for each season was conducted. Results from that suggested this hypothesis was not necessarily correct. The many factors that influence harbor seals' propensity to haul out may be just as variable during October and April, when local seal numbers are lower or seals are spending less time ashore, as they are during the peak haul-out months of June and August.

The environmental factors affecting harbor seal haul-out behavior were not as clearly defined and easily interpreted as we expected them to be, based on results of other studies that have been conducted primarily during the molt period. Tide height (Fig. 5) and hour of day (Fig. 6) provided some insight. The effect of tide height was most defined during August and the pattern was as expected with the highest counts occurring at low tide. A similar pattern was also observed in June, October and April but the uncertainty was greater. Hour of day seemed to have a strong influence on the counts in April with higher counts in the afternoon. The June counts appeared relatively stable across the hours. The results of the analysis for August and October, however, were unusual. The counts in August were higher in the late afternoon and evening. And, the October counts indicated two peaks in the morning hours. This may be a result of conducting the surveys within relatively narrow tidal and temporal periods.

The results presented in this report primarily address the abundance and behavior of seals ashore. Seals spend a majority of their time in the water. A more complete understanding of harbor seal ecology and seasonal space-use in Cook Inlet will come with the analysis of movement, haul-out and dive behavior from satellite tagged harbor seals (Task III). The haul-out data from tagged seals should also provide improved clarification between haul-out probability and the various environmental covariates. The surveys for this study were flown within specific, relatively narrow tidal periods, and for less than ten days per season. The haul-out data from the satellite tags will provide continuous data for periods up to 12 months from each seal. Models of haul out behavior developed from these data should enable more definitive description of the patterns and responses that were inconclusive based solely on the survey counts.

The movement analysis will also support more detailed examination of seasonal use and distribution of seals. The surveys have provided an extensive database of harbor seal haul-out locations in Cook Inlet. We expect that the list is nearly exhaustive for our period of surveys, though we have become aware of one site that was not included: Local residents in Kenai have recently observed seals hauled out near the mouth of the Kenai River during part of the year. These seals were not observed on our surveys; however, we do have a few haul-out locations at the mouth of the Kenai River from tags deployed on seals as part of Task III. The combination of information from the survey counts and analysis of satellite tag data will provide the most complete picture of harbor seal movement and use in Cook Inlet. Lastly, the tag-derived models will allow us to appropriately calculate a correction factor for seals in the water during the survey. This will provide statistically sound estimates of seasonal abundance for harbor seals in Cook Inlet.

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PRESENTATIONS AND PUBLICATIONS

Boveng, P. A summary of harbor seal research conducted in Alaska by NOAA Fisheries. Oral presentation, Eighteenth Working Group Meeting, Project 02.05-61, “Marine Mammals,” under Area V of the U.S.-Russia Agreement on Cooperation in the Field of Environmental Protection Seattle, Washington, September 23-26, 2004.

Boveng, P.L., M.A. Simpkins, and J.L. Bengtson. Seasonal dynamics of harbor seals in Cook Inlet. Poster presentation, Alaska Marine Science Symposium, 24-26 January 2005, Anchorage, Alaska.

Boveng, P.L., J.L. Bengtson, and M.A. Simpkins. Distribution and abundance of harbor seals in Cook Inlet: Seasonal variability in relation to key life history events. Oral presentation, Minerals Management Service, Alaska OCS Region, Tenth Information Transfer Meeting, March 14-16, 2005, Anchorage, AK. OCS Study MMS 2005-036.

Boveng, P.L. A summary of harbor seal research conducted by NOAA Fisheries in Alaska. Oral presentation to the Alaska Harbor Seal Research Planning meeting (NOAA NMFS Alaska Fisheries Science Center, NOAA NMFS Alaska Region, Alaska Department of Fish and Game, Alaska Native Harbor Seal Commission, and Alaska Sea Life Center) in Juneau, 29 March 2005.

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APPENDIX 1 – *Montgomery, R. A., J. M. Ver Hoef, and P. L. Boveng. 2007. Spatial modeling of haul-out site use by harbor seals in Cook Inlet, Alaska. Marine Ecology Progress Series 341:257-264.*

ABSTRACT: Harbor seals *Phoca vitulina* haul out on land to give birth to and rear their pups, rest, escape aquatic predation and molt. The choice of a haul-out site is therefore fundamental to survival and reproduction. Aerial surveys of harbor seals were conducted in Cook Inlet, Alaska, to investigate the seals' selection of various environmental characteristics of haul-out sites. Eight surveys from April, June, August and October were performed to understand how haul-out site use varies seasonally. A GIS database describing all potential haul-out habitats in the study area was created by acquiring separate data sets on bathymetry, sea-bed type, proximity to sources of anthropogenic disturbance, prey availability, biological wave exposure and substrate type. Because harbor seal abundance and several environmental features varied temporally, 4 separate models were developed to account for conditions specific to each survey month. Spatial regression analyses, which allowed data to be spatially auto-correlated, were used to identify the relationships between harbor seal abundance and environmental variables associated with haul-out sites. Harbor seals were found to haul out near available prey and to avoid areas high in anthropogenic disturbance. The seals also selected haul-out sites of rock substrate and those that were near deep water.

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