Mass Stranding of Marine Birds Caused by a Surfactant-Producing Red Tide

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Abstract

In November-December 2007 a widespread seabird mortality event occurred in Monterey Bay, California, USA, coincident with a massive red tide caused by the dinoflagellate *Akashiwo sanguinea*. Affected birds had a slimy yellow-green material on their feathers, which were saturated with water, and they were severely hypothermic. We determined that foam containing surfactant-like proteins, derived from organic matter of the red tide, coated their feathers and neutralized natural water repellency and insulation. No evidence of petroleum or other oils or biotoxin was found. This is the first documented case of its kind, but previous similar events may have gone undetected. The frequency and amplitude of red tides have increased in Monterey Bay since 2004, suggesting that impacts on wintering marine birds may continue or increase.

Introduction

Harmful algal blooms (HABs) caused by a variety of dinoflagellates occur worldwide and can cause morbidity and mortality of fish, invertebrates, marine birds, marine mammals and humans [1-2]. Morbidity and mortality may result from ingestion, inhalation or absorption of toxins, including the potent neurotoxins domoic acid, saxitoxin, and brevetoxin [3-6] or from hypoxia/anoxia that develops during bloom respiration and senescence [1]. Herein we present the first report of harmful effects caused by external coating of marine birds by a proteinaceous foam derived from a red tide bloom that occurred November 2007 in Monterey Bay, CA (USA). Monterey Bay is an important foraging and moulting area for a diversity of migratory birds, second only to San Francisco Bay in importance to sea ducks and near shore species wintering along the west coast of the United States. Although this red tide bloom was ostensibly nontoxic, it was very harmful, causing morbidity and mortality of more than 700 seabirds. Affected birds had a slimy yellow-green material on their feathers, which were saturated with water, and they were severely hypothermic. Foam containing surfactant-like proteins, derived from organic matter of the red tide, coated their feathers and neutralized natural water repellency and insulation. No evidence of petroleum, other oils or biotoxin was found. This is the first documented case of its kind, but previous similar events worldwide may have gone undetected. The frequency and amplitude of red tides have increased in Monterey Bay since 2004 [7], suggesting that impacts on wintering marine birds may continue or increase.

Results

Fourteen seabird species were affected during the 2007 red tide, particularly those that feed in near shore habitat, such as surf scoters (*Melanitta perspicillata*), Pacific and red-throated loons (*Gavia* spp.), and Clark’s and western grebes (*Aechmorphorus* spp.). Some of these, including the loons, grebes and northern fulmar (*Fulmarus glacialis*), had just completed their southward migration and were in poor nutritional condition. Also, both species of loons and grebes undergo a catastrophic moult, simultaneously losing their flight feathers shortly after arriving in Monterey Bay. As a result, many birds were flightless and could not escape or compensate for loss of water repellency and body heat. Although the proteinaceous material was relatively easy to remove from the birds using abbreviated oil spill washing procedures, seabird mortality was still substantial.

Live-stranded birds were severely hypothermic, wet and hypoglycaemic, with variable patches of a slimy pale yellow-green material on their feathers (Figure 1) with a "bathtub ring" distribution, primarily on the breast area and ventral surfaces of wings and tail. Many had a pungent odour similar to that of linseed oil while still wet, but with time, this material dried, leaving a fine crust with minimal smell. Upon washing, rehydration, warming, and nutritional supplementation, many affected birds recovered, suggesting that the product was minimally toxic or nontoxic. Gross post-mortem and microscopic pathology examinations of affected birds revealed no significant lesions other than mild to moderate emaciation, diffuse pallor suggestive of mild to moderate anaemia, and a mild erythematous rash or mild, raised pox-like lesions. With supportive care the skin lesions, cachexia and anaemia resolved spontaneously.

Three distinct pulses of live and dead bird strandings occurred in spatial and temporal coincidence with the development and circulation of an intense "red tide". The first pulse of red tide and bird strandings was most concentrated in northern Monterey Bay (Figure 2A). The second pulse was marked by expansion of the red tide and increased seabird strandings along the southern portion of bay (Figures 2B and 2E). The third pulse occurred in both areas simultaneously (Figure 2C). Standardized periodic surveys documented marine bird stranding rates 2 to 24 times greater than the 10-year average for Western/Clark's grebes on most northern beaches in Monterey Bay (Figure 2D). These species typically forage along the shoreline where dense patches of senescing algae and foam were observed. In contrast, northern fulmar are a more pelagic species that forage near the centre of Monterey Bay. Fulmar appeared to have encountered the red tide and its attendant foam in the southern and central bay as supported by the MERIS satellite data (Figure 2B). Fulmar stranded in numbers 2 to 4 times greater than the 10-year average for the months of November-December, but were more highly localized to specific beaches (Figures 2E).

Plankton samples collected at various Monterey Bay nearshore and offshore stations during November 2007 were consistently dominated (both numerically and by biomass) by *Akashiwo sanguinea* (=*Gymnodinium sanguineum*), an autotrophic dinoflagellate (Figure 3, circular inset). Significantly elevated levels of other biotoxin-producing dinoflagellates were not detected in Monterey Bay during this event. *Akashiwo sanguinea* is capable of producing large quantities of mycosporine-like amino acids (MAAs), which are water-soluble and serve as powerful surfactants [8]. *Akashiwo sanguinea*-associated blooms have also been linked to coral bleaching due to the formation of proteinaceous material [9], similar to that found in this event. In this event surface foam accumulated adjacent to the most densely concentrated portions of the bloom along frontal edges (Figure 3) and in the surf zone where wave action presumably produced foam through turbulent mixing of the organic-rich seawater. Affected birds were observed swimming in the thick foam near the shoreline. When normal seabird feathers were dipped in the foam, the contour feathers and underlying down lost their normal water repellency (Figure 4D) and became soaked. Clean seawater (Figure 4A, 4B, 4C) and deionised (Milli-Q) water did not have this effect.

Extracts of seawater from four areas in northern Monterey Bay heavily impacted by the red tide were analyzed for polar and non-polar compounds by gas- and liquid chromatography-mass spectroscopy and were found to be negative for petroleum compounds, commercial surfactants, pesticides, domoic acid, okadaic acid, and microcystin toxins. However, samples of the co-occurring surface foam present at these same sites contained significant concentrations of an organic compound with a predominant chromatographic peak at 1230 mw, corresponding to a m/z 616 dimer composed of carbon, hydrogen, nitrogen and oxygen. Fragmentation of the m/z 616 parent compound resulted in loss of several m/z 59 fragments characteristic of peptide chains. When foam samples were allowed to sit for several days at ambient temperature, these peptides became difficult to detect. Analysis of the surface foam and feathers from affected birds coated with the yellow-green proteinaceous material revealed high concentrations of the same 616 m/z protein dimer, but seawater collected from unaffected areas and normal feathers of healthy seabirds of the same species were negative for this compound.

Samples of the foam were also analyzed by UV-VIS spectroscopy, and exhibited characteristic UV-absorption spectra indicative of MAAs that are commonly associated with dinoflagellate blooms. As with the proteins detected by mass spectrometry, the MAA-like absorption features degraded (within 24 hours) when stored in the dark at 4°C. Uni-algal, xenic laboratory cultures of *A. sanguinea* isolated from Monterey Bay produced compounds with the same UV-absorption signature (indicative of MAA compounds) as the field-collected algal, feather and foam samples. When senescent laboratory cultures of *A. sanguinea* were vigorously agitated for 30 seconds and then left to rest for 2 hours, they produced surface foam (Figure 4E) that had the same wetting properties on normal bird feathers as the naturally occurring foam (Figure 4F); the foam was still intact at the end of the two hour rest period. In contrast, agitation of healthy *A. sanguinea* cultures did not result in foam production beyond transient bubble formation which did not persist for more than ca. 15 seconds, and exposing normal bird feathers to vigorously shaken healthy cultures or to sterile seawater media did not result in wetting.

Discussion

Northeastern Monterey Bay has previously been identified as a “red tide incubator” [10]. Analysis of remote sensing data (ocean color, temperature and currents) suggests relatively weak circulation, and presumably enhanced retention of the prolonged red tide bloom during the marine bird stranding event. The bloom was first detected by satellite in this area before the harmful effects on the marine birds were detected, and it persisted throughout the event. The first and third pulses of marine bird morbidity and mortality occurred primarily within this incubator region (Figure 2).

Because the gross lesions in affected birds were vague and nonspecific, and the worldwide distribution of *A. sanguinea* is broad, similar mortality events may have previously been unrecognized. Mass stranding of recently moulted grebes, loons and scoters with wet, “apparently oiled” feathers also occurred in Monterey Bay in 1997 and was temporally associated with an uncharacterized red tide. Red tides of similar magnitude were observed in Monterey Bay in August-September 2004 [11] and in September 2006, with no substantial increase in reports of bird mortalities. The lateness, duration and intensity of the 2007 *A. sanguinea* red tide and the natural history of the most heavily affected bird species evidently exacerbated the impacts of the bloom.

Prediction of the harmful effects of harmful algal blooms requires a better understanding of linkages between climate variability, phytoplankton blooms and natural history of higher animals. An “unprecedented” red tide produced by *A. sanguinea* in San Francisco Bay during September 2004 was attributed to an upper-atmosphere high-pressure anomaly off the U.S. west coast, following a summer of weak coastal upwelling [12]. The circulatory, nutrient, weather and surf conditions that existed in November 2007 favoured an especially intense and prolonged event that produced large amounts of foam from a very large, senescing dinoflagellate bloom by extending the red tide into a period of increased winter swell. It remains to be seen whether the combination of events we describe for 2007 is a result of climate change, but the frequency, amplitude and duration of “red tides” have increased substantially within Monterey Bay since 2004 [7] and continue to increase globally [4], suggesting that the harmful effects of dinoflagellate blooms may become more common.

Materials and Methods

Bird data. Live and dead bird stranding data were spatially binned according to where the stranding locations formed clusters, and were temporally binned according to three distinct pulses of stranding activity. Two species (western/Clark's grebes and northern fulmars) were examined in more detail. The Beach Coastal Ocean Mammal and Bird Education and Research Surveys program [13] record dead strandings during monthly beach surveys. Data from November and December 2007 surveys are presented in relation to the monthly mean (1997-2006) stranding data from the same beaches for the same months.

Description of the red tide. We primarily used 300 m and 1200 m images from the MERIS satellite sensor. Average MCI [14-15] corresponding to the three pulses of bird strandings was calculated. For the first stranding period (7-18 November 2007), two images preceding (2-3 Nov) and one image during this pulse (12 Nov) were averaged. Three MCI images (19, 21, 22 Nov) within the second period (19-23 Nov) were averaged. For the third period (24 Nov – 2 Dec), MCI coverage was not adequate, and we used 500-m resolution MODIS true-color images.

Chemical analysis. Foam collected by boat and from shore and material from live and dead stranded birds was analyzed following standard protocols for identification of marine toxins, contaminants, and petroleum products. This included analysis by gas chromatography with ion trap detector (ITD), electron capture detector (ECD), and flame photometric detector (FPD), as well as liquid chromatography/mass spectrometry (LC/MS), LC/MS/MS, and UV/VIS absorption.

Foam reproduction. A monospecific strain of *Akashiwo sanguinea* (AkaMB1106) was grown on L1 media. The culture was allowed to enter stationary phase and senesce. 500 mL each from senescent and healthy cultures was agitated for approximately 30-60 seconds, until foam was produced in the senescent culture. L1 media with no cells was used as a control.

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Figure legends

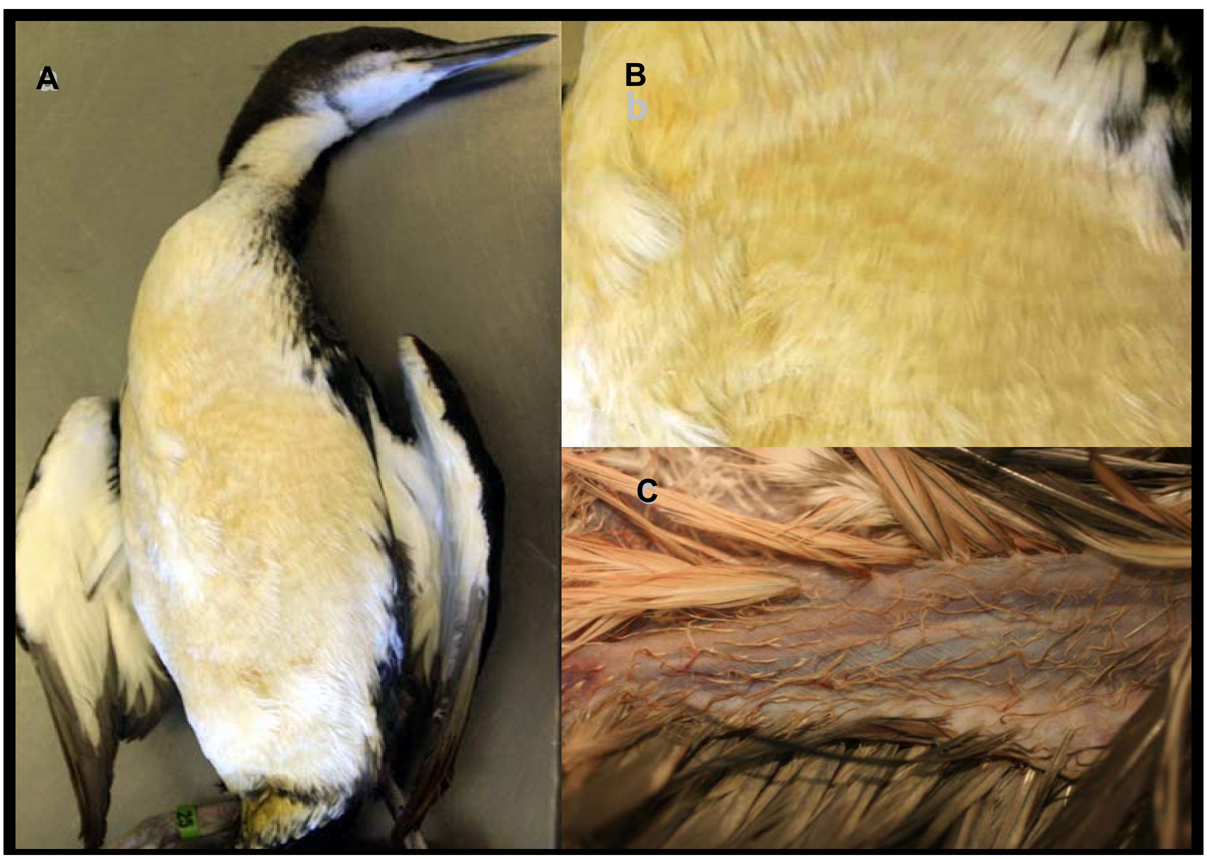
Figure 1: Dead seabirds with signs of protein-induced loss of waterproofing. A) A Pacific loon found dead in Monterey Bay, CA in November, 2007 with yellow-green staining of ventral breast feathers typical of over 700 marine birds affected by this event. B) Closer view of the stained feathers from (A), illustrating the yellow-green discoloration and the oily appearance of affected feathers. C) Discolored, wet and matted feathers on the ventral wing of a western grebe recovered during the same stranding event.

Figure 2. Correspondence between the spatial and temporal patterns of seabird strandings and red tide during November-December 2007 in Monterey Bay. Black circles represent the approximate location and magnitude of morbidity and mortality, and satellite data represent the red tide for panels (A-C). Three pulses of seabird stranding were observed: A) focused along the northern bay, B) focused in the south-central portion of the bay, and C) in both northern and central portions of the bay. In (A) and (B) the MERIS data indicate extreme bloom conditions above MCI level of ~0.3. Although ideal for red tide detection, MERIS coverage was not adequate for the third pulse. In (C) the reddish discoloration on the MODIS true color image during the third pulse (28 Nov) shows the spatial extent and location of the red tide. Panels (D) and (E) show increased seabird stranding during the November-December 2007 red tide event. Light bars are 10-year average (1997-2006) standardized monthly stranding counts on nine Monterey Bay beaches. Dark bars are 2007 counts for western/Clark’s grebes and Northern fulmar, the species most affected during the mass-stranding event. Panel (D)

corresponds to the first stranding event, while panel (E) corresponds to the second and third waves of strandings.

Figure 3. Aerial photograph taken 26 November, 2007 off Pajaro Dunes Colony (rectangular inset) in central Monterey Bay. A dense front of red tide is visible in the left foreground. A distinct line of surface foam is spatially associated with the red tide, along with aggregations of marine birds. Circular inset: a single non-senescent *Akashiwo sanguinea* cell.

Figure 4. Natural and laboratory produced wetting of normal feathers. A) Normal breast feather from a brown pelican after dipping in clean seawater. Note the minimal wetting and matting of feather barbs. B) Normal seawater after agitation for 30 seconds, then resting for 2 hours. Note the absence of surface foam. C) Normal-appearing breast feathers from a Northern fulmar after dipping in the test tube containing normal seawater. D) Normal breast feather from a brown pelican after dipping in surface foam collected near an *A. sanguinea* bloom in Monterey Bay. Contact with the foam resulted in severe wetting and matting of feather barbs. E) Senescent laboratory culture of *A. sanguinea* after agitation for 30 seconds, then resting for 2 hours. Note the persistence of a thick surface layer of foam. F) Normal breast feathers from a Northern fulmar after dipping in the surface foam derived from the senescent *A. sanguinea* culture, resulting in severe wetting and matting of feather barbs.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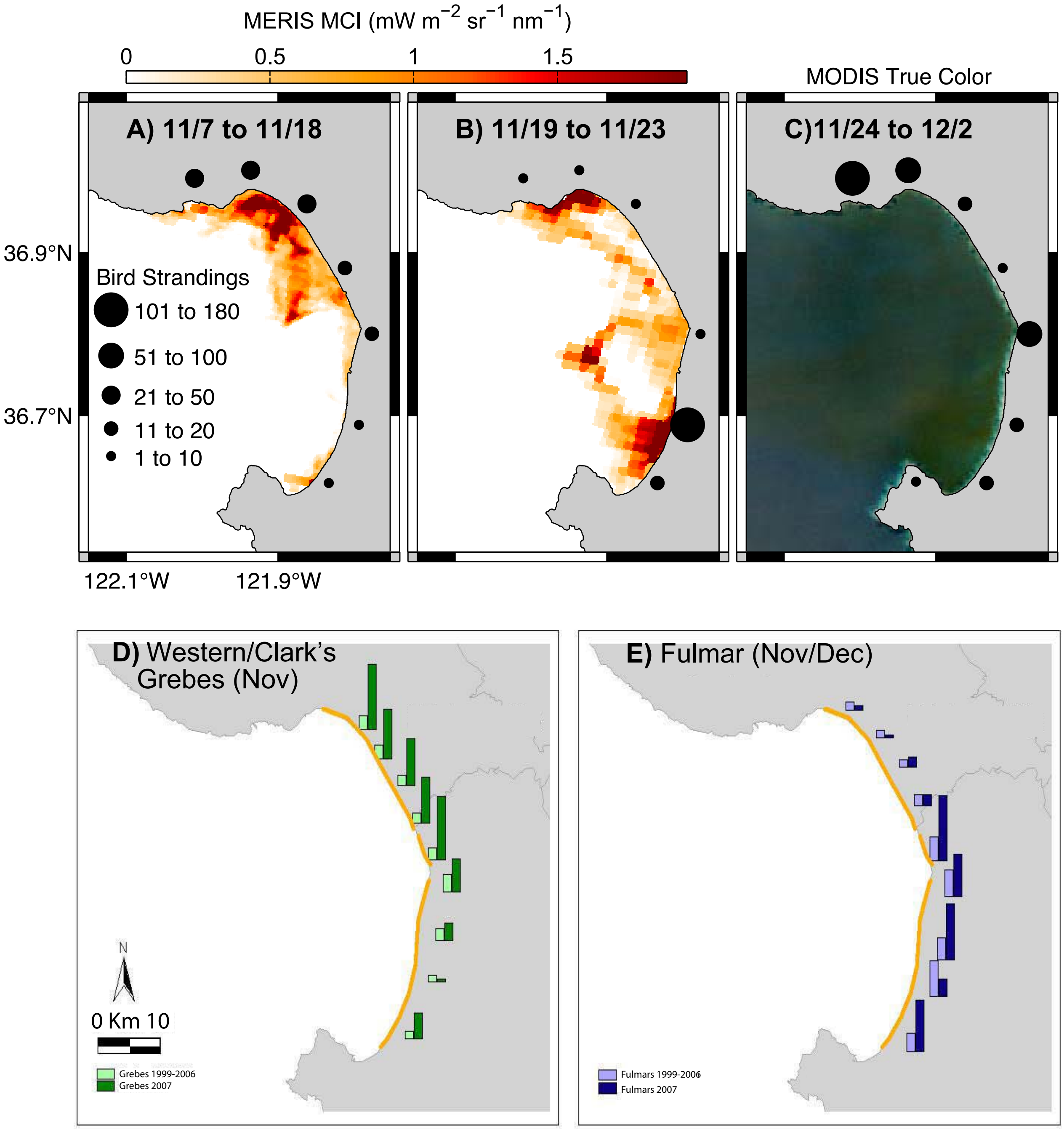
MERIS MCI (mW m^{-2} sr^{-1} nm^{-1})
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A) 11/7 to 11/18
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C)11/24 to 12/2
36.9°N
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Bird Strandings
101 to 180
51 to 100
21 to 50
11 to 20
1 to 10
122.1°W
121.9°W
D) Western/Clark's Grebes (Nov)
E) Fulmar (Nov/Dec)
N
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N


Seawater
A
B
C
D
E
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Surface foam