Title
Mystery behind Hitchcock's birds

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To the Editor — On 18 August 1961, a Californian newspaper reported that thousands of "crazed seabirds pelted the shores of North Monterey Bay, California" regurgitating anchovies. Soon after reading the report (Supplementary Fig. S1), local visitor Alfred Hitchcock was inspired to produce his famous thriller *The Birds*. Three decades later, in 1991, another mass poisoning occurred in the same area — this time, of fish-eating, disoriented and dying brown pelicans. But on this occasion the culprit was identified: the pelicans had ingested domoic acid, a neurotoxin that is produced by the diatom *Pseudo-nitzschia*. Large quantities of this diatom, and the associated toxin, were found in the stomachs of fish in the region. It has been suggested that diatom-generated domoic acid was also responsible for the 1961 event[1], but direct evidence has been lacking. Here we show that plankton samples from the 1961 poisoning contained toxin-producing *Pseudo-nitzschia*, supporting the contention that these toxic diatoms were responsible for the bird frenzy that motivated Hitchcock's thriller.

Algal toxins such as domoic acid are increasingly recognized as the cause of marine poisoning events. Domoic acid is a chemical analogue of glutamate and, as such, binds with high affinity to glutamate receptors in the brain[2]. When domoic acid passes through the blood–brain barrier and binds to these receptors in birds and mammals, it causes symptoms such as confusion, disorientation, scratching, seizures, coma and even death[3].

Over the past decade, Monterey Bay, a productive coastal environment in the California Current upwelling system, has been affected by recurrent blooms of *Pseudo-nitzschia* species that produce domoic acid. These blooms have led to the death or stranding of brown pelicans, Brandt's cormorants and sea-lions[4–7]. Although *Pseudo-nitzschia* has resided in the waters off California for millennia, domoic acid was only detected in diatoms in the region in 1991[8]. Prior to this, episodes of seabird mortality off the shores of California were attributed to other factors such as fog, infectious diseases, oil spills and fishing practices[9]. One such event was that involving the influx of disorientated seabirds into Monterey Bay in the summer of 1961, which entered into cinematic history.

Sooty shearwaters, *Puffinus griseus*, are common visitors to Monterey Bay. These birds travel from their breeding grounds in the south-west Pacific to the productive waters of the north-east Pacific, including the California Current, during the summer and early autumn to feed[10]. In Monterey Bay, huge flocks of sooty shearwaters feed on krill, squid and fish[11]. In the summer of 1961 the birds were found regurgitating anchovies, flying into objects and dying on the streets, capturing the attention of summer resident Alfred Hitchcock; *The Birds* was released two years later.

Here, we show that toxin-producing species of *Pseudo-nitzschia* were indeed present in high numbers at the time of the 1961 bird frenzy. In the absence of water samples, we examined archival samples of herbivorous zooplankton — which feed on diatoms, and are preyed on by sea turtles and some fish and birds — collected during ship surveys at the time[12] (Supplementary Fig. S2). By analysing the gut contents of these animals, we were able to reconstruct regional flora (Supplementary Information). Toxin-producing species of *Pseudo-nitzschia* accounted for 79% of the diatoms present in the guts of these organisms (Fig. 1a). Species included *P. turgidula* (Fig. 1b,c), *P. pseudodelicatissima* (Fig. 1d,e; Supplementary Fig.S3), *P. pungens, P. delicatissima, P. australis* and *P. multiseries* (Supplementary Table S1); the latter two dominated blooms during the 1991 poisoning of brown pelicans. The most abundant *Pseudo-nitzschia* species identified during the 1961 outbreak were *P. turgidula*, which accounted for 49% of the diatoms present and was recently shown to produce domoic acid in the subarctic Pacific[13], and *P. pseudodelicatissima*, which accounted for 38%. We suggest that domoic acid generated by these diatoms accumulated in the food chain, and led to the poisoning of

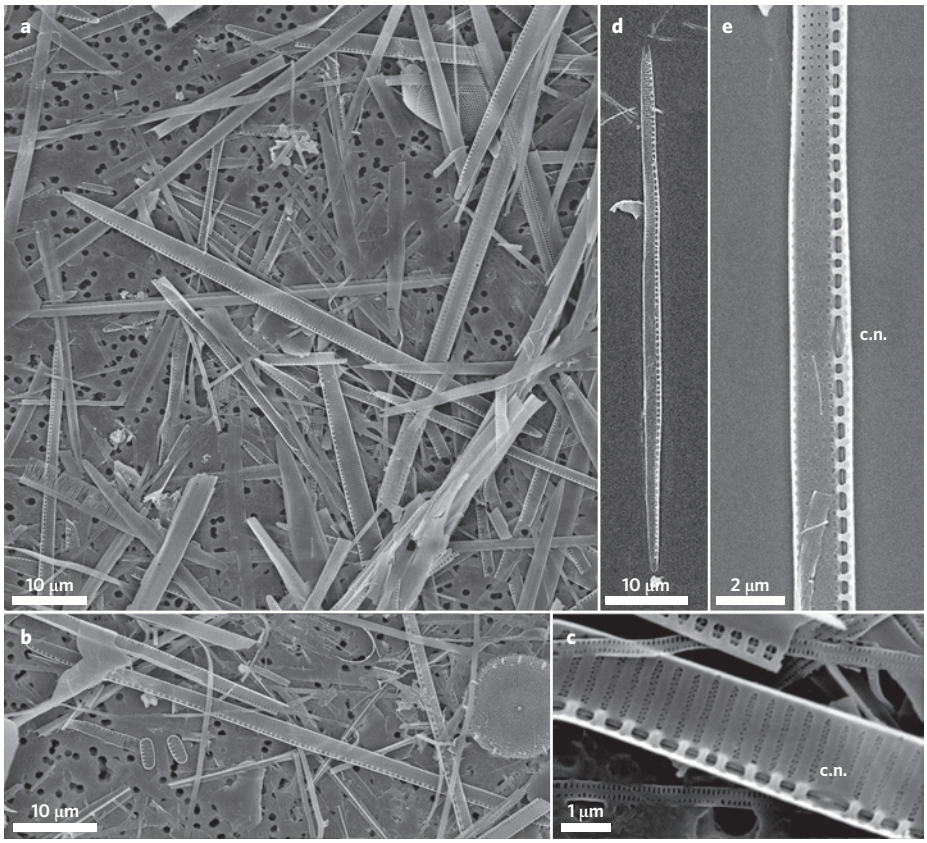

Figure 1 | Toxic *Pseudo-nitzschia* and Hitchcock's bird frenzy. Scanning electron microscopy images of zooplankton gut contents collected in July–August 1961 from Monterey Bay, California. **a**, Overview image showing the relative abundance of *Pseudo-nitzschia*. **b**,**c**, *P. turgidula* and **d**,**e**, *P. pseudodelicatissima* – the two most abundant *Pseudo-nitzschia* species found in the zooplankton. Notice the presence of poroid rows within the striae of the latter two species; a central nodulus (c.n.) is also present in both. Both features were used to help identify the species.

migratory flocks of shearwater that foraged in these waters.

We show that *Pseudo-nitzschia* abundance during the summer of 1961 was of the same order of magnitude as that observed during more recent animal stranding events related to domoic acid poisoning[14]. The upwelling of bottom waters declined at the time, and the inflow of oceanic surface waters increased, probably leading to the development of warm-water, low-wind conditions[15]. We suggest that this, in turn, promoted *Pseudo-nitzschia* growth and prolonged the residence time of the visiting seabirds. Similar conditions led to the mass poisoning event in 1991[4].

Given the similarities between events in 1961 and the domoic acid-induced poisoning of 1991, we suggest that toxic *Pseudo-nitzschia* were probably responsible for the odd behaviour and death of Sooty shearwaters in August 1961. This brief study therefore supports the contention that domoic acid caused the seabird frenzy that eventually led Hitchcock to make his film[1], and strongly suggests that domoic-acid-producing phytoplankton have been an agent of marine animal mortality in the California Current system for at least the past fifty years. ❐

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Author Contributions

S.B., M.W.S. and D.L.G. designed the overall project; S.B., M.W.S., M.D.O. and C.R.B.-N performed research; S.B., M.W.S. and M.D.O. analysed data. All authors participated in discussions, contributed ideas along the way and edited the manuscript.

Additional information

Supplementary information accompanies this paper on www.nature.com/naturegeoscience.

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SUPPLEMENTARY INFORMATION

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Supplementary Methods

Zooplankton Sample Collection: Zooplankton were collected in or near Monterey Bay (line 66.7 station 50, 36.817º N, 122.083º W, 4 July 1961; line 66.7 station 55, 36.650º N, 122.433º N, 4 July 1961; line 63.3 station 55, 37.217º N, 122.833º N, 5 July 1961) (Supplementary Fig. 2), with a 1-m diameter, 0.550-mm mesh ring net towed obliquely from the sea surface to a maximum depth between 140 m and 61 m. Samples were fixed in 1.8% formaldehyde buffered with saturated sodium tetraborate and archived in the Pelagic Invertebrates Collection, Scripps Institution of Oceanography.

Zooplankton Gut Content Analyses: Herbivorous zooplankton are ideal collectors of *Pseudo-nitzschia* because they provide an integrated sample of the phytoplankton in the surface water column. Salps are particularly efficient collectors, since they are non-selective filter feeders of cells >2 µm[1], and we have found that krill also sample *Pseudo-nitzschia* during toxic events[2].

Salp (*Salpa fusiformis*) gut contents were examined from all three stations sampled (n = 10 for 66.7 50, n = 10 for 66.7 55, and n = 5 for 63.3 55) and krill (*Euphausia pacifica*) gut contents were examined from only 63.3 55 (n = 5) to assess the presence of *Pseudo-nitzschia* in their diet. Individual specimens were chosen at random and were dissected to remove the viscera. Gut contents were cleaned for both scanning (SEM) and transmission (TEM) electron microscopy and observed using methods from[2]. All SEM micrographs were obtained with a Cambridge Stereoscan 260 scanning electron microscope at 10 kV. For TEM analysis of the frustules, a drop of cleaned material was pipetted onto copper grids (mesh size 100) with formvar coating and stabilized with an

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evaporated carbon film. The grids were left to air-dry and then viewed with a JEOL 100-CX transmission electron microscope. *Pseudo-nitzschia* spp. cells were found in all salp and euphausiid gut contents examined. The most abundant of species were found to be *P. turgidula* and *P. pseudodelicatissima* (Supplementary Fig. 3) (Table 1).

Supplementary Acknowledgements:

The authors would like to thank Annie Townsend and Linsey Sala for their help in zooplankton sample sorting. The authors also would like to thank Covello and Covello Photography for allowing us to use their reconstruction of Santa Cruz Sentinel front page from August 18, 1961.

Supplementary References

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Supplementary Table 1: Morphometrics used for *Pseudo-nitzschia* species confirmations using electron microscopy (SEM) from zooplankton gut contents sampled in July 1961 and their relative abundances.

Species	Length (µm)		Width (µm)		Striae in 10 µm		Fibulae in 10 µm		Poroids in 1 µm		Rows of Poroids	Central Interspace	Relative Abundance
	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max			
P. turgidula	54	72	2.2	3.4	24	28	17	18	7	10	2	present	49%
P. pseudodelicatissima	63	84	1.7	2.1	28	36	16	20	4	5	1	present	38%
P. fraudulenta	66	83	4	5	22	26	14	16	6	8	2	present	3.2%
P. australis	74	76	6	6	11	17	12	17	4	5	2	absent	2.6%
P. pungens	-	-	2.9	3	15	18	14	19	5	5	2	absent	2.6%
*P.*cf. *sicula*	27	28	5	5	12	13	13	13	5	6	2	present	2.6%
P. multiseries	72	78	4	5.7	12	18	12	18	5	7	3 or 4	absent	1.3%
P. delicatissima	-	65	1.8	2.2	30	36	20	24	9	12	2	present	0.6%

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Santa Cruz Sentinel

Seabird Invasion Hits Coastal Homes

He Got The Bird—Or Was It Vice Versa

Thousands Of Birds Floundering In Streets

Did Lights Bring Birds Ashore

Brick Wall Being Built By German Reds To Reinforce Barbed Wire Barricades

Agency Okays SL Park Pact With Shaffer

University May Use Cabrillo Facilities To Open Its Doors

1-Way Street Questionaires Now In Mail

Bakersfield Man Named Chief Of County's Juvenile Hall

Green Murder Suspect Caught

Birds, Birds And More Birds

Marilyn Demos Named Miss Playground 1961

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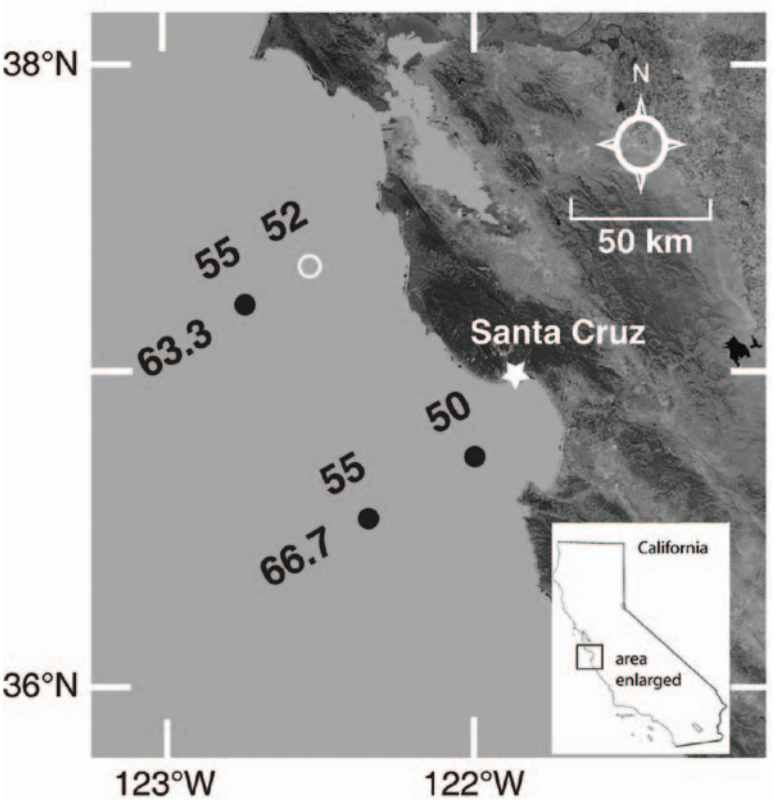
Vice President To Visit Berlin

Supplementary Figure 1: Reconstruction of Santa Cruz Sentinel front page from August 18, 1961. The text was reset to make it readable and the images reprinted from original negatives (Photos from Covello and Covello Photography with permission).



Supplementary Figure 2: Map of the CalCOFI survey lines.Net tow collections provided zooplankton samples used in the present study, samples from line 66.7 (stations 50 and 55) and 63.3 (station 55, black dots); no sample was analyzed from station 52.

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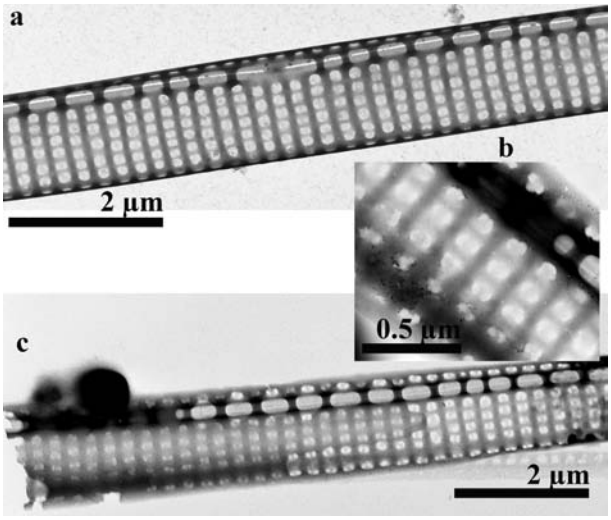

Supplementary Figure 3: Transmission electron microscopy image of salp gut content collected in July 1961 from Monterey Bay, California. (a) and (b, c): Images showing *P. pseudodelicatissima* - notice the presence of 1 row of poroids within the striae, hymen of poroids are divided into two large perforated parts. A central nodulus is present.