

**NATAL ORIGIN OF ATLANTIC BLUEFIN TUNA (*THUNNUS THYNNUS*)
FROM THE GULF OF ST. LAWRENCE USING $\delta^{13}\text{C}$ AND $\delta^{18}\text{O}$ IN OTOLITHS**

A Thesis

by

RYAN WALTER SCHLOESSER

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

December 2008

Major Subject: Wildlife and Fisheries Sciences

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Approved by:

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ABSTRACT

Natal Origin of Atlantic Bluefin Tuna (*Thunnus thynnus*) from the Gulf of St. Lawrence

Using $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ in Otoliths. (December 2008)

Ryan Walter Schloesser, B.S., Texas A&M University

Chair of Advisory Committee: Dr. Jay Rooker

Increased knowledge of stock mixing and migration patterns of Atlantic bluefin tuna (*Thunnus thynnus*) is required to appropriately manage and conserve declining populations. The nursery origin of giant bluefin tuna present in the Gulf of St. Lawrence was identified using stable carbon ($\delta^{13}\text{C}$) and oxygen ($\delta^{18}\text{O}$) isotopes in sagittal otoliths. Anthropogenic and natural processes are capable of impacting atmospheric and oceanic concentrations of $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$, affecting otolith concentrations. Therefore, inter-decadal variation of $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ in the otolith cores (corresponding to the first year of life) of bluefin tuna was examined prior to stock predictions and temporal variability was detected in both isotope ratios. Significant changes in both $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ were recorded in the otolith cores of individuals with birthdates between 1947 and 2003. Both $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ varied significantly as a function of year of birth, with $\delta^{13}\text{C}$ decreasing and $\delta^{18}\text{O}$ increasing over the time period investigated (-2.39×10^{-2} and 5.78×10^{-3} per year, respectively). The rate of change in otolith $\delta^{13}\text{C}$ was nearly identical to the reported rates of atmospheric $\delta^{13}\text{C}$ depletion, recently attributed to the burning of fossil fuels (referred to as the Suess effect). Observed shifts in otolith $\delta^{18}\text{O}$ were less pronounced

and likely linked to changing physicochemical conditions (i.e. salinity) in oceanic reservoirs over the time period investigated. The results show that otolith cores of bluefin tuna effectively track inter-decadal trends and record past oceanic $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ levels. After adjusting for inter-decadal trends, the isotopic composition of milled otolith cores of giants from three decades (1970s, 1980s, 2000s) and three regions were compared to otolith $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values of yearling bluefin tuna collected from eastern and western nurseries. Maximum likelihood estimates indicated that 99% of bluefin tuna caught in the Gulf of St. Lawrence fishery originated from the western nursery, with no significant differences among the decades and regions examined. Results suggest that little to no mixing of eastern and western populations of adult bluefin tuna occurs in the Gulf of St. Lawrence, making it important for the management and conservation of the declining western population.

DEDICATION

This thesis is dedicated to my loving wife, Jessica Schloesser, for her care and support, and to my parents Thomas and Renee Schloesser for their help and encouragement throughout the years.

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I would like to thank my committee chair, Dr. Jay Rooker, and my committee members, Dr. Jaime Alvarado Bremer and Dr. Patrick Louchuarn, for their help, guidance, and insight throughout the course of this research.

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I want to extend my gratitude to the Department of Fisheries and Oceans, Canada, and NOAA fisheries for providing samples, as well as the University of New Hampshire Large Pelagics Research Group and NOAA SEFSC for providing funding to Dr. Jay Rooker to support this research. In addition, support to Dr. John Neilson from the Department of Fisheries and Oceans (Canada) International Fisheries Governance Fund and the ICCAT Bluefin Year Program assisted with recent sampling efforts in the Gulf of St. Lawrence.

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CHAPTER I

INTRODUCTION

Atlantic bluefin tuna (*Thunnus thynnus*) are large, long-lived, highly adapted pelagic predators. Reaching over 3 m in length, 600 kg in weight, and exceeding 30 years of age, they are the largest members of family Scombridae (NRC 1994). The possession of counter-current heat exchangers allows bluefin tuna to maintain significantly elevated muscle temperatures via vascular thermoregulation (Carey 1971). As a result, this species occupies a vast area of the Atlantic Ocean, ranging from Newfoundland and Norway to tropical Brazil and the West African coast (Fromentin and Powers 2005). Spawning occurs in two known locations, the Gulf of Mexico (April to July) and the Mediterranean Sea (June to August) (Clay 1991, Rooker et al. 2007). After spawning, bluefin tuna often migrate to rich feeding grounds throughout the North Atlantic where they are subject to intense fishing pressure (Block et al. 2005).

In the North Atlantic Ocean and associated marginal seas, declines in bluefin tuna abundance have drawn attention to the sustainability of tuna fisheries. Recent estimates by the International Commission for the Conservation of Atlantic Tunas (ICCAT) suggest that population abundance has declined 90% from expected unexploited levels (ICCAT 2006). Currently, ICCAT manages bluefin tuna as two separate stocks, divided at 45°W longitude, and has enacted a fishing quota of 2,700 mt for the western stock and 32,000 mt for the eastern stock for recovery and management

This thesis follows the style of Canadian Journal of Fisheries and Aquatic Sciences.

purposes (ICCAT 2006). Despite several decades of management by ICCAT, bluefin tuna populations have not recovered, leading many to question current stock assessments and the biological data used in population models.

Population structure and the degree of mixing between eastern and western bluefin tuna populations are critical ecological parameters needed by assessment scientists. Daily geolocation estimates from archival tags indicate that mixing occurs off the North American continental shelf from the mid-Atlantic Bight to the Scotian Shelf, and possibly extending to the Flemish Cap (Block et al. 2005, Rooker et al. 2007). However, the degree of mixing is unresolved in this broadly defined foraging zone, which includes important bluefin tuna fishing grounds such as the Gulf of St. Lawrence. The Gulf of St. Lawrence has supported the leading fishery for extremely large bluefin tuna since the 1970s (Mather et al. 1995), and currently represents approximately 15% of the western Atlantic total allowable catch (ICCAT 2006). Stock structure in the Gulf of St. Lawrence is assumed to be comprised primarily of bluefin tuna from the west, suggesting this area may represent critical habitat for members of the smaller western population (Rooker et al. 2008b).

Three methods have been used to examine the population structure of bluefin tuna: genetics, tagging, and otolith chemistry. Of these, otolith chemistry may be the most powerful approach for assessing population mixing of bluefin tuna because material in the otolith cores can be used to predict an individual's origin. Otolith chemistry quantifies the elements and isotopes incorporated into the otolith from the surrounding water mass, therefore, material formed during the first year of life acts as a

natural tag for the nursery. Trace elements have been used to discriminate bluefin tuna from Mediterranean and Gulf of Mexico nurseries (i.e. Li, Mg, Ba); however, classification accuracy was modest and interannual variability was high (Rooker et al. 2003). Using $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$, Rooker and Secor (2004) reported 98% classification success for yearling bluefin tuna from the eastern and western Atlantic to their respective nurseries, indicating that stable isotopes can be used to effectively examine the population structure of bluefin tuna.

The purpose of this study was to investigate the use of $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ in otoliths as a marker of natal origin for bluefin tuna from the Gulf of St. Lawrence. Milled otolith cores (representing the first year of life) of bluefin tuna were examined for trends in stable isotope signatures over five decades. Then, $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values in otoliths of giant bluefin tuna from the Gulf of St. Lawrence were adjusted for observed trends and compared to yearling signatures from eastern and western nurseries (established baseline from Rooker et al. 2008a) to determine whether individuals originated from spawning grounds in the Mediterranean Sea or Gulf of Mexico. The working hypothesis is that contributions to the Gulf of St. Lawrence will be markedly higher for the western population because of fidelity to this foraging ground.

CHAPTER II
INTER-DECADAL VARIATION IN AMBIENT OCEANIC $\delta^{13}\text{C}$ AND $\delta^{18}\text{O}$
RECORDED IN FISH OTOLITHS

Introduction

Atmospheric and oceanic reservoirs of stable carbon ($\delta^{13}\text{C}$) and oxygen ($\delta^{18}\text{O}$) isotope ratios are known to fluctuate in concentration over time due to natural and anthropogenic processes (Quay et al. 1992, Francey et al. 1999, Delaygue et al. 2000). Over the last century, the $\delta^{13}\text{C}$ values of atmospheric CO_2 have decreased significantly due to the increased inputs of isotopically light carbon from both the burning of fossil fuels and the reduction of forest and soil carbon reservoirs (Suess effect, Druffel and Benavides 1986, Francey et al. 1999). This effect, which has accelerated in recent decades, has translated into a parallel shift in $\delta^{13}\text{C}$ signatures in diverse biomass reservoirs including terrestrial and aquatic ecosystems (Francey and Farquhar 1982, Bauch et al. 2000, Bump et al. 2007). For example, decreased $\delta^{13}\text{C}$ levels in the surface ocean (Quay et al. 1992) have been observed in the tissues of producers (phytoplankton; Beveridge and Shackleton 1994, Bauch et al. 2000) and low-level consumers (sponges; Druffel and Benavides 1986). However, shifts in $\delta^{13}\text{C}$ are seldom studied beyond the base of the food chain, and no link to the Suess effect has been documented in marine vertebrates. Similar to $\delta^{13}\text{C}$, a complex relationship exists coupling atmospheric and seawater $\delta^{18}\text{O}$ reservoirs (Jouzel et al. 2002), and carbonates precipitated in equilibrium with these reservoirs are affected by ambient concentrations, as well as seawater

temperature (Kim and O'Neil 1997, Owen et al. 2008). Although historical temperature records have been reconstructed using $\delta^{18}\text{O}$ levels in biogenic carbonates (coral, shells, otoliths), few studies have attempted to describe short-term (i.e. decadal) changes in modern seawater $\delta^{18}\text{O}$ concentrations using these structures (Schone et al. 2005, Sun et al. 2005, Surge and Walker 2005).

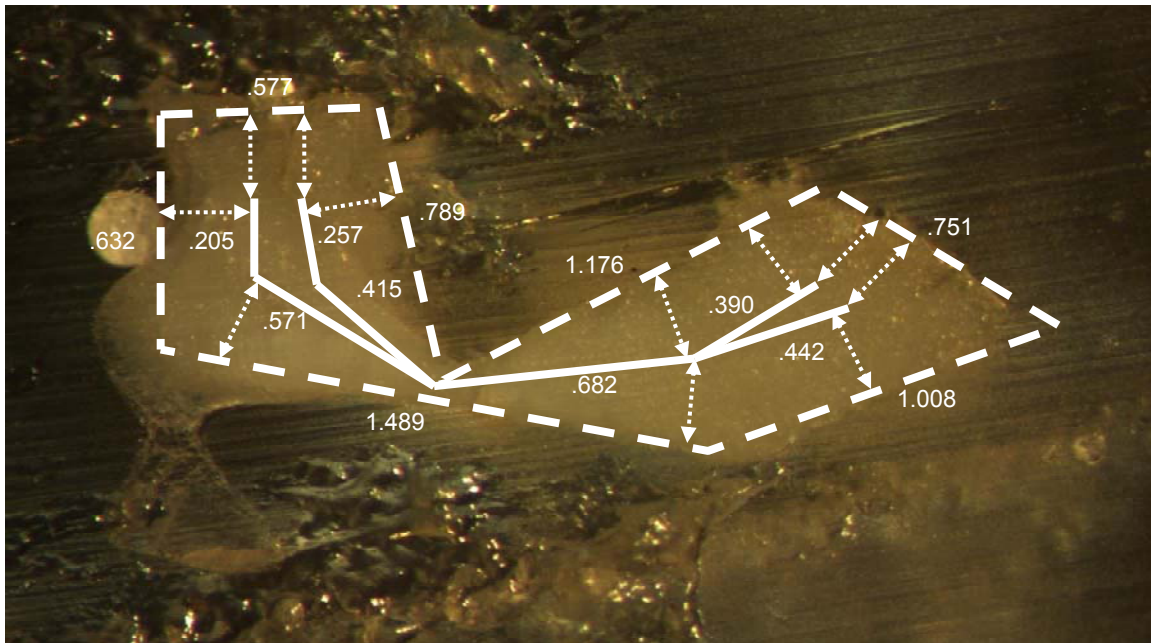
Stable isotopic signatures in the otoliths (ear stones) of marine fishes are often linked to water mass properties, and similar to other biogenic carbonates, chemical information contained in these structures has been used to reconstruct past climates and environmental conditions (Gao and Beamish 1999, Surge and Walker 2005). Temperature, salinity, and ambient ocean isotope concentration have all been linked to changes in stable isotope concentration of otoliths (Kalish 1991, Thorrold et al. 1997, Elsdon and Gillanders 2002). While otolith $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ are also regulated by metabolic and physiological processes (Radtke et al. 1987, Kalish 1991, Weidman and Millner 2000), these properties still yield consistent isotope concentrations in otoliths over annual time periods, justifying their use as natural tags for specific water masses (Kerr et al. 2007; Rooker et al. 2008a). Given the potential usefulness of stable isotopes in otoliths for historical reconstructions (i.e. climate, physicochemical), evaluating the temporal variability of these signatures over decadal periods is critically needed.

Methods

We examined temporal variation in stable isotope signatures in the otolith cores (representing the nursery period) of a pelagic fish, Atlantic bluefin tuna (*Thunnus*

thynnus), over 5 decades. This species represents an ideal model for evaluating long-term changes in oceanic $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ because juveniles frequent the upper mixed layer of the water column during early life (90% time in less than 15m; Brill et al. 2002), and archived otoliths comprised of individuals from year classes spanning 50 years were available. Otoliths used here were collected from three regions at different time periods: 1) yearlings (n= 85) in the U.S. Atlantic from 1999 to 2004, 2) adults from the spawning area in the Gulf of Mexico (n= 42) from 1999 to 2002 and 2007, and 3) adults from a foraging ground in the Gulf of St. Lawrence (n= 224) from 1975 to 1984 and 2006 to 2007. Based on Rooker et al. (2008b), individuals from selected areas are comprised almost exclusively of the western population of bluefin tuna (i.e. no mixing of migrants from the Mediterranean Sea). For yearling bluefin tuna, the entire otolith was powdered using a mortar and pestle to obtain material for the nursery signature. In contrast, otoliths from adults were sectioned and the core milled using a New Wave Research micromill. The region corresponding to the nursery period (identified from measurements of transverse sections of yearling bluefin tuna otoliths; Fig. 1) was powdered using a series of drill passes over a pre-programmed drill path by a 500 μm diameter Brasseler carbide bit until approximately 750 μm depth was reached. Age assignments of adult bluefin tuna were based on counts of annual growth increments when available, or approximated using a length to age conversion (Rooker et al. 2007). Powders from whole otoliths (yearlings) and otolith sections (adults) were analyzed for $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ concentrations using an automated carbonate preparation device coupled

Fig. 1. Transverse section of *T. thynnus* otolith with pre-programmed drill path used to mill core material (age-1 period). Solid lines represent the micromill drill path to be powdered. Small dashed lines show the 250 μm distance the drill bit will reach. Large dashed lines highlight the otolith's outer edge.

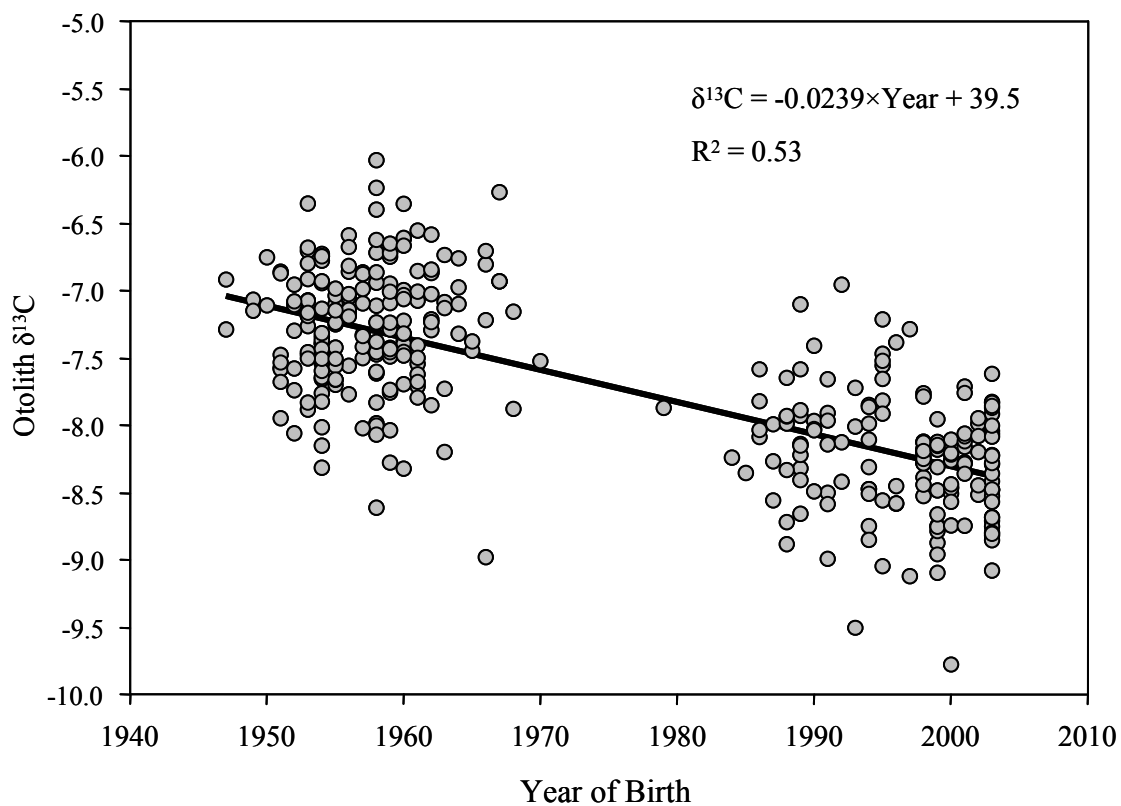


to a gas-ratio mass spectrometer and standardized among multiple facilities (Rooker et al. 2008a). Powdered samples were reacted with dehydrated phosphoric acid under vacuum at 70°C. Analytical precision of the mass spectrometer was $\pm 0.1\text{‰}$ for $\delta^{18}\text{O}$ and $\pm 0.06\text{‰}$ for $\delta^{13}\text{C}$. Isotope ratio measurements were calibrated based on repeated measurements of NBS-19 (National Bureau of Standards-19) and NBS-18 and reported relative to the Pee Dee Belemnite (PDB) standard. Isotope concentrations lying more than three standard deviations from the mean value for that year were removed from the dataset ($n=1$).

Results and Discussion

A significant relationship was detected by a linear regression of $\delta^{13}\text{C}$ against year of birth with a slope of -2.39×10^{-2} ($n=351$, $R^2=0.53$, $p<0.05$, Fig. 2), corresponding to an approximate 1.34‰ depletion in $\delta^{13}\text{C}$ over the 56 year period investigated in this study (1947 to 2003). Despite the ability of physicochemical factors (i.e. temperature and salinity) to affect seawater $\delta^{13}\text{C}$ (Thorrold et al. 1997; Elsdon and Gillanders 2002), they do not appear linked to the observed decadal shift in mean $\delta^{13}\text{C}$ values across decades. Changes in oceanic temperature and salinity have been documented over the time period analyzed. The largest mean temperature increase was found to be 0.37 °C for the 0-300 m depth layer of the North Atlantic in 1998 (Levitus et al. 2000). However, using the relationship between $\delta^{13}\text{C}$ and temperature from Thorrold et al. (1997) and assuming constant water $\delta^{13}\text{C}$ concentration, this temperature change would

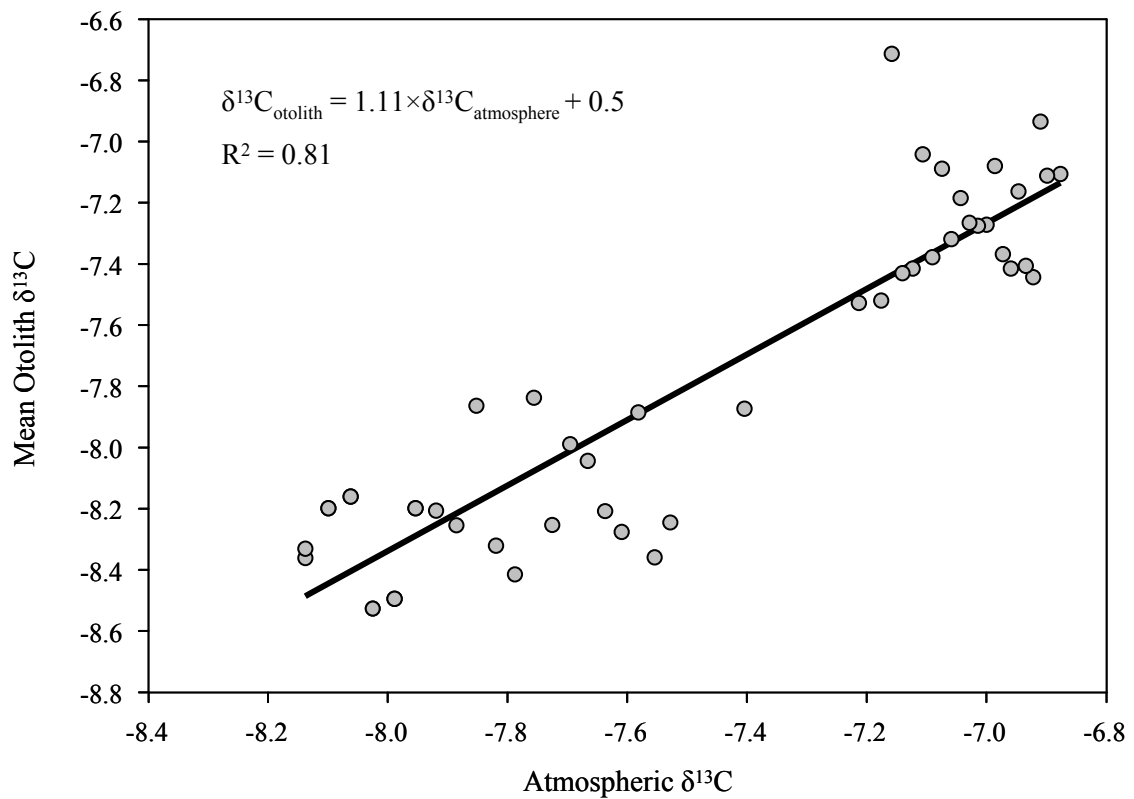
Fig. 2. Linear regression of $\delta^{13}\text{C}$ in milled otolith cores from *T. thynnus* against year of birth from 1947-2003 (n= 351). *T. thynnus* were collected from the western Atlantic, with ages derived from annuli counts or length to age conversion.



account for a decrease in $\delta^{13}\text{C}$ of approximately 0.067‰, only 5% of the observed change. An increase in salinity of 0.1 to 0.4 p.s.u. occurred for subtropical Atlantic waters south of 35°N concentrated around the Gulf Stream, with an average 0.03 p.s.u. decrease in salinity occurring north of 40°N (Curry et al. 2003). The slight freshening of waters north of 40°N is likely outweighed by salinity increases around the Gulf Stream, which would result in increased $\delta^{13}\text{C}$ concentrations (Elsdon and Gillanders 2002), rather than the decreasing trend in this study. Therefore, temperature and salinity do not appear to be the predominant factors controlling the observed $\delta^{13}\text{C}$ shift in otoliths.

Decreasing $\delta^{13}\text{C}$ signatures in various oceanic systems have been identified (Quay et al. 1992; Bauch et al. 2000) and attributed to the combined effect of fossil fuel burning and deforestation which have released an increased proportion of ^{13}C -depleted CO_2 into the atmosphere in the last century (Suess effect, Druffel and Benavides 1986, Beveridge and Shackleton 1994, Francey et al. 1999). Evidence from this study suggests that the Suess effect also influences $\delta^{13}\text{C}$ levels in carbonate structures of vertebrates. Sharp declines in atmospheric $\delta^{13}\text{C}$ first began in the early 1900's, and have since resulted in a total depletion of 1.32‰ over the time period examined (1947-2003; based on a linear fit to Verburg's (2007) polynomial $\delta^{13}\text{CO}_2$ estimator), which is virtually identical to the observed 1.34‰ decline in bluefin tuna otoliths. Direct comparison of the mean shift in otolith $\delta^{13}\text{C}$ versus the change in atmospheric $\delta^{13}\text{C}$ yielded a nearly one to one slope (slope= 1.11, $R^2= 0.81$, Fig. 3), indicating that otoliths of bluefin tuna effectively track atmospheric changes in $\delta^{13}\text{C}$. In addition, otoliths are only slightly

Fig. 3. Mean $\delta^{13}\text{C}$ in milled otolith cores from *T. thynnus* collected in the western Atlantic compared to atmospheric $\delta^{13}\text{C}$ for years with samples available from 1947-2003. Atmospheric $\delta^{13}\text{C}$ values derived from Verburg's (2007) polynomial estimator of $\delta^{13}\text{CO}_2$.

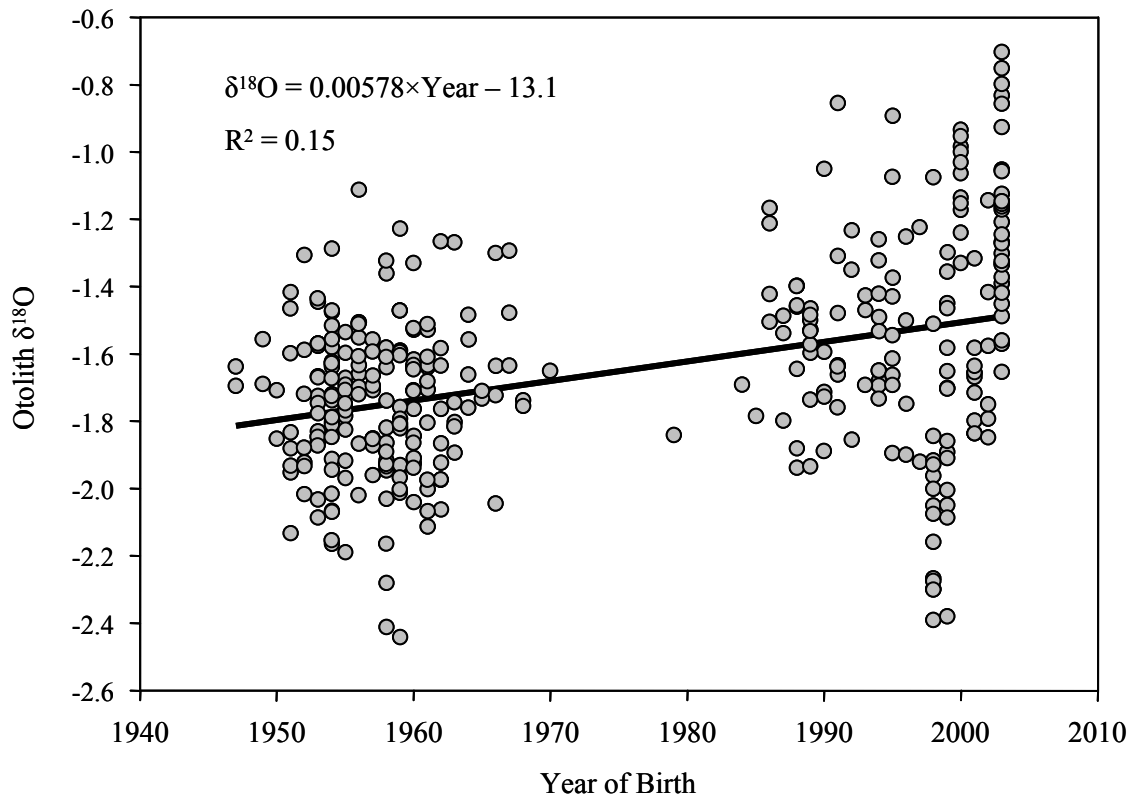


depleted ($\approx 0.4\%$) with respect to atmospheric $\delta^{13}\text{C}$ values suggesting that they are in relatively close equilibrium with ambient conditions, despite the incorporation of metabolic carbon (38.5%, based on Kalish 1991) which drives signatures out of equilibrium with ambient conditions.

Results from a linear regression of $\delta^{18}\text{O}$ against year of birth suggested that a minimal, yet significant, change also occurred ($n = 351$, $R^2 = 0.15$, $p < 0.05$, Fig. 4). Otolith $\delta^{18}\text{O}$ increased by 5.78×10^{-3} per year, with an overall change of 0.32% from 1947-2003. It is commonly accepted that $\delta^{18}\text{O}$ accretion in otoliths is related to seawater $\delta^{18}\text{O}$, which is closely linked to temperature and salinity. However, adjusting for temperature changes ($0.37\text{ }^\circ\text{C}$ increase; Levitus et al. 2000) using established temperature- $\delta^{18}\text{O}$ relationships would result in a depletion in $\delta^{18}\text{O}$ signatures (0.08% , Kalish 1991; 0.12% , Thorrold et al. 1997), not an enrichment. However, shifts in salinity such as those reported around the Gulf Stream (0.1 to 0.4 p.s.u. increase; Curry et al. 2003) would increase seawater $\delta^{18}\text{O}$ signatures up to 0.24% (Delaygue et al. 2000). Therefore, the observed enrichment in otolith $\delta^{18}\text{O}$ values may be due in part by salinity changes over time. Unfortunately, little information exists concerning current trends in ambient $\delta^{18}\text{O}$ concentrations to fully explain $\delta^{18}\text{O}$ shifts in otoliths.

The ability of $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ concentrations to change over time emphasizes the need to understand long-term isotopic trends if stable isotopes are to be used as natural markers for water masses, or for recreating past climate records and physicochemical conditions. The ability of otoliths to detect these inter-decadal trends highlights their role as environmental recorders, and supports the premise that otolith chemistry is a

Fig. 4. Linear regression of $\delta^{18}\text{O}$ in milled otolith cores from *T. thynnus* against year of birth from 1947-2003 (n= 351). *T. thynnus* were collected from the western Atlantic, with ages were derived from annuli counts or length to age conversion.



powerful tool to investigate environmental histories. Results also indicate that due to temporal variation in both $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$, adjustments are required when using these natural markers for assessments of origin or environmental history of organisms over several decades.

CHAPTER III
NATAL ORIGIN OF ATLANTIC BLUEFIN TUNA (*THUNNUS THYNNUS*)
FROM THE GULF OF ST. LAWRENCE

Introduction

Top-down regulation by apex predators influences the structure of marine communities (Jackson et al. 2001), and recent declines in high order consumers have been shown to alter the stability and productivity of pelagic ecosystems (Frank et al. 2005). In the North Atlantic Ocean, overfishing has reduced predator biomass by 89% since 1900, with two-thirds of the decline occurring in the second half of the twentieth century (Christensen et al. 2003). These recent declines have brought attention to the sustainability and management of important fisheries, including Atlantic bluefin tuna (*Thunnus thynnus*).

Efforts to regulate Atlantic bluefin tuna populations are headed by the International Commission for the Conservation of Atlantic Tunas (ICCAT). Bluefin tuna are currently managed as two separate stocks in the Atlantic Ocean, divided at 45°W longitude. The two-stock management strategy is based on eastern and western populations spawning in the Mediterranean Sea and Gulf of Mexico, respectively, with the eastern population being an order of magnitude larger than the western population (ICCAT 2006). Recent estimates from ICCAT placed the 2004 western stock at 18% of the population level in the 1970s, and the eastern stock at 48% (ICCAT 2006). In response, ICCAT enacted fishing quotas of 2,700 mt for the western stock and 32,000 mt

for the eastern stock for recovery and management purposes (ICCAT 2006). Despite being managed by ICCAT for several decades, bluefin tuna populations have not recovered, leading many to question current stock assessments and the biological data used in population models.

Uncertainty regarding the population structure and degree of mixing between eastern and western populations is a major concern for assessment scientists. Evidence indicates that mixing occurs off the North American continental shelf from the mid-Atlantic Bight to the Scotian Shelf, and possibly extending to the Flemish Cap (Block et al. 2005; Rooker et al. 2007). However, the degree of mixing is unresolved in this broadly defined foraging zone, which includes important fishing grounds of bluefin tuna from the Gulf of St. Lawrence to the Mid Atlantic Bight. It is possible that contribution rates of eastern and western migrants are region and time specific within the western Atlantic, and thus population composition may vary spatially and temporally. Stock structure in the Gulf of St. Lawrence is assumed to be comprised primarily of bluefin tuna from the declining western population (Rooker et al. 2008b), making it of particular importance to management strategies.

The Gulf of St. Lawrence has supported a fishery for giant bluefin tuna (refers to mature adults >141 kg) for over 40 years (Mather et al. 1995) and catches from this region represent approximately 15% of total allowable catch for the western stock (ICCAT 2006). The long-term consistency of catches in the Gulf of St. Lawrence fishery has led to its use by ICCAT as an estimator for western stock abundance indices (ICCAT 2006). However, these indices may be biased if catches in the Gulf of St.

Lawrence are comprised of individuals from both eastern and western populations. Therefore, information on the stock structure of bluefin tuna in the Gulf of St. Lawrence is critically needed by managers, particularly if this region represents an essential foraging ground for the declining western population.

Three methods are currently being used to address mixing and population structure of bluefin tuna: genetics, tagging, and otolith chemistry. Findings from all three approaches support to the two-stock premise, but none have resolved the issue or determined the level of exchange between the two regions. Molecular genetics data, using both mitochondrial DNA and microsatellites, shows a weak but statistically significant differentiation between eastern and western stocks when using samples of adult and juvenile bluefin tuna caught on respective spawning grounds (Boustany et al. 2007; Carlsson et al. 2007). Conventional and electronic pop-up archival transmitting tags have confirmed bluefin tuna crossing the eastern and western stock boundary, and documented spawning site fidelity over a three year period (Stokesbury et al. 2004; Block et al. 2005). Otolith chemistry has shown that differences in ambient conditions between the eastern and western Atlantic result in unique signatures in otoliths which have been used to evaluate bluefin tuna stock structure (Rooker et al. 2003, 2007). Recent research has also shown that stable isotopes in otoliths serve as natural markers of natal origin and show considerable promise for understanding natal homing and connectivity of eastern and western bluefin tuna populations (Rooker et al. 2008b).

This study investigated the use of $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ signatures in otoliths as markers of natal origin for bluefin tuna from the Gulf of St. Lawrence. Stable isotope signatures

in milled otolith cores of giant bluefin tuna were compared to yearling signatures from eastern and western nurseries (established baseline from Rooker et al. 2008a) to determine whether individuals originated from spawning grounds in the Mediterranean Sea or Gulf of Mexico. Inter-decadal and spatial variations in contribution rates to the Gulf of St. Lawrence fishery were also assessed by predicting the origin of bluefin tuna collected in the 1970s, 1980s, and 2000s among multiple regions. The working hypothesis is that the western population shows fidelity to the Gulf of St. Lawrence foraging ground, and thus contribution rates will be markedly higher for the western population.

Methods

Otolith collecting and processing

Yearling bluefin tuna otoliths were collected from eastern (eastern Atlantic and Mediterranean Sea, n= 112) and western (western Atlantic, n= 81) nurseries between 1999 and 2004 (Rooker et al. 2008a). Giant bluefin tuna were collected from Gulf of St. Lawrence fisheries out of North Lake, Prince Edward Island in 2006 and 2007 (n= 31). In addition, archived otoliths of bluefin tuna collected in the Gulf of St. Lawrence from 1975-1984 were provided by the Department of Fisheries and Oceans, Canada (n = 193). Samples were representative of 5 fishing ports which were grouped into 3 regions (Caraquet and Tignish = West, Havre Boucher and North Lake = East, St. Margarets Bay = Exterior; Fig. 5, Table 1). Approximately 80% of the specimens were known to be over 250 cm fork length (approximately 15 years of age; Table 2). Sagittal otoliths

Fig. 5. Locations of the five ports from which *T. thynnus* otolith samples were obtained and their regional groupings indicated by dotted circles.

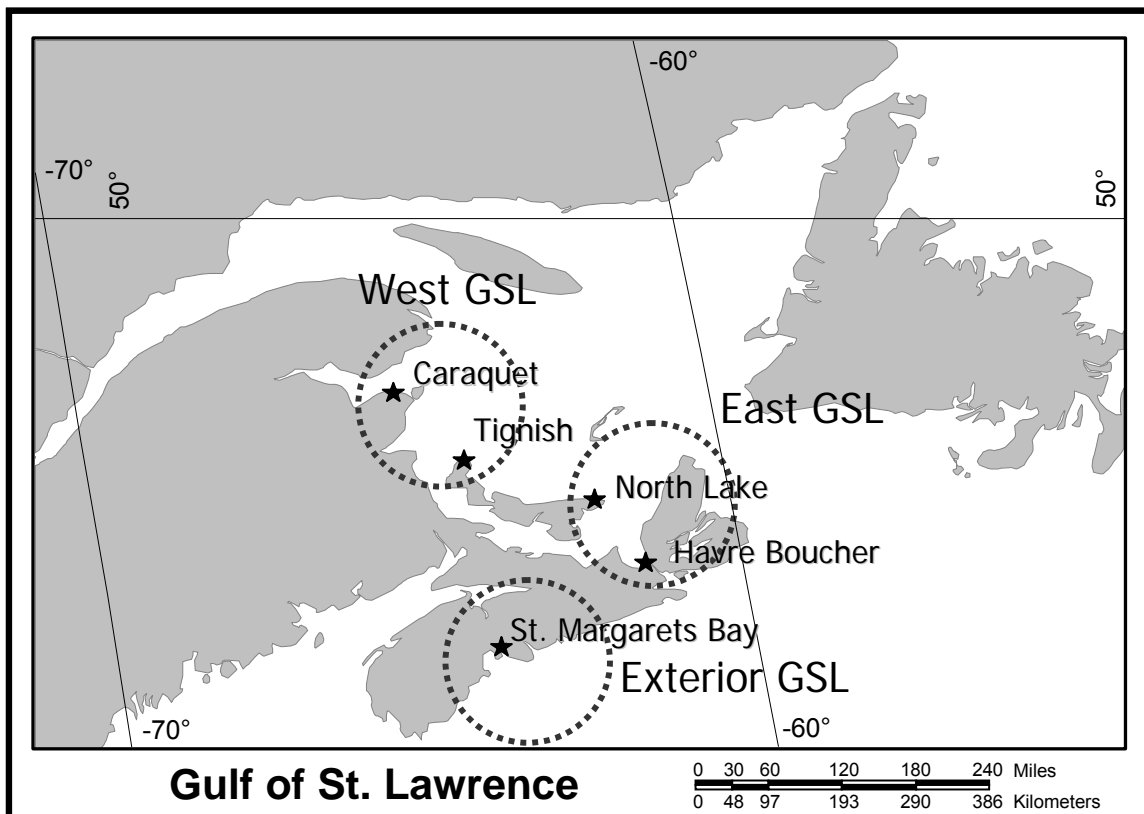


Table 1. Number of *T. thynnus* otoliths collected at each sampling location in the Gulf of St. Lawrence.

Location	Year											Total	
	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	2006		2007
Caraquet	8	10	10	8	8								44
Havre Boucher							4						4
North Lake	12	10	12	9	10	1					11	20	85
St. Margarets Bay	5	7	14	11	4	3	5						49
Tignish								7	31	4			42
Total	25	27	36	28	22	4	9	7	31	4	11	20	224

Table 2. Number of *T. thynnus* otoliths collected in the Gulf of St. Lawrence by fork length (cm) as measured or converted from curved fork length.

Length (cm)	Year											Total	
	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	2006		2007
No Length	20	8					1		1				30
200											1		1
210												2	2
220													0
230							1				3	1	5
240			1								3	5	9
250	2	2	3	3	2		1	1	1		1	5	21
260	2	4	10	8	3		1		3	2	2	6	41
270		7	11	8	6	3	1	4	11	2	1	1	55
280		4	5	4	5		1	1	7				27
290	1	1	5	5	5	1		1	6				25
300		1	1		1		2		2				7
310													0
320							1						1
Total	25	27	36	28	22	4	9	7	31	4	11	20	224

were removed from all bluefin tuna and fork length (cm) and weight (kg) recorded for each specimen.

A single sagittal otolith (right or left) was randomly selected from each pair for analysis. Selected otoliths were cleaned of excess tissue and rinsed with deionized water (dH₂O). Otoliths from giant bluefin tuna were embedded in Struers epoxy resin. A 1.5 mm thick section of resin containing the otolith core was cut along a transverse plane using a Buehler Isomet saw, and then attached to a sample plate using Crystalbond thermoplastic glue. The region corresponding to the first year of growth (identified from measurements of transverse sections of otoliths from yearling bluefin tuna; Figure 1) was isolated and powdered using a New Wave Research MicroMill. A series of drill passes was run over a pre-programmed drill path by a 500 µm diameter Brasseler carbide bit until approximately 750 µm depth was reached. Powder was collected with a microspatula and loaded into sample trays. All sampling equipment was cleaned with 70% ethanol between samples to prevent cross contamination.

Otolith powders were analyzed for $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ signatures using an automated carbonate preparation device (KIEL-III) coupled to a gas-ratio mass spectrometer (Finnigan MAT 252) at the University of Arizona (supervised by D. Dettman). Powdered samples were reacted with dehydrated phosphoric acid under vacuum at 70°C. Analytical precision of the mass spectrometer was $\pm 0.1\text{‰}$ for $\delta^{18}\text{O}$ and $\pm 0.06\text{‰}$ for $\delta^{13}\text{C}$ (1 SD). Isotope ratios were calibrated based on repeated measurements of NBS-19 and NBS-18 and reported relative to the Pee Dee Belemnite (PDB) standard.

Data analysis

Analysis of variance (ANOVA) and multivariate analysis of variance (MANOVA) were used to determine whether $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values in the otoliths of giant bluefin tuna differed among sampling regions and decades. Isotope signatures ($\delta^{13}\text{C}$ and $\delta^{18}\text{O}$) in cores of giant bluefin tuna collected from the Gulf of St. Lawrence differed significantly among decades (Fig. 6; MANOVA $p < 0.05$), suggesting the need to adjust for changes in $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ over time. All isotope signatures of otoliths were adjusted to modern day values using a correction of -0.0239‰ per year for $\delta^{13}\text{C}$ and 0.0058‰ per year for $\delta^{18}\text{O}$ (see Chapter I). Hereafter, all reporting and testing of otolith core $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values for giant bluefin tuna will be presented as adjusted values. Otolith $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values from yearling (age-1; use justified in Fig. A-1, A-2) bluefin tuna collected from eastern and western nurseries (from Rooker et al. 2008a; Fig. 7) were used as a baseline set for classifying giants from the Gulf of St. Lawrence. Adjusted $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values from giants of unknown origin were compared to yearling baseline samples and classified to eastern or western nurseries using maximum likelihood estimates (MLE) from the mixed-stock analysis program HISEA as described by Millar (1990). HISEA was run under bootstrap mode to obtain standard deviations around estimated proportions with 1000 simulations.

Results

No significant differences in adjusted otolith core $\delta^{13}\text{C}$ or $\delta^{18}\text{O}$ values were detected across decades (MANOVA $p > 0.05$) or regions (MANOVA $p > 0.05$). Otolith

Fig. 6. Comparison of unadjusted and adjusted $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ signatures in the otolith cores of giant *T. thynnus* collected from the Gulf of St. Lawrence ($n=224$) in the 1970s (light grey, $n=138$), 1980s (dark grey, $n=55$), and 2000s (black, $n=31$).

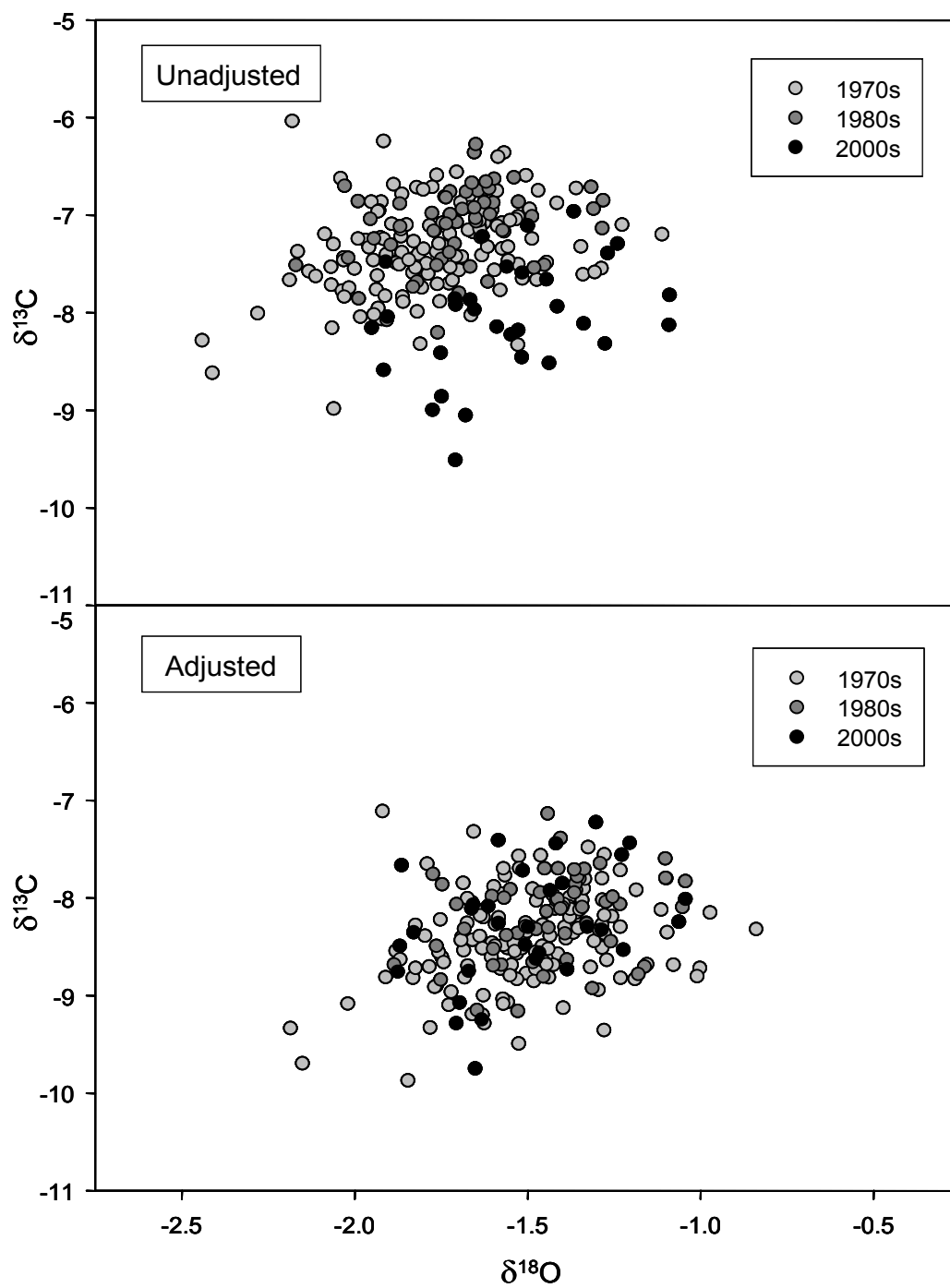
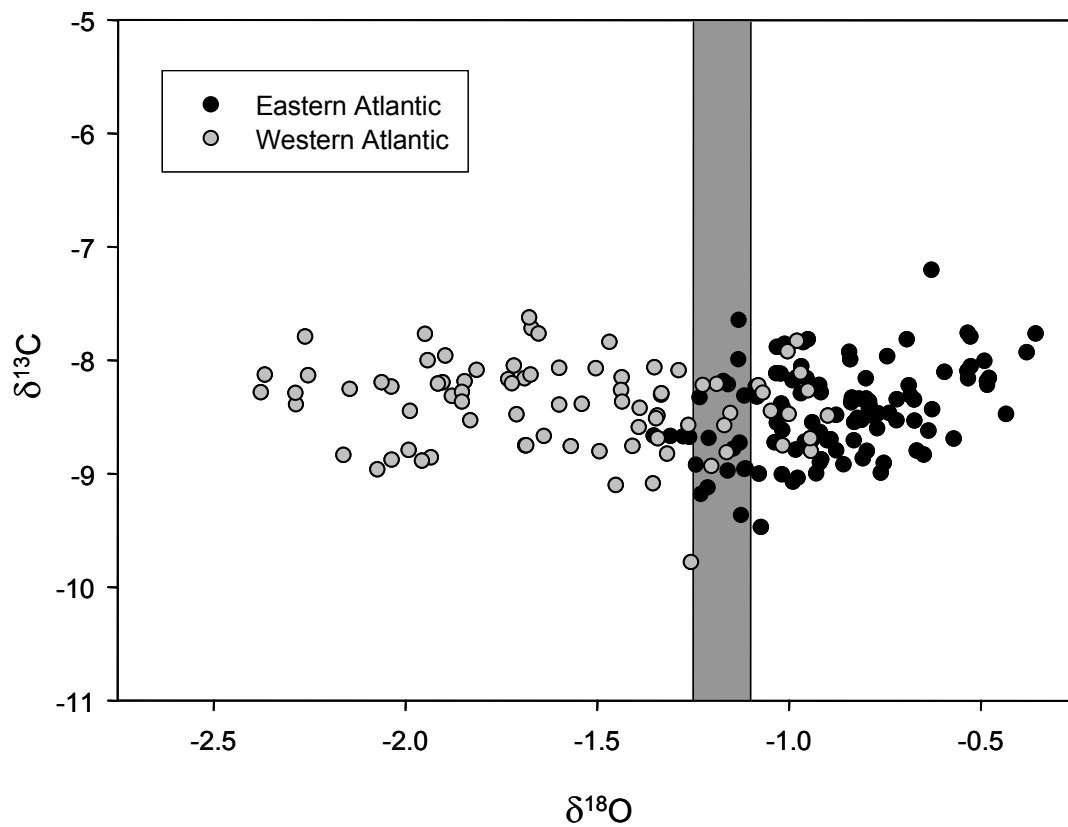


Fig. 7. $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ signatures in the whole otoliths of yearling *T. thynnus* collected from the Mediterranean Sea (black, n= 112) and western Atlantic (light grey, n= 81) (Rooker et al., 2007). Shaded region shows overlap zone of confidence ellipses (1 SD) on yearling *T. thynnus* (-1.1 to -1.25).



core $\delta^{13}\text{C}$ values were similar across decades (ANOVA $p > 0.05$), which was expected given that inter-decadal variation was accounted for in the adjustment; mean values ranged from -8.32‰ to -8.42‰ across the three decades (Fig. 8,9,10, Table 3). Similarly, $\delta^{13}\text{C}$ values did not differ significantly (ANOVA $p > 0.05$) among the regions examined in the Gulf of St. Lawrence (GSL): West GSL (mean= -8.39‰ , Fig. 11), East GSL (mean= -8.37‰ , Fig. 12), and Exterior GSL (mean= -8.23‰ , Fig. 13) (Fig. 14, Table 4). Otolith core $\delta^{18}\text{O}$ values adjusted for inter-decadal variation were also similar across decades (ANOVA $p > 0.05$): 1970 (mean= -1.5‰), 1980 (mean= -1.5‰), and 2000 (mean= -1.6‰) (Table 3). No significant differences in otolith core $\delta^{18}\text{O}$ values were detected among regions (ANOVA $p > 0.05$), with mean values ranging from -1.4‰ to -1.5‰ (Table 4).

Comparing otolith core $\delta^{13}\text{C}$ or $\delta^{18}\text{O}$ values from giant bluefin tuna to the yearling baseline (Rooker et al. 2008a) via maximum likelihood estimates (MLE) for all decades combined indicated 99.3% of giant bluefin tuna in the Gulf of St. Lawrence samples originated from the western nursery, with the remaining 0.7% from the eastern nursery. The standard deviation around estimated proportions was 3.2% for all decades combined, meaning there is a 68% probability the actual contribution of the western nursery to the Gulf of St. Lawrence lies between 96.1% and 100%. High classification to the western nursery remained relatively consistent across decades: 1970s (97.2%, SD= 8.9%), 1980s (100%, SD= 0.0%), 2000s (98.7%, SD= 5.7%).

Estimates of origin by region were also assessed using MLE, and the percentage of giants in the Gulf of St. Lawrence samples originating from the western nursery was

Fig. 8. $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ signatures in the otolith cores of giant *T. thynnus* collected from the Gulf of St. Lawrence in the 1970s (n= 138). Shaded region shows overlap zone of confidence ellipses (1 SD) from yearling *T. thynnus* (-1.1 to -1.25).

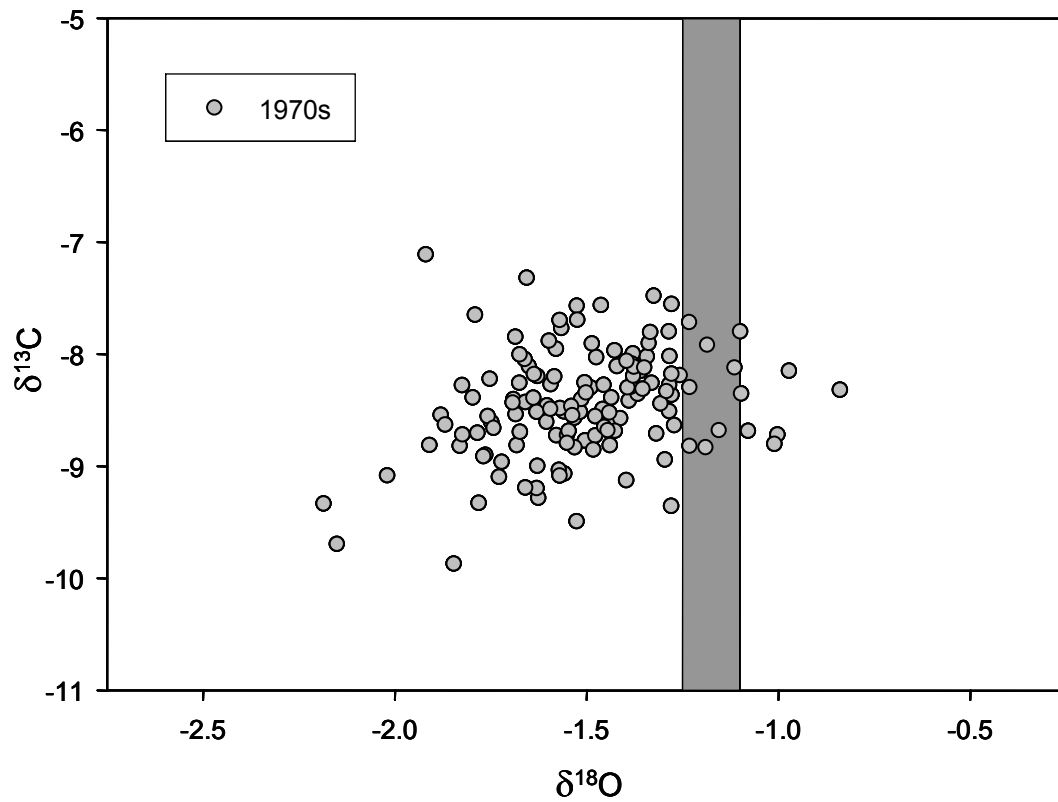


Fig. 9. $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ signatures in the otolith cores of giant *T. thynnus* collected from the Gulf of St. Lawrence in the 1980s (n= 55). Shaded region shows overlap zone of confidence ellipses (1 SD) from yearling *T. thynnus* (-1.1 to -1.25).

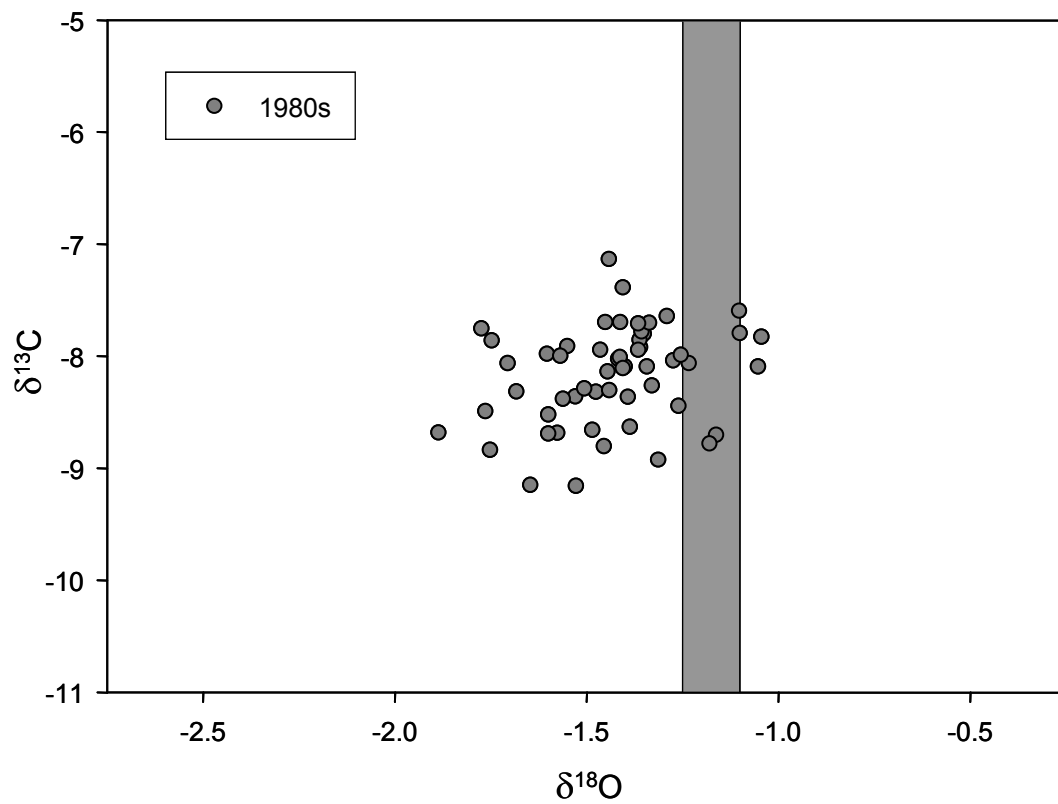


Fig. 10. $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ signatures in the otolith cores of giant *T. thynnus* collected from the Gulf of St. Lawrence in the 2000s (n= 31). Shaded region shows overlap zone of confidence ellipses (1 SD) from yearling *T. thynnus* (-1.1 to -1.25).

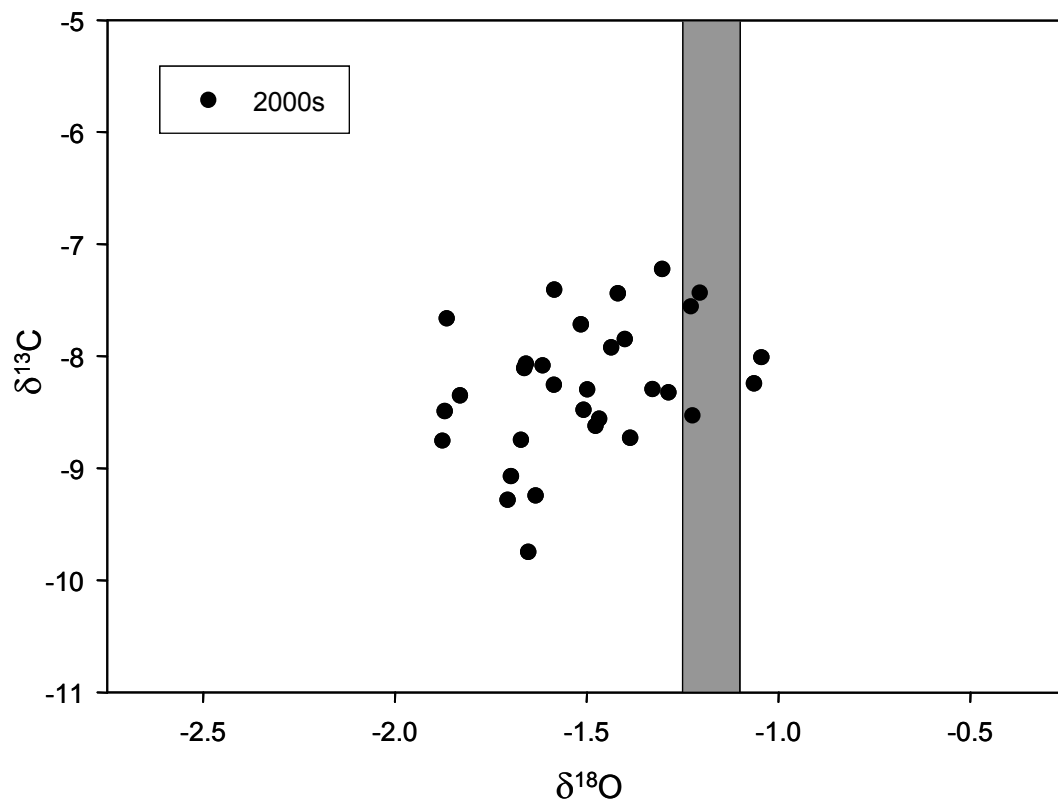


Table 3. Summary data for $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ signatures from otoliths of *T. thynnus* collected from the Gulf of St. Lawrence in the 1970s, 1980s, and 2000s. Data includes the number of samples, minimum and maximum values, the mean value, and the standard deviation around the mean.

	1970s		1980s		2000s		All	
	$\delta^{13}\text{C}$	$\delta^{18}\text{O}$	$\delta^{13}\text{C}$	$\delta^{18}\text{O}$	$\delta^{13}\text{C}$	$\delta^{18}\text{O}$	$\delta^{13}\text{C}$	$\delta^{18}\text{O}$
Number	138	138	55	55	31	31	224	224
Minimum	-9.87	-2.2	-9.75	-2.2	-9.19	-2.0	-9.87	-2.2
Maximum	-7.11	-1.0	-7.22	-0.8	-7.65	-1.0	-7.11	-0.8
Mean	-8.32	-1.5	-8.37	-1.5	-8.42	-1.6	-8.35	-1.5
Standard Deviation	0.48	0.2	0.60	0.2	0.36	0.2	0.49	0.2

Fig. 11. $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ signatures in the otolith cores of giant *T. thynnus* collected from the western region of the Gulf of St. Lawrence (n= 86). Shaded region shows overlap zone of confidence ellipses (1 SD) from yearling *T. thynnus* (-1.1 to -1.25).

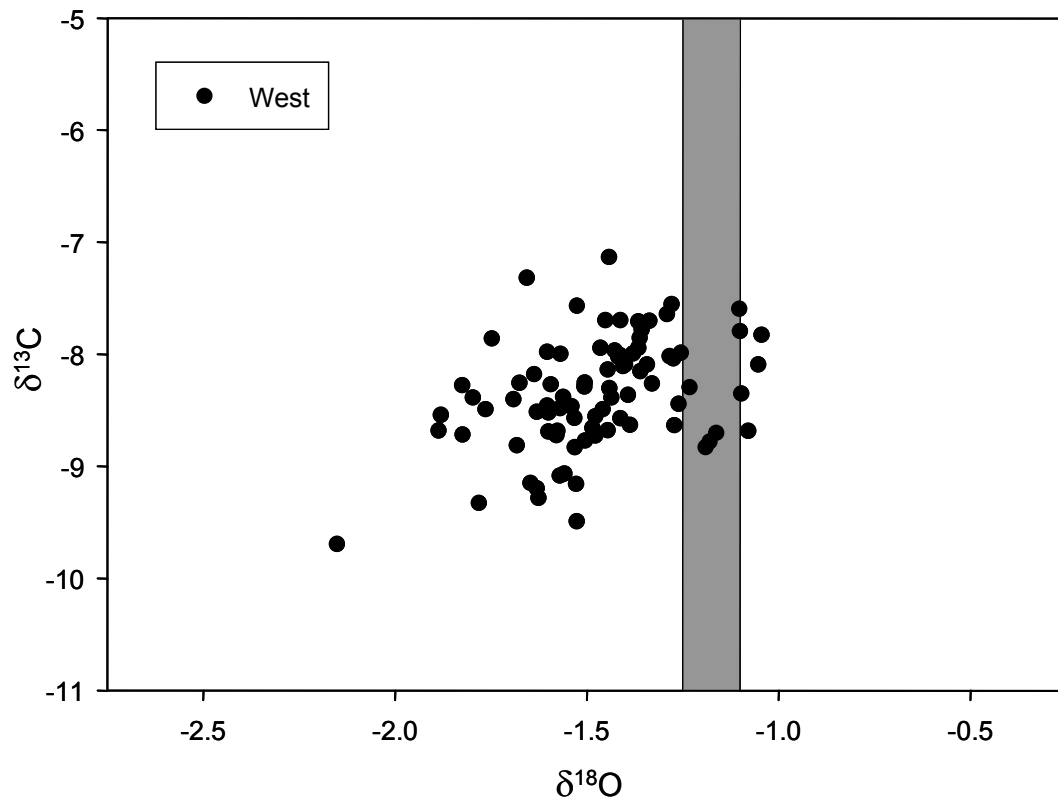


Fig. 12. $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ signatures in the otolith cores of giant *T. thynnus* collected from the eastern region of the Gulf of St. Lawrence (n= 89). Shaded region shows overlap zone of confidence ellipses (1 SD) from yearling *T. thynnus* (-1.1 to -1.25).

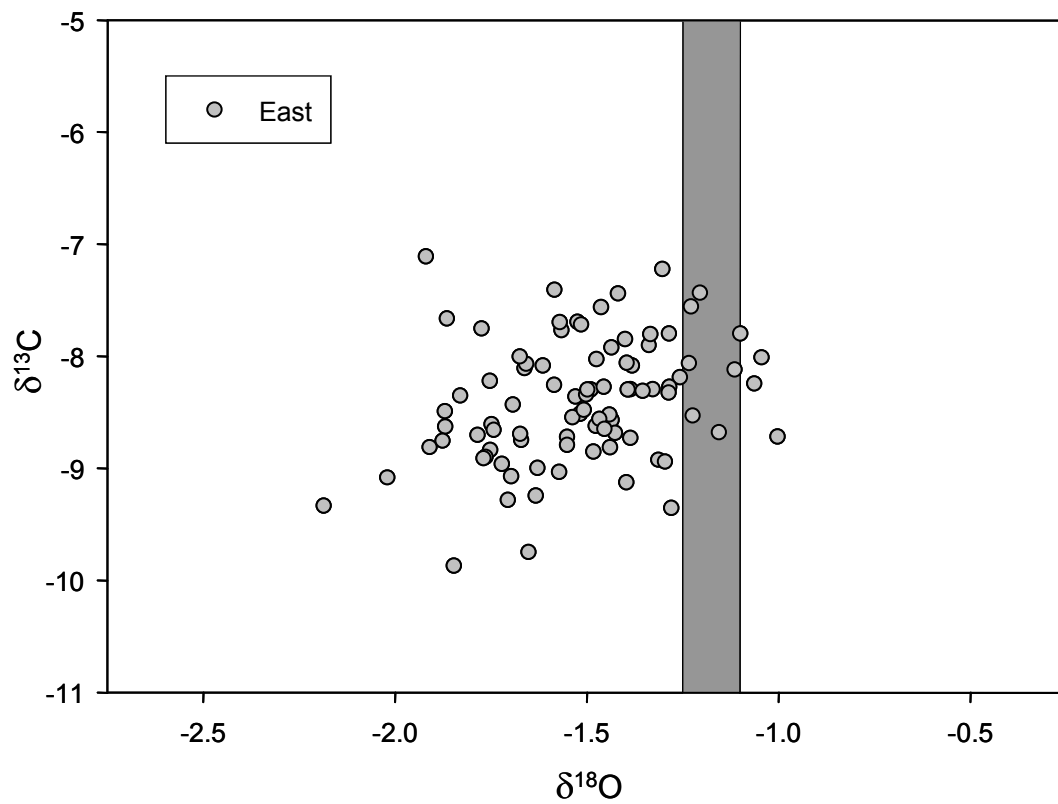


Fig. 13. $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ signatures in the otolith cores of giant *T. thynnus* collected from the exterior region of the Gulf of St. Lawrence (n= 49). Shaded region shows overlap zone of confidence ellipses (1 SD) from yearling *T. thynnus* (-1.1 to -1.25).

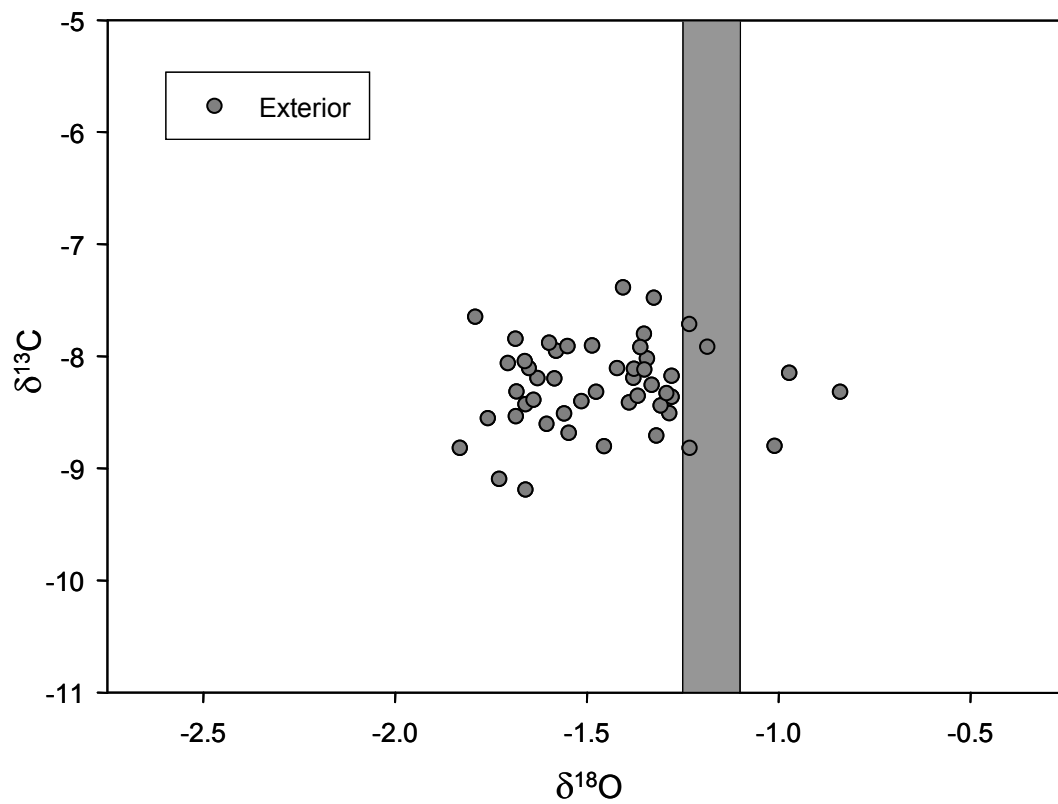


Fig. 14. Comparison of unadjusted and adjusted $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ signatures in the otolith cores of giant *T. thynnus* collected from the eastern (light grey, $n=86$), exterior (dark grey, $n=49$), and western (black, $n=89$) Gulf of St. Lawrence. Shaded region shows overlap zone of confidence ellipses (1 SD) from yearling *T. thynnus* (-1.1 to -1.25).

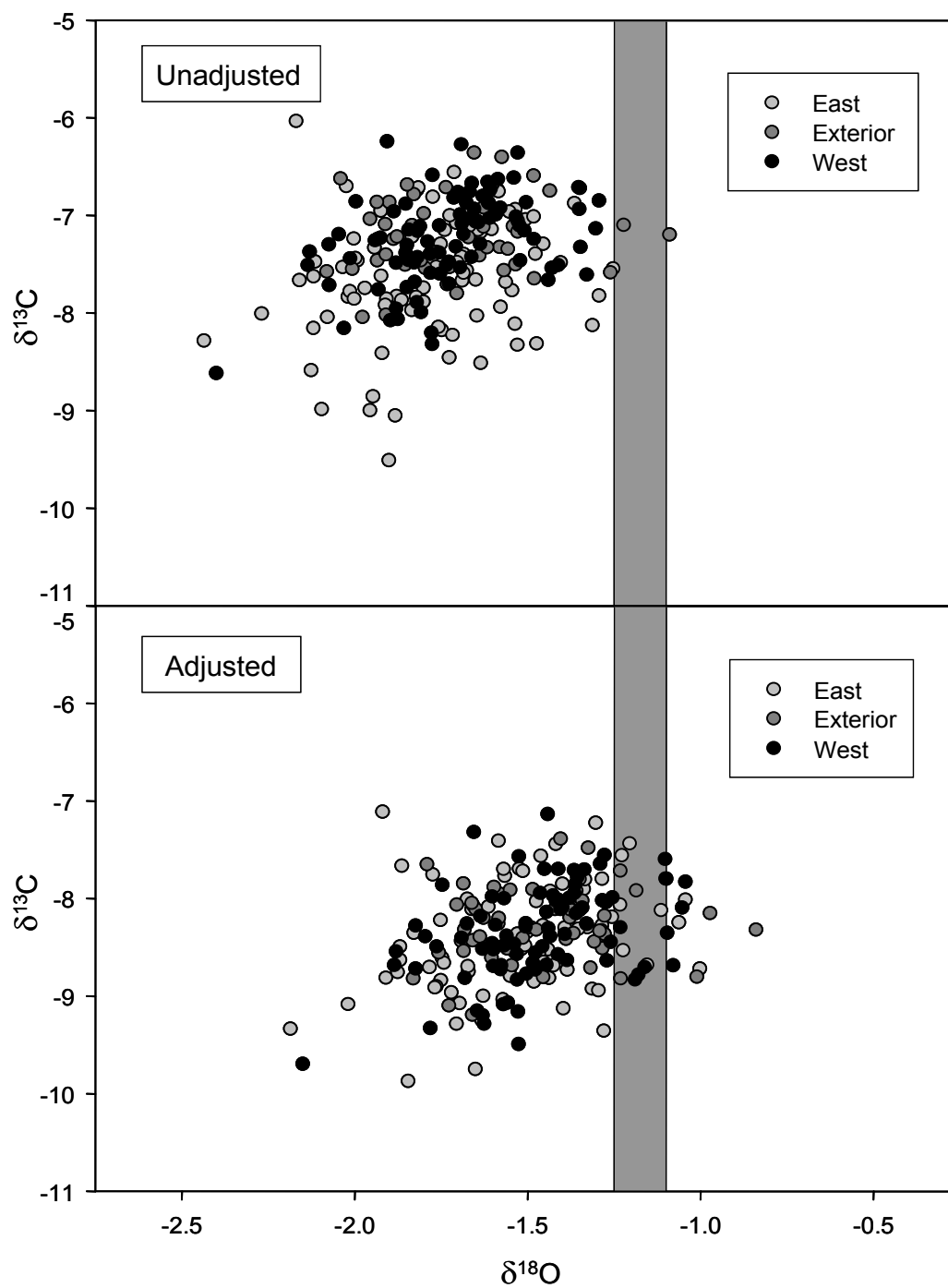


Table 4. Summary data for $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ signatures from otoliths of *T. thynnus* collected from the Gulf of St. Lawrence in the western, eastern, and exterior regions. Data includes the number of samples, minimum and maximum values, the mean value, and the standard deviation around the mean.

	West		East		Exterior		All	
	$\delta^{13}\text{C}$	$\delta^{18}\text{O}$	$\delta^{13}\text{C}$	$\delta^{18}\text{O}$	$\delta^{13}\text{C}$	$\delta^{18}\text{O}$	$\delta^{13}\text{C}$	$\delta^{18}\text{O}$
Number	86	86	89	89	49	49	224	224
Minimum	-9.75	-2.2	-9.87	-2.2	-9.16	-1.9	-9.87	-2.2
Maximum	-7.22	-0.8	-7.11	-1.0	-7.48	-1.0	-7.11	-0.8
Mean	-8.39	-1.5	-8.37	-1.5	-8.23	-1.4	-8.35	-1.5
Standard Deviation	0.52	0.2	0.50	0.2	0.42	0.2	0.49	0.2

greater than 97% in each of the three regions. Western contribution was lowest in the East GSL but still very high (97.5%, SD= 5.3%), indicating that only a small fraction (2.5%) of bluefin tuna in this region originated from the eastern nursery. Given a standard deviation around the estimated proportions of 5.3%, there was a 68% probability that the eastern contribution of bluefin tuna in the sample ranged from 0.0% to 7.8%. Similarly, the contribution of eastern Atlantic migrants to the other regions was also less than 2%; West GSL (1.3%, SD= 5.3%), Exterior GSL (0.5%, SD= 1.8%).

Discussion

Adjusted otolith core $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values showed little variation among decades and regions. The lack of differences in stable isotope signatures among decades suggest that mixing rates of bluefin tuna migrating to the Gulf of St. Lawrence have not changed during the time period covered. With over 98% of the bluefin tuna being from the western population in the Gulf of St. Lawrence, it appears that a specific migratory contingent of the western population relies on this area as a feeding ground (Rooker et al. 2007). Furthermore, otolith core $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values were similar among regions suggesting that the bluefin tuna fisheries examined in the Gulf of St. Lawrence are targeting a single contingent that migrates each year from the Gulf of Mexico spawning ground to forage in this region. Regardless, the lack of differences among regions indicates that catches from Gulf of St. Lawrence fisheries are primarily composed of the western population, with little to no mixing with the eastern population. Therefore, the

use of Gulf of St. Lawrence fisheries as an indicator of western population abundance in assessments by ICCAT appears valid (ICCAT 2006).

Isotopic signatures in the otoliths of giant bluefin tuna from the Gulf of St. Lawrence indicated these individuals were almost exclusively of western origin, which differs from estimates of exchange in the northwest Atlantic. Evidence from tagging studies has shown mixing throughout the majority of the northwest Atlantic, including important foraging grounds from the Mid-Atlantic Bight to the Scotian Shelf (Block et al. 2005; Rooker et al. 2007). Additionally, otolith chemistry results from Rooker et al. (2008b) report that trans-Atlantic movement and population mixing is significant and size dependent with a substantial number of adolescent bluefin tuna collected in the US Atlantic originating from the Mediterranean Sea. Therefore, it is not surprising that bluefin tuna in the Gulf of St. Lawrence samples were of western origin because these individuals were exclusively older, mature fish rather than adolescents. The results suggest that bluefin tuna of eastern origin do not mix with their western counterparts at the northern extent of their range in the western Atlantic.

Multiple studies have described migration routes of fishes, linking movement to specific cues. It has commonly been hypothesized that physicochemical variables (i.e. temperature) influence migration pathways of bluefin tuna (Marsac 1999; Ravier and Fromentin 2004). In addition, Dodson (1988) hypothesized that bluefin tuna may also either intrinsically follow migration routes due to imprinting (natal homing) or spatial learning through schooling experiences (repeat homing). Repeated returns of bluefin tuna to spawning grounds supports natal homing (Rooker et al. 2008b), but driving

forces for movements after spawning are poorly understood. Fromentin and Powers (2005) theorized that bluefin tuna are likely to perform repeat homing. This seems to be supported by multiple studies which show that fish are capable of learning migration paths (Helfman and Schultz 1984; Mazeroll and Montgomery 1995) and that experienced individuals can entrain behaviors in more numerous naïve fish (Laland and Williams 1997; Reeb 2000). Therefore, returns of giant bluefin tuna to the Gulf of St. Lawrence for over thirty years may be due to familiarity of the migration route by older, experienced individuals. If this hypothesis is true, further declines in the numbers of adults due to overfishing may alter migratory pathways and ultimately influence where these individuals forage as well as population dynamics of bluefin tuna in the Gulf of St. Lawrence.

There are two documented accounts of extirpating bluefin tuna from regional fishing grounds without posterior mass returns: the Nordic fishery and the Brazilian episode (Fromentin and Powers 2005, MacKenzie and Myers 2007), both of which collapsed after large catches in the 1960s. The removal of bluefin tuna that were accustomed to Nordic or Brazilian migrations would result in stopped usage of that migration route, with similar concerns placed on the Gulf of St. Lawrence. Removing key components of a population may result in population bottlenecks that can jeopardize recovery efforts (Gardmark et al. 2003). Reduced population numbers are of particular concern for the smaller western population because there are only a few known feeding grounds for western bluefin tuna. It appears likely that the Gulf of St. Lawrence serves as an essential habitat for a critical component of the western population. Consequently,

the Gulf of St. Lawrence as well as other critical habitats of bluefin tuna (i.e. Gulf of Mexico) must be protected to ensure the sustainability of this fishery and the western population.

CHAPTER IV

SUMMARY AND CONCLUSIONS

This study provides critical information on the temporal variation of stable carbon ($\delta^{13}\text{C}$) and oxygen ($\delta^{18}\text{O}$) isotopes in the western Atlantic Ocean. Using otoliths cores (representing the first year of life) from Atlantic bluefin tuna (*Thunnus thynnus*) as a proxy for ambient oceanic conditions, significant changes in both $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ signatures were shown between 1947 and 2003. The concentration of $\delta^{13}\text{C}$ in oceanic reservoirs was shown to decrease at a rate of $2.37 \times 10^{-2}\%$ per year, while the $\delta^{18}\text{O}$ concentration increased at a rate of $5.96 \times 10^{-3}\%$ per year. The depletion rate of otolith $\delta^{13}\text{C}$ was nearly identical to rates of atmospheric $\delta^{13}\text{C}$ depletion, recently attributed to the burning of fossil fuels, while the less pronounced shifts in otolith $\delta^{18}\text{O}$ were likely linked to changing physicochemical conditions.

The ability of otoliths to record these inter-decadal changes in $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ signatures highlights their potential for reconstructing past climatic and physicochemical conditions. Results also support the use of otolith chemistry as a tracer for atmospheric and oceanic stable isotope ratios, and suggest that stable isotopic ratios in fish otoliths are reflective of specific water masses. Due to temporal variation in both $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$, these natural markers must be adjusted when assessments of origin or environmental history of organisms are conducted over long periods of time (i.e. several decades).

This study also examined mixing rates of Atlantic bluefin tuna in the Gulf of St. Lawrence. After adjusting for inter-decadal trends, it was determined that nearly 100%

of bluefin tuna caught in the Gulf of St. Lawrence fishery originated from the western nursery during the time periods examined (1975-1984, 2006-2007). Therefore, giant bluefin tuna in the Gulf of St. Lawrence appear to be sustained by production from the Gulf of Mexico, with no definite mixing or subsidy of giants from the eastern stock. No significant differences were observed among the ports examined, suggesting spatial congruency in stock composition.

These results clearly show that the Gulf of St. Lawrence is a unique foraging ground comprised almost exclusively of western bluefin tuna. As a result, this region represents critical habitat of bluefin tuna spawners from the smaller, more vulnerable western population. The Gulf of St. Lawrence likely represents an important refuge for the conservation of the severely depressed western population, and controls must be put in place to reduce fishing mortality (i.e. bycatch) of adults in this region as well as their spawning ground in the Gulf of Mexico.

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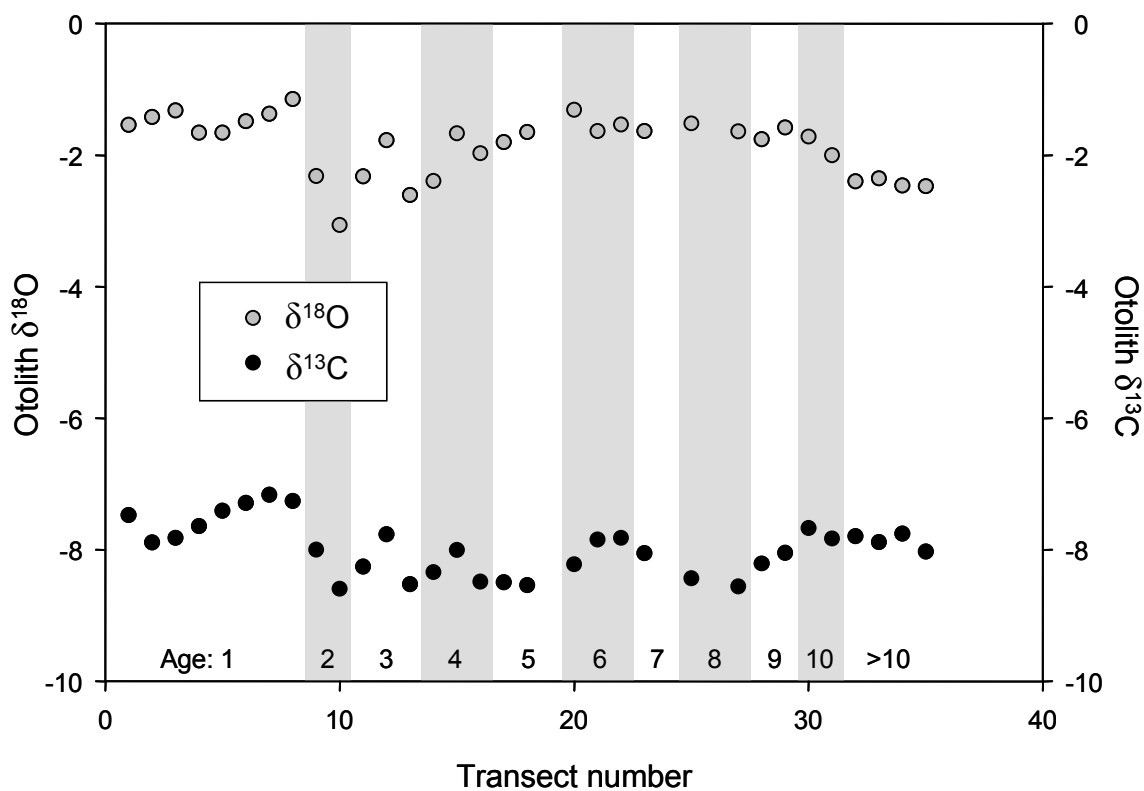
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APPENDIX A

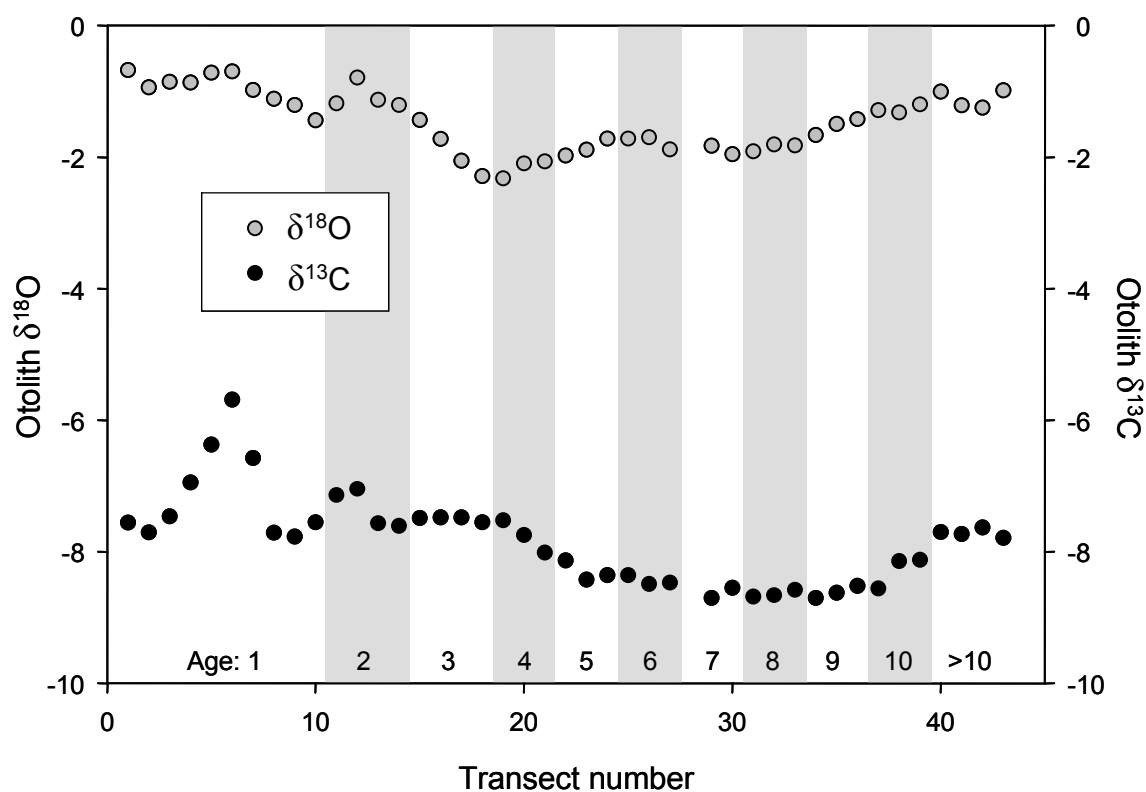
$\delta^{13}\text{C}$ AND $\delta^{18}\text{O}$ FROM LIFE HISTORY TRANSECT OF A BLUEFIN TUNA
OTOLITH FROM THE GULF OF MEXICO

Fig. A-1. Concentration of $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ sampled along annuli in the otolith of a *T. thynnus* collected in the Gulf of Mexico, emphasizing depleted $\delta^{18}\text{O}$ concentrations through age 1.



$\delta^{13}\text{C}$ AND $\delta^{18}\text{O}$ FROM LIFE HISTORY TRANSECT OF A BLUEFIN TUNA
OTOLITH FROM THE MEDITERRANEAN SEA

Fig. A-2. Concentration of $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ sampled along annuli in the otolith of a *T. thynnus* collected in the Mediterranean Sea, emphasizing enriched $\delta^{18}\text{O}$ concentrations through age 1.



APPENDIX B

**SUPPLEMENTAL DATA FOR BLUEFIN TUNA SAMPLES COLLECTED IN
THE GULF OF ST. LAWRENCE**

Table B-1. Supplemental data for *T. thynnus* samples collected in the Gulf of St. Lawrence.

Collection Site	Year Caught	Year of Birth	Age	Length (cm)	Weight (kg)	Orig. $\delta^{13}\text{C}$	Orig. $\delta^{18}\text{O}$	Adj. $\delta^{13}\text{C}$	Adj. $\delta^{18}\text{O}$
Caraquet	1976	1952	24	281.7	437.3	-8.063	-1.922	-9.282	-1.626
Caraquet	1977	1954	23	279.2	368.2	-7.371	-2.165	-8.542	-1.881
Caraquet	1977	1956	21	281.7	418.2	-7.027	-1.633	-8.150	-1.361
Caraquet	1977	1959	18	274.2	370.5	-7.760	-1.938	-8.811	-1.682
Caraquet	1977	1958	19	294.1	390.9	-7.988	-1.819	-9.064	-1.558
Caraquet	1975	1954	21		418.2	-7.659	-1.474	-8.830	-1.190
Caraquet	1978	1953	25	291.5	468.2	-6.800	-1.670	-7.995	-1.380
Caraquet	1978	1951	27	271.8	375.9	-7.479	-1.880	-8.722	-1.579
Caraquet	1978	1954	24	269.4	370.5	-7.462	-1.556	-8.633	-1.272
Caraquet	1978	1961	17	274.2	413.6	-7.712	-2.068	-8.716	-1.824
Caraquet	1978	1958	20	291.5	406.8	-7.382	-1.864	-8.457	-1.603
Caraquet	1978	1954	24	279.2	453.6	-7.599	-1.788	-8.770	-1.504
Caraquet	1978	1962	16	271.8	370.5	-6.587	-1.763	-7.567	-1.526
Caraquet	1975	1955	20		372.7	-7.255	-1.969	-8.403	-1.691
Caraquet	1979	1960	19	284.2	422.7	-7.486	-1.880	-8.513	-1.631
Caraquet	1979	1961	18	271.8	391.8	-7.012	-1.528	-8.016	-1.284
Caraquet	1979	1959	20	247.0	385.9	-7.241	-1.488	-8.293	-1.232
Caraquet	1979	1960	19	290.9	511.4	-7.697	-1.727	-8.725	-1.478
Caraquet	1975	1953	22		436.4	-7.191	-1.726	-8.386	-1.436
Caraquet	1979	1960	19	267.5	378.2	-7.322	-1.347	-8.349	-1.097
Caraquet	1979	1958	21	255.8	325.0	-7.607	-1.340	-8.683	-1.079
Caraquet	1979	1954	25	266.5	350.0	-7.318	-1.742	-8.489	-1.458
Caraquet	1979	1959	20	288.9	456.4	-7.429	-1.825	-8.480	-1.569
Caraquet	1975	1954	21		386.4	-7.396	-1.816	-8.567	-1.532
Caraquet	1975	1951	24		490.9	-7.587	-1.833	-8.830	-1.531
Caraquet	1975	1955	20		440.9	-7.104	-1.784	-8.251	-1.506
Caraquet	1975	1954	21		425.0	-8.154	-2.066	-9.325	-1.782
Caraquet	1975	1958	17		377.3	-7.476	-1.739	-8.552	-1.478
Caraquet	1976	1958	18			-6.241	-1.917	-7.316	-1.656
Caraquet	1976	1954	22			-8.317	-1.811	-9.488	-1.526
Caraquet	1976	1955	21			-7.425	-1.691	-8.572	-1.413

Caraquet	1976	1956	20			-7.144	-1.866	-8.268	-1.594
Caraquet	1976	1958	18			-8.615	-2.412	-9.691	-2.151
Caraquet	1976	1951	25			-7.953	-1.932	-9.195	-1.631
Caraquet	1976	1953	23			-7.267	-1.830	-8.462	-1.540
Caraquet	1976	1960	16			-7.228	-1.925	-8.256	-1.676
Caraquet	1976	1953	23	274.2	436.4	-7.887	-1.861	-9.082	-1.571
Caraquet	1977	1960	17	259.4	385.5	-7.458	-1.844	-8.485	-1.595
Caraquet	1977	1953	24	301.5	520.5	-7.192	-2.087	-8.387	-1.797
Caraquet	1977	1952	25	289.1	438.6	-6.959	-1.933	-8.178	-1.637
Caraquet	1977	1962	15	271.8	409.1	-7.297	-2.062	-8.277	-1.825
Caraquet	1977	1957	20	274.2	413.6	-6.867	-1.694	-7.966	-1.427
Caraquet	1977	1955	22	266.8	355.5	-7.531	-1.724	-8.679	-1.446
Havre Boucher	1981	1959	22	298.9	563.6	-6.698	-2.030	-7.750	-1.775
Havre Boucher	1981	1962	19	318.8	645.9	-7.853	-1.989	-8.833	-1.752
Havre Boucher	1981	1951	30	280.5	475.0	-7.681	-1.615	-8.924	-1.314
Havre Boucher	1981	1965	16	295.2	579.5	-7.450	-1.750	-8.359	-1.530
North Lake	1978	1959	19	253.9	327.3	-8.282	-2.441	-9.333	-2.186
North Lake	1978	1954	24	274.3	386.4	-7.544	-1.287	-8.715	-1.003
North Lake	1978	1961	17	256.8	404.5	-7.624	-2.113	-8.628	-1.869
North Lake	1978	1954	24	265.6	379.5	-7.529	-2.069	-8.700	-1.785
North Lake	1978	1957	21	274.3	433.6	-8.025	-1.664	-9.124	-1.397
North Lake	1978	1959	19	278.2	431.8	-6.714	-1.821	-7.766	-1.566
North Lake	1978	1955	23	264.6	422.7	-7.150	-1.768	-8.297	-1.490
North Lake	1978	1955	23	288.9	531.8	-7.664	-2.189	-8.811	-1.910
North Lake	1978	1953	25	289.1	509.1	-6.357	-1.569	-7.552	-1.279
North Lake	1979	1966	13	256.8	345.5	-8.983	-2.061	-9.868	-1.846
North Lake	1978	1953	25	292.8	529.5	-7.835	-1.862	-9.030	-1.572
North Lake	1979	1967	12	262.7	361.4	-6.935	-1.495	-7.796	-1.286
North Lake	1979	1954	25	270.4	463.6	-7.434	-2.032	-8.606	-1.748
North Lake	1979	1956	23	288.9	495.5	-7.774	-2.037	-8.897	-1.764
North Lake	1979	1958	21	301.6	438.6	-6.033	-2.181	-7.109	-1.920
North Lake	1979	1960	19	283.1	363.6	-6.998	-1.725	-8.025	-1.475
North Lake	1979	1966	13	270.0	297.7	-6.808	-1.740	-7.692	-1.525
North Lake	1979	1968	11	254.9	327.3	-7.882	-1.755	-8.719	-1.552
North Lake	1979	1962	17	272.4	334.1	-7.238	-1.991	-8.218	-1.753
North Lake	1979	1961	18	285.0	413.6	-7.078	-1.626	-8.082	-1.382
North Lake	1980	1959	21	272.4	345.5	-7.011	-1.488	-8.063	-1.233
North Lake	1975	1955	20		350.0	-7.040	-1.535	-8.188	-1.257
North Lake	1975	1954	21		400.0	-7.767	-1.580	-8.938	-1.296
North Lake	1975	1953	22		386.4	-7.077	-1.746	-8.272	-1.456
North Lake	1975	1953	22		382.3	-7.078	-1.575	-8.273	-1.285
North Lake	1975	1956	19		353.2	-7.171	-1.659	-8.295	-1.387
North Lake	1975	1955	20		436.4	-7.149	-1.672	-8.296	-1.393
North Lake	1975	1954	21		359.1	-6.731	-1.623	-7.902	-1.338
North Lake	1975	1952	23		354.5	-7.742	-2.017	-8.961	-1.721
North Lake	1975	1954	21		352.7	-7.344	-1.802	-8.515	-1.518
North Lake	1975	1954	21		370.5	-7.396	-1.719	-8.567	-1.435
North Lake	1975	1955	20		400.0	-7.704	-1.761	-8.851	-1.483

North Lake	1975	1959	16		361.4	-6.750	-1.590	-7.802	-1.335
North Lake	2006	1992	14	250.0	253.6	-6.960	-1.367	-7.223	-1.303
North Lake	1976	1955	21	267.0	356.4	-7.665	-1.718	-8.812	-1.439
North Lake	1976	1960	16	269.5	384.5	-8.325	-1.529	-9.353	-1.280
North Lake	1976	1959	17	274.3	419.1	-7.291	-1.757	-8.343	-1.502
North Lake	1976	1961	15	279.2	420.0	-6.556	-1.706	-7.560	-1.463
North Lake	2006	1997	9	204.3	140.5	-7.289	-1.240	-7.433	-1.205
North Lake	2006	1995	11	228.6	182.3	-7.473	-1.911	-7.664	-1.865
North Lake	1976	1956	20	295.7	517.7	-7.562	-1.699	-8.685	-1.426
North Lake	1976	1954	22	281.6	422.7	-7.826	-1.913	-8.998	-1.629
North Lake	1976	1951	25	291.4	518.2	-6.875	-1.416	-8.117	-1.115
North Lake	2007	1996	11	236.4	201.4	-7.390	-1.269	-7.557	-1.228
North Lake	2007	1994	13	246.1	265.5	-8.109	-1.339	-8.324	-1.287
North Lake	1976	1957	19	279.2	422.7	-7.421	-1.708	-8.520	-1.441
North Lake	1976	1958	18	266.5	370.9	-6.721	-1.361	-7.796	-1.100
North Lake	1976	1959	17	254.9	325.0	-7.492	-1.793	-8.543	-1.538
North Lake	2007	1998	9	211.1	268.6	-8.176	-1.528	-8.295	-1.499
North Lake	2007	1996	11	236.4	205.5	-8.586	-1.917	-8.753	-1.876
North Lake	2007	1989	18	266.5	274	-8.142	-1.589	-8.477	-1.508
North Lake	2006	1989	17	262.7	380.5	-7.587	-1.517	-7.922	-1.436
North Lake	2007	1998	9	208.2	214	-8.125	-1.092	-8.244	-1.063
North Lake	2006	1988	18	266.5	326.8	-7.935	-1.415	-8.294	-1.328
North Lake	2007	1989	18	264.6	281.4	-8.410	-1.752	-8.744	-1.671
North Lake	2007	1991	16	257.8	348.6	-8.995	-1.776	-9.281	-1.706
North Lake	2007	1994	13	248.1	290.9	-8.855	-1.750	-9.070	-1.697
North Lake	2007	1996	11	232.5	218.2	-8.454	-1.518	-8.622	-1.477
North Lake	2007	1991	16	257.8	265	-7.968	-1.655	-8.255	-1.585
North Lake	2007	1994	13	247.1	300.0	-7.866	-1.667	-8.081	-1.615
North Lake	2007	1990	17	262.7	328.6	-8.040	-1.905	-8.351	-1.830
North Lake	2007	1995	12	240.3	247	-9.050	-1.680	-9.241	-1.633
North Lake	2007	1993	14	250.0	270.0	-9.507	-1.710	-9.746	-1.652
North Lake	2007	1995	12	242.2	253.2	-7.525	-1.561	-7.716	-1.515
North Lake	2006	1995	11	227.6	182.3	-7.819	-1.091	-8.010	-1.044
North Lake	2006	1989	17	260.7	313.2	-7.106	-1.500	-7.440	-1.419
North Lake	2007	1995	12	237.4	204.1	-7.917	-1.709	-8.108	-1.662
North Lake	2007	1989	18	264.6	295.9	-8.223	-1.549	-8.558	-1.467
North Lake	2007	1994	13	247.1	260.5	-8.512	-1.439	-8.727	-1.386
North Lake	2007	1989	18	264.6	304.0	-8.154	-1.951	-8.489	-1.870
North Lake	2006	1995	11	233.5	235.9	-7.216	-1.631	-7.408	-1.585
North Lake	2006	1994	12	240.3	230.9	-8.313	-1.277	-8.528	-1.224
North Lake	2006	1994	12	243.2	236.8	-7.852	-1.710	-8.067	-1.658
North Lake	2006	1995	11	236.4	229.1	-7.658	-1.446	-7.849	-1.400
North Lake	1977	1958	19	287.9	422.7	-7.618	-1.935	-8.694	-1.674
North Lake	1977	1953	24	271.4	442.3	-7.481	-1.445	-8.676	-1.155
North Lake	1977	1957	20	268.5	410.9	-7.330	-1.959	-8.430	-1.693
North Lake	1977	1958	19	261.7	413.2	-8.006	-2.281	-9.081	-2.020
North Lake	1977	1953	24	267.5	440.9	-7.461	-2.033	-8.656	-1.743
North Lake	1977	1958	19	276.3	406.8	-7.833	-2.030	-8.909	-1.769

North Lake	1977	1954	23	259.7	388.6	-7.477	-1.738	-8.648	-1.454
North Lake	1977	1963	14	271.4	434.1	-6.737	-1.802	-7.693	-1.570
North Lake	1977	1959	18	267.5	427.7	-7.740	-1.806	-8.792	-1.551
North Lake	1977	1959	18	269.5	445.9	-6.950	-1.930	-8.002	-1.675
North Lake	1977	1954	23	256.8	409.1	-7.139	-1.639	-8.310	-1.354
North Lake	1977	1961	16	258.8	411.8	-7.056	-1.640	-8.060	-1.396
St. Margarets Bay	1978	1962	16	257.8	361.4	-6.863	-1.924	-7.843	-1.686
St. Margarets Bay	1978	1954	24	272.4	469.1	-7.646	-1.516	-8.818	-1.232
St. Margarets Bay	1978	1955	23	259.7	326.8	-7.560	-1.597	-8.708	-1.319
St. Margarets Bay	1978	1956	22	261.7	355.0	-6.591	-1.506	-7.714	-1.233
St. Margarets Bay	1978	1958	20	275.3	364.1	-6.945	-1.604	-8.020	-1.343
St. Margarets Bay	1975	1951	24	254.9	350.0	-7.574	-2.133	-8.817	-1.831
St. Margarets Bay	1978	1961	17	283.1	446.8	-7.409	-1.633	-8.413	-1.390
St. Margarets Bay	1978	1960	18	258.3	375.0	-7.325	-1.617	-8.353	-1.368
St. Margarets Bay	1978	1962	16	259.7	352.3	-7.217	-1.866	-8.197	-1.628
St. Margarets Bay	1978	1959	19	254.9	362.3	-7.460	-1.814	-8.512	-1.559
St. Margarets Bay	1978	1953	25	255.8	431.8	-7.166	-1.569	-8.361	-1.279
St. Margarets Bay	1978	1961	17	254.9	375.0	-7.502	-1.528	-8.506	-1.285
St. Margarets Bay	1979	1957	22	292.8	477.3	-7.340	-1.575	-8.440	-1.308
St. Margarets Bay	1979	1954	25	282.1	463.2	-6.781	-1.864	-7.952	-1.580
St. Margarets Bay	1979	1953	26	278.2	407.3	-6.684	-1.888	-7.879	-1.598
St. Margarets Bay	1979	1959	20	282.1	433.2	-8.041	-1.984	-9.092	-1.728
St. Margarets Bay	1980	1956	24	287.9	510.0	-6.677	-1.624	-7.800	-1.351
St. Margarets Bay	1980	1961	19	274.3	452.3	-7.797	-1.699	-8.801	-1.455
St. Margarets Bay	1980	1958	22	266.5	450.0	-7.239	-1.944	-8.315	-1.683
St. Margarets Bay	1981	1954	27		265.9	-6.748	-1.644	-7.919	-1.360
St. Margarets Bay	1981	1964	17	262.7	456.8	-6.978	-1.777	-7.910	-1.551
St. Margarets Bay	1981	1960	21	251.0	420.5	-7.036	-1.955	-8.063	-1.706
St. Margarets Bay	1981	1970	11	234.4	270.5	-7.527	-1.667	-8.316	-1.476
St. Margarets Bay	1981	1960	21	271.4	404.5	-6.357	-1.655	-7.385	-1.405
St. Margarets Bay	1976	1957	19	257.8	231.8	-7.505	-1.872	-8.604	-1.605
St. Margarets Bay	1976	1956	20	264.6	238.6	-7.052	-1.551	-8.176	-1.279
St. Margarets Bay	1976	1954	22	264.6	365.9	-6.747	-1.470	-7.918	-1.186
St. Margarets Bay	1976	1953	23	261.7	337.7	-6.710	-1.776	-7.905	-1.486
St. Margarets Bay	1976	1958	18	267.5	411.8	-7.116	-1.639	-8.191	-1.378

St. Margarets Bay	1976	1951	25	265.6	372.7	-6.863	-1.953	-8.105	-1.651
St. Margarets Bay	1975	1958	17	262.7	295.5	-6.402	-1.586	-7.478	-1.325
St. Margarets Bay	1975	1960	15	253.9	256.8	-7.375	-1.764	-8.402	-1.514
St. Margarets Bay	1977	1956	21	275.3		-7.195	-1.112	-8.318	-0.840
St. Margarets Bay	1977	1963	14	262.7	328.2	-7.088	-1.894	-8.044	-1.662
St. Margarets Bay	1977	1959	18	258.8	375.0	-7.096	-1.228	-8.147	-0.973
St. Margarets Bay	1977	1966	11	239.3	272.7	-7.222	-1.636	-8.106	-1.421
St. Margarets Bay	1977	1964	13	251.5	320.5	-7.324	-1.557	-8.256	-1.331
St. Margarets Bay	1977	1957	20	252.9	325.0	-7.098	-1.851	-8.198	-1.584
St. Margarets Bay	1975	1952	23	261.7	314.5	-7.110	-1.588	-8.329	-1.292
St. Margarets Bay	1977	1954	23	285.0	480.5	-8.017	-1.944	-9.189	-1.660
St. Margarets Bay	1977	1958	19	262.7	383.2	-7.460	-1.946	-8.535	-1.685
St. Margarets Bay	1977	1953	24	270.4	331.8	-6.917	-1.667	-8.112	-1.377
St. Margarets Bay	1977	1955	22	279.2	487.7	-7.537	-1.825	-8.684	-1.547
St. Margarets Bay	1977	1960	17	291.4	460.9	-7.400	-1.909	-8.427	-1.660
St. Margarets Bay	1977	1960	17	262.7	350.9	-6.620	-2.041	-7.648	-1.791
St. Margarets Bay	1977	1961	16	262.7	390.0	-7.547	-2.001	-8.551	-1.758
St. Margarets Bay	1977	1952	25	252.9	299.1	-7.581	-1.307	-8.800	-1.011
St. Margarets Bay	1976	1955	21	245.1	351.8	-7.241	-1.917	-8.388	-1.639
St. Margarets Bay	1975	1954	21	290.9	522.7	-6.946	-1.634	-8.117	-1.350
Tignish	1982	1962	20	268.5	400.0	-6.872	-1.600	-7.852	-1.362
Tignish	1982	1960	22	270.4	361.4	-7.064	-1.650	-8.092	-1.400
Tignish	1982	1959	23	271.4	370.5	-6.726	-1.612	-7.778	-1.357
Tignish	1982	1958	24	280.2	331.8	-6.626	-1.598	-7.702	-1.337
Tignish	1982	1957	25	287.9	454.5	-6.990	-1.610	-8.090	-1.343
Tignish	1982	1967	15	254.9	368.2	-6.272	-1.651	-7.132	-1.442
Tignish	1982	1963	19	269.5	352.3	-7.133	-1.285	-8.089	-1.053
Tignish	1983	1954	29	264.6	390.5	-7.509	-2.170	-8.680	-1.886
Tignish	1983	1950	33	280.7	421.8	-7.113	-1.869	-8.380	-1.562
Tignish	1983	1949	34	277.2	402.3	-7.071	-1.706	-8.361	-1.393
Tignish	1983	1955	28	280.2	424.1	-6.989	-1.724	-8.137	-1.446
Tignish	1983	1953	30	253.9	297.7	-7.508	-1.452	-8.703	-1.162
Tignish	1983	1952	31	286.0	485.5	-7.084	-1.736	-8.303	-1.441
Tignish	1983	1958	25	272.4	430.0	-8.072	-1.908	-9.148	-1.647
Tignish	1983	1964	19	285.5	414.5	-7.104	-1.501	-8.036	-1.274
Tignish	1983	1952	31	288.9	421.4	-7.302	-1.896	-8.520	-1.600
Tignish	1983	1950	33	281.1	421.8	-6.757	-1.725	-8.024	-1.418
Tignish	1983	1956	27	274.3	358.6	-6.864	-1.527	-7.987	-1.255
Tignish	1983	1964	19	279.7	412.7	-6.762	-1.678	-7.694	-1.452

Tignish	1983	1957	26	270.4	363.6	-6.880	-1.870	-7.979	-1.603
Tignish	1983	1961	22	283.6	428.2	-7.681	-1.821	-8.685	-1.577
Tignish	1983	1956	27	272.4	362.7	-6.819	-1.737	-7.942	-1.464
Tignish	1983	1963	20	269.5	388.2	-8.202	-1.760	-9.158	-1.528
Tignish	1983	1949	34		414.1	-7.153	-1.573	-8.444	-1.260
Tignish	1983	1959	24	262.7	373.2	-6.656	-1.621	-7.707	-1.366
Tignish	1983	1961	22	273.8	374.1	-6.857	-1.991	-7.861	-1.747
Tignish	1983	1951	32	288.9	464.1	-7.536	-1.482	-8.779	-1.180
Tignish	1983	1960	23	293.8	429.5	-6.613	-1.540	-7.640	-1.291
Tignish	1983	1962	21	272.4		-6.848	-1.282	-7.828	-1.044
Tignish	1983	1947	36	270.4	335.9	-7.292	-1.712	-8.630	-1.387
Tignish	1983	1962	21	299.6	527.3	-7.028	-1.651	-8.008	-1.414
Tignish	1983	1960	23	298.2	443.6	-6.668	-1.662	-7.695	-1.412
Tignish	1983	1963	20	288.4	442.3	-7.733	-1.832	-8.689	-1.600
Tignish	1983	1955	28	279.2	417.3	-7.510	-1.763	-8.657	-1.485
Tignish	1983	1954	29	265.6	427.3	-6.935	-1.689	-8.106	-1.405
Tignish	1983	1958	25	272.4	464.5	-6.866	-1.626	-7.942	-1.365
Tignish	1983	1959	24	269.5	381.8	-7.438	-2.019	-8.489	-1.764
Tignish	1983	1947	36	257.8	402.7	-6.921	-1.655	-8.260	-1.330
Tignish	1984	1968	16	256.8	462.3	-7.159	-1.772	-7.996	-1.569
Tignish	1984	1966	18	266.5	424.1	-6.709	-1.317	-7.594	-1.103
Tignish	1984	1965	19	269.5	452.7	-7.380	-1.727	-8.288	-1.506
Tignish	1984	1967	17	262.7	395.9	-6.933	-1.310	-7.794	-1.101

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