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## RECRUITMENT OF LARVAL FISHES INTO A NORTH CAROLINA ESTUARY DURING A BLOOM OF THE RED TIDE DINOFLAGELLATE, *GYMNODINIUM BREVE*

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### ABSTRACT

An unprecedented bloom of the toxic dinoflagellate *Gymnodinium breve* in coastal waters of North Carolina occurred during year three (fall–winter 1987–1988) of an eight-year larval fish study. This event was the basis for examining the possible effects of red tide on the estuarine recruitment of nine species of larval fishes. Densities of larvae for 1987–1988 were compared to their corresponding average densities for the two seasons prior to and five seasons after the red tide. Larval fish recruitment for most species over the entire 1987–1988 season was not unusually low, although two of nine species did exhibit their 8-yr minima during this time. Densities for 1987–1988 were compared with the densities averaged (by week) over the other 7 yrs and revealed three general patterns of response. Two species, *Paralichthys albigutta* (gulf flounder) and *Citharichthys spilopterus* (bay whiff) had consistently low densities throughout their normal period of recruitment, suggesting that their estuarine recruitment may have been impacted by the effects of *G. breve* even after the bloom ended. In contrast, *Micropogonias undulatus* (Atlantic croaker) and *Lagodon rhomboides* (pinfish) densities were generally normal, or above normal, both during the bloom and for the remainder of the larval recruitment season. Five other species (*Brevoortia tyrannus*, Atlantic menhaden; *Paralichthys lethostigma*, southern flounder; *Leiostomus xanthurus*, spot; *Mugil cephalus*, striped mullet; *Myrophis punctatus*, speckled worm eel) had low densities during the bloom, but increased markedly later in the season. This pattern suggested these five species suffered immediate effects when the red tide was extant, but had high recruitment success later in the season. In the first post-red tide year, six of the nine species had their highest mean catches over the first 14 wks of all 8 yrs and suggested a possible post-red tide beneficial effect on larval fish estuarine recruitment.

In the fall of 1987 the red tide organism, *Gymnodinium breve*, bloomed in the coastal waters of North Carolina. This was the first bloom of *G. breve* ever recorded north of Florida and resulted in 48 documented cases of neurotoxic shellfish poisoning, closure of waters to shellfish harvesting and economic losses exceeding \$24 million (Tester and Fowler, 1990). Unlike the blooms in Gulf of Mexico waters, no extensive fish kills were reported for the November 1987 to early January 1988 period when *G. breve* cell counts were highest in coastal waters of North Carolina. Perhaps this was because by November–December juveniles and adults of many of the coastal fishes had already completed their migration out of nearshore waters following the normal seasonal decline in water temperature. While there is little evidence to suggest that adult fish populations were adversely impacted by the red tide, the fall–winter season is the spawning time for a number of coastal fishes. Estuarine-dependent larvae of fall–winter spawning fishes on the continental shelf were likely exposed to this bloom as they moved into nearshore waters toward their nursery grounds (Warlen and Burke, 1990).

Although there is laboratory evidence that larval fishes are vulnerable to toxins of dinoflagellates (Ray and Wilson, 1957; Mills and Klein-MacPhee, 1979; Gosselin et al., 1989; Robineau et al., 1991a; 1991b; 1993), only Riley et al. (1989) have documented the

impact of *G. breve* red tides on fish larvae in the wild. Mass mortalities of marine fish larvae are difficult to observe, since dead or dying larvae may be consumed quickly by predators, scavengers, or bacteria. The 1987–1988 *G. breve* red tide off North Carolina provided an unprecedented opportunity to examine the possible effects of this toxic dinoflagellate on larval fish abundance in the field. This red tide bloom occurred 2 yrs after the start of an 8-yr sampling program to measure the densities of larval fishes recruited to the estuary inside Beaufort Inlet, North Carolina (34°43'N, 76°41'W).

In this paper we report on the temporal and spatial co-occurrence of the larvae of estuarine-dependent fishes and *G. breve* cells during a red tide event. The densities of larvae of nine species of offshore spawning fishes that recruited through Beaufort Inlet during the 1987–1988 red tide period were compared with their corresponding densities for the 2-yr pre- and 5-yr post-red tide, to assess the potential impacts of the red tide on estuarine recruitment.

#### MATERIALS AND METHODS

Larvae of fall-winter spawning marine fishes were collected at a station adjacent to Pivers Island (Fig. 1) as they recruited (immigrated) to the Newport River estuary from the ocean. Nighttime sampling was conducted weekly at mid-flood tide during the period from mid-November through April for eight consecutive seasons beginning with 1985–1986. Samples were collected with a 1 × 2 m neuston net with 947- $\mu\text{m}$  mesh fished from a bridge platform, except in 1985–1986 when a 60-cm bongo frame with paired 505- $\mu\text{m}$  mesh nets was fished from a boat. Simultaneous collections made with these bongo and neuston nets showed no significant difference in the density of Atlantic menhaden caught between gear (Warlen, 1994). From this we assumed that there were no significant differences in the catchability of the nets for larvae of the other fish species. Details of the sampling protocol are given in Warlen and Burke (1990) and Warlen (1994). Densities of larvae of each of the nine most abundant immigrating species (*Leiostomus xanthurus*, *Micropogonias undulatus*, *Brevoortia tyrannus*, *Lagodon rhomboides*, *Myrophis punctatus*, *Paralichthys lethostigma*, *P. albigutta*, *Citharichthys spilopterus*, *Mugil cephalus*) were expressed as the number 100 m<sup>-3</sup> water fished. Another bothid, *Paralichthys dentatus*, was not included in this study, since its larvae are not usually present in inlet collections until after mid-January. To facilitate comparisons between red tide and non-red tide years, data were grouped into estuarine recruitment “seasons” that ran from November of one year through April of the next.

The *G. breve* densities are subsets of the counts made in coastal waters between 33°52'N and 35°16'N (Tester et al., 1991). Cell counts from Beaufort Inlet were used for comparison with the larval fish data collected at Pivers Island because of the proximity of these sampling sites (~3 km apart). Data from inlets adjacent to Beaufort Inlet (Barden Inlet and Bogue Inlet) are included to show similarities in the spatial distribution of red tide cells along the coast (Fig. 1). Surface water samples (500 ml) were collected two to four times each week from 2 November 1987 through 22 February 1988 when concentrations declined to near zero. Samples were preserved in the field with Utermöhl's solution (5ml L<sup>-1</sup>; Guillard, 1973), concentrated in an Utermöhl settling chamber, and *G. breve* cells were counted using an inverted microscope (see Lund et al., 1958). Mean weekly *G. breve* densities were calculated for comparison with weekly larval fish densities.

#### RESULTS

There was spatial and temporal coincidence in the recruitment of larval fishes and the red tide bloom in the Beaufort Inlet area during the fall-winter 1987–1988, although the red tide preceded the time when maximum densities of the nine species were normally observed at Pivers Island. *G. breve* concentrations were high and persistent in coastal

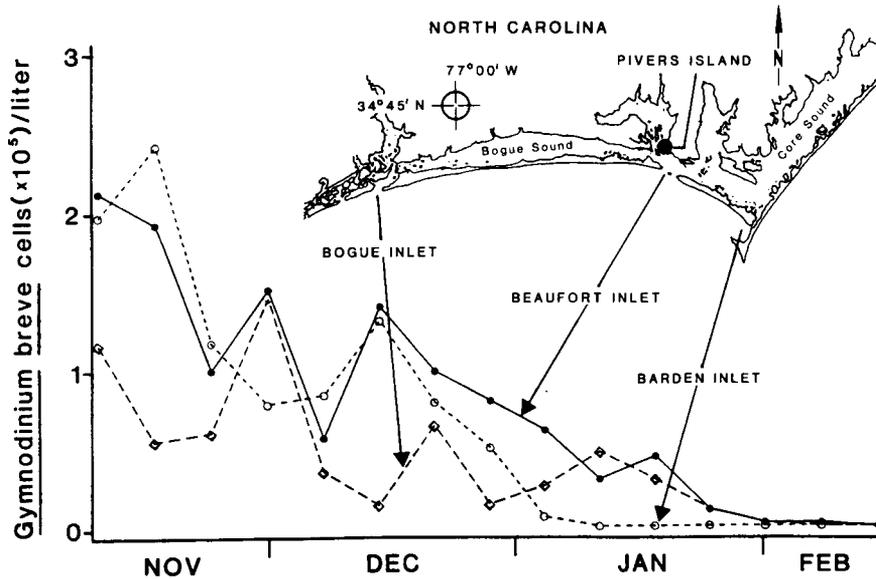


Figure 1. Weekly mean cell counts of *Gymnodinium breve* at Bogue Inlet, Beaufort Inlet, and Barden Inlet in North Carolina for the period 7 November 1987 to 15 February 1988.

waters offshore of Beaufort Inlet (Tester et al., 1989). Early in the bloom, concentrated patches with as many as  $2 \times 10^7$  *G. breve* cells  $L^{-1}$  were observed just outside Beaufort Inlet while cell counts at Beaufort Inlet and Barden Inlet ( $\sim 16$  km apart) were generally  $>5 \times 10^4 L^{-1}$  from November through the end of December 1987 (Fig. 1). At Bogue Inlet ( $\sim 32$  km west of Beaufort Inlet) cell counts were generally lower than at the other two inlets in the early weeks of the bloom, but increased in January to numbers similar to those at Beaufort Inlet before declining (Fig. 1). By 11 February 1988, *G. breve* densities had declined to undetectable levels at all three inlets. The red tide also invaded estuaries and was found in high concentrations ( $\approx 4 \times 10^5$  cells  $L^{-1}$ ) at the Atlantic Beach bridge (Bogue Sound) and at Marshallberg (Core Sound) which are about 8 km to the west and 10 km to the east, respectively, inside Beaufort Inlet.

The question of whether *G. breve* adversely impacted the nine-species fish community as a whole was addressed first by comparing the catch densities during the 14 wks of the 1987–1988 season when *G. breve* was present, with the catch densities during the 14-week intervals for the two pre- and five post-red tide seasons. Only two of the nine species (*P. albigutta*, *M. cephalus*) exhibited their minimum densities during the season of the red tide (Fig. 2). The probability of this result under the null hypothesis (i.e., that season-to-season variation for the nine species was random) is 0.22 (binomial theorem). While the data do not suggest a catastrophic reduction in the larval fish community as a whole during the red tide, there is evidence of less severe effects that warrant closer scrutiny. The possibility of species-specific responses to the red tide was examined by regarding the mean weekly larval fish densities over the seven non-red tide seasons as being representative of the normal seasonal recruitment for a given species and was compared with densities observed during the 1987–1988 red tide season. The graphs for the individual species revealed three distinct patterns of response.

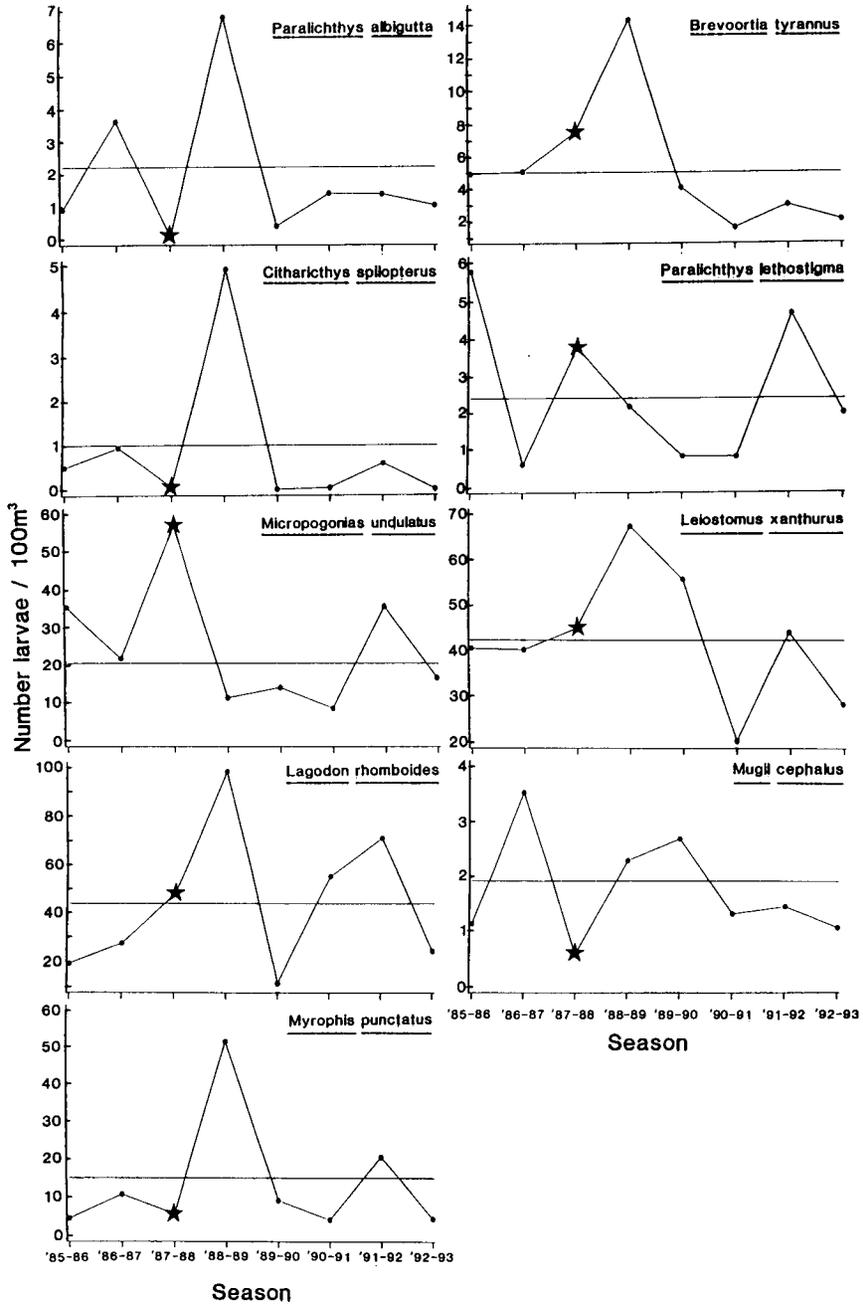


Figure 2. Mean density of larvae of nine fish species for the period from mid-November to mid-February of the red tide season (1987-1988) —denoted by a star— and for the seven non-red tide years. The horizontal dashed line represents the average for the seven non-red tide years. Note changes in the density scale from species to species.

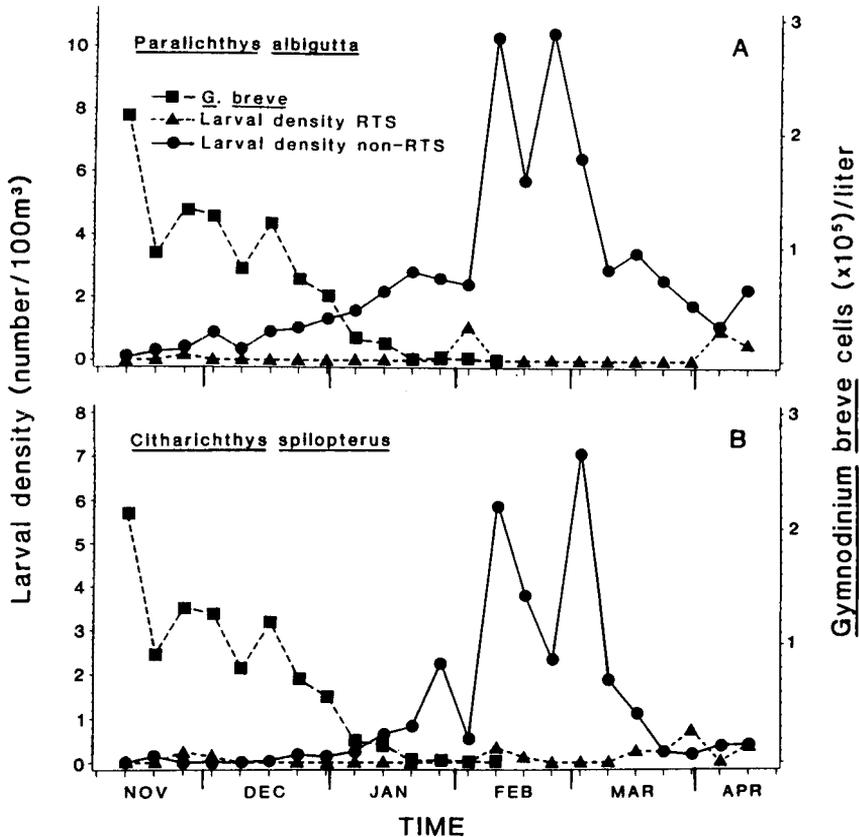


Figure 3. Weekly *Gymnodinium breve* cell counts during the 1987–1988 red tide event and the weekly mean density for larval *Paralichthys albigutta* (a) and *Citharichthys spilopterus* (b) during the red tide season (RTS) and the average of the weekly means for the seven non-red tide seasons (non-RTS).

In the first pattern, two species (*P. albigutta* and *C. spilopterus*) exhibited low densities throughout the red tide season (Fig. 3). In fact, the former species was collected during only 4 wks of the 23-wk sampling period whereas in the non-red tide seasons of other years it had always been collected during at least 17 of the 23 wks. This kind of evidence for the latter species was less convincing; it was collected during only 8 of the 23 wks in the red tide season, and 8 wks in the 1990–1991 season and in only 4 wks during the 1989–1990 season.

In contrast, two other species, *M. undulatus* and *L. rhomboides*, are usually found at normally high densities during that part of the season when *G. breve* was abundant (Fig. 4). In the early part of the 1987–1988 season their densities varied above and below the trend for the other seven seasons and they remained relatively high throughout the remainder of the season. The density patterns of these two species for the 1987–1988 season thus provided no evidence of adverse impact by the red tide. In fact *M. undulatus* densities that year were the highest recorded during the 8-yr study.

The remaining five species showed lower than normal densities for the first 11 to 17 wks of the red tide season, but later in the recruitment season exhibited marked increases

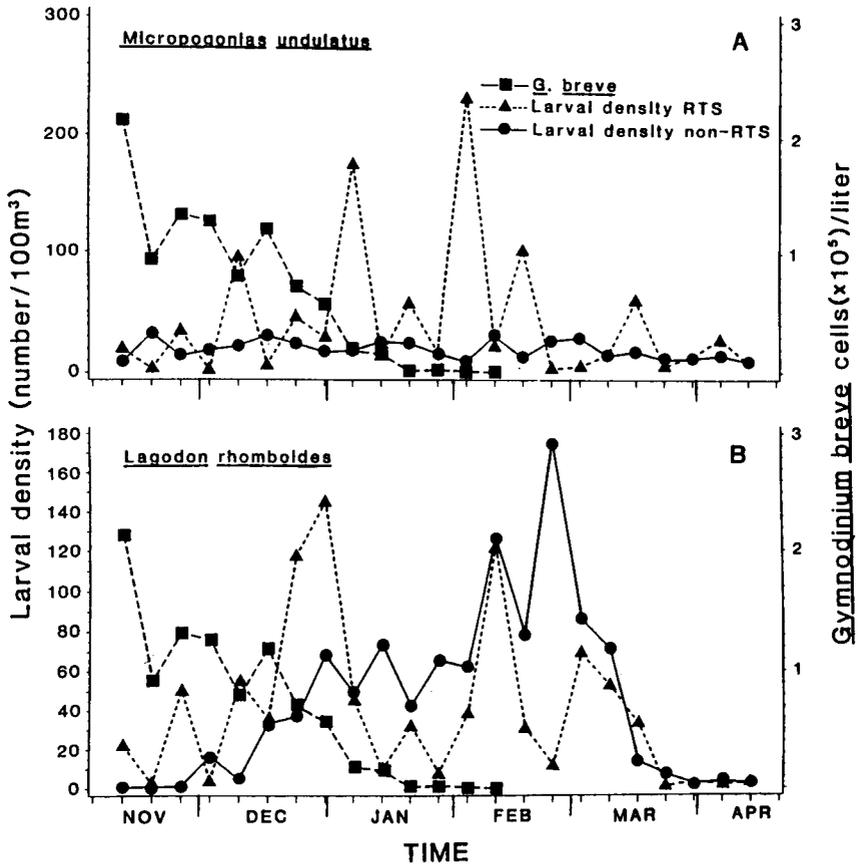


Figure 4. Weekly *Gymnodinium breve* cell counts during the 1987–1988 red tide event and the weekly mean density for larval *Micropogonias undulatus* (a) and *Lagodon rhomboides* (b) during the red tide season (RTS) and the average of the weekly means for the seven non-red tide seasons (non-RTS).

of 1–3 wks in duration (Fig. 5). This was particularly striking for *B. tyrannus*, *L. xanthurus* and *M. cephalus*. The pattern for *P. lethostigma* in 1987–1988 was generally consistent in timing and magnitude with its average pattern over the other seven seasons, but nonetheless exhibited consistently low densities during the first 10 wks when *G. breve* cell concentrations were  $>1 \times 10^4$  cells  $L^{-1}$ . Densities of *M. punctatus* leptocephali generally remained below the norm throughout the season, although they too exhibited a spike of higher density in mid-February.

There was also a substantial above average weekly mean recruitment of larval fishes in the first 14 wks of the year following the red tide (1988–1989). Six of the nine species had their highest mean catches over all 8 yrs (Fig. 2) and included three (*B. tyrannus*, *L. xanthurus*, *M. punctatus*) of the five species of the group with marked late red tide season recruitment, both species that had low densities throughout the entire red tide season (*P. albigutta*, *C. spilopterus*) and one species (*L. rhomboides*) with about overall average recruitment during the entire red tide season. The probability of this result, under the null

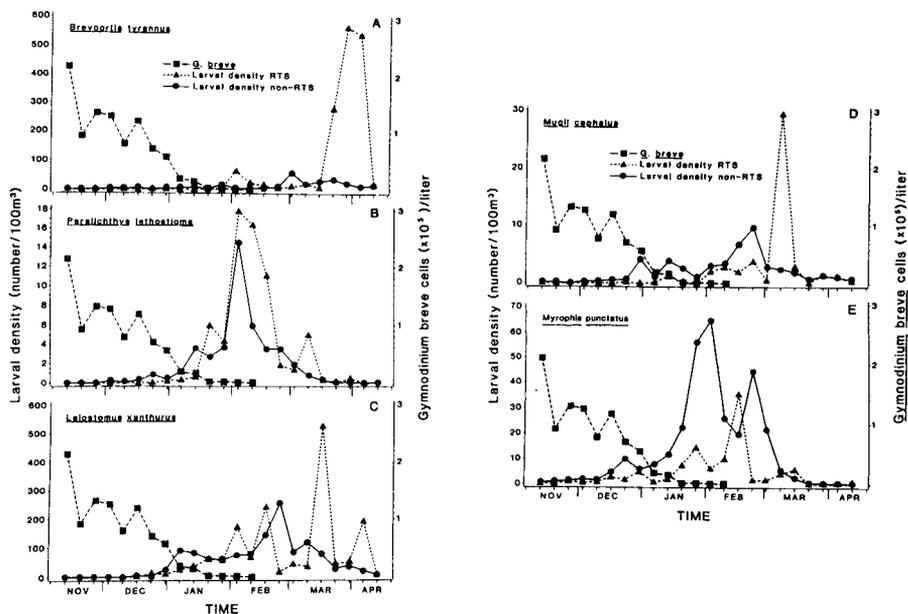


Figure 5. Weekly *Gymnodinium breve* cell counts during the 1987–1988 red tide event and the weekly mean density for larval *Brevoortia tyrannus* (a), *Paralichthys lethostigma* (b), *Leiostomus xanthurus* (c), *Mugil cephalus* (d) and *Myrophis punctatus* (e) during the red tide season (RTS) and the average of the weekly means for the seven non-red tide seasons (non-RTS).

hypothesis that season-to-season variation for the nine species was random, was highly significant ( $P = 0.0002$ , binomial theorem).

## DISCUSSION

Fish kills associated with discolored water due to red tides have been known since biblical times (Exodus 7:20–21). This phenomenon occurs in coastal seas worldwide and, in some cases, fish kills can be quite extensive with mortality of millions of individuals from a number of families (Harper and Guillen, 1989). Kills of large numbers of fishes have been observed in the Gulf of Mexico since 1844 (Taylor, 1919), where they occur sporadically along the southwest coast of Florida and off the Texas coast (Gunter et al., 1948; Rounsefell and Nelson, 1966; Steidinger and Ingle 1972) extending well southward into Mexican waters (Wilson and Ray, 1956). Although *G. breve* was not identified as the causative agent of red tides in the Gulf of Mexico until 1948 (Davis, 1948), Rounsefell and Nelson (1966) suggest that many of the earlier red tides were due to blooms of this dinoflagellate.

*Gymnodinium breve* red tides are usually confined to the Gulf of Mexico, but occasionally blooms originating off the southwest coast of Florida are transported around the Florida peninsula by the Florida Current-Gulf Stream system (Murphy et al., 1975; Steidinger et al. 1995) and result in short-lived blooms off the Florida east coast (Roberts, 1979; Steidinger and Haddad, 1981). In the fall of 1987, this system transported *G. breve* from Florida's west coast to coastal waters off North Carolina (Tester et al., 1991). This

first bloom of *G. breve* north of Florida, a range of extension of >800 km, persisted for 3.5 mo. The Florida Current-Gulf Stream system was implicated in the transport of *G. breve* cells from a later summer bloom off the southwest coast of Florida. About 30 d after the Florida bloom, satellite images of sea-surface temperatures substantiated the shoreward movement of a filament of warm Gulf Stream water onto the narrow continental shelf off Cape Lookout, North Carolina (Tester et al., 1991). This filament remained intact and in nearshore waters for >19 d, an unusually long time. In a detailed study of sea surface temperature in Onslow Bay during the 1987–1988 season Franklin (1996) reported a large magnitude and long duration shoreward pulse of warm water in December 1987, the second warmest year (global surface air temperature) in the history of instrument records. There was an unusual jump in annual mean temperature of 0.4°C and the sustained level of high temperature at low latitudes exceeded even those of 1983, the strongest El Niño of the century.

The coastal weather patterns were also unusual during the fall of 1987. It was drier than normal, wind speeds were lower, and there was a strong sea surface temperature anomaly during October and November off North Carolina that may have contributed to the stability of the Gulf Stream filament on the middle to inner shelf region (Tester, 1996). The same meteorological events were associated with a toxic phytoplankton bloom near Prince Edward Island during the fall of 1987 (Smith, 1993).

Since red tides in the Gulf of Mexico are known to produce mass mortality of adult fishes, we expected that larval recruitment may also have been greatly diminished. However, a comparison of average densities of the nine species of larval fishes for the 14-wk *G. breve* period with the corresponding statistics for other years produced no compelling evidence that the toxic dinoflagellate had a devastating effect on larval fish densities. It should be emphasized that these nine species of fishes have an extended recruitment period (4–5 mo; Warlen and Burke, 1990) and normally exhibit their highest seasonal densities after November–December when *G. breve* concentrations were the highest in Beaufort Inlet. Thus, the potential exposure of the larval fishes to the highest concentrations of dinoflagellate (nearshore) may have been somewhat restricted, making the circumstances for detecting an effect less than optimal. Inverse relationships between fish densities and concentrations of *G. breve* were unreliable indicators of impact because they failed to account for the expected normal seasonal increases in fish densities during the weeks of *G. breve* decline (Figs. 3–5). Consequently, it was necessary to assess the potential impact on recruitment by examining each species individually, giving attention to its normal pattern of recruitment.

Comparison of the temporal patterns of recruitment of the fishes in the 1987–1988 season with their corresponding patterns averaged over the seven other recruitment seasons indicated that there were three patterns of response. The first of these was simply very low densities over the entire season. This pattern, which was exhibited by *P. albigutta* and *C. spilopterus*, provided the strongest evidence that the red tide may have adversely affected the larvae of some species. The fact that densities remained low throughout the season suggested that the entire populations of recruitable larvae of these two species may have been impacted. The evidence that *P. albigutta* was impacted was further strengthened by the fact that this species was collected during only four of 23 wks of the red tide year, whereas in each of the other 7 yrs this species was collected during 14 to 23 wks. *C. spilopterus* also showed a pattern of densities in the red tide year that were well below

average. It is not certain that this was due solely to the red tide since densities of this species were also very low in several other years.

The second pattern was toward the opposite extreme and was characterized by relatively high densities both during the red tide and afterwards. There is no evidence that *M. undulatus* and *L. rhomboides*, which exhibited this pattern, were negatively affected by the red tide.

The third pattern was most common and subtle in providing evidence of an impact of red tide. This pattern was marked by generally lower than normal densities during the red tide, followed by unusually high peaks of 1–3 wks duration later in the season. The five species, that demonstrated this pattern, may have experienced early season mortality due to red tide exposure followed by increased recruitment later in the season. The increase in late season recruitment may have been due to either delayed spawning or delayed estuarine entry. *Brevoortia tyrannus* (Warlen, 1994) and *L. xanthurus* (Flores-Coto and Warlen, 1993) are known to have spawned off the coast of North Carolina in November–December 1987 during the red tide event. At least for one species (*B. tyrannus*), the 1987–1988 spawning season was no later than in other years; however, the entry of a large number of *B. tyrannus* larvae into the estuary through Beaufort Inlet was delayed until very late in the season when relatively old, large larvae were recruited (Warlen, 1994). *Brevoortia tyrannus* larvae were, on average, about 30 d older than in non-red tide years. This is a pivotal observation because such older, larger larvae have not been recorded in any other year (Warlen, 1994; unpubl. data, S. M. Warlen, National Marine Fisheries Service, Beaufort, NC). The increased time on the continental shelf before estuarine recruitment suggested several things: (1) spawning occurred further from Beaufort Inlet and probably outside the band of red tide patches, (2) the local conditions were not as favorable in 1987–1988 for rapid across-continental shelf transport of larval fish as in other years, and/or (3) avoidance behavior or disinclination of the larger larvae to swim through areas (especially close to shore) with high concentrations of *G. breve*. The same scenario may have occurred for *P. lethostigma* and *M. cephalus*, both of which showed relatively high late-season recruitment to the estuary. The recruitment density pattern for *M. punctatus* leptocephali was the least typical of this group. Its density compared to the mean of the non-red tide years was low and on only two occasions (mid-February and mid-March), did it exceed the mean for the non-red tide years.

The factors that may have been responsible for the late season enhanced larval fish recruitment in the red tide year, may have been extant in the following year. In fact, we observed record high larval fish recruitment densities for six of the nine species in the early part of the year following the red tide in North Carolina. Reduced predation and interspecific competition as well as higher food availability could have increased survival of larval fishes on the continental shelf prior to their estuarine recruitment. Steidinger (1983) suggests these factors may have contributed to the post-red tide increase in yields of shrimp and rock crabs reported by Florida fishermen. It has also been suggested that *G. breve* may play a dual role in the west Florida shelf ecosystem by acting as a regulator of the shelf food web and a significant source of photosynthetically fixed carbon (Vargo et al., 1987).

Specific sensitivity and ontogenetic trends in vulnerability and exposure are consistent with some of our observations. It is unlikely that larvae of the nine species in this study experienced mortality by directly ingesting *G. breve*. It is questionable whether four of the species feed on dinoflagellates in the coastal ocean. In the Gulf of Mexico *M. undulatus*

does not feed on dinoflagellates, only *L. xanthurus* of  $\leq 5$  mm and *B. patronus* (whose diet may be similar to *B. tyrannus*) of  $< 10$  mm feeds on them (Govoni et al., 1983). In our samples, *B. tyrannus* and *L. xanthurus* were always larger than the reported sizes at which they might be expected to ingest dinoflagellates. The diet of *M. punctatus* is unknown but observations of other anguilloid larvae suggest dinoflagellates are not part of their diet (Mochioka and Iwamizu, 1996). While direct exposure may not equate to direct intake of *G. breve* cells, concentrations in excess of  $4 \times 10^4$  cells  $L^{-1}$  caused abnormal swimming behavior followed by paralysis then death of newly-hatched red drum larvae (*Sciaenops ocellatus*; Riley et al., 1989). Ray and Wilson (1957) found exposure of *G. breve* ( $0.6$  to  $2.1 \times 10^6$  cells  $L^{-1}$ ) was fatal to all five test species but there was a species-specific sensitivity and rough silversides (*Membras vagrans*) and striped mullet (*Mugil cephalus*) were the most quickly affected. Not all fish thus exposed to *G. breve* and then transferred to sea water survived in their study. Recovery depended on *G. breve* cell numbers and length of exposure. "Many mullet were reported killed" was a frequent comment made by early observers of red tides off the southwest Florida coast (Gunter et al., 1948). Correspondingly, there were very low densities of striped mullet larvae during the 1987–1988 red tide season. Ray and Wilson (1957) made another important finding, that the toxicity of *G. breve* cultures did not depend on the presence of intact cells. Because *G. breve* is a unarmored dinoflagellate, cells may be lysed by wave action and thereby release brevetoxins into the water. Behavioral characteristics of both *G. breve* and fish larvae may influence the degree of exposure and consequently, their recruitment. Like most dinoflagellates, *G. breve* are motile, positively phototactic and/or negatively geotactic, and they can concentrate near the surface during the day (Steidinger and Ingle, 1972; Hiel 1986). Cell counts offshore on 9 November 1987 demonstrate this:  $8.4 \times 10^6$  cells  $L^{-1}$  were recorded at the surface, whereas  $5.7 \times 10^6$ ,  $1.3 \times 10^6$  and  $0.7 \times 10^6$  cells  $L^{-1}$  were found at 1, 2 and 4 m depths, respectively. Even at 4 m the cell concentration exceeded the lethal exposure ( $\sim 250 \times 10^3$  cells  $L^{-1}$  for adults) by nearly three-fold. Consequently, physical factors such as insolation, wind currents and tides affect the concentration and distribution of *G. breve* cells (Tester et al., 1989). However, in relatively shallow, well-mixed areas *G. breve* are more evenly distributed with depth (Geesey and Tester, 1993). Diel vertical migration of larval fishes may increase their exposure to higher *G. breve* concentrations. *Brevoortia tyrannus* did show reduced densities during the red tide period compared to similar periods in non-red tide years. For this species there is evidence that a diel migration to the surface is required to fill its swimbladder each night (Hoss et al., 1989). An active response to light may also induce vertical migrations where some larval fishes move deeper in the water column during the day and closer to the surface during the night. Weinstein et al. (1980) suggest that *L. xanthurus*, *M. undulatus* and *Paralichthys* spp. exhibit distinct behavioral patterns to photoperiod and tide in the lower estuary. They found those species closer to the bottom during day, but at night *L. xanthurus* and *Paralichthys* spp. were nearer the surface, while *M. undulatus* was nearer the bottom. A tendency of *M. undulatus* to spend more time closer to the bottom could possibly reduce its exposure to *G. breve* and may explain why this species exhibited above normal densities during the period when *G. breve* was present in high concentrations. Larval *L. rhomboides* are found most often near the surface (Hettler and Barker, 1993), however, there appears to be no red tide effect on its density.

No severe impact on the larval fish community as a whole was evident during the red tide year. While this is somewhat surprising, there were species-specific differences ob-

served among the larval fishes in an apparent response to the presence of *G. breve*. This may have been due to direct effects of red tide on the larvae modulated by differences in their sensitivity or exposure to *G. breve* or other second order considerations related to the timing and place of spawning or changes in food availability or predator abundance. Some species appeared to be unaffected; others may have benefitted (later in the red tide year and even into the next year) from conditions that produced the red tide. Yet, two species experienced their lowest recruitment during the red tide bloom and two of those appear to have been so adversely impacted that they did not recover during the 1987–1988 season.

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