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Review

Karenia brevis red tides, brevetoxins in the food web, and impacts on natural resources: Decadal advancements

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ABSTRACT

As recently as a decade ago, *Karenia brevis* red tides and their effects on animal resources in the Gulf of Mexico were principally perceived as acute blooms that caused massive fish kills. Although occasional mortalities of higher vertebrates were documented, it has only been in the past decade that conclusive evidence has unequivocally demonstrated that red tides and their brevetoxins are lethal to these organisms. Brevetoxins can be transferred through the food chain and are accumulated in or transferred by biota at many trophic levels. The trophic transfer of brevetoxins in the food web is a complex phenomenon, one that is far more complicated than originally conceived. Unexplained fish kills and other animal mortalities in areas where red tide is endemic are being increasingly linked with post-bloom exposures of biota to brevetoxins. Mass mortality events of endangered Florida manatees (*Trichechus manatus latirostris*) follow a consistent spatial and temporal pattern, occurring primarily in the spring in southwestern Florida. Persistent blooms can also cause a cascade of environmental changes, affecting the ecosystem and causing widespread die-offs of benthic communities. Ongoing fish kills from sustained blooms can lead to short-term declines in local populations. Although animal populations in areas where red tide is endemic are unquestionably at risk, it remains to be determined to what extent populations can continue to recover from these sustained effects.

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1. Introduction

As recently as a decade ago, red tides and their effects on animal resources in the Gulf of Mexico, were principally perceived as acute blooms that caused massive fish kills and occasional mortalities of higher vertebrates (Steidinger et al., 1973; Landsberg, 2002). Although in earlier decades, mass mortality events involving, for example, turtles and a few bottlenose dolphins (*Tursiops truncatus*) (1946–1947), manatees (*Trichechus manatus latirostris*) (1982), and bottlenose dolphins (1987), co-occurred with red tides, definitive proof that brevetoxins were lethal to marine mammals was still lacking (Gunter et al., 1948; Geraci, 1989; O'Shea et al., 1991).

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Information on the fate and effects of brevetoxins in the environment was minimal. There was no real clear understanding about the stability of brevetoxins outside of *Karenia brevis* cells or recognition that toxins could be transferred through the food chain and accumulated or transferred by biota at many trophic levels.

Annual kills caused by *K. brevis* red tides involve hundreds of thousands of fish and other animal species. However, data describing declines in fisheries, and the evident rebound of selected fish species every year have provided no indication that frequent red tides could lead to an unsustainable reduction in fish populations or even threaten the long-term survival of local populations of imperiled species.

During the past decade, the following have enabled us to address critical research questions about red tide: the improved availability of funding for research through federal initiatives such as the Ecology and Oceanography of Harmful Algal Blooms and from Florida's state legislature; the increased support from local grass-roots movements such as Solutions To Avoid Red Tide; and the enhancements in technological and analytical capabilities. Such initiatives have provided the impetus to resolve many outstanding questions about the transfer of brevetoxins in the food web and to assess their widespread effects on natural resources.

This paper summarizes key research findings and breakthroughs of the past decade that have provided opportunities for revising management strategies and for making further strides in protecting critical fisheries, endangered species, and key habitats from the sustained effects from Florida red tides.

2. Verification that red tides are lethal to higher vertebrates

Brevetoxins acutely affect humans from neurotoxic shellfish poisoning (NSP) (Steidinger et al., 1998; Poli et al., 2000) or respiratory irritation as well as other chronic sequelae (Backer et al., 2003; Fleming et al., 2005, 2007). However, no fatalities have been documented, probably because humans are not typically exposed to lethal doses.

Since they were first reported in the Gulf of Mexico in 1648 (Magaña et al., 2003), *K. brevis* red tides have been documented to have killed hundreds of animals at higher trophic levels, such as marine birds, turtles, and mammals (Gunter et al., 1948; Quick and Henderson, 1974; Forrester et al., 1977; Kreuder et al., 2002; Landsberg, 2002). Despite the overwhelming evidence for the co-occurrence of red tides with wide-scale animal die-offs, definitive proof that brevetoxins can kill a wide diversity of aquatic organisms as well as terrestrial species connected via the food chain has been hard to obtain.

Brevetoxins were proposed to be a primary causative agent in an unprecedented die-off of more than 740 bottlenose dolphins from June 1987 to February 1988 throughout the southeastern USA (Geraci, 1989). The event coincided in part with an ongoing red tide bloom that was transported from Florida to North Carolina during 1987, a rare occurrence (Tester et al., 1991). The evidence for brevetoxin involvement remained equivocal because the analytical methods available at the time were inadequate to confirm its identity (Van Dolah et al., 2003). Other etiologies, particularly for a viral pathogenesis, were considered as primary contributing factors (Lipscomb et al., 1994).

We have yet to determine via controlled experiments the level of brevetoxins that would be lethal to specific species. The ability to determine toxin concentrations in tissues, fluids, and stomach contents in carcasses found during red tide-mass mortality events has improved considerably because of rapid response, refinement of field protocols, and accurate analysis using reliable technologies. Presumptively acute lethal brevetoxin concentrations can be evaluated against tissue concentrations from "control" animals that died from other causes in endemic red tide areas.

During the past few years, several mortality events involving higher vertebrate have provided more epizootiological field data. Extensive efforts have been undertaken to obtain fresh tissues for toxin analyses, to make accurate assessments of the distribution of carcasses, to compare the spatial and temporal distributions of *K. brevis* cell concentrations with brevetoxin levels in water and tissues, to obtain relevant environmental data, and to identify toxin vectors in the food chain.

In Florida, wide-scale mass mortalities caused by *K. brevis* blooms that were associated with brevetoxicosis occurred for manatees in 1996, 2002, 2003, and 2005 (Bossart et al., 1998, 2002; Landsberg and Steidinger, 1998; Flewelling et al., 2005; Florida Fish and Wildlife Conservation Commission [FWC], unpublished) and for bottlenose dolphins in 1999–2000, 2004, and 2005–2006 (Mase, Leighfield, and Baran, National Oceanic and Atmospheric Administration [NOAA], personal communications; Flewelling et al., 2005) (Table 1).

In some cases, the manatee die-offs occurred concurrently with a *K. brevis* bloom, but in others, lag effects resulted in a delayed toxin exposure (see below). In years when the manatee mortality coincided with a red tide, it was postulated that animals were exposed to brevetoxins through inhalation as well as by ingestion (Landsberg and Steidinger, 1998), although the effects induced by each of these routes of exposure are not easily separated. In 1996, the presence of very low concentrations of brevetoxins in the nasal and lung tissue demonstrated that aerosol could cause consistent inflammatory lesions of the upper mammalian respiratory tract (Bossart et al., 1998). Thus far, there is no indication that inhalation of aerosolized brevetoxins alone can produce lethal doses, but this route of exposure can potentially debilitate manatees, cause pathologies, and lead to fatal secondary effects.

During August 1999–February 2000, more than 120 bottlenose dolphins stranded along the Florida Panhandle, coincident with a

Table 1
Summary of major mass mortality events of marine mammals associated with red tides.

Species	Year	Period	Number	Location	Reference
Tursiops truncatus	1946–1947	Nov–Aug	<5	SWFL	Gunter et al. (1948)
Trichechus m. latirostris	1963	March–April	7	SWFL	Layne (1965)
Trichechus m. latirostris	1982	Feb–April	39	SWFL	O'Shea et al. (1991)
Tursiops truncatus	1987–1988	June–Feb	>740*	Eastern U.S.	Geraci (1989)
Trichechus m. latirostris	1996	March–May	149	SWFL	Landsberg and Steidinger (1998); FWC, unpublished
Tursiops truncatus	1999–2000	Aug–Feb	>120	NWFL	NOAA, unpublished
Trichechus m. latirostris	2002	March–April	30	SWFL	Flewelling et al. (2005); FWC, unpublished
Trichechus m. latirostris	2003	March–April	69	SWFL	FWC, unpublished
Tursiops truncatus	2004	March–April	107	NWFL	NOAA, unpublished
Trichechus m. latirostris	2005	March-April	45	SWFL	FWC, unpublished
Tursiops truncatus	2005–2006	July–June	136**	SWFL	NOAA, unpublished
Tursiops truncatus	2005–2006	Sept–April	93**	NWFL	NOAA, unpublished

* Brevetoxin suspected but not definitively proven (Geraci, 1989).
** Preliminary data from NOAA.