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At-sea Observations of Marine Birds and Their Habitats before and after the 2008 Eruption of Kasatochi Volcano, Alaska

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Abstract

Kasatochi volcano, an island volcano in the Aleutian chain, erupted on 7–8 August 2008. The resulting ash and pyroclastic flows blanketed the island, covering terrestrial habitats. We surveyed the marine environment surrounding Kasatochi Island in June and July of 2009 to document changes in abundance or distribution of nutrients, fish, and marine birds near the island when compared to patterns observed on earlier surveys conducted in 1996 and 2003. Analysis of SeaWiFS satellite imagery indicated that a large chlorophyll-*a* anomaly may have been the result of ash fertilization during the eruption. We found no evidence of continuing marine fertilization from terrestrial runoff 10 months after the eruption. At-sea surveys in June 2009 established that the most common species of seabirds at Kasatochi prior to the eruption, namely crested auklets (*Aethia cristatella*) and least auklets (*Aethia pusilla*) had returned to Kasatochi in relatively high numbers. Densities from more extensive surveys in July 2009 were compared with pre-eruption densities around Kasatochi and neighboring Ulak and Koniuji islands, but we found no evidence of an eruption effect. Crested and least auklet populations were not significantly reduced by the initial explosion and they returned to attempt breeding in 2009, even though nesting habitat had been rendered unusable. Maps of pre- and post-eruption seabird distribution anomalies indicated considerable variation, but we found no evidence that observed distributions were affected by the 2008 eruption.

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Introduction

The Aleutian Islands sit atop a narrow submerged ridge separating the Bering Sea from the North Pacific. The surrounding waters provide highly productive habitats for fish, marine mammals, and birds. The oceanography of the archipelago, particularly in the central Aleutians, is characterized by strong tidal currents moving through passes that bring nutrient-rich water up to the surface, concentrating plankton and fish (Hunt et al., 1998; Ladd et al., 2005). An estimated 10 million marine birds of 26 species breed in the many islands across the Aleutian arc (Byrd et al., 2005). Much of this marine bird productivity and diversity is due to the close proximity to abundant and reliable prey resources (Hunt et al., 1999; Springer et al., 1996).

Kasatochi Island, in the central Aleutian Islands, is a part of the Alaska Maritime National Wildlife Refuge (AMNWR). The U.S. Fish and Wildlife Service (USFWS) and the National Marine Fisheries Service have studied marine birds and marine mammals there since 1996. Additionally, extensive marine surveys of the area were conducted in 1996 and 2003 (Renner et al., 2008). On 7–8 August 2008, Kasatochi volcano erupted explosively, covering the island with volcanic deposits (Waythomas et al., 2010 [this issue]). The ashfall and pyroclastic flows from the eruption eliminated nesting habitat for all of the birds on the island including a minimum of 100,000 crested auklets and 150,000 least auklets (see Williams et al., 2010 [this issue]). Bogoslof Island, which last erupted in 1992, is the only site in the Aleutians where the response of marine birds to a volcanic eruption has been studied, but it is a much smaller island with a different complement of nesting species that does not include auklets (Byrd et al., 1980). In general, recovery of marine birds at Bogoslof was relatively quick, but that may have been due to the smaller scale of the eruption and, unlike Kasatochi, only part of the island was affected, leaving some nesting areas usable.

Recent research on ash deposition in ocean waters suggests that ash from eruptions can act as a fertilizer (Frogner et al., 2001; Langmann et al., 2010). Fertilization from ash additions to seawater tends to be ephemeral and thus difficult to document (Frogner et al., 2001). The large amounts of ash covering the island and clearly visible sediment plumes in the ocean on satellite imagery led us to also consider the possibility of long-term localized fertilization due to persistent runoff, though this has not been well studied.

Here we report on the first post-eruption survey of nutrients, pelagic fish and zooplankton, and marine birds around Kasatochi Island and draw comparisons to the two previous at-sea surveys. Our goals were to address three questions: (1) Have there been any impacts, direct or indirect, on the nutrients, productivity, and fish around Kasatochi? (2) Was there evidence of declines of marine birds in the waters around Kasatochi either directly from the eruption or through inhibition of birds returning due to loss of nesting habitat? (3) Have the distributions of marine birds at sea been altered?

Materials and Methods

STUDY AREA

Kasatochi Island is a 2.9 km by 2.6 km volcano located 80 km northeast of Adak (Fig. 1). Situated 20 km north of Atka and

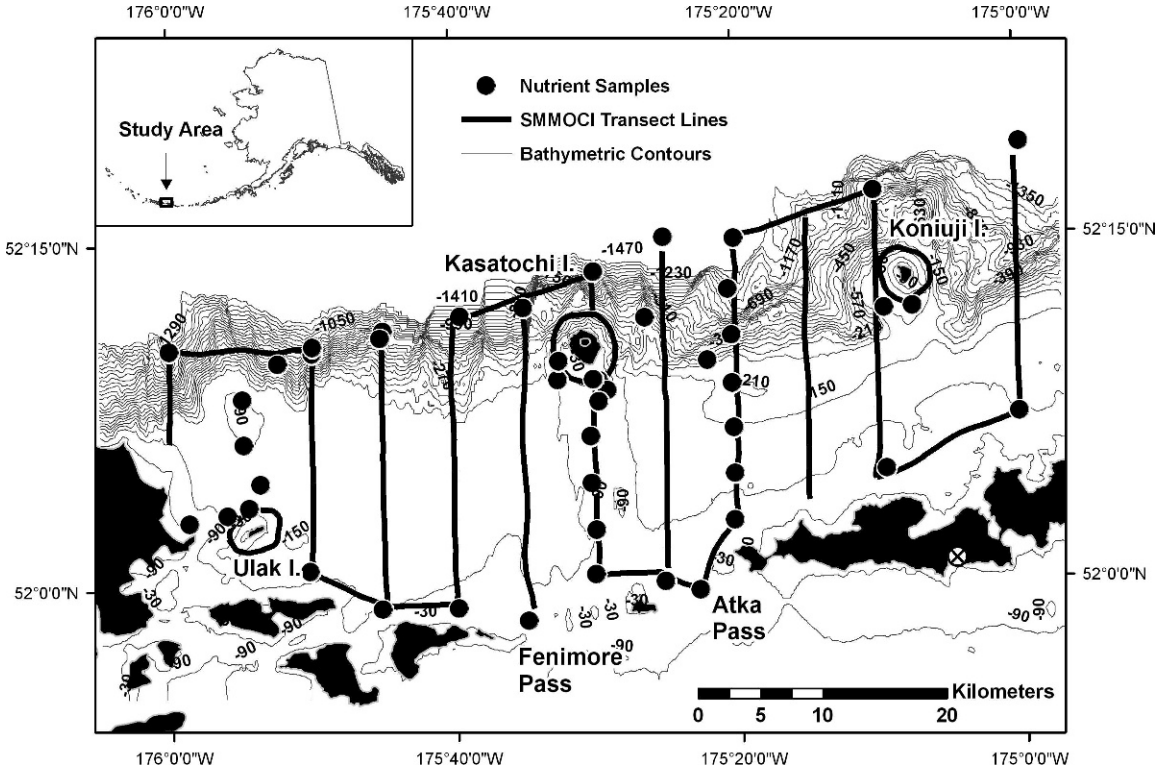

FIGURE 1. Location of the Kasatochi study area in the central Aleutian Islands with place names, sampling stations, and transects in the study area. Bathometric contours illustrate the position of Kasatochi atop the Aleutian Ridge. Data were collected in 1996, 2003, and 2009.

Fenimore Passes, Kasatochi Island lies in an area influenced by North Pacific and southern Bering Sea water masses (Fig. 1). The surface circulation on the Pacific side of the passes is part of the Alaskan Stream (Ladd et al., 2005; Stabeno et al., 2005) and flows westward. To the north of Kasatochi in the Bering Sea, the Aleutian North Slope Current is characterized by an eastward flow (Favorite, 1974; Stabeno et al., 2005). Within the passes, both northward and southward tidal flow occurs, but the overall net flow of water through the passes is northward (Reed, 1990; Stabeno et al., 2005). The result of the channeling of these tidal currents through relatively shallow central Aleutian passes is a well mixed, nutrient-rich water column (Ladd et al., 2005). Especially in shallow passes, tidal currents concentrate otherwise inaccessible zooplankton near the surface, where they become available to shallow-diving predators like marine birds (Hunt et al., 1998; Jahncke et al., 2005).

We collected data using two sampling designs. Between 11 and 17 June 2009, we conducted surveys using a radial design with six transects arrayed in a spoke pattern, hereafter referred to as "spokes," centered on Kasatochi Island. The asymmetric design was laid out to match the trajectories of terrestrial transects in an effort to connect terrestrial and marine environments along slope gradients. Spokes began approximately 800 m offshore and extended to 5 km offshore. At the beginning and end of each spoke, we collected nutrient data. Along the length of each spoke we surveyed marine birds. In July we collected data along more extensive transect lines established under the Seabird, Marine Mammal, and Oceanography Coordinated Investigations program (SMMOCI; Fig. 1).

NUTRIENTS

Water samples were collected for dissolved mineral-based nutrients silicate (SiO_4^{2-}) and phosphate (PO_4^{3-}) in a 5-L Niskin bottle at depths of 10 m. Water samples (50 mL) were transferred to new 60 mL sample bottles after rinsing with sample seawater. Samples were immediately frozen. All samples were sent to the University of Washington for analysis. Analysis was done using a Technicon AutoAnalyzer II. In June 2009 nutrient samples were collected at stations surrounding Kasatochi at the beginning and end of each spoke to identify any differences based on proximity to the island. In July samples were collected along marine bird survey transects at sites sampled previously in 2003 (Fig. 1). This more extensive data collection allowed us to characterize the larger study area with regard to mineral base nutrients. We mapped the distributions of silicate and phosphate with inverse distance weighted models (IDW) using ArcMap® (ESRI, Redlands, California).

The inability to sample nutrients immediately following the eruption led us to examine ocean color data for anomalously high chlorophyll concentrations that can result from volcanic fertilization (Frogner et al., 2001; Duggen, et al., 2010). We gathered satellite data on chlorophyll concentrations (SeaWiFS.R2009) from the Giovanni online data system, developed and maintained by the National Aeronautics and Space Administration Goddard Earth Sciences Data and Information Services Center (NASA GESDIS). The NASA data are available as monthly mean chlorophyll-*a* concentrations with 9 km × 9 km cells. We developed a map of "expected" chlorophyll concentrations by averaging five years of data for the month of September in the study area prior to the eruption (2003–2007). We created an anomaly layer by subtracting the pre-eruption mean from the post-eruption data for September 2008.

FISH AND ZOOPLANKTON

The relative abundance of fish and zooplankton in the vicinity of Kasatochi before and after the eruption was compared

using hydroacoustics and long-line fishing. Hydroacoustic data were collected concurrently with bird observations along the same transects in 1996, 2003, and 2009 (Fig. 1). We used the hydroacoustic data to construct maps indicating relative spatial distributions within each sample year.

During 1996, acoustic data were collected using a hull mounted BIOSONICS Model 281 Echosounder (120 kHz transducer located 4 m below the sea surface). Transmit power was set at 217 dB, gain at −125.4 dB, bandwidth at 5 kHz, trigger interval at 0.5 s, and pulse width at 0.5 ms for all surveys. Fish and plankton echosignals were integrated in real time over 10 min intervals and 10 m depth strata using a BIOSONICS Model 121 Digital Echo Integrator with 20 LogR amplification. Signals were integrated over each time/depth block and later converted to relative acoustic biomass using a target strength of -64 dB g^{-1}. In both 2003 and 2009 a dual frequency (38 and 120 kHz) Simrad EK500 echosounder was used to collect acoustic data. Only data from 120 kHz were used for analysis because our primary interest was in zooplankton and small forage fish that are the prey of marine birds. We used a threshold of −80 dB and data were integrated in 100 m long × 10 m deep bins. Due to surface turbulence the first stratum was dropped from the analysis, and we limited integration to a maximum of 50 m, as biomass below that level is not accessible to the majority of marine birds in the study area. We used average acoustic biomass (sum of biomass/number of bins) to make data comparable regardless of depth. We compared 1996 and 2009 data by contrasting the distribution of relative acoustic biomass, using the nautical area scattering coefficient around Kasatochi in each of the years sampled.

In 2009 we sampled demersal fish with single long-line sets near Ulak and Kasatochi islands, as was done in previous surveys in 1996 and 2003. These sets were designed to provide a snapshot of the large, predatory fish community. Rigorous comparisons were not appropriate due to the small number of samples; therefore, we treated the long-line sets as qualitative data. If dramatic changes to the local resources did occur at Kasatochi as a result of the eruption, we expected that the fish sampling might reflect this difference. Sets were placed in waters 25–90 m deep near each island. For each long-line set, we deployed a single skate of approximately 100 hooks (sizes 3.0 and 5.0) baited with salted herring and soaked for two to three hours. We identified fishes to species, measured them to the nearest mm (total length), and weighed them.

MARINE BIRDS

During June 2009, in conjunction with land-based studies at Kasatochi (Williams et al., 2010 [this issue]), we counted birds along spokes extending approximately 5 km from the island. In July we surveyed transects used in 1996 and 2003 to evaluate marine bird distribution and abundance in the larger study area. All surveys were conducted from the M/V *Tiĝlax̂* using standard protocols (Gould and Forsell, 1989). Two observers, stationed one on each side of the flying bridge of the ship, continuously recorded all birds observed on the water within 150 m on both sides and 300 m in front of the vessel. During surveys, vessel speed was kept as consistent as possible, about 7–9 knots. We used a modified method of counting flying birds (Gould and Forsell, 1989) that differed between pre- and post-eruption surveys. During pre-eruption surveys in 1996 and 2003, flying birds were counted every 3 minutes in a 300 m × 600 m rectangle (300 m fore and aft of the ship). During post-eruption surveys we counted flying birds every 30 seconds in only a 300 m × 150 m rectangle in front of the ship. Sightings were recorded using a computer-based system (dLog, R. G. Ford Consulting, Portland, Oregon), which assigned GPS positions in real time.

The June sampling provided at-sea observation data during egg laying for crested and least auklets allowing us to document the return of potential nesting birds during the early nesting period. A second survey was conducted 16–20 July 2009. This survey was conducted using the survey design used in 1996 and 2003 as part of the AMNWR's SMMOCI monitoring program (Fig. 1). This second survey provided a greater spatial scope that included Ulak, Kasatochi, and Koniuji Islands. To assess the possibility that birds from Kasatochi might be shifting to either Ulak Island or Koniuji Island for nesting, we compared density estimates for crested auklets, least auklets, and a taxon grouping comprised of 13 seabird species that did not nest or only nested in small numbers on Kasatochi prior to the eruption, hereafter referred to as "uncommon/non-nesters" (Table 2). Prior to the eruption, crested and least auklets were the dominant nesting seabirds on Kasatochi. Therefore they were most likely to be affected by the loss of nesting habitat. Uncommon/non-nesters provided a control since regional populations should not have been as affected by the loss of nesting sites, but could reflect changes in forage resources. Seabird observations were based on circumnavigations of Ulak, Kasatochi, and Koniuji Islands conducted in 1996, 2003, and 2009. Circumnavigations were conducted at approximately 1.8 km from the shore of each island and were split into 10 minute segments. Species numbers were summed and divided by the area sampled to determine densities. The combination of the sample sizes and high variance precluded the use of parametric tests. Instead, we constructed 90% confidence intervals (CI) by bootstrapping segment densities for each island, year, and taxa, and identified non-overlapping CIs as significant (Davison and Hinkley, 1997). If the eruption had an impact on crested or least auklet populations or their return to the island, we would expect to detect significant changes in their average density around Kasatochi.

Seabird observations from the July 2009 survey of the study area were used to construct distribution maps of crested auklets, least auklets, and uncommon/non-nesters. Density surfaces were mapped with an IDW model using ArcMap® (ESRI, Redlands, California). Specifically, we sought to identify anomalies in the distributions of these taxa that may have reflected altered habitats related to the 2008 eruption. The data from 1996 and 2003 provided us with a template for expected habitat use. If the crested auklets and least auklets were responding to the 2008 eruption, through exclusion from traditional nesting sites or alteration of local marine habitats, it should be reflected in the distribution maps. The density layers from 1996 and 2003 were averaged and then the 2009 layer was subtracted to yield an anomaly layer with positive values indicating areas of lower use post-eruption and negative values indicating areas of increased use post-eruption. If the affects of the eruption were negative we expected distributions to shift away from Kasatochi.

Results

NUTRIENTS

Surface silicate concentrations ranged from 49 to 60 μm in June and 14 to 54 μm in July. Phosphate concentrations ranged from 1.8 to 2.4 μm in June and 1.5 to 2.1 μm in July. These values are similar to those reported for other central Aleutian passes and considerably higher than those found in eastern Aleutian passes (Mordy et al., 2005). Data from the June sampling sites comparing nutrient samples from the shallow waters near Kasatochi to

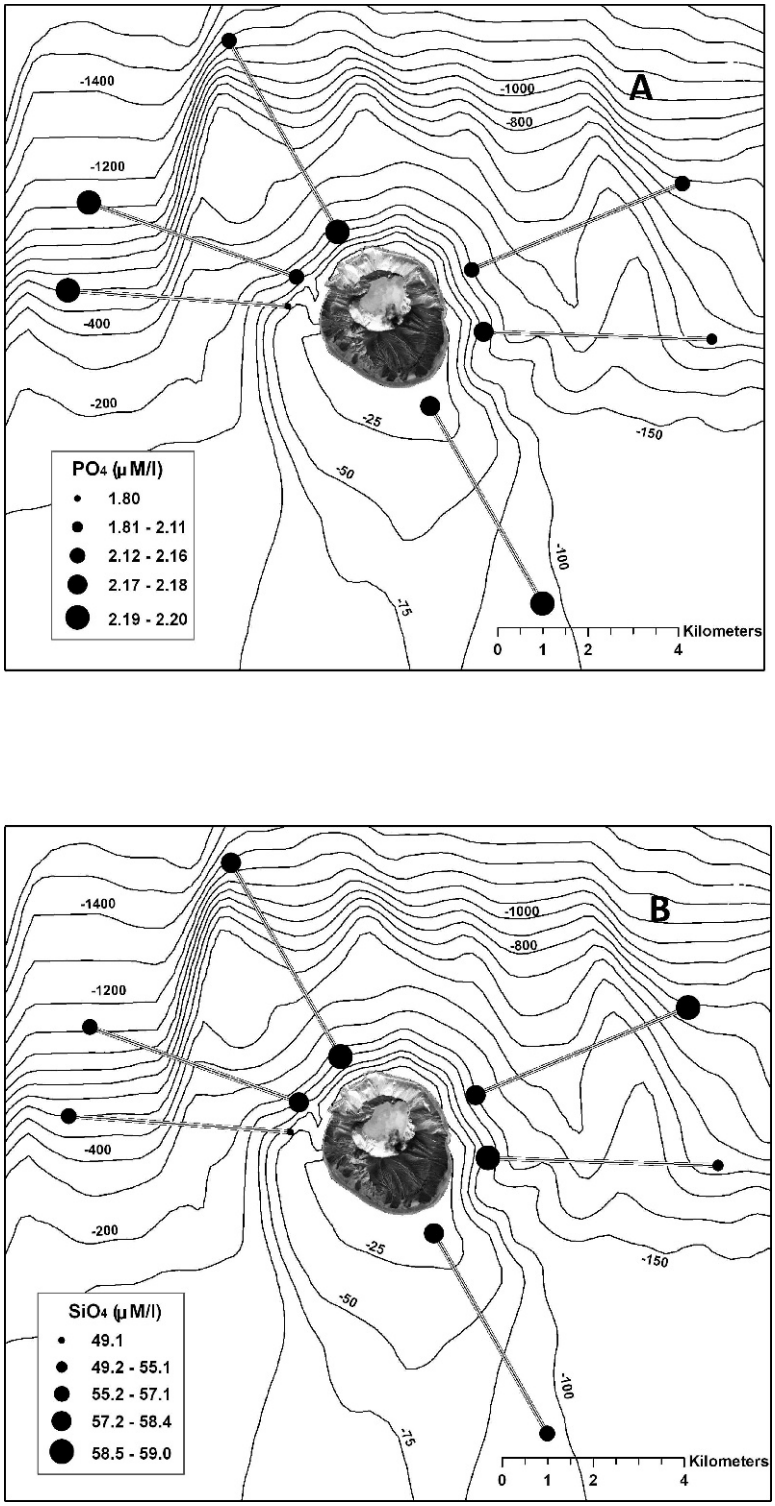

FIGURE 2. Post-eruption nutrient concentrations from water samples collected in June 2009 (Phosphorous–A, Silicate–B). Water was collected at 10 m. Lines between sampling points indicate the spokes surveyed for seabirds.

samples radiating >5 km offshore indicated that five of the six spokes had higher offshore than inshore silicate and phosphate concentrations (Fig. 2). If the ash from the island were providing substantial nutrient additions to the waters surrounding the island, we would expect the samples taken closest to the island (approximately 0.8 km from shore) would have higher silicate and phosphate concentrations than samples taken at the ends of spokes, 5 km further offshore. Maps of nutrient concentrations were created by interpolating data from the more extensive July nutrient samples (n = 17); they indicated that the peak nutrient concentrations for phosphate and silicate were in the area of the passes (Fig. 3). To look retrospectively for effects of the eruption we created an anomaly layer from archived SeaWiFS satellite imagery. The anomaly layer, based on pre and post-eruption chlorophyll-*a* reflectance, indicated a 3240 km^2 area approximately 200 km to the northeast of Kasatochi with elevated chlorophyll-*a* concentrations (Fig. 4).

FISH AND ZOOPLANKTON

Comparing the relative hydroacoustic biomass in the top 50 m of the study area in 1996, 2003, and 2009 indicated that there were

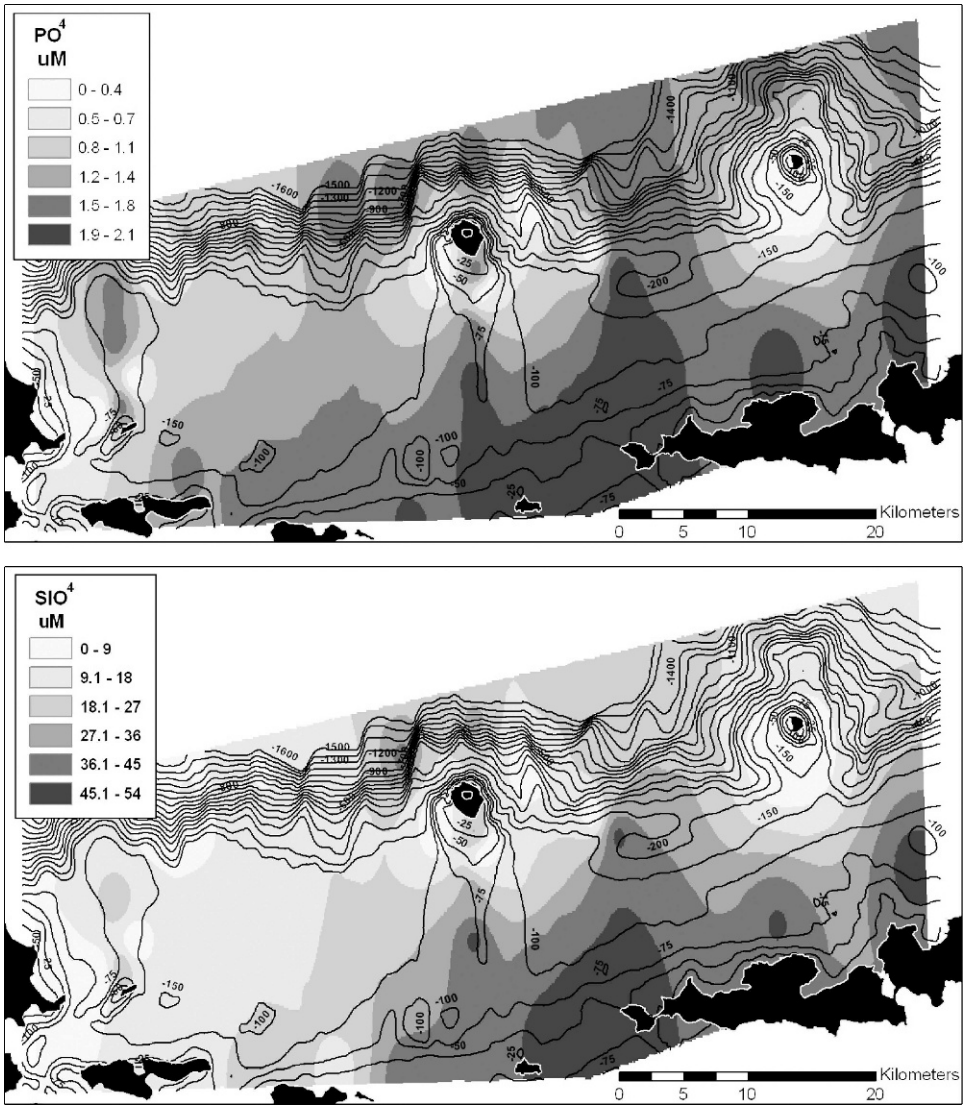

FIGURE 3. Distribution of major nutrients in the Kastochi study area July 2009. Bathymetric contours (m) are displayed for reference. Samples were taken at 10 m depth. See Figure 1 for station locations.

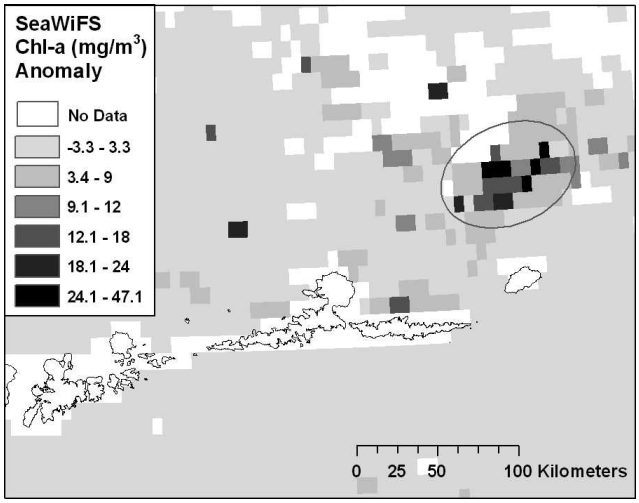

FIGURE 4. Anomaly map (post-eruption minus pre-eruption) of chlorophyll-*a* concentrations following the 7–8 August 2008 eruption. Pre-eruption layer was the mean of September 2003–2007. Dark colors indicate areas of anomalously high chlorophyll-*a* concentration estimated with SeaWiFS imagery. The ellipse designates a contiguous area of anomalously high chlorophyll-*a*.

two areas of consistently high acoustic biomass in all years. One was in the area of Fenimore and Atka Passes, the other was approximately 20 km east of Atka Pass on the north side of Atka Island (Fig. 5). The area immediately surrounding Kasatochi had relatively high acoustic biomass in just one year, 2003. In both 1999 and 2009 there was also high acoustic biomass west of Kasatochi where the ridge descends sharply (Fig. 5). Because of change among years in acoustic hardware systems, we have restricted ourselves here to qualitative comparisons. Our results suggest that the hydroacoustic biomass changed little or not at all in response to the 2008 eruption.

For demersal fish, the long-line sets showed considerable variation in species composition both by year and island, but prior to the eruption no set had failed to catch less than 13 fish. This changed with the 2009 post-eruption set at Kasatochi which failed to catch any fish (Table 1).

MARINE BIRDS

June 2009 seabird surveys along spokes provide evidence that both crested and least auklets had returned to Kasatochi in large numbers, with mean at-sea density estimates of 50.1 birds per km^2 and 45.3 birds per km^2, respectively. These densities were not

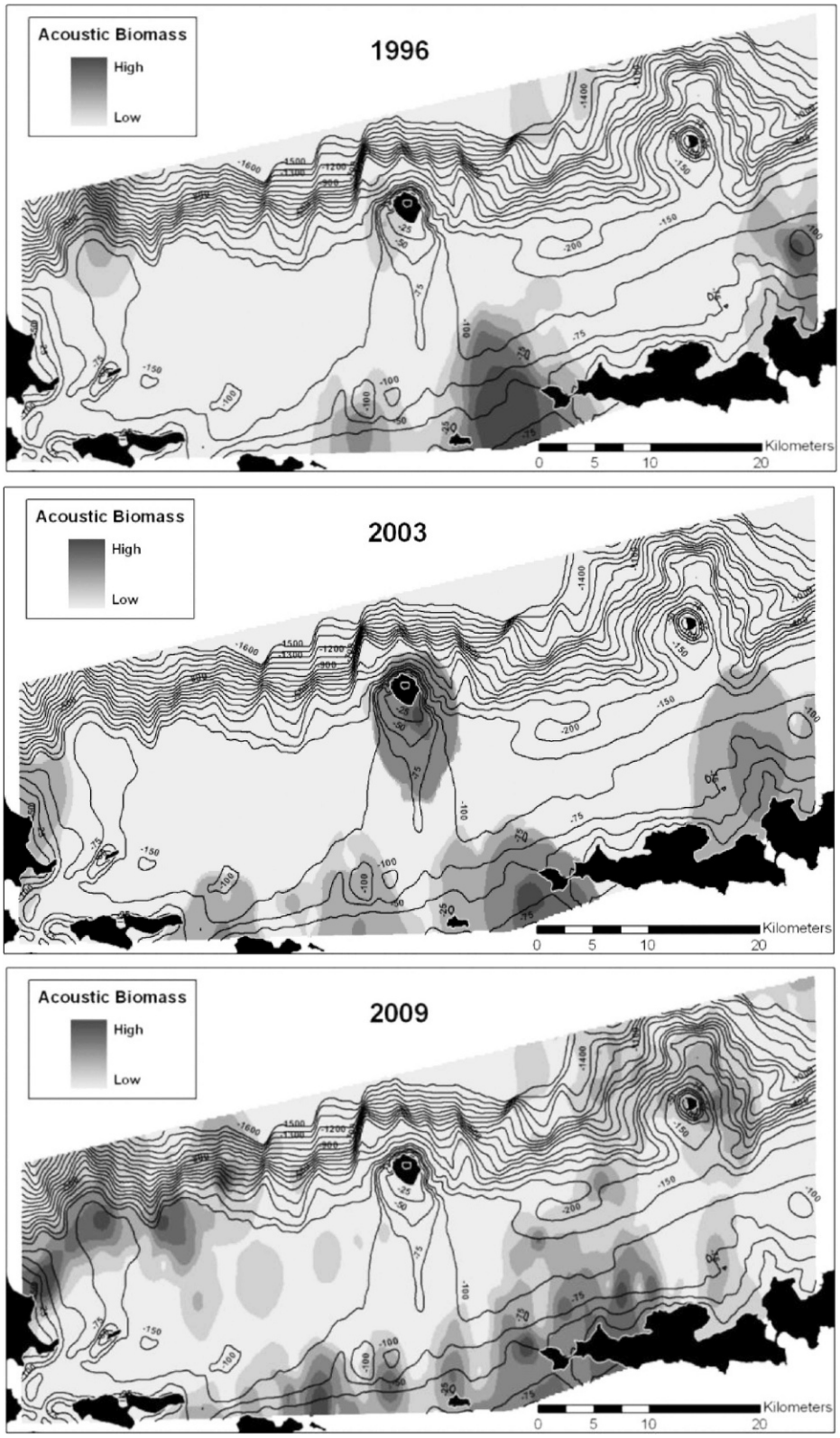

FIGURE 5. Distribution of acoustic biomass for the top 50 m of the water column for the Kasatochi study area. Maps are based on IDW interpolation of relative acoustic biomass. Relative measurements are presented owing to use of different hydroacoustic systems or instrument settings in each year.

significantly different from those calculated for July surveys, indicating that these species remained in the area surrounding Kasatochi throughout the breeding season.

Circumnavigations of Ulak, Kasatochi, and Koniuji Islands conducted in July suggested that post-eruption (2009) densities for the uncommon/non-nesters around all islands were not different than pre-eruption densities (1996 and 2003). Both crested auklets and least auklets were rare around Ulak in all years, with densities ranging from 0.0 to 0.4 birds per km^2 and 0 to 1.1 birds per km^2, respectively. Crested auklets around Kasatochi and Koniuji islands showed similar patterns of density, being highest in 1996 and lowest in 2003, with 2009 falling in-between (Fig 6). Crested auklet annual densities ranged from 54 to 709 birds per km^2 around Kasatochi and 3 to 310 birds per km^2 near Koniuji. The only difference in densities for crested auklets was between pre-eruption surveys in 1996 and 2003 at Kasatochi Island ($P < 0.1$).

TABLE 1

Fish species captured during long-line sets ($n = 6$) offshore of Ulak and Kasatochi islands. Sampling was done in July 1996, July–August 2003, and July 2009.

Species	Ulak			Kasatochi		
	1996	2003	2009	1996	2003	2009
Alaska skate (*Bathyraja parmifera*)	2	6	0	0	0	0
Pacific cod (*Gadus macrocephalus*)	9	25	7	31	12	0
Dusky rockfish (*Sebastes ciliatus*)	0	0	0	1	1	0
Kelp greenling (*Hexagrammos decagrammus*)	0	0	0	1	0	0
Rock greenling (*Hexagrammos lagocephalus*)	1	0	0	1	0	0
Red Irish lord (*Hemilepidotus hemilepidotus*)	0	0	0	13	0	0
Yellow Irish lord (*Hemilepidotus jordani*)	0	3	18	5	0	0
Pacific halibut (*Hippoglossus stenolepis*)	2	10	12	5	0	0
Southern rock sole (*Lepidopsetta bilineata*)	0	0	0	0	0	0
Total	14	44	37	57	13	0

Around Kasatochi Island, least auklets showed little change in densities ranging from 26 to 34 birds per km^2. Least auklets around Koniuji Island showed the greatest variability ranging from 3 to 68 birds per km^2, with 2009 post-eruption densities significantly higher than pre-eruption densities ($P < 0.1$).

For the uncommon/non-nesters, the post-eruption anomaly map indicated somewhat higher densities in Atka Pass and north of Fenimore Pass than observed on the pre-eruption surveys (Fig. 7). Distributions around Kasatochi and the other islands were essentially unchanged. The anomaly map for crested auklets indicated that post-eruption (July 2009) densities were higher just north of Kasatochi Island (Fig. 7). In our post-eruption sample, crested auklets were less dense in the Fenimore and Atka Pass area and in the waters to the southeast of Koniuji Island (Fig. 7). The anomaly map for least auklets indicated little change around Kasatochi Island (Fig. 7). Similar to crested auklets, least auklets were less dense in the Fenimore and Atka Pass area post-eruption. Unlike crested auklets, least auklets were more common in the waters to the northeast of Ulak Island and east of Koniuji post-eruption (Fig. 7).

Discussion

The August 2008 eruption of Kasatochi volcano extensively impacted the island, with large amounts of ash and pyroclastic debris burying terrestrial habitats 10–20 m deep and depositing an unknown amount of material in the marine habitats surrounding the island. Our 2009 surveys of the marine habitats and resources in the vicinity of Kasatochi were designed to identify short-term changes in marine resources and develop a new baseline of data to help identify long-term effects and recovery from the eruption.

There were no pre-eruption data on marine nutrients in our study area. However, data from passes east and west of the study area provide some context for what we should have expected prior to the eruption (Mordy et al., 2005). Compared to other central

TABLE 2

List of 13 species of birds grouped as uncommon/non-nesters for the purposes of comparison. Although some of these species have nested on Kasatochi, none have done it consistently or in large numbers.

Species	Scientific name
Laysan albatross	*Phoebastria immutabilis*
Black-footed albatross	*Phoebastria nigripes*
Northern fulmar	*Fulmarus glacialis*
Short-tailed shearwater	*Puffinus tenuirostris*
Red phalarope	*Phalaropus lobatus*
Black-legged kittiwake	*Rissa tridactyla*
Common murre	*Uria aalge*
Thick-billed murre	*Uria lomvia*
Pigeon guillemot	*Cepphus columba*
Ancient murrelet	*Synthliboramphus antiquus*
Cassin's auklet	*Ptychoramphus aleuticus*
Horned puffin	*Fratercula corniculata*
Tufted puffin	*Fratercula cirrhata*

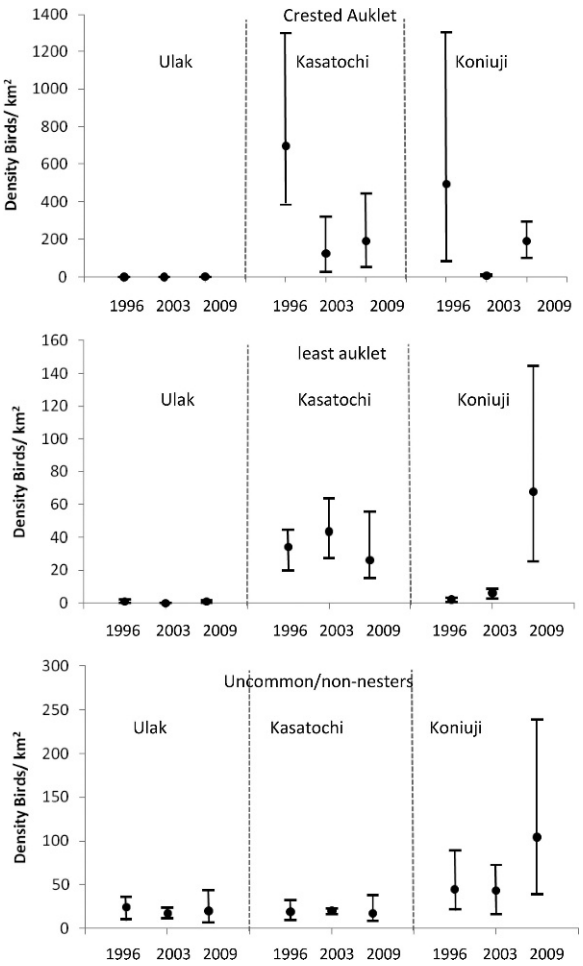

FIGURE 6. Densities for least auklet, crested auklet and uncommon/non-nesters for the three colony islands within the study area (Ulak, Kasatochi and Koniuji) for the three sampled years (1996, 2003, and 2009). Error bars represent 90% CIs of densities.

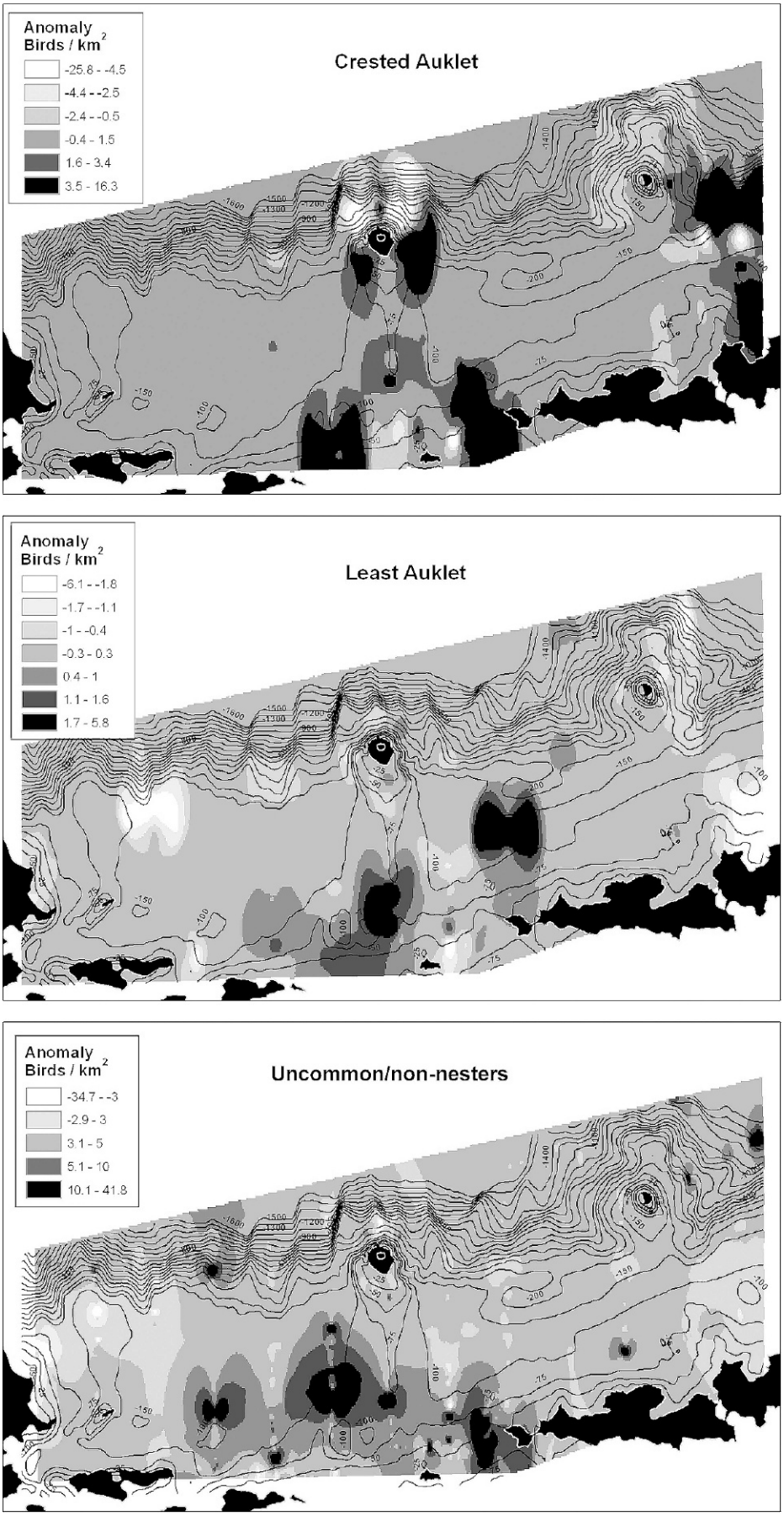

FIGURE 7. Anomaly maps (pre-eruption minus post-eruption) of seabird distributions in the study area. Light colors indicate areas of higher densities following post-eruption, dark colors indicate areas that had lower densities following the 2008 eruption.

Aleutian passes, those in our study area are shallow (50 m) leading to high degrees of mixing. In particular, we were looking for heightened phosphorus and silica, both nutrients of mineral origin. We had anticipated that there might be some nutrient signal due to the initial deposition of materials in marine habitats soon after the eruption. Logistically, we were not able to sample nutrients in the period just after the eruption; however, Frogner et al. (2001) illustrated that satellite-derived chlorophyll-*a* concentrations could detect areas affected by ash fertilization. Comparing the September 2009 SeaWiFS image with a mean of September pre-eruption images (2003–2007), we were able to identify an area of anomalously high chlorophyll-*a* concentration to the northeast, directly downstream from the Aleutian North Slope Current. Given the easterly flow of the Aleutian North Slope Currents surface waters, at an average velocity of 11 cm s^{-1} (Stabeno et al., 2009), it would take approximately 21 days for water around Kasatochi to move to that area. This would make the anomaly consistent with a fertilization event in the time period of the eruption. This finding corroborates the results of Langmann et al. (2010) who also identified fertilization from this eruption using MODAS satellite imagery at a much broader scale. However, we found no evidence of elevated nutrients around Kasatochi Island in June 2009 despite the considerable erosion of volcanic sediments into the sea (Waythomas et al., 2010 [this issue]).

Nutrient sampling in June allowed us to determine that marine waters close to Kasatochi did not have elevated levels of phosphorus or silicate, indicating that at least by spring 2009 runoff and erosion on Kasatochi did not make large nutrient contributions to the marine environment. Frogner et al. (2001) found that substantial amounts of nutrients can be released from ash within 1–2 hours. However, exposed ash may have released most of its water soluble nutrients long before we were able to sample 10–11 months later in 2009, and this may account for the lack of elevated nutrient concentrations near the island. Nutrient concentrations in the central Aleutian passes tend to be relatively high due to the upwelling of deep nutrient-rich water from the Alaska Stream up over the shallow shelf and through the passes into the Bering Sea (Mordy et al., 2005). Such high background nutrient concentrations may mask the addition from the volcanic ash, particularly when they are moving along strong and persistent currents. Additional sampling of runoff directly from ravines or at the shore, and coordinated research with soil scientists working on the island may be required to isolate any nutrient contributions from volcanic ash.

With our fish sampling limited to a single long-line set at each island and year, we were unable to test for differences between islands. That said, the failure to capture any large predatory fish on the Kasatochi Island long-line set in 2009 could have been related to bottom habitat changes in the area. Although species composition was not consistent by year or island, this set was the only one that failed to catch any demersal fish. Divers working in the area south of Kasatochi reported sand-like ocean bottoms with little vegetation (Jewett et al., 2010 [this issue]). This contrasted with reports of a much more complex habitat with substantial marine vegetation prior to the eruption (W. Pepper, personal communication). The apparent change in use of the local area by large fish may have been based on a loss of cover, affecting the availability of their prey, small forage fish. Additional sampling in subsequent years and a more intensive effort to map the submarine habitat will be necessary to identify the extent and implications of the habitat alteration.

Our results indicate that the marine avifauna in the Kasatochi Island area is highly dynamic and will require more sampling in the future to determine the ultimate fate of the seabirds nesting on Kasatochi. The uncommon/non-nesters or "control group" indicated no post eruption changes in density for any of the islands. Neither crested nor least auklets exhibited significantly different post-eruption densities around Kasatochi. While there was a difference between the 1996 and 2003 pre-eruption density estimates for crested auklets, this serves to illustrate the variability of aggregated species like crested auklets, and suggests that repeated samples would be helpful in tightening the CI of the estimates. Although we detected no difference in the density of either auklet species around Ulak, the densities were uniformly low, possibly due to lack of nesting habitat. Koniuji Island, to the northeast of Kasatochi appears to be the most likely area for auklets to go in search of nesting sites, since moderate numbers of crested auklets and least auklets already breed on the island. No differences were found in the density estimates for crested auklets around Koniuji Island. Thus, there was no evidence that the distribution of crested auklets had shifted from Kasatochi Island to another island in the study area. We did find that densities of least auklets were significantly higher around Koniuji Island post-eruption, which suggests that some of these birds might have shifted there. However, we did not find a concurrent decline in least auklet density at Kasatochi. We suggest either the 2009 count of least auklets may reflect normal variation inherent in at-sea surveys, or least auklets may have been spending additional time in the Koniuji area assessing nesting opportunities. Only additional sampling will be able to clarify this.

Anomaly plots for all taxa suggested considerable spatial and temporal variability; thus, we could not attribute changes in bird distribution to the 2008 eruption. Additional surveys will be required to establish whether the anomalies we found reflect long-term population change or simply reflect a dynamic system.

The return of crested and least auklets to Kasatochi Island in 2009 was not completely unexpected given the strong nest site fidelity generally exhibited by these two species (Sealy, 1975; Roby and Brink, 1986; Piatt et al., 1990; Jones, 1993). Post-eruption densities were similar to pre-eruption densities, suggesting that most adult birds survived the eruption, but lack of recruitment suggests that this is not likely to continue. Given that nest-sites were unavailable (Williams et al., 2010 [this issue]) and may remain so for the lifespan of the crested and least auklets that were present in 2008, these birds are faced with three possible scenarios: (1) Continue returning to Kasatochi; with no nest sites available populations will decline steadily towards extirpation, (2) Continue returning to Kasatochi until nesting habitat is exposed through erosion, and then, based on the amount of nesting habitat, populations should stabilize at a lower level and perhaps eventually increase, or (3) Abandon the colony and seek out new nesting habitat at other islands, resulting in a swift decline over the next few years and an increase in densities around alternative sites, e.g. Koniuji Island.

As long-lived marine birds crested and least auklets must weigh the risk of returning to Kasatochi Island and waiting for nesting crevices to be re-established, against the risk of seeking out new nesting opportunities on other islands. Crested and least auklets already nest on Koniuji Island, however, nesting habitat there is thought to be limited (J. Williams pers. comm. 2009). The choices made by these birds will provide new insights into the costs and benefits of nest site selection to these species. We recommend that a monitoring schedule be established to track the densities of marine birds around Kasatochi and Koniuji islands periodically during the next 15 years. With sufficient sampling we may be able to identify the decisions made by auklets and other marine bird species, i.e. to return or leave Kasatochi Island, and better

understand the processes governing marine bird colony extinction and creation in an area of episodic ecological disturbance.

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