Radiocarbon from nuclear testing applied to age validation of black drum, *Pogonias cromis*

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Abstract.—Radiocarbon (^{14}C) in the world's oceans increased sharply between 1950 and 1970 as a result of the atmospheric testing of nuclear weapons. Through comparison with the ^{14}C time series reconstructed from atmospheric measurements and marine carbonates, Kalish, in 1993, used the ^{14}C concentration measured in fish otolith cores as a means of confirming the annulus-based age estimates for some South Pacific fish species. Here we report the pre- and postbomb ^{14}C chronology of North Atlantic adult black drum (*Pogonias cromis*), assumed to be between 15 and 42 yr of age on the basis of otolith annulus counts. According to accelerator mass spectrometry (AMS) assays, ^{14}C in otolith cores increased sharply between 1958 and 1964, with a timing and magnitude which was very similar to that of the atmospheric bomb ^{14}C signal. The correspondence between the two ^{14}C chronologies indicates that the annulus-based age assignments were accurate on average to within 1–3 yr. Differences between the black drum $\Delta^{14}C$ chronology and that of other marine carbonates in the North Atlantic are explained by the estuarine habitat of young-of-the-year black drum and by the fact that estuarine $\Delta^{14}C$ values more closely reflect atmospheric values than surface ocean values. At present, there is no other age-validation technique that can confirm the absolute age of long-lived fish species with comparable levels of accuracy.

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Despite the international acceptance of otolith annuli as the best means for estimating the age of most fish species, the correct interpretation of annuli is far from easy and can result in serious and systematic ageing errors (Beamish and McFarlane, 1995). Indeed, aside from the use of tagged, hatchery-reared fish released into the wild, confirmation of the accuracy of a method of annulus interpretation for marine fish species is often problematic. Mark-recapture of chemically tagged individuals has generally been considered to be the most accurate means of confirming the frequency of formation of presumed annuli, owing to a correspondence between time at liberty and the number of annuli distal to the chemical check (Foreman, 1996). Although the approach is sound, extremely low recapture rates for fish at liberty more than 2–3 years can make it difficult to acquire sufficient samples for an adequate test. Moreover, the technique validates the time elapsed since tagging, not the absolute age of the fish. Alternatively, radiochemical dating based on ^{210}Pb:^{226}Ra or ^{228}Th:^{228}Ra ratios can be used to differentiate between very different age interpretations (Bennett et al., 1982; Campana et al., 1990), but these assays are too imprecise for detailed or individual age confirmations. The most widely used approach, that of the seasonal progression of marginal increments (Beckman and Wilson, 1995) is well suited only to fast-growing fish and suffers from the lack of an objective means of evaluation. Thus there is a well-defined gap in our ability to confirm the age interpretations of the majority of marine fish species, particularly those that are long-lived. However, the recent finding that nuclear testing left a dated mark in the otolith (Kalish, 1993) provides a significant breakthrough in our ability to determine accurate, absolute ages for individual long-lived fish.

Kalish (1993) was the first to describe the use of bomb radiocarbon (^{14}C or carbon-14) as a dated marker in fish otoliths and its value for confirming age interpretations. His findings were based on earlier work that had documented a 100% increase in atmospheric radiocarbon as a result of the widespread atmospheric testing of atomic bombs in the 1950's and 1960's (Nydal and Lovseth, 1983). This product of nuclear testing was subsequently incorporated into the world's oceans in a manner which has been well described at large spatial scales (Broecker et al., 1985; Duffy et al., 1995). Through analysis of annular growth rings in coral, other workers demonstrated that bomb radiocarbon was incorporated into the accreting coralline structure in concentrations proportional to those present in the water column (Druffel and Linick, 1978; Nozaki et al., 1978). Thus the time series of bomb radiocarbon in the coral was shown to reflect that present in the surface marine environment, which increased by about 20% between 1950 and 1970. Using accelerator mass spectrometry (AMS) as a sensitive and accurate assay tool, Kalish (1993) was able to demonstrate that the otoliths of a New Zealand fish species also incorporated ^{14}C and that the time series of radiocarbon reconstructed from the presumed otolith annuli was similar to that present in nearby corals. Thus he was able to infer that the otolith annuli had been interpreted and aged correctly because systematic under- or over-ageing would have resulted in a phase shift between the otolith ^{14}C and the coral ^{14}C time series.

Subsequent work by both Kalish (1995a, 1995b; Kalish et al., 1996) and Campana (1997) has confirmed the value of the bomb radiocarbon technique for solving problems of age validation in a variety of fish species. Furthermore, recent work by Campana (1997) has confirmed that the assumption of synchronicity between otolith and marine carbonate ^{14}C chronologies is justified, because the period of rapid increase in the ^{14}C chronology recorded in age-1 haddock (*Melanogrammus aeglefinus*) otoliths was synchronous with that reported for other taxa in the North Atlantic, whether based on corals (Druffel, 1989) or bivalves (Weidman and Jones, 1993). Such large-scale synchronicity implies that the ^{14}C time series reconstructed from the otolith cores of old fish can be compared to one of the other North Atlantic time series; errors in annulus-based age determinations would manifest themselves as noncoherent time series. The only constraint to such an age determination procedure is the requirement for otoliths of fish spawned during and adjacent to the 1958–65 period, so as to take advantage of the unique ^{14}C values during that period.

The black drum, *Pogonias cromis*, with its putative lifespan of some 60 yr and estuarine dependence during early life (Jones et al., 1997), is an ideal candidate for age validation with ^{14}C. This large sciaenid is distributed along the east coast of the U.S. (Jones et al., 1997) and throughout the Gulf of Mexico, where it is fished commercially. However its relatively low abundance results in low recapture rates after tagging. Accordingly, attempts to validate annulus formation with mark-recapture techniques in the older age groups have been unsuccessful. Yet such validation is critical to the proper management of this fish in the Chesapeake Bay region, where the greatest numbers of presumably old fish are harvested.

Here we report the first pre- and post[atom]bomb ^{14}C otolith chronology for black drum, and the first such chronology for any long-lived fish species in the North Atlantic. We use this ^{14}C chronology to determine the absolute ages of individual fish, and through comparison with otolith annulus counts from the same fish, we then confirm the accuracy of otolith annuli as indicators of absolute age in this species.

Materials and methods

Adult black drum (n=31) with a mean ±SE total length of 111 ±1 cm (range=95–119 cm) were collected with anchored and drifted gill nets during research surveys of the eastern shore of Chesapeake Bay in Apr–May 1990. To estimate age based on annuli, one randomly selected sagittal otolith of each otolith pair was sectioned transversely through the core, and the annuli were counted under reflected light. The radius of the presumed first annulus was confirmed through measurements of the dimensions of intact sagittae collected from young-of-the-year black drum, which indicated that the first annulus in a transverse section should be approximately 7 mm wide and 2 mm thick. After ageing with reflected light microscopy, the remaining halves of each otolith were stored dry in paper envelopes in preparation for ^{14}C assay.

To extract a sample of the first year's growth from each otolith, a transverse section 1-mm thick was made with an Isomet saw immediately adjacent to that made for ageing. Although this second section was adjacent to the otolith core, the length of the age-1 otolith (~8 mm) indicates that most of the first year's growth was still present in the section. After recording a digital image of the annuli, a Dremel tool was used to remove all otolith material distal to the first annulus. The remaining core material was then stored in aluminum foil and submitted for ^{14}C assay by AMS. All samples were also individually assayed for $\delta^{13}C$, which was used to correct for isotopic fractionation effects. Radiocarbon values were subsequently reported as $\Delta^{14}C$, which is the per mil (‰) deviation of the sample from the radiocarbon concentration of 19th-century wood, corrected for sample decay prior to 1950 according to methods outlined by Stuiver and Polach (1977).

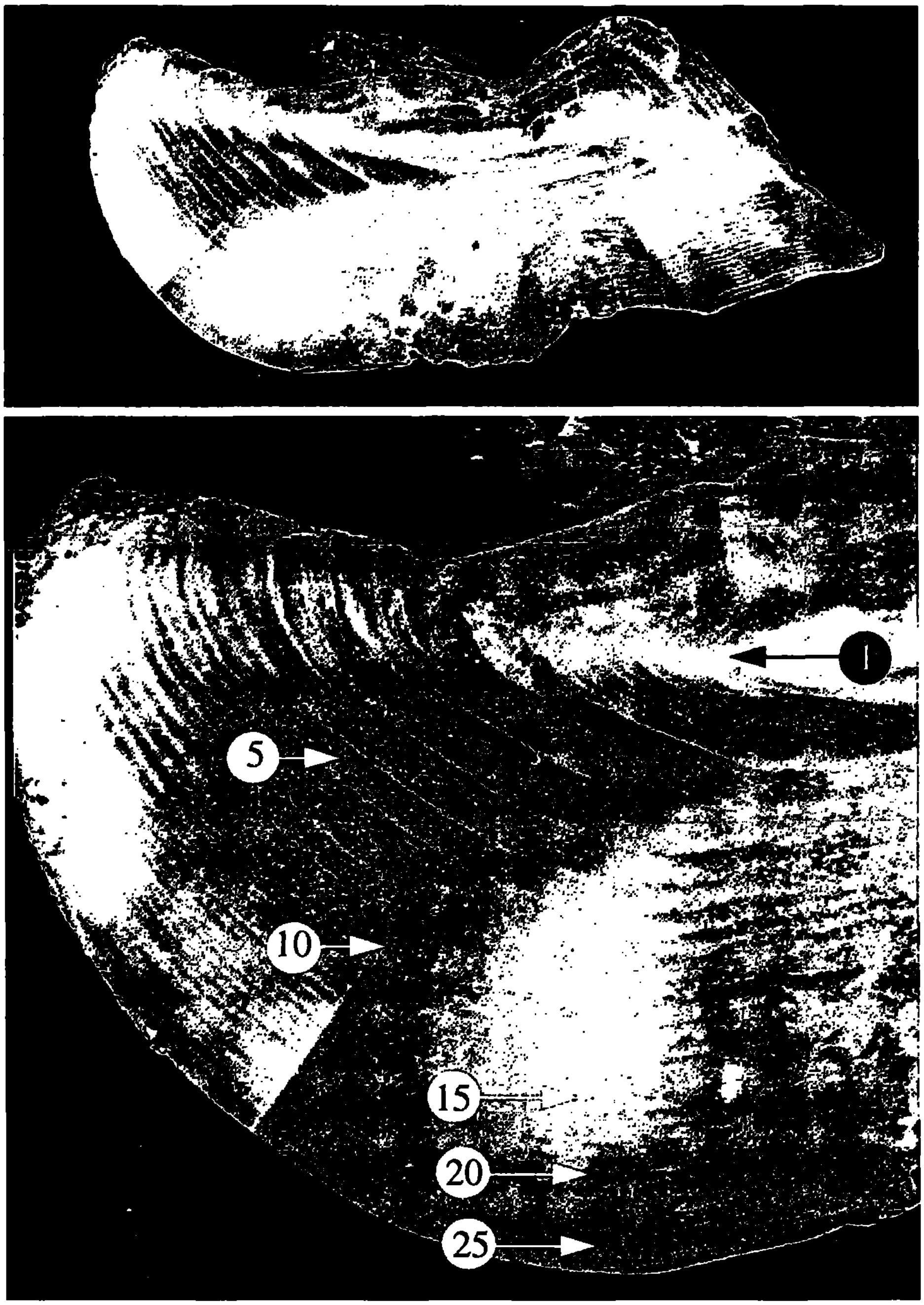

Figure 1

(A) Transverse section of an adult black drum otolith presumed to be 27 years old. **(B)** A magnified view of the ventral side of the sulcus, a region in which the annuli (indicated by arrows) tend to be most clear. Bar = 2 mm.

Results

The presumed annuli in the black drum otolith sections were clear and unambiguous (Fig. 1). Age bias plots (Campana et al., 1995) of the counts of the two independent age readers showed no bias and high precision (CV=1.6%) over an age range of 15–42 years. Although the number of annuli was generally consistent on both the dorsal and ventral sides of the sulcus, the latter was usually the clearer of the two. Therefore, all age and year-class estimates were based on annulus counts along the ventral aspect of the core-medial axis.

The assay results for mean $\delta^{13}C$ were consistent with those observed previously in fish otoliths (mean ± SD=–3.48±1.50‰) (Table 1). Although the presence of a slight but significant decrease across years (b= –0.09, P=0.04, r^2=0.13) was somewhat larger than the long-term ocean trend reported by Quay et al. (1992) and was of different slope than that reported for North Atlantic haddock otoliths (Campana, 1997), the biological significance of the observed trend is questionable given the relatively large coefficient of variation (CV=43%) among the samples. In contrast, $\Delta^{14}C$ differed strongly and systematically though time; concentrations were relatively low and constant prior to the late 1950's but increased sharply to a peak in the mid-1960's (Table 1; Fig. 2). Subsequent values continued to decline to the end of the time series in 1975. The maximum rate of increase occurred between 1958 and 1964 and was easily differentiated from the adjacent time periods. Therefore, the $\Delta^{14}C$ of the cores of the black drum otoliths was characteristic of the period of incorporation and could reasonably be considered a dated marker.

Table 1

Summary of $\Delta^{14}C$ and $\delta^{13}C$ assay results for each black drum otolith core.

Year class	Annulus age (yr)	$\Delta^{14}C$	SD	$\delta^{13}C$
1948	42	–38.8	5.9	–0.9
1950	40	–78.2	8.3	–2.7
1952	38	–36.7	6.4	–2.4
1954	36	–71.9	5.9	–5.9
1954	36	–62.8	6.1	–2.1
1957	33	1.9	4.6	–2.7
1958	32	45.2	7.8	–2.2
1959	31	–3.1	6.4	–3.0
1959	31	101.9	7.2	–1.9
1960	30	46.1	6.8	–3.3
1960	30	18.1	6.6	–4.3
1960	30	70.8	6.8	–1.9
1961	29	175.3	7.5	–3.3
1962	28	62.4	4.5	–5.9
1962	28	182.5	7.5	–4.4
1963	27	299.3	8.5	–0.8
1963	27	136.2	7.3	–2.6
1963	27	95.7	7.1	–5.8
1964	26	111.4	6.8	–6.0
1964	26	194.2	7.6	–2.3
1964	26	371.4	9.1	–4.8
1965	25	340.6	8.6	–4.4
1965	25	106.4	7.1	–4.9
1966	24	366.5	9.1	–4.4
1967	23	291.1	8.5	–3.3
1968	22	297.2	10.2	–2.9
1968	22	261.8	8.2	–2.9
1968	22	207.5	8.0	–3.2
1970	20	213.1	7.8	–2.4
1973	17	255.2	8.1	–4.0
1975	15	150.4	6.5	–6.3

The $\Delta^{14}C$ from the otolith cores from the prebomb, pre-1957 year classes (–57.7±19.0‰) was very similar to that which has been measured in other North Atlantic otoliths, corals, and bivalves (Fig. 3). However, considerably more ^{14}C was incorporated into black drum otoliths during the 1960's than has been measured in most other marine carbonates. Indeed, peak $\Delta^{14}C$ values in black drum (~340‰; Fig. 2) were almost twice as high as those recorded in contemporaneous corals, and almost four times as high as those measured in haddock otoliths of the same year classes. After normalizing the black drum and marine carbonate time series to the same scale, the black drum $\Delta^{14}C$ chronology appeared to both begin its increase and reach a peak approximately 2–3 yr before that of the other carbonates. In addition, unlike the $\Delta^{14}C$ in the other taxa, the $\Delta^{14}C$ in the black drum otoliths declined significantly (to +150‰ in 1975) after reaching a peak in the mid-1960's. Thus in terms of phase coherence, peak magnitude, and subsequent decline, the black drum $\Delta^{14}C$ chronology more closely resembled that of the atmosphere than of other marine carbonates.

To assess the level of correspondence between the black drum $\Delta^{14}C$ chronology and that of the atmosphere, the two time series were scaled to comparable magnitudes. The resulting correspondence was striking (Fig. 4), both in its rate of increase and subsequent decline. The phase shift between the two chronologies was approximately 1 yr, with black drum lagging behind atmosphere.

Discussion

In light of the sharp rate of increase of the ^{14}C signal associated with the onset of nuclear testing, interpretation of the ^{14}C chronology in otolith cores is relatively simple; the otolith chronology should match other published chronologies for the region as long as the annular age assignments (=year class) are correct. Any under-ageing would phase-shift the otolith ^{14}C chronology towards more recent years, whereas over-ageing would phase-shift it towards earlier years. Because marine waters with $\Delta^{14}C$ values greater than 0‰ did not generally exist prior to the late 1950's, coastal fish otolith cores with subzero values must have formed before the late 1950's. Contamination with material of more recent origin could only increase the $\Delta^{14}C$ value, not decrease it. Thus the $\Delta^{14}C$ value sets a minimum age for the sample, and the years 1958–65 become the most sensitive years for $\Delta^{14}C$-based ageing. It is on this basis that workers in other disciplines have used bomb radiocarbon assays to infer age and the frequency of growth-ring formation in both bivalves (Turekian et al., 1982; Peck and Brey, 1996) and mammals (Bada et al., 1990).

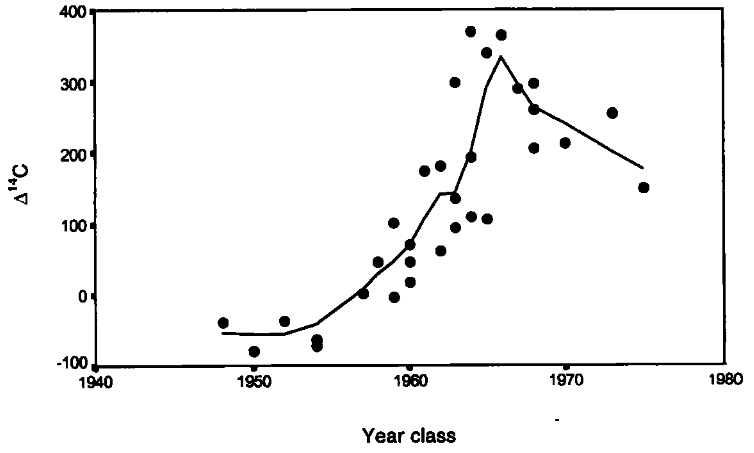

Figure 2

$\Delta^{14}C$ in the otolith cores of adult black drum in relation to the year class estimated from counts of presumed annuli. The $\Delta^{14}C$ values have been fitted with a LOWESS curve.

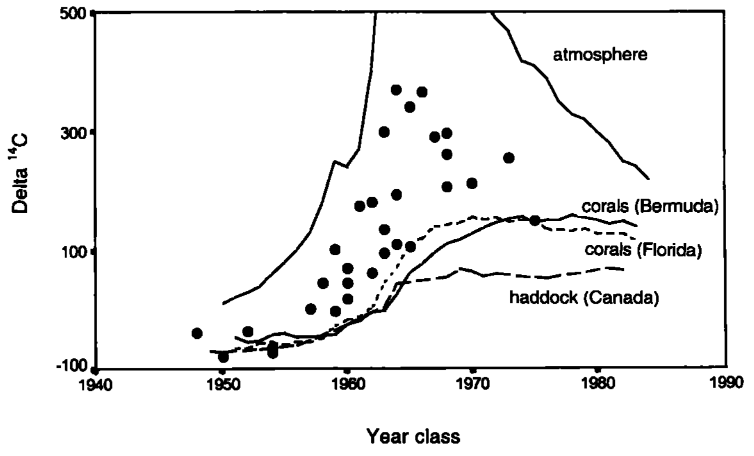

Figure 3

$\Delta^{14}C$ values in the otolith cores of adult black drum in relation to published $\Delta^{14}C$ chronologies for the atmosphere, corals from Bermuda and Florida, and haddock otoliths from eastern Canada. Whereas peak $\Delta^{14}C$ values differed among the time series, all shared a similar period of increasing values, with the source of the ^{14}C (the atmosphere) predating the coral and haddock time series by 2–4 years. The black drum chronology lies intermediate in phase and value to the atmospheric and marine carbonate time series, reflecting an estuarine origin. The two coral chronologies are drawn from Druffel (1989), and the chronologies for the atmosphere and haddock are from Nydal (1993) and Campana (1997), respectively.

The coherence between the otolith-based ^{14}C time series reconstruction reported here and that reported elsewhere in the North Atlantic for bivalves (Weidman and Jones, 1993), corals (Druffel, 1989), and haddock otoliths (Campana, 1997) indicates that black drum age assignments were, on average, reasonably accurate (Fig. 3). The similar prebomb $\Delta^{14}C$ histories for these taxa reflect a common baseline value, whereas differences in post-1970 histories reflect geographic variability in water mixing times (Weidman and Jones, 1993). However, the differences in phase, magnitude, and postbomb decline among the various $\Delta^{14}C$ chronologies are both significant and meaningful and suggest that more accurate age interpretations may be possible. To improve ageing accuracy, however, three additional assumptions must be met: 1) the extracted otolith core must not be contaminated with material of more recent origin; 2) annulus interpretations and any associated errors must be made consistently across all ages examined; 3) the ^{14}C "reference" chronologies must be synchronous with that of the fish species under study. The first assumption has only been tested by Campana (1997) for haddock but was found to hold in part; intact age-1 otoliths and the extracted core of older fish from the same year class were characterized by similar $\Delta^{14}C$ values, although there was a tendency for more recent $\Delta^{14}C$ values to be found in the older cores, suggesting limited contamination. The second assumption is implicit in all ageing studies, because it implies that a given growth increment is interpreted in the same way, whether observed in a young or an old fish. However, the third assumption, that of synchronicity among all North Atlantic ^{14}C chronologies, is more interesting. This assumption has been tested and found to hold in all ^{14}C

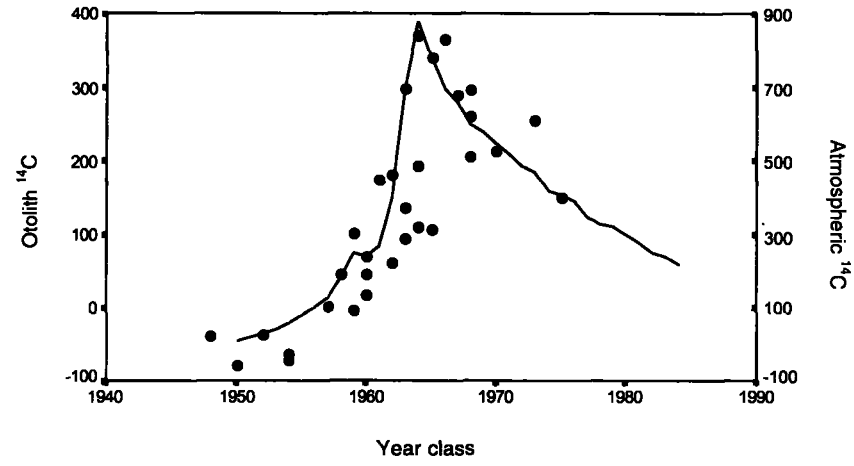

Figure 4

Δ^{14}C values in the otolith cores of adult black drum in relation to the published Δ^{14}C chronology for the atmosphere (data from Nydal [1993]). The data have been scaled so as to emphasize the similarities in the rate of increase and decline in the two time series. Otolith cores formed in riverine or estuarine waters would be expected to reflect more closely the atmospheric pattern of Δ^{14}C than that found in marine carbonates.

otolith ageing studies reported to date, whether in the North Atlantic (Fig. 3) or in the South Pacific (Kalish, 1993, 1995a, 1995b; Kalish et al., 1996). However, the Δ^{14}C chronology reconstructed from the black drum otoliths was noticeably different; whereas prebomb ^{14}C values were comparable among all taxa, all postbomb year classes of black drum were significantly higher than those observed in any other open-ocean carbonate, and appeared to be phase-shifted 2–4 yr towards earlier years. This difference cannot be explained on the basis of ageing error, because the peak Δ^{14}C values in the otolith were as much as four times higher than those recorded in any year of any other open-ocean species. However, the apparent anomaly is fully explicable when the life history of the black drum is considered. The black drum is a marine fish but spends the first year of its life in rivers or estuaries (Richards, 1973). Thus the elemental and isotopic composition of the otolith core reflects the riverine or estuarine environment, not that of the open ocean. Because estuaries are shallow, well-mixed areas with strong riverine input, there is a rapid and relatively complete exchange of radiocarbon between the atmosphere and the water. As a result, the ^{14}C chronology of an estuary is a much closer reflection of the atmospheric chronology than of the marine chronology (Erlenkeuser, 1976; Spiker, 1980; Tanaka et al., 1986). Thus it is to be expected that the Δ^{14}C values of the black drum otolith core would lie intermediate, in magnitude and phase, to those of the atmosphere and the marine series, although closer to the former. This is indeed what was observed; thus black drum age assignments based on annular counts appear to be considerably more accurate than was originally thought, and not biased by 2–4 yr as would have been indicated by comparison with the marine carbonate chronologies. Nonetheless, the black drum measurements are the first demonstration of this phenomenon in fish and confirm Kalish's (1995b) suggestion that precise age calibrations against bomb radiocarbon signals must take into account the nature of the habitat in which the young fish has lived.

Whereas the the collection of black drum cores provided an unambiguous view of the period of Δ^{14}C increase, individual variability within any given year class was large and greatly exceeded the analytical error of the ^{14}C assays. Individual ageing errors undoubtedly contributed to this variability because even a 1-yr ageing error (in a 30-yr-old fish) would have resulted in a Δ^{14}C change of about 40 during the early 1960's. A similar argument applies to errors associated with the isolation of the otolith core from the surrounding, more recent, material. However, we believe that environmental heterogeneity and estuarine food sources were the dominant source of variability in the year-class-specific measurements. Variability in the isotopic composition of estuarine waters can be much larger than that of the open ocean: Spiker (1980) documented nearly twofold variability in the Δ^{14}C of total dissolved inorganic carbon (DIC) among locations in the Chesapeake Bay nursery area of black drum. The potential for variability due to diet in an estuary is also large. Because terrigenous carbon sources reflect atmospheric (enriched) Δ^{14}C in their isotopic composition and because terrigenous input and Δ^{14}C tend to decrease with increasing salinity, the isotopic composition of an animal's diet is bound to be more variable in an estuary than in a more homogeneous environment like the open ocean. Approximately half of the carbon incorporated into the shells of estuarine bivalves is derived from ^{14}C-enriched metabolic (dietary) sources, as opposed to DIC, with the result that there is a high variability among individuals (Erlenkeuser, 1976; Tanaka et al., 1986). Similar arguments undoubtedly apply to fish otoliths because metabolic carbon is thought to provide about one third of the carbon to the otoliths (Kalish, 1991; Schwarcz et al., 1998).

Although the ^{14}C assays reported here provided absolute age determinations for black drum between the ages of 15 and 42 yr, they were of greater value for their use in confirming the accuracy of the criteria generally used to interpret otolith annuli. Compared with otoliths of many other fish species, black drum otoliths form remarkably clear annuli; thus it would have been somewhat surprising if their interpretation had proven to be incorrect. Indeed, on the basis of marginal increment analysis, an annual rate of otolith annulus formation has already been demonstrated for black drum (Beckman et al., 1990), as well as for the closely related red drum, *Sciaenops ocellatus* (Murphy and Taylor, 1991). An annual rate of formation has also been reported for annuli in young black drum scales (Matlock et al., 1993), despite the fact that scale annuli indicate a maximum age of only 10 yr for black drum in Chesapeake Bay. In any event, confirmation of the frequency of annulus formation cannot be used to infer absolute age with the same accuracy as a direct measure of absolute age. In light of the statistical uncertainty around the correspondence between the black drum ^{14}C chronology and that expected of an estuary, it appears reasonable to conclude that otolith annuli can be used to determine the age of a sample of black drum with an accuracy of at least ±1–3 yr, corresponding to 3–7% for a collection of 40-yr-old fish. The confidence interval for an individual fish would be, of course, somewhat larger.

Although techniques such as the mark-recapture of chemically tagged fish can be used to validate the annual frequency of formation of growth increments in the otolith accurately, especially in young or abundant fishes, only radiocarbon from nuclear testing has the potential to confirm both annulus formation and absolute age in individual fish. The results of this study suggest that bomb radiocarbon can be used to determine the accuracy of an alternative ageing technique to within 1–3 yr. In addition, the presence of a strong phase coherence across a broad array of organisms and areas has excellent implications for the age determination of other North Atlantic fish species. The only constraints to this procedure are the relatively high costs (~\$700–\$1,000 per otolith) and the requirement for fish hatched during the 1958–65 period, so as to take advantage of the unique ^{14}C values during that period. Although the availability of suitable otolith samples may limit the applicability of this approach to specific stocks and species, use of bomb-derived radiocarbon as a dated otolith marker appears to provide one of the most accurate and logistically feasible methods for age validation that is currently available.

Acknowledgments

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