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Growth Patterns of Three Species of Catfish (Ictaluridae) from Three Virginia Tributaries of the Chesapeake Bay

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GROWTH PATTERNS OF THREE SPECIES OF CATFISH (ICTALURIDAE) FROM THREE VIRGINIA TRIBUTARIES OF THE CHESAPEAKE BAY

A Thesis Presented to
The Faculty of the School of Marine Science
The College of William and Mary

In Partial Fulfillment of the
Degree Requirements for the Degree of
Master of Science

by
William John Connelly
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This thesis is submitted in partial fulfillment of
the requirements for the degree of
Master of Science

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Dedication

I would like to dedicate this thesis to my parents, William and Shirley Connelly, who introduced me to the wonderful world of fishes and have always given me everything I could ever possibly need to pursue my interests and dreams.
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  love is the voice under all silences,
  the hope which has no opposite in fear;
  the strength so strong mere force is feebleness:
  the truth more first than sun more last than star
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Abstract

Blue catfish (*Ictalurus furcatus*) were introduced into the James, Rappahannock, and York rivers during the 1970s and 1980s to enhance sportfishing in these rivers. Since 1991, annual catch rates of blue catfish by the VIMS Trawl Survey have increased exponentially. Meanwhile, annual catch rates of the naturalized channel catfish (*Ictalurus punctatus*) and the native white catfish (*Ameiurus catus*) have declined. The growth patterns recorded by calcified structures of each species were thought to contain information regarding connections between the increasing blue catfish populations and the decreasing populations of channel and white catfishes.

North American catfishes are traditionally aged from sections cut from the pectoral spine; however, there are a number of problems with this technique that can lead to inaccurate age estimations. Otolith sections were examined to determine if they would be a suitable alternative. Otolith radius increased with both length and age of blue, channel, and white catfishes. Otolith annuli were deposited once a year between June and August for all three species. Within- and between-reader precision were higher for otolith sections than for pectoral spine sections. No significant, systematic biases were detected within readers for all three structures for each species, but a significant bias was detected between the two readers for all three structures for blue catfish. Reader 2 consistently produced lower age estimates than Reader 1 for blue catfish otolith, articulating process (alternative pectoral spine section), and basal recess (traditional pectoral spine section) sections. This trend existed for the other two species, but there was not enough statistical power to detect this trend due to low sample sizes. Finally, age estimates determined by each reader from otolith sections of all three species were consistently higher than those produced from either pectoral spine sections. In all, estimating age from otolith sections proved to be a superior alternative method for aging blue, channel, and white catfishes.

Somatic and otolith growth patterns were compared across species, sexes, and rivers. Male and female somatic and otolith growth curves were indistinguishable for all three species. Catfishes from the York River system tended to have the fastest somatic and otolith growth rates, while catfishes from the Rappahannock River tended to have the slowest.

Otolith growth increments were analyzed in an attempt to reveal patterns in the interannual variations in growth rates, which may be related to environmental variations, for each species. However, within-year variation in growth was much larger than between-year variation in growth for each species; therefore, no connections with environmental fluctuations could be established.
GROWTH PATTERNS OF THREE SPECIES OF CATFISH (ICTALURIDAE) FROM THREE VIRGINIA TRIBUTARIES OF THE CHESAPEAKE BAY
General Introduction

**Catfishes in Virginia Tributaries of the Chesapeake Bay**

Several species of large (>250mm maximum total length) catfishes (Ictaluridae) inhabit the tidal James, Rappahannock, and York rivers (Figure 1) including white catfish (*Ameiurus catus*), yellow bullhead (*Ameiurus natalis*), brown bullhead (*Ameiurus nebulosus*), blue catfish (*Ictalurus furcatus*), channel catfish (*Ictalurus punctatus*), and flathead catfish (*Pylodictus olivaris*). Only the white catfish, yellow bullhead, and brown bullhead are native species. The Virginia Department of Game and Inland Fisheries (VDGIF) introduced juvenile blue catfish into the James River in 1975, 1985, and 1989; the Rappahannock River in 1974, 1975, and 1977; and the Mattaponi River in 1985 to provide additional sportfishing opportunities in these rivers (VDGIF 1974; VDGIF 1977; VDGIF 1985; VDGIF 1989; Jenkins and Burkhead 1994). In 1994, blue catfish were discovered in the Pamunkey River by the Virginia Institute of Marine Science (VIMS) Juvenile Finfish and Blue Crab Trawl Survey (Land et al. 1995). Blue catfish have become established in all three rivers (Jenkins and Burkhead 1994). Channel catfish were introduced into the James, Rappahannock, and York Rivers in the 1890s, and also have become widely distributed in all three rivers (Jenkins and Burkhead 1994). Flathead catfish were both accidentally and intentionally introduced into the tidal James River from 1965-1977 and have
Figure 1. Map of study area.
become established only in a small area near Richmond (Jenkins and Burkhead 1994). Of the previously mentioned catfishes, the VIMS Trawl Survey and the VIMS Juvenile Striped Bass Seine Survey catch only blue, channel, and white catfishes on a regular basis.

Ecological Characteristics for Blue, Channel, and White Catfishes

Blue, channel, and white catfishes inhabit the James, Rappahannock, and York Rivers from the fall line to the mesohaline portions of each river. White and channel catfishes are also found above the fall line of each river. Blue catfish have been observed in waters with salinities of up to 11.4psu (Jenkins and Burkhead 1994), and lab experiments have shown that blue catfish can survive in salinities as high as 14.0psu (Allen and Avault 1971). The VIMS Trawl Survey has caught only two blue catfish in salinities exceeding 11.4psu (Figure 2). Musick (1972) reported finding channel catfish in portions of Chesapeake Bay tributaries where salinities were as high as 15.1psu, but six channel catfish have been caught in higher salinities by the VIMS Trawl Survey since that time (Figure 2). White catfish in North Carolina have been found in salinities as high as 27psu and 14.5psu in Maryland (Schwartz and Jachowski 1965; Schwartz 1981). In Virginia, white catfish have been caught in salinities of up to 22psu (Figure 2).

Channel catfish spawn when water temperatures range between 21°C and 30°C (Hubert 1999; Murdy et al. 1997; Jenkins and Burkhead 1994), and Menzel (1945) found that peak spawning occurs from late June to early July in the James River. Clemens (1968) stated that blue catfish and channel catfish spawn at
Figure 2. Loess-smoothed (span = 0.3) distributions of catches for each catfish species by the VIMS Trawl Survey from all rivers combined versus surface salinity at the time of catch.
similar water temperatures. Males of both species construct nests in cavities, such as those found near submerged logs, rootwads, and undercut banks, and males guard the eggs and young until the offspring leave the nest.

Minimum spawning temperature for white catfish is 21°C, and spawning occurs in Virginia from late May into July (Jenkins and Burkhead 1994). Both sexes construct the nest, which is about 1m in diameter and 0.5m deep, in sand or gravel, and eggs are guarded and fanned by one or both parents (Jenkins and Burkhead 1994).

Changes in Abundance of Three Species of Catfishes

Catch rates of blue catfish by the VIMS Trawl Survey in the James and Rappahannock Rivers were low and sporadic during the late 1970s and throughout the 1980s; however, commercial fishermen caught large as well as small blue catfish in the tidal freshwater portions of these rivers throughout the 1980s (Jenkins and Burkhead 1994). During the 1990s, the annual catch rate of juvenile blue catfish in the James and Rappahannock Rivers increased exponentially (Figure 3). The regressions shown in Figure 3 were calculated using only those stations sampled consistently from April to November since 1991. Since the effort was constant each year, the data shown represents an “annual catch rate.” Monthly catches of blue catfish by the VIMS Trawl Survey in the Pamunkey River, however, are still fewer than one per trawl per month. Currently, the Mattaponi River is not sampled by the VIMS Trawl Survey, so data concerning changes in abundance of blue catfish in this river are unavailable.
Total* Annual Catches (April-November) of Blue Catfish by the VIMS Trawl Survey

Figure 3. Annual catches of blue catfish by the VIMS Trawl Survey in the Rappahannock and James Rivers.

*Totals were calculated using only the catches from April to November and only those stations which were sampled consistently since 1991.
Catch rates of channel and white catfishes by the VIMS Trawl Survey have also changed during the past decade (Figure 4). The data portrayed in Figure 4 was calculated in a similar manner to that of Figure 3 and illustrates three changes in the catch rates of both channel and white catfishes: decrease in mean annual catch, reduced variance in mean annual catch, and decline in catches of both species. The reduced mean and variance in catches since 1991 is due in part to a change in the trawl gear. Starting in 1991, smaller trawl doors were used, which resulted in a smaller net opening. However, the persistent decline in catches of both species since 1991 is not the result of gear changes since no changes in gear or effort have been made since 1991. Thus, the declining catch rates of channel and white catfishes implies declining abundance of each species.

Implications of Exotic Introductions

The exponential growth of the blue catfish populations in the Rappahannock and James Rivers is typical of that of many introduced species, both aquatic and terrestrial (Adams and Maitland 1998; Lensink 1998). The interval between the introduction of blue catfish and their consistent presence in VIMS Trawl Survey catches may represent the time required for these populations to grow large enough to be observed by this type of survey. Alternatively, conditions for rapid population growth of this species may not have been present until the 1990s (Moyle and Light 1996).
Figure 4. Time-series of annual catches of channel and white catfishes by the VIMS Trawl Survey. Smaller trawl doors were used starting in 1991. *Totals were calculated using only the catches from April to November and only those stations which were sampled consistently since 1982.
The introduction of non-native species carries a multitude of potential consequences that may cascade through the ecosystem (Lasenby et al. 1986; Spencer et al. 1991; Hale et al. 1995). By acting as new nodes in the food web, successfully introduced exotic species alter the energy flow through the food web, which may restructure the community (Lasenby et al. 1986; Spencer et al. 1991; Hale et al. 1995). Competition between exotic and native species may lead to reduced growth rates of the native species (Werner 1986). In addition to altering the food web and reducing growth rates of native species, introduced species may affect reproductive success of the native species present. In aquatic environments, competition for food and spawning areas may result in reduced egg quality or fecundity (Scott 1962; Bagenal 1969; Rothschild 1986; Hale et al. 1995; Brooks et al. 1997) for native species, and offspring survival may be impaired due to high predation rates or starvation (Crowder 1980; Kohler and Ney 1980; Anderson 1988; Houde and Zastrow 1993; Sogard 1997).

**Growth Records**

The otolith of a fish contains not only a record of the age of a fish, but also a detailed account of the quality of the growing conditions during the life of the fish. Both the age of the fish and the quality of the environment in which the fish lives affect somatic and otolith growth (Weisberg 1986; Weisberg and Frie 1987; Weisberg 1993; DeVries and Frie 1996). Fish grow rapidly during periods of favorable environmental conditions, and this rapid growth is mirrored by the addition of a wide increment in the otolith of the fish (Weisberg 1986; Weisberg
and Frie 1987; Weisberg 1993; DeVries and Frie 1996). In unfavorable conditions, fish grow slower and the increment added to the otolith is narrower (Weisberg 1986; Weisberg and Frie 1987; Weisberg 1993). By combining environmental and ecological data with growth increment (width) measurements from the otoliths of a fish, the growing conditions experienced by that fish can be quantitatively, or at least qualitatively, described. Furthermore, trends in the growth rates calculated from otolith increment measurements may be explained by trends in biotic and abiotic environmental variables (LeBreton and Beamish 2000; LeBreton et al. 1999; Guyette and Rabeni 1995; Putman et al. 1995; Rutherford et al. 1995). Thus, otoliths provide information on past growing conditions that may otherwise be unobtainable.

**Aging Catfish**

The ictalurid catfishes are traditionally aged from a section taken from the pectoral spine (Sneed 1951); however, there are problems associated with this technique, including erosion of early annuli and presence of false rings, that may result in inaccurate age estimations (Marzolf 1955). Using alternative spine sections (Turner 1982) eliminates the problems associated erosion of early annuli, but several other problems, including presence of false rings, may still prevent accurate age estimation. However, accurate age estimations for many species of fishes can be obtained by examining sections from the otoliths of fishes (DeVries and Frie 1996), and examining otolith sections may prove to be a more suitable method for aging ictalurid catfishes.
Objectives

The presence of a newly introduced catfish species in the same habitats as a naturalized exotic species and a native species, all of which are from the same family, provides a unique opportunity to study the interannual variations in growth of several related species experiencing similar environmental conditions. Furthermore, few studies have been published concerning the growth of any ictalurid species in estuarine environments (Schwartz and Jachowski 1965; Kelley, Jr. and Carver 1966; Hughes and Carlson 1986). Conditions in the Chesapeake Bay and its tributaries, while conducive to high productivity, are highly variable, even on a diurnal scale. Coping with such variability requires energy that might otherwise be available for growth, and it is not known how catfish growth rates under estuarine conditions compare to those in other environments. Finally, aging catfish from the traditional pectoral spine section location has limitations, and the utility of aging catfish from otoliths and alternative pectoral spine sections has not been adequately addressed for all three species. Therefore, this study has four objectives:

1. To validate otoliths as an accurate record for aging blue, channel, and white catfishes;

2. To compare pectoral spine sections and otolith sections for use in age determination;

3. To examine patterns in catfish growth rates (variation among species, years, rivers, sexes, etc);

4. To evaluate relationships between catfish growth and environmental variables (temperature, salinity, precipitation, abundance, etc).
Chapter 1

Validation of Otoliths, Calcified Structure Comparisons, and Other Biological Information
**Introduction**

**Using Calcified Structures for Aging Fish**

During the 1890s, fisheries scientists observed a strong relationship between the concentric rings (annuli) on fish scales and the age of a fish. The growth rate of a fish could also be estimated by measuring the distance between each annulus. Furthermore, scales are easy to collect, and removing a few scales leaves the fish relatively unharmed. Researchers eventually discovered problems with using scales to age some fishes, such as the occurrence of false annuli, scale erosion, scale regeneration, and resorption of scales during times of stress, all of which prevent accurate aging (DeVries and Frie 1996).

Currently, fisheries scientists use a variety of hard parts for aging fish, all of which have their respective advantages and disadvantages. Heincke (1904) was one of the first researchers to use vertebrae, and many others have followed suit (Appelgate and Smith 1951; Marzolf 1955). However, collecting vertebrae requires killing the fish and mutilating the carcass, which may be undesirable if samples are taken from rare species or from commercial sources. Vertebrae also require much preparation before reading and often contain false annuli (Appelgate and Smith 1951; Marzolf 1955). Opercular bones have also been used for aging, but these bones have the same disadvantages as vertebrae. Fin rays and spines can be removed without excessive harm to a fish, but these
structures are exposed to the environment and may display false annuli and erosion. Fin rays are also very difficult to section due to their small size. Fin spines are typically vascularized, and the early annuli are lost because the central blood vessel grows as the fish grows (Brothers 1983). As the fish grows, the lumen (hollow center) of the spine expands to accommodate the widening blood vessel. Expansion of the lumen consumes the early annuli. Furthermore, all bones may be resorbed during times of stress.

Otoliths, or ear stones, are structures in the inner ear of fish that are used for hearing and orientation. Otoliths are not resorbed during times of stress (Bagenal and Tesch 1978), and their crystalline structure makes them relatively translucent (DeVries and Frie 1996). The otoliths of many species require little preparation prior to their use in aging studies and often have high precision between readers, but the fish must be sacrificed to obtain the otoliths (DeVries and Frie 1996). Another disadvantage of using otoliths to age fish is that the relationship between the instantaneous growth rate of the otolith and the instantaneous growth rate of the body is not always isometric. Casselman (1990) found that otolith growth is slower than somatic growth during periods of rapid growth and faster than somatic growth during slow growth periods for juvenile northern pike, *Esox lucius*. Other researchers have found similar results in other species (Casselman 1978; Marshall and Parker 1982; Neilson et al. 1985; Penny and Evans 1985; Mosegaard et al. 1988). However, all of these studies focused on larval or juvenile stages when the length of the fish is increasing very rapidly. Otolith growth may reflect total growth of the fish,
including increases in girth, weight, and gonadal development as well as length. Furthermore, the exact relationship between growth of the otolith and growth of the body is not important as long as otolith growth reflects somatic growth in a relative sense.

**Aging Catfishes**

Ictalurid catfishes do not have scales, so early researchers had to find other methods for aging catfishes. In an exploratory study, Archibald (1934) aged channel catfish using several different hard parts including the vertebrae, cleithra, opercula, sagittal otoliths, and asterisci otoliths. The vertebrae, cleithra, and opercula required much cleaning and polishing prior to reading, but there was good agreement among ages determined from each structure (Archibald 1934). Vertebrae were the structures of choice because they had the highest contrast between translucent and opaque zones, which increases precision in age assignment (Archibald 1934).

Appelgate and Smith (1951) determined the age and growth rate of channel catfish taken from the upper Mississippi River, Iowa, based on estimates made from the fifth vertebra. They found that vertebrae were suitable for aging despite the amount of preparation required and the presence of false annuli (Appelgate and Smith 1951). Preparation involved removing the ribs attached to the fifth vertebra and separating the vertebra from the rest of the spine (Appelgate and Smith 1951). After removing the remaining tissue surrounding the vertebra and its centrum (the flat face of the vertebra), the vertebra is placed
in a watch glass under water or alcohol and viewed whole (Appelgate and Smith 1951). R. C. Marzolf (1955) also used this method to determine age and growth of channel catfish taken from the Niangua arm of the Lake of the Ozarks but found numerous false annuli.

Sneed (1951) first documented the use of pectoral spines to determine age and growth of channel catfish from Grand Lake, Oklahoma. This technique has been utilized for numerous studies (Marzolf 1955; Conder and Hoffarth 1965; Gray 1965; Kelley, Jr. and Carver 1966; Turner 1982; Crumpton et al. 1987; Stevenson and Day 1987; Hale and Timmons 1990; Munger et al. 1994) and is still the most common method for aging catfishes. Marzolf (1955) found that pectoral spines and vertebrae were both “satisfactory for aging” but stated that spines were preferable because they required less preparation. The pectoral spine is dislocated from the fish, the excess tissue is cut away from the articulating process, and the spine is sectioned (approximately 0.7mm thick) at the end of the basal recess (Figure 5). The section is then mounted on a slide and polished if necessary. The major disadvantage of this technique is that the spine is vascularized, and Marzolf (1955) was one of the earliest to note that the central lumen (location of the blood vessel in the spine) of the pectoral spine grows as the fish grows, eventually destroying early annuli. This did not impede aging but made growth measurements more difficult (Marzolf 1955). Turner (1982) proposed that the section be taken through the articulating process (Figure 5) rather than at the end of the basal recess, and found that this new method eliminated the problems caused by the expanding lumen because the
Figure 5. Locations of pectoral spine cross-sections (modified from Figure 1 of Turner (1982)). Cross-section B at the end of the basal recess has been the cross-section typically used for ictalurid catfish age and growth studies.
blood vessel enters the spine just distal of the articulating process. Using pectoral spines has other disadvantages, including presence of false rings and resorption during times of stress. However, a major advantage of using spines for aging catfish is that removal of a spine does not impact long-term growth or survival of the individual (Stevenson and Day 1987).

Few researchers have used otoliths to age catfish (Archibald 1934; Warburton 1978; Crumpton et al. 1987; Reis 1986; Holland-Bartels and Duval 1988; Buckmeier and Irwin 1999; Nash and Irwin 1999), and the otolith used may have been misidentified in some studies (Warburton 1978; Crumpton et al. 1987; Holland-Bartels and Duval 1988; Nash and Irwin 1999). Ictalurid catfish belong to the series Otophysi of the superorder Ostariophysi. The series Otophysi includes Cypriniformes (minnows, carps, and suckers), Characiformes (characins), and Siluriformes (catfishes). The largest otolith of non-Otophysan fishes is the sagittal otolith; however, the sagittae of Otophysans are greatly reduced (Secor et al. 1991). The largest otolith in channel catfish and white sucker is the lapillus (Gauldie et al. 1993; Thompson and Beckman 1995). Two of the earliest studies concerning catfish otoliths involved tropical marine catfishes (Warburton 1978; Reis 1986). Warburton (1978) successfully used whole otoliths to age the sea catfish, Galeichthys caerulescens, from west Mexican coastal lagoons. Warburton (1978) stated that sagittae were used in the study. On closer inspection, the otolith pictured in Plate 1 (Warburton 1978, Appendix A1) does not appear to be an Otophysan sagitta. Reis (1986) used sectioned lapilli to age the sea catfish, Netuma barba, from the Patos Lagoon,
Brazil. The sectioned lapillus portrayed in Figure 2 of Reis (1986) closely resembles the lapilli of blue, channel, and white catfishes (Appendix A2).

Studies using otoliths to age ictalurid catfishes have had varying success (Crumpton et al. 1987; Holland-Bartels and Duval 1988; Nash and Irwin 1999; Buckmeier and Irwin 1999). Crumpton et al. (1987) attempted to age brown bullheads, channel catfish, and white catfish in Florida using whole, longitudinal, and cross-sectioned otoliths and pectoral spine sections taken from the articulating process and basal recess. They found that annuli on the otoliths were often incomplete and very faint; consequently, precision of age estimates were low (Crumpton et al. 1987). Based on Figure 2 of Crumpton et al. (1987), the otoliths used in the study appear to be lapilli even though the authors refer to the otoliths as sagittae (Appendix A3). Holland-Bartels and Duval (1988) used otoliths for counting daily increments of young-of-the-year channel catfish from the upper Mississippi River but referred to the otoliths as sagittae. Nash and Irwin (1999) sectioned otoliths to age flathead catfish from the Tallapoosa River, Alabama, and found sectioned otoliths to be more efficient, precise, and accurate than pectoral spine sections taken from either the articulating process or basal recess area. Nash and Irwin (1999) claimed to have used sagittal otoliths; however, the otoliths shown in Figures 1 and 2 of this work closely resemble the lapilli of blue, channel, and white catfishes (Appendix A4). Buckmeier and Irwin (1999) used sectioned otoliths to age channel catfish from Alabama up to age three but obtained higher precision when estimating the age of these fish from pectoral spine sections taken from the articulating process. Thompson and
Beckman (1995) used sectioned lapilli to age white suckers (*Catostomus commersoni*), and the lapillus shown in Figure 1 of Thompson and Beckman (1995) is remarkably similar to the lapilli of blue, channel, and white catfishes (Appendix A5).

**Validation of Calcified Structures**

The most frequently forgotten step in age and growth studies is validation of the hard part as an accurate record of age (Beamish and McFarlane 1983; Casselman 1983). Methods for validating hard parts include captive observation, mark and recapture, and chemical marking. However, all of these methods are expensive and time-consuming. A cheaper, less laborious alternative is marginal increment analysis (Brothers 1983). The marginal increment is the distance from the last formed mark to the edge of the hard part. To perform marginal increment analysis, fish of different sizes and sexes are collected on a monthly basis and aged. The time of year at which a new mark is formed can be determined by measuring this distance each month for every size class. The marginal increment is minimized immediately following the deposition of a new mark.

Alternatively, calculating standardized increments by dividing the marginal increment width by the width of the penultimate increment for each fish measured allows the comparison of marginal increments from different age classes. This relationship is based on the property of the von Bertalanffy growth curve that postulates that the amount of annual growth is a linear function of size at the beginning of the year (Ricker 1975). If the histogram of standardized increments
are plotted for each month, the distribution of standardized increments should be approximately bimodal during the month of annulus formation (J. M. Hoenig, Fisheries Science Department, Virginia Institute of Marine Science, personal communication). Annual growth marks of a wide variety of fresh- and saltwater species have been validated using marginal increment analysis (Warburton 1978; Mayo et al. 1981; Reis 1986; Crawford et al. 1989; Morales-Nin and Ralston 1990; Hyndes et al. 1992; Barbieri et al. 1994; Ross and Stevens 1995; Thompson and Beckman 1995), but only one has attempted to validate the otoliths of adult ictalurid catfishes (Buckmeier and Irwin 1999).

Appelgate and Smith (1951), Sneed (1951), and Marzolf (1955), by counting the annuli of fish of known age, validated spines and vertebrae as accurate aging records for channel catfish up to age five. These three studies also attempted validation via other methods, including comparing back-calculated length-at-age to current length-at-age for each year class, length-frequency analysis, and persistence of year classes in samples across multiple years (Appelgate and Smith 1951; Sneed 1951; Marzolf 1955). These techniques are not direct validation, but offer good supporting evidence (Brothers 1983).

Using marginal increment analysis, Warburton (1978) confirmed the yearly deposition of annuli on the otoliths of the sea catfish, *Galeichthys caerulescens*, from west Mexican coastal lagoons. Reis (1986) also used marginal increment analysis to validate that one translucent zone and one opaque zone were formed yearly on the otoliths (lapilli) of the sea catfish, *Netuma barba*, from the Patos Lagoon, Brazil. Holland-Bartels and Duval (1988) validated daily rings on young-
of-year channel catfish by raising fry in the laboratory, removing otoliths from fish daily, and counting the rings. Buckmeier and Irwin (1999) used marginal increment analysis to confirm that one translucent zone and one opaque zone were formed annually on the pectoral spines of channel catfish up to age three in Alabama, but annual marks on the otoliths of channel catfish were difficult to discern.

Study Objectives

Fisheries scientists have known the problems of using pectoral spines to age ictalurid catfishes since the technique was discovered; however, few studies have attempted to find alternative aging methods for these fishes. Chapter One details the first two objectives of this study, which are to validate otoliths as an accurate record of age for three species of ictalurid catfish found in Chesapeake Bay tributaries and to compare age estimates based on otoliths with age estimates based on traditional methods.
Methods

Sample Collection

Blue, channel, and white catfishes were collected by the various VIMS, VDGIF, and United States Department of Fish and Wildlife monitoring surveys from June 1998 through September 2000 (Table 1). Table 1 indicates the gear used by each survey, the frequency of sampling, and the rivers from which catfish samples were taken. An additional sample of large blue catfish from the Rappahannock River was purchased from a commercial fisherman on 25 April 2000 (Table 1).

Processing Procedures

Catch location, gear, total length (TL), fork length (FL), total weight (TW), eviscerated weight, sex, and gonad weight were recorded for each fish, and the lapilli and pectoral spines were removed, labeled, and stored dry. Erosion of the distal part of the caudal fin was common, so a conversion from fork length to total length based on intact specimens was calculated using linear regression. All calculations are based on fork length unless otherwise noted.

Otoliths were encased in Buehler Epoxide and transversely sectioned using a Buehler isomet saw equipped with a pair of 4in, low-concentration diamond wafering blades spaced approximately 0.7mm apart (Figure 6). Each
<table>
<thead>
<tr>
<th>Survey</th>
<th>Gear</th>
<th>Sampling Frequency</th>
<th>Sampling Period</th>
<th>Catfish Sample Locations</th>
</tr>
</thead>
<tbody>
<tr>
<td>VIMS Juvenile Finfish and Blue Crab Trawl Survey</td>
<td>30', lined otter trawl</td>
<td>Monthly</td>
<td>All year</td>
<td>James, Pamunkey, Rappahannock, and York Rivers</td>
</tr>
<tr>
<td>VIMS Juvenile Striped Bass Seine Survey</td>
<td>100' x 4' beach seine</td>
<td>Twice monthly</td>
<td>July-September</td>
<td>James, Mattaponi, Pamunkey, and Rappahannock Rivers</td>
</tr>
<tr>
<td>VIMS Pfiesteria Cohort Survey</td>
<td>3, 100', variable-mesh gill nets</td>
<td>Twice monthly</td>
<td>May-October</td>
<td>James and Rappahannock Rivers</td>
</tr>
<tr>
<td>VIMS Adult American Shad Monitoring Survey</td>
<td>912', single-mesh, staked gill net</td>
<td>Twice weekly</td>
<td>February-May</td>
<td>Rappahannock River</td>
</tr>
<tr>
<td>VIMS Striped Bass Spawning Stock Survey</td>
<td>300', variable-mesh, anchored gill net</td>
<td>Twice weekly</td>
<td>March-May</td>
<td>Rappahannock River</td>
</tr>
<tr>
<td>VIMS American Shad Reproduction Study</td>
<td>500', single-mesh, drift gill net</td>
<td>Twice weekly</td>
<td>March-May</td>
<td>Mattaponi and Pamunkey Rivers</td>
</tr>
<tr>
<td>VDGIF Catfish Monitoring Program</td>
<td>Low-frequency boat electrofisher</td>
<td>Variable</td>
<td>May-October</td>
<td>James, Mattaponi, Pamunkey, and Rappahannock Rivers</td>
</tr>
<tr>
<td>US Fish and Wildlife Service Sturgeon Restoration Project</td>
<td>Large-mesh gill net</td>
<td>Variable</td>
<td>March-May</td>
<td>James River</td>
</tr>
<tr>
<td>Commercial Catch</td>
<td>Pound net</td>
<td>Once</td>
<td>April 25, 2000</td>
<td>Rappahannock River</td>
</tr>
</tbody>
</table>
Figure 6. Otolith (lapillus) section location and resulting cross-section. The yellow line indicates the radius along which increments were measured.
otolith section was affixed to a glass slide using Crystal Bond and polished using 400 grit and 800 grit sandpaper, then further polished with alumina powder (0.3μm). Pectoral spines were sectioned at the articulating process and at the distal end of the basal groove (Figure 5) and prepared in the same manner as the otolith sections. Spines from fish under 100mm FL were encased in epoxide, sectioned, and polished. The left (port) otolith and right (starboard) pectoral spine were chosen to process in the majority of the fish because of conformation features on each structure that facilitated accurate sectioning. All sections were viewed using a dissecting microscope with 25x-50x magnification and transmitted light. Otolith growth increments were measured along the line shown in Figure 6 using Image Pro Plus™ optical pattern recognition system (OPRS) and a dissecting microscope with 50x magnification and transmitted light.

**Hard Part Comparisons**

A size-stratified subsample of 100 blue catfish otoliths and spines, 50 channel catfish otolith and spines, and 40 white catfish otoliths and spines were randomly chosen for comparison of age estimates for these calcified structures. Suitability of a given calcified structure for aging purposes is typically assessed based on accuracy (increase of hard part radius with fish age and length and formation of annuli on a predictable basis) and precision between and within readers. Only otoliths were validated in this study because pectoral spines have been previously validated through age five, and limitations of pectoral spine sections have been well documented. Regression techniques confirmed that otolith radius increases with age and length of the fish sampled (Hill et al. 1989;
Marginal increment analysis was used to confirm the deposition of one annulus per year by examining monthly distributions of standardized increments. Each selection of sections was read twice by each of two readers; readings of each reader were then used to estimate within-reader precision. When age estimates from the previous two readings disagreed, sections were read a third time for a final age determination. These final determinations were used for comparisons between readers and among structures. Comparisons of age estimates between readers and within readers were conducted using a two-way test of symmetry (Hoenig et al. 1995), and ages estimated from the three different methods were compared using a three-way test of symmetry (equation 8, Evans and Hoenig 1998). Tests of symmetry provide a quantitative method for assessing systematic disagreement between readers or aging methods and aid in determining a range of ages for which the readers or methods are comparable (Hoenig et al. 1995). If systematic bias exists between structures or readers, visual inspection of graphs of the data will illustrate the nature of the deviations. An $\alpha$ of 0.05 will be used for all tests and regressions.

**Other Analyses**

Relationships between total length and fork length and total weight and eviscerated weight were quantified using linear regression. The relationship between eviscerated weight and fork length was modeled by the following equation:
\[ W = aL^b \]

where:

- \( W \) = eviscerated weight
- \( a \) = non-biological parameter
- \( L \) = fork length
- \( b \) = indicator of shape change with age (\( b > 3 \) indicates that fish become more rotund with increasing length).
Results

Sample Sizes and Size Distributions

From June 1998 to September 2000, 1159 blue catfish, 364 channel catfish and 401 white catfish were collected (Table 2). Fork lengths for blue catfish captured during this study ranged from 24mm to 938mm, with a mean of 261mm. Channel catfish ranged in fork length from 19mm to 600mm, with a mean of 266mm. Minimum, maximum, and mean fork lengths for white catfish were 16mm, 433mm, and 234mm, respectively. Eviscerated weights for blue catfish ranged from 0.14g to 18,050.0g, with a mean of 668.8g. Mean eviscerated weight for channel catfish was 303.4g and ranged from 0.92g to 3313.0g. White catfish eviscerated weight ranged from 0.15g to 1600.0g, with a mean of 249.5g. Length and weight histograms for each species are shown in Figures 7 through 12. Relationships between fork length and total length, eviscerated weight and total weight, and fork length and eviscerated weight are shown in Figures 13, 14, and 15, respectively, and also given in Tables 3 and 4.

Otolith Radius/Age/Fork Length Relationships

The otolith radius for each species exhibited asymptotic behavior with age, so a von Bertalanffy growth curve (Ricker 1975),

\[ L_t = L_\infty (1 - e^{-k(t-t_0)}) \]
<table>
<thead>
<tr>
<th>Species</th>
<th>Blue Catfish</th>
<th>Channel Catfish</th>
<th>White Catfish</th>
<th>River Totals</th>
</tr>
</thead>
<tbody>
<tr>
<td>York River</td>
<td>394</td>
<td>71</td>
<td>75</td>
<td>540</td>
</tr>
<tr>
<td>System</td>
<td></td>
<td></td>
<td></td>
<td>Grand Total</td>
</tr>
<tr>
<td>Jim River</td>
<td>672</td>
<td>235</td>
<td>144</td>
<td>1051</td>
</tr>
<tr>
<td>Species Total</td>
<td>1159</td>
<td>364</td>
<td>401</td>
<td>1924</td>
</tr>
</tbody>
</table>

Table 2. Catfish sample sizes by species and river.
Figure 7. Length-frequencies for blue catfish by sex.
Length-Frequencies for Channel Catfish by Sex

Males

Females

Unidentified

Figure 8. Length-frequencies for channel catfish by sex.
Length-Frequencies for White Catfish by Sex

Males

Females

Unidentified

Figure 9. Length-frequencies for white catfish by sex.
Weight-Frequencies for Blue Catfish by Sex

Figure 10. Weight-frequencies for blue catfish by sex.
Figure 11. Weight-frequencies for channel catfish by sex.
Figure 12. Weight-frequencies for white catfish by sex.
Total Length vs. Fork Length for Blue, Channel, and White Catfishes

Blue Catfish, n = 419
TL = 1.07FL + 20.07
R² = 99.85%, p < 0.00001

Channel Catfish, n = 157
TL = 1.09FL + 16.75
R² = 99.49%, p < 0.00001

White Catfish, n = 199
TL = 1.07FL + 5.41
R² = 99.66%, p < 0.00001

Figure 13. Total length/fork length comparisons for each species. The regression line is drawn in red.
Total Weight vs. Eviscerated Weight for Blue, Channel, and White Catfishes

Blue Catfish, n = 1010
TW = 1.24EW - 21.97
R² = 98.79%, p < 0.00001

Channel Catfish, n = 354
TW = 1.20EW - 8.41
R² = 99.05%, p < 0.00001

White Catfish, n = 387
TW = 1.17EW - 2.71
R² = 99.84%, p < 0.00001

Figure 14. Total weight/eviscerated weight comparisons for each species. The regression line is drawn in red.
Eviscerated Weight vs. Fork Length for Blue, Channel, and White Catfishes

Blue Catfish, n = 1036
EW = 2.35E-7 * FL^{3.65}
R^2 = 97.96%, p < 0.0001

Channel Catfish, n = 357
EW = 4.59E-7 * FL^{3.53}
R^2 = 94.42%, p < 0.0001

White Catfish, n = 392
EW = 1.32E-6 * FL^{3.42}
R^2 = 95.61%, p < 0.0001

Figure 15. Eviscerated weight/fork length comparisons for each species. The regression line is drawn in red.
Table 3. Relationships between total length and fork length and total weight and eviscerated weight for each species.

<table>
<thead>
<tr>
<th>Species</th>
<th>Relationship</th>
<th>n</th>
<th>Equation</th>
<th>95% C.I. (slope)</th>
<th>r²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blue Catfish</td>
<td>TL-FL</td>
<td>419</td>
<td>TL = 1.07FL + 20.07</td>
<td>(1.066, 1.074)</td>
<td>0.9985</td>
</tr>
<tr>
<td>Channel Catfish</td>
<td>TL-FL</td>
<td>157</td>
<td>TL = 1.09FL + 16.75</td>
<td>(1.08, 1.10)</td>
<td>0.9949</td>
</tr>
<tr>
<td>White Catfish</td>
<td>TL-FL</td>
<td>199</td>
<td>TL = 1.07FL + 5.41</td>
<td>(1.06, 1.08)</td>
<td>0.9966</td>
</tr>
<tr>
<td>Blue Catfish</td>
<td>TW-EW</td>
<td>1010</td>
<td>TW = 1.24EW - 21.97</td>
<td>(1.23, 1.25)</td>
<td>0.9879</td>
</tr>
<tr>
<td>Channel Catfish</td>
<td>TW-EW</td>
<td>354</td>
<td>TW = 1.20EW - 8.41</td>
<td>(1.19, 1.21)</td>
<td>0.9905</td>
</tr>
<tr>
<td>White Catfish</td>
<td>TW-EW</td>
<td>387</td>
<td>TW = 1.17EW - 2.71</td>
<td>(1.16, 1.18)</td>
<td>0.9964</td>
</tr>
</tbody>
</table>

Table 4. Parameters for eviscerated weight/fork length relationship (EW = a × FLᵇ) for each species.

<table>
<thead>
<tr>
<th>Species</th>
<th>n</th>
<th>a</th>
<th>b</th>
<th>95% C.I. (b)</th>
<th>r²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blue Catfish</td>
<td>1036</td>
<td>2.35E-7</td>
<td>3.65</td>
<td>(3.60, 3.70)</td>
<td>0.9796</td>
</tr>
<tr>
<td>Channel Catfish</td>
<td>357</td>
<td>4.59E-7</td>
<td>3.53</td>
<td>(3.53, 3.62)</td>
<td>0.9442</td>
</tr>
<tr>
<td>White Catfish</td>
<td>392</td>
<td>1.32E-6</td>
<td>3.42</td>
<td>(3.33, 3.51)</td>
<td>0.9561</td>
</tr>
</tbody>
</table>
where:

\[ L_t = \text{length (radius) at age } t \]
\[ L_\infty = \text{hypothetical maximum mean length (radius)} \]
\[ k = \text{Brody growth coefficient} \]
\[ t = \text{estimated age (years)} \]
\[ t_0 = \text{hypothetical age at size 0} \]

was fitted to the data using non-linear least squares regression (SAS 1989, PROC NLIN).

The von Bertalanffy growth curve accounted for at least 95% of the variance observed in the otolith radius-age data for all three species (Figure 16). Parameter estimates for the von Bertalanffy growth curves fitted to the otolith radius-age data are shown in Table 5. Otoliths of channel and white catfishes have similar radii at a given age (Figure 17); however, the otoliths of both species are generally smaller than those of blue catfish otoliths after age seven (Figure 17).

Otolith radius was also significantly related to fork length for all three species (Figure 18, Table 6). A von Bertalanffy growth curve captured 88.30% of the variance observed in the blue catfish otolith radius-fork length data (Figure 18, Table 6). The growth curve was a poorer fit for the channel catfish data \( r^2 = 70.50\% \), Figure 18, Table 6). A linear regression was also fitted to the channel catfish data, with a resulting coefficient of determination just slightly less than that of the growth curve fit (Figure 18, Table 6). A von Bertalanffy growth curve was initially fit to the white catfish otolith radius/fork length data, but the resulting fit was essentially linear and all of the estimated parameters contained zero in their
Figure 16. Otolith radius/age relationships for each species. Dashed lines indicate 95% confidence interval around the regression line.
Table 5. Growth curve parameter estimates for otolith radius/age relationships for each species.

<table>
<thead>
<tr>
<th>Species</th>
<th>n (increments)</th>
<th>$L_\infty$</th>
<th>$k$</th>
<th>$t_0$</th>
<th>$r^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blue Catfish</td>
<td>1768</td>
<td>1.99</td>
<td>0.10</td>
<td>-0.45</td>
<td>0.9642</td>
</tr>
<tr>
<td>Channel Catfish</td>
<td>1009</td>
<td>1.70</td>
<td>0.13</td>
<td>-0.43</td>
<td>0.9563</td>
</tr>
<tr>
<td>White Catfish</td>
<td>1144</td>
<td>1.65</td>
<td>0.13</td>
<td>-0.54</td>
<td>0.9623</td>
</tr>
</tbody>
</table>
Comparison of Otolith Growth Curves by Species

Figure 17. Comparison of otolith growth curves by species. The dashed lines surrounding each curve represent the 95% confidence interval around the expected value.
Figure 18. Otolith radius/fork length relationships for each species. Blue catfish were fitted with a von Bertalanffy growth curve. Channel catfish were fitted with both a VB curve (red) and straight line (blue) due to the ambiguous structure of the data cloud. Results for each regression for channel catfish are shown in the matching color. White catfish were fitted with only a straight line because the VB curve gave nonsensical results and was essentially linear through the data cloud.
Table 6. Parameter estimates for otolith radius/fork length relationships.

<table>
<thead>
<tr>
<th>Species</th>
<th>n</th>
<th>L_∞</th>
<th>k</th>
<th>t_0</th>
<th>r^2</th>
<th>Linear Regression</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Slope</td>
<td>Intercept</td>
<td>r^2</td>
</tr>
<tr>
<td>Blue Catfish</td>
<td>442</td>
<td>1.59</td>
<td>0.002</td>
<td>27.64</td>
<td>0.8830</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Channel Catfish</td>
<td>207</td>
<td>2.02</td>
<td>0.002</td>
<td>18.11</td>
<td>0.7050</td>
<td>0.0026</td>
<td>0.13</td>
<td>0.6929</td>
</tr>
<tr>
<td>White Catfish</td>
<td>206</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>0.0036</td>
<td>0.02</td>
<td>0.7630</td>
</tr>
</tbody>
</table>
95% confidence intervals. Therefore, a linear regression was applied to the data with a significant fit capturing 76.30% of the variance in the data (Figure 18, Table 6).

Patterns in both the otolith radius/age and otolith radius/fork length data across gear, river, and species will be further explored in the following chapter.

Otolith Validation

All three catfish species added one annulus to their otoliths per year (Figures 19-21). The monthly standardized increment histograms for blue catfish exhibited bimodality during June and July of each year (Figure 19), indicating completion of one annulus and the beginning of another. Annulus formation appears complete by August (Figure 19). The mode of the standardized increment distribution increased steadily from July through March the following year, after which the mode remained steady until the new mode appeared again in June (Figure 19). Channel catfish appear to follow the same pattern (Figure 20); however, the pattern is less distinct due to smaller monthly sample sizes. The distribution of channel catfish standardized increments appears bimodal only during June and July of 1999 (Figure 20). The distribution does shift toward larger standardized increments starting in July and continuing through November, where it remained approximately stationary until the following July (Figure 20). The seasonal pattern is more obvious for white catfish (Figure 21). The distribution of standardized increments appear bimodal during June of 1999 (Figure 21). No white catfish were collected during June 1998 or 2000, but the
Figure 19. Monthly distributions of standardized increments for blue catfish. Months with strongly bimodal distributions indicate the period of annulus formation.
Monthly Histograms of Standardized Increments for Channel Catfish

1998 1999 2000

Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec

Standardized Increment

Figure 20. Monthly distributions of standardized increments for channel catfish. Months with strongly bimodal distributions indicate the period of annulus formation.
Monthly Histograms of Standardized Increments for White Catfish

1998 1999 2000

Jan

Feb

Mar

Apr

May

Jun

Jul

Aug

Sep

Oct

Nov

Dec

Standardized Increment

Figure 21. Monthly distributions of standardized increments for white catfish. Months with strongly bimodal distributions indicate the period of annulus formation.
mode of the standardized increment distribution is at a minimum during July of both years, which suggests that the distribution was probably bimodal during June 1998 and 2000 (Figure 21). The relatively low standardized increment values during July of each year signify that annulus formation is complete during July for the majority of the white catfish sampled (Figure 21).

**Within-reader Precision**

Within-reader precision was highest for blue catfish otolith sections for both Readers 1 and 2, with 98% and 84% agreement, respectively (Figure 22, Table 7). Within-reader precision (Figure 23, Table 8) was substantially lower for the articulating process sections for blue catfish, where percent agreement was 64% and 79% for Readers 1 and 2, respectively. Within-reader precision for blue catfish was lowest for basal recess sections (Figure 24, Table 9). Percent agreement between the first and second readings was 61% for Reader 1 and 68% for Reader 2 (Figure 24, Table 9). Tests of symmetry detected no significant systematic biases between the first and second readings of all three structures by either reader (Tables 7-9).

Within-reader precision for channel catfish followed a pattern similar to that for blue catfish. No significant biases were found between the first and second readings of all three structures by either reader (Tables 7-9). Within-reader precision for channel catfish otolith sections were slightly lower than that for blue catfish otolith sections, with the first and second readings agreeing 93% and 80% of the time for Readers 1 and 2, respectively (Figure 25, Table 7).
Table 7. Within- and between-reader precision for otolith sections for all species. P-values from tests of symmetry are presented in the columns labeled “Symm. p-value.”

<table>
<thead>
<tr>
<th>Species</th>
<th>Within-Reader Precision</th>
<th>Between-Reader Precision</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Reader 1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>% Agree.</td>
<td>Symm. p-value</td>
</tr>
<tr>
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<td>98</td>
<td>0.37</td>
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<tr>
<td>Channel Catfish</td>
<td>93</td>
<td>0.39</td>
</tr>
<tr>
<td>White Catfish</td>
<td>89</td>
<td>0.26</td>
</tr>
</tbody>
</table>

Table 8. Within- and between-reader precision for articulating process sections for all species. P-values from tests of symmetry are presented in the columns labeled “Symm. p-value.”

<table>
<thead>
<tr>
<th>Species</th>
<th>Within-Reader Precision</th>
<th>Between-Reader Precision</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Reader 1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>% Agree.</td>
<td>Symm. p-value</td>
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<tr>
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<td>64</td>
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<tr>
<td>Channel Catfish</td>
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<td>White Catfish</td>
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Table 9. Within- and between-reader precision for basal recess sections for all species. P-values from tests of symmetry are presented in the columns labeled “Symm. p-value.”

<table>
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<tr>
<th>Species</th>
<th>Within-Reader Precision</th>
<th>Between-Reader Precision</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Reader 1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>% Agree.</td>
<td>Symm. p-value</td>
</tr>
<tr>
<td>Blue Catfish</td>
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<td>0.40</td>
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<tr>
<td>Channel Catfish</td>
<td>65</td>
<td>0.50</td>
</tr>
<tr>
<td>White Catfish</td>
<td>47</td>
<td>0.12</td>
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</tbody>
</table>
Figure 22. Comparisons of the first and second reading of the blue catfish otolith sections by each reader. Observations falling on the 45° dotted line indicate perfect agreement between readings.
Figure 23. Comparisons of the first and second reading of the blue catfish articulating process sections by each reader. Observations falling on the 45° dotted line indicate perfect agreement between readings.
Figure 24. Comparisons of the first and second reading of the blue catfish basal recess sections by each reader. Observations falling on the 45° dotted line indicate perfect agreement between readings.
Within-Reader Precision for Channel Catfish Otolith Sections

Reader 1, 93% Agreement

Reader 2, 80% Agreement

Figure 25. Comparisons of the first and second reading of the channel catfish otolith sections by each reader. Observations falling on the 45° dotted line indicate perfect agreement between readings.
Percent agreement for channel catfish articulating process sections was substantially lower than percent agreement for channel catfish otolith sections. Readers 1 and 2 agreed only 63% and 61%, respectively, between their first and second readings (Figure 26, Table 8). Basal recess sections for channel catfish had within-reader precision comparable with that for articulating process sections, with 65% of age estimates by Reader 1 agreeing between the first and second reading, and 61% of age estimates by Reader 2 agreeing between readings (Figure 27, Table 9).

Within-reader precision was lowest overall for white catfish structure sections, but no significant systematic biases were found between the first and second readings of all three structures by either reader (Tables 7-9). Percent agreement between readings of white catfish otolith sections was 89% for Reader 1 and 76% for Reader 2 (Figure 28, Table 7). Within-reader precision for white catfish articulating process sections was substantially lower than within-reader precision for the articulating process sections for the other two species, with only 42% of the age estimates from the first and second readings by Reader 1 agreeing and 37% of the age estimates by Reader 2 agreeing between readings (Figure 29, Table 8). Within-reader precision for white catfish basal recess sections was comparable with that of the articulating process sections. Reader 1 had 47% agreement between the first and second readings, and Reader 2 had 39% agreement between readings (Figure 30, Table 9).
Figure 26. Comparisons of the first and second reading of the channel catfish articulating process sections by each reader. Observations falling on the 45° dotted line indicate perfect agreement between readings.
Figure 27. Comparisons of the first and second reading of the channel catfish basal recess sections by each reader. Observations falling on the 45° dotted line indicate perfect agreement between readings.
Figure 28. Comparisons of the first and second reading of the white catfish otolith sections by each reader. Observations falling on the 45° dotted line indicate perfect agreement between readings.
Within-Reader Precision for White Catfish
Articulating Process Sections

Reader 1,
42% Agreement

Reader 2,
37% Agreement

Figure 29. Comparisons of the first and second reading of the white catfish articulating process sections by each reader. Observations falling on the 45° dotted line indicate perfect agreement between readings.
Within-Reader Precision for White Catfish Basal Recess Sections

Figure 30. Comparisons of the first and second reading of the white catfish basal recess sections by each reader. Observations falling on the 45° dotted line indicate perfect agreement between readings.
Between-reader Precision

Of the three sections compared for blue catfish, otolith sections had the highest agreement between readers, (Figure 31, Table 7) with the two readers agreeing 84% of the time. However, significant systematic differences were detected with a test of symmetry (Table 7). Inspection of Figure 31 reveals that ages assigned by Reader 2 were lower by one year than those assigned by Reader 1 in all but five cases. The majority of disagreement between Readers 1 and 2 for articulating process sections were also within one year (Figure 31). Percent agreement for articulating process sections was 56%, and all but thirteen disagreements occurred within one year of the 100% agreement line (Figure 31). Significant differences were detected between readers by a test of symmetry (Table 8), and visual inspection of Figure 31 shows that ages assigned by Reader 2 were consistently lower than those assigned by Reader 1. Comparison between the two readers for basal recess sections followed the same pattern (Figure 31, Table 9). Basal recess sections had the lowest between-reader precision (45%), and distributions of age estimates were significantly different for the two readers (Figure 31, Table 9). Twenty-three of the 55 disagreements were more than one year apart (Figure 31).

No significant, systematic biases were found between readers for all three channel catfish structures (Tables 7-9); however, age estimates by Reader 2 tended to be one to two years lower than age estimates by Reader 1 (Figure 32). Age estimates by both readers for channel catfish otolith sections agreed 78% of the time (Table 7), which was slightly higher than reader agreement for blue
Figure 31. Comparisons of the final readings of each blue catfish structure by each reader. Observations falling on the 45° dotted line indicate perfect agreement between readings.
Figure 32. Comparisons of the final readings of each channel catfish structure by each reader. Observations falling on the 45° dotted line indicate perfect agreement between readings.
catfish. All but four differing age estimates were more than one year from the 100% agreement line (Figure 32). Percent agreement was substantially lower for channel catfish articulating process sections, with the two readers agreeing on 52% of the sections (Figure 32, Table 8). Approximately the same number of age estimates differed by one year as by two years (Figure 32). Percent agreement for channel catfish basal groove sections was 63% (Figure 32, Table 9). All but three differing age estimates were within one year of the 100% agreement line (Figure 32).

For all three white catfish structures, age estimates by the second reader were once again consistently lower than age estimates by Reader 1 (Figure 33). Tests of symmetry for age estimates by each reader for each structure revealed no significant biases between readers (Tables 7-9); however, the p-value (0.0504) for basal recess was just marginally larger than $\alpha$. Percent agreement (71%) for white catfish otolith sections was the lowest for the otolith sections of all three species (Table 7). Five out of eleven disagreements occurred for fish estimated age nine by Reader 1 (Figure 33). Percent agreement for white catfish articulating process sections, 45%, was also the lowest of all three species (Figure 33, Table 8). Age estimates differed by as much as three years between readers (Figure 33). Readers 1 and 2 agreed on 45% of the white catfish basal recess sections, which was similar to percent agreement for blue catfish but much lower than that of channel catfish (Table 9). Twelve out of twenty disagreements were within one year from the 100% agreement line (Figure 33).
Figure 33. Comparisons of the final readings of each white catfish structure by each reader. Observations falling on the 45° dotted line indicate perfect agreement between readings.
Between-structure Precision

A three-way test of symmetry found significant biases in the final age estimates by each reader for the otolith, articulating process, and basal recess sections for blue catfish (Table 10). Pair-wise agreement for Reader 1 was 74% between otolith sections and articulating process sections, 49% between otolith sections and basal recess sections, and 54% for articulating process sections and basal recess sections (Figure 34). Pair-wise agreements for Reader 2 were lower than those for Reader 1, with Reader 2 having 56% agreement between otolith sections and articulating process sections, 29% agreement between otolith sections and basal recess sections, and 36% agreement between articulating process sections and basal recess sections (Figure 35). Visual inspection of Figures 34 and 35 reveals that pectoral spine sections, relative to otolith sections, tended to underage fish old (large) fish by several years relative to otolith sections and overage young (small) fish. A similar pattern occurred in comparisons of pectoral spine sections aged by each reader (Figures 34-35).

Age estimates from basal recess sections had a slight tendency at early ages to be higher than estimates from articulating process sections and to be substantially lower than estimates from articulating process sections at older ages (Figures 34-35).

A three-way test of symmetry detected no significant biases in the age estimates determined from each channel catfish structure by Reader 1, but significant biases existed for Reader 2 (Table 10). Pair-wise percent agreement between channel catfish otolith sections and articulating process sections was
Table 10. Agreement and symmetry among age estimates from otolith, articulating process, and basal recess section for each species by both readers. P-values from three-way tests of symmetry are presented in the columns labeled “Symm. p-value.”

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<th>Symm. p-value</th>
<th>Overall Agreement</th>
<th>Symm. p-value</th>
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<tbody>
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<td>45%</td>
<td>&lt;0.0001</td>
<td>24%</td>
<td>&lt;0.0001</td>
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<tr>
<td>Channel Catfish</td>
<td>33%</td>
<td>0.063</td>
<td>39%</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>White Catfish</td>
<td>11%</td>
<td>&lt;0.0001</td>
<td>11%</td>
<td>&lt;0.0001</td>
</tr>
</tbody>
</table>
Figure 34. Pair-wise comparisons of the final readings of each blue catfish structure by Reader 1. Observations falling on the 45° dotted line indicate perfect agreement between readings.
Comparison of Blue Catfish Structures: Final Readings for Reader 2

- AP vs. OTO, 56% Agreement
- BR vs. OTO, 29% Agreement
- BR vs. AP, 36% Agreement

Figure 35. Comparisons of the final readings of each blue catfish structure by Reader 2. Observations falling on the 45° dotted line indicate perfect agreement between readings.
48% for both readers (Figures 36-37). Similarly, age estimates determined from channel catfish otolith sections and basal recess sections agreed 41% of the time for both readers (Figures 36 and 37). Percent agreement between channel catfish articulating process sections and basal recess sections was 48% for Reader 1 and 54% for Reader 2 (Figures 36 and 37). Age estimates by both readers for articulating process sections and basal recess sections tended to be higher than age estimates from otolith sections for fish aged 3 years old or less based on otolith sections (Figures 36 and 37). Articulating process and basal recess sections had lower age estimates than otolith sections for fish aged five years old and older by otolith sections (Figures 36 and 37). A similar phenomenon existed for age estimate comparisons between articulating process sections and basal recess sections (Figures 36 and 37). Overall, age estimates produced from basal recess sections were lower than those based on either articulating process sections or otolith sections (Figures 36 and 37).

Based on a three-way test of symmetry, significant systematic biases were found among age estimates determined from all three white catfish structures for both readers (Table 10). Pair-wise percent agreement for white catfish structures were lower than agreement for both blue and channel catfishes. Percent agreement between structures was lower for Reader 1 than for Reader 2 (Figures 38 and 39). Percent agreement for Reader 1 for otolith and articulating process sections, otolith and basal recess sections, and articulating process and basal recess sections was 23%, 18%, and 26%, respectively (Figure 38). Reader 2 had 26% agreement between otolith and articulating process sections,
Comparison of Channel Catfish Structures:
Final Readings for Reader 1

AP vs. OTO, 48% Agreement

BR vs. OTO, 41% Agreement

BR vs. AP, 48% Agreement

Figure 36. Pair-wise comparisons of the final readings of each channel catfish structure by Reader 1. Observations falling on the 45° dotted line indicate perfect agreement between readings.
Comparison of Channel Catfish Structures: Final Readings for Reader 2

Figure 37. Pair-wise comparisons of the final readings of each channel catfish structure by Reader 2. Observations falling on the 45° dotted line indicate perfect agreement between readings.
Comparison of White Catfish Structures:
Final Readings for Reader 1

AP vs. OTO, 23% Agreement

BR vs. OTO, 18% Agreement

BR vs. AP, 26% Agreement

Figure 38. Pair-wise comparisons of the final readings of each white catfish structure by Reader 1. Observations falling on the 45° dotted line indicate perfect agreement between readings.
Comparison of White Catfish Structures:
Final Readings for Reader 2

Figure 39. Pair-wise comparisons of the final readings of each white catfish structure by Reader 2. Observations falling on the 45° dotted line indicate perfect agreement between readings.
23% agreement for otolith and basal recess sections, and 31% agreement for articulating process and basal recess sections (Figure 39). Relationships between white catfish otolith and pectoral spine sections and relationships between pectoral spine sections were similar to those described for blue and channel catfishes (Figures 38 and 39).

Age Distributions and Length-at-age

Five hundred and fifty-five blue catfish, 217 channel catfish, and 221 white catfish were successfully aged from otolith sections. Blue catfish ages ranged from young-of-year to age sixteen, with an average age of three years. Channel catfish ranged in age from 0-15yrs (mean = 5.0). Mean age for white catfish was 6 and ranged from 0 to 15. Age histograms by sex for each species are shown in Figures 40-42. Minimum, maximum, and mean length-at-age are given in Tables 11-13. Increase in fork length with age was adequately modeled by von Bertalanffy growth curves when all aged samples were pooled by species (Figure 43). Growth curve parameter estimates are shown in Table 14. Comparison of growth curves across species shows that blue catfish are longer at a given age after three years than both channel and white catfishes (Figure 44). Channel catfish obtain a greater length-at-age than white catfish starting at age two, but both species are similar in size by age 11 (Figure 44). Growth patterns across rivers, gear, and sexes for each species will be further investigated in the next chapter.
Figure 40. Age-frequencies for blue catfish by sex.
Figure 41. Age-frequencies for channel catfish by sex.
Figure 42. Age-frequencies for white catfish by sex.
Table 11. Minimum, mean, and maximum length-at-age for blue catfish. All length values and 95% confidence intervals are fork lengths measured in millimeters.

<table>
<thead>
<tr>
<th>Age</th>
<th>n</th>
<th>Minimum Length</th>
<th>Mean Length</th>
<th>Maximum Length</th>
<th>95% C.I.</th>
</tr>
</thead>
<tbody>
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<td>147</td>
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<td>109</td>
<td>222</td>
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<td>800</td>
<td>909</td>
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<td>1</td>
<td>810</td>
<td>810</td>
<td>810</td>
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</table>
Table 12: Minimum, mean, and maximum length-at-age for channel catfish. All length values and 95% confidence intervals are fork lengths measured in millimeters.

<table>
<thead>
<tr>
<th>Age</th>
<th>n</th>
<th>Minimum Length</th>
<th>Mean Length</th>
<th>Maximum Length</th>
<th>95% C.I.</th>
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Table 13. Minimum, mean, and maximum length-at-age for white catfish. All length values and 95% confidence intervals are fork lengths measured in millimeters.

<table>
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<tr>
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<th>Mean Length</th>
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<th>95% C.I.</th>
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<td>349</td>
<td>375</td>
<td>400</td>
<td>265-484</td>
</tr>
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</table>
Figure 43. Length-at-age data and von Bertalanffy growth curves for each catfish species.

Blue Catfish
n = 555

$L_\infty = 1090\text{mm}, k = 0.09, t_0 = -0.48, R^2 = 75.47\%$

Channel Catfish
n = 217

$L_\infty = 376\text{mm}, k = 0.40, t_0 = 0.02, R^2 = 59.23\%$

White Catfish
n = 221

$L_\infty = 380\text{mm}, k = 0.17, t_0 = -1.64, R^2 = 70.94\%$
Table 14. Estimated parameters for von Bertalanffy growth curves for each species (pooled across rivers).

<table>
<thead>
<tr>
<th>Species</th>
<th>n</th>
<th>$L_\infty$</th>
<th>k</th>
<th>$t_0$</th>
<th>p-value</th>
<th>$r^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blue Catfish</td>
<td>555</td>
<td>1090mm</td>
<td>0.09</td>
<td>-0.48</td>
<td>&lt;0.0001</td>
<td>0.7547</td>
</tr>
<tr>
<td>Channel Catfish</td>
<td>217</td>
<td>376mm</td>
<td>0.40</td>
<td>0.02</td>
<td>&lt;0.0001</td>
<td>0.5923</td>
</tr>
<tr>
<td>White Catfish</td>
<td>221</td>
<td>380mm</td>
<td>0.17</td>
<td>-1.64</td>
<td>&lt;0.0001</td>
<td>0.7094</td>
</tr>
</tbody>
</table>
Figure 44. Comparison of somatic growth curves by species. The dashed lines surrounding each curve represent the 95% confidence interval around the expected value.
Discussion

Otoliths of all three species passed all tests required of a calcified structure to be considered to be a suitable record of age: otolith radius increased with both age and length of the fish, annuli were added on a regular basis, and within- and between-reader precision were relatively high. While precision for age estimates based on otolith sections for each species was not as high as precision estimates for other, non-ictalurid fishes (Thompson and Beckman 1995; Barbieri et al. 1994, Lowerre-Barbieri et al. 1994), otolith-based age estimates were far more repeatable than age estimates based on two different pectoral spine sections for each species.

The non-linear growth of otolith radius with age is a subject that is often unmentioned in age and growth studies; however, the non-linear behavior is hardly unexpected. If the somatic length increment added by a fish during a year is a fraction of the increment added during the previous year and otolith radius is positively related to somatic length, then it should be expected that the otolith increment added during a year will be a fraction of the increment added during the previous year, resulting in an asymptotic relationship between otolith radius and age.

A von Bertalanffy growth curve was used to model the relationship between otolith radius and fork length for blue catfish and channel catfish only.
because the shape of the growth curve was similar to the shape of the data cloud. That is, the data cloud exhibited asymptotic behavior, which the von Bertalanffy growth curve describes. There is no theoretical basis for the application of the von Bertalanffy growth curve to this type of data, and other similarly shaped functions may describe the data equally well. However, there is a practical limit to how large the otolith can grow simply because the otolith is restricted to the volume inside the head of the catfish.

The nonlinear tendencies of the otolith radius/fork length data hint at an interesting relationship between the two variables. Marzolf (1955) found a nonlinear relationship between pectoral spine radius at the basal recess and total length of channel catfish in Missouri that indicated that the pectoral spine radius increased faster than total length; however, dramatic changes in slope were not evident. A nonlinear relationship between vertebral radius and total length was observed in white catfish from the Sacramento-San Joaquin Delta, California, but, once again, no dramatic changes in slope were observed (Borgeson and McCammon 1967). In a study of blue catfish from Kentucky Lake, Tennessee, a noticeable change in slope in the relationship between pectoral spine radius and total length occurred at approximately 460mm (Conder and Hoffarth 1965). In contrast, the relationship between pectoral spine radius and total length was linear in a study of channel catfish age and growth in Oklahoma (Sneed 1951). For blue catfish in this study, the relationship between otolith radius and fork length appears to be approximately linear for fish of 100-400mm fork length. After 400mm fork length, the slope of the relationship changes so that fork length
appears to increase faster than otolith radius. This change in slope in the blue
catfish data may indicate a slight decoupling of otolith growth rate and somatic
growth rate. At 400mm fork length, a blue catfish is between five and eight years
old. Blue catfish mature between four and six years old, so a 400mm fish has
matured relatively recently (Graham 1999; Jenkins and Burkhead 1994). If a
decoupling of the otolith radius/fork length relationship were to occur, a logical
time for such a change would be near the time a fish matures and begins to
devote more resources to development of reproductive organs and less toward
somatic growth. However, the change in slope would be in the opposite direction
of what is observed in the blue catfish data, with the otolith radius increasing
faster than fork length. There are several possible alternative explanations. The
presence of the Weberian ossicles may restrict the volume available for otolith
expansion, or an ontogenetic diet shift occurs that results in enough energy for
both gonad development and an annual increase in fork length. The data for
channel catfish, a species congenic with blue catfish, indicate that the lapilli
may have a limited volume in which to grow; however, the indication does not
appear to be overwhelmingly strong. A straight line appears to fit the white
catfish data reasonably well, but white catfish belong to a different genus and
have a different morphology. An ontogenetic diet shift around 400mm fork length
may occur for two reasons. Adult blue catfish are largely piscivorous, and
400mm may be the size at which a blue catfish becomes an effective piscivore.
Alternatively, blue catfish over 400mm catfish may occupy a different habitat than
smaller blue catfish, and the adult habitat may have a different selection of prey
or better foraging conditions. Large catfish (>500mm) are often found around river bends where the channel is in close proximity to the river bank and the depth is over 6m, while smaller catfish (<300mm) are often found near shallower flats and straighter, more shallow parts of rivers (personal observation).

All three catfish species had standardized increment histograms that indicated that otolith annulus formation was complete by July or August for the majority of the fish in this study (Figures 19-21). Prentice and Whiteside (1975) found that channel catfish collected from central Texas farm ponds in 1972 formed an annulus between late March and early May. The timing of annulus formation found in this study closely corresponds to the time of peak spawning activity of all three species in Virginia (Hubert 1999; Murdy et al. 1997; Jenkins and Burkhead 1994), so the time up until the completion of the first annulus is nearly a complete year.

Estimates of within- and between-reader precision presented in this study are somewhat conservative, especially for otolith sections. Reader 1 (the author) processed all the samples used in this study and has processed and viewed otoliths from several other species, but Reader 2 had relatively little experience aging fish. Since using otolith sections for aging Ictalurid catfishes is a relatively new technique, it is expected that most fisheries scientists desiring to age catfish will have had little experience using catfish otolith sections. Therefore, having a relatively inexperienced second reader provided a more realistic test of the feasibility of using otolith sections to age ictalurid catfishes in managerial settings. Within reader precision estimates for both readers were much more
similar for pectoral spine sections for all three species because both readers had about the same amount of experience reading pectoral spine sections. Early in this study, pectoral spine sections were found to be unsuitable for aging purposes, and most of the pectoral spine sections processed by Reader 1 were those used for the precision estimates. Between-reader precision for all three species in this study were similar to the between-reader precision reported by Nash and Irwin (1999), which is the only other study to date to successfully age ictalurid catfish to date using otolith sections. Nash and Irwin (1999) reported 85%, 61%, and 55% agreement between readers of flathead catfish (*Pylodictus olivaris*) otolith, articulating process, and basal recess sections, respectively.

Reader 2 produced consistently lower age estimates than Reader 1 for all structures for all species; however, significant, systematic bias between readers was detected for only blue catfish (Figure 31, Tables 7-9). Systematic bias may have remained undetected for the calcified structures for the other two species due to the relatively small sample sizes used for channel and white catfishes (46 and 38 fish, respectively). Singular disagreements contribute little to the test statistic, which may result in undetected bias if the majority of disagreements are singular (Evans and Hoenig 1998; Hoenig et al. 1995). Figures 32 and 33 for channel and white catfish show that bias may indeed be present, but there are too few samples to detect the bias. Many of the disagreements between readers for otolith sections of all three species could be traced to the assessment of margin status by each reader. For many of the disagreements, Reader 2 described the margin as dark, indicating the annulus formation was not yet
complete. In contrast, Reader 1 described the same margin as being clear but very small, thus indicating annulus formation had been recently completed. Low contrast and frequent occurrence of false annuli were the most likely causes for the high disagreement between readers for both pectoral spine sections for all three species. False annuli on catfish pectoral spine sections have been acknowledged as a problem since their first use (Marzolf 1955; Sneed 1951).

Several other difficulties with pectoral spines sections made otolith sections an obvious choice for aging purposes and growth measurements for this study. Not only does the expanding lumen prohibit obtaining accurate age estimates and growth increment measurements from basal recess sections, it was often impossible to find one radius along which to count annuli. This was a common problem with articulating process sections, as well. Annuli often changed in contrast or shape due to defects in the crystal structure of the pectoral spine or the addition of new growth axes to the pectoral spine radius. Furthermore, it was often difficult to section the pectoral spines of each species in a consistent location due to the morphology of the pectoral spine. Once sectioned, great care had to be taken when polishing the pectoral spine section because the sections were easily overpolished or suddenly became translucent when reduced to a particular thickness. The articulating process sections of each species appear to undergo deterioration near the center of the section similar to that caused by the lumen in basal recess sections. The deterioration of the center of the articulating sections may have been caused by the inner curve of the interlocking end of the articulating process. The inner curve of the
interlocking end of the articulating process increased with the size of the pectoral spine so that the section location may have had to move as the pectoral spine increased in size. This deterioration and movement, like that of the lumen of the basal recess section, resulted in consistently lower age estimates from pectoral spine sections than from otolith sections. Finally, annuli near the margins of both pectoral spine sections were far more difficult to discern than those near the margins of otolith sections.

The hypothetical mean maximum length (Lm) for each species may be appreciably underestimated due to the lack of citation or trophy sized fish in the sample, especially for channel catfish. The Virginia state record channel catfish weighed 15kg, which is five times heavier than the largest channel catfish in this study. Although record-winning fish may deviate strongly from the mean, the hypothetical mean maximum length should be somewhat higher for channel catfish since numerous fish in this study were nearly 200mm longer than the estimated mean maximum length (Figure 43). Estimates of the mean maximum length for blue catfish and white catfish are probably closer to the true mean than the estimate for channel catfish (Jenkins and Burkhead 1994). Because of these caveats, the length, weight, and age distributions given for each species (Figures 7-12, 40-42) are given to illustrate the range of sizes and ages encountered during this study rather than provide explicit information concerning the size or age distributions for the populations of each species.
Chapter 2

Somatic and Otolith Growth Patterns
Introduction

An often overlooked piece of information available from age and growth studies is yearly variation in growth. Appelgate and Smith (1951) noticed considerable annual variation in growth of channel catfish (as determined from otolith increment measurements) from a navigation pool on the Mississippi River, Iowa, which was strikingly similar to the annual variation in growth observed in freshwater drum taken from the same area of the Mississippi River. Despite such observations, there have been few investigations into the causes of interannual variations in growth. As a poikilothermic animal with asymptotic growth, the size of a growth increment added by a fish during a year is dependent upon variables intrinsic to a fish (age/size) and a multitude of extrinsic factors that vary annually (temperature, food availability, competition, discharge, etc.) (Weisberg 1986; Weisberg and Frie 1987; Weisberg 1993). If a population of fish exists in a completely stable, unvarying environment, then it is expected that the observed differences in annual otolith (growth) increment widths would result entirely from intrinsic differences related to age, as growth rate in fishes generally decreases with age (Weisberg and Frie 1987). Similarly, if increment width depends solely on environmental conditions during growth, then increment widths formed during a given year would be the same across all age groups of fish regardless of age (Weisberg and Frie 1987). Using growth increment data
from 441 smallmouth bass collected over three years from Bearskin Lake, Minnesota, Weisberg (1993) created a general linear model containing an age effect, year (environmental) effect, and an age-year interaction. The magnitude of the coefficients calculated by the model indicate the strength of the effect each year and age had in determining the amount of growth represented by a given increment. Furthermore, these coefficients can be used to compare the growth of different populations (Weisberg and Frie 1987; Weisberg 1986). Similar methods and results are presented in Weisberg and Frie (1987) for walleye (Stizostedion vitreum) from Lake of the Woods, Minnesota and in Weisberg (1986) for bluegill sunfish (Lepomis macrochirus), from Camp Lake and Lake Mary, Minnesota. One key disadvantage to Weisberg’s model, however, is that it requires otolith growth increments to be linearly related, which only occurs for relatively short periods of the growth record due to increasingly smaller increments being added each year to the otolith.

An alternative to Weisberg’s method is a technique traditionally used by dendrochronologists. Growth increments are detrended to eliminate age effects from the increments, then the residuals are analyzed in conjunction with environmental variables. Using this method, environmental variables such as air temperature (LeBreton and Beamish 2000; Guyette and Rabeni 1995, McCauley and Kilgour 1990), stream discharge (Guyette and Rabeni 1995; Beacham 1981) and other habitat variables (Putman et al. 1995; Rutherford et al. 1995) have been found to be correlated with residuals from growth curves of various fish species. However, correlation-based models used in fisheries science and
management often fail shortly after publication due to the relatively short time-series on which those studies were based. Furthermore, correlation-based studies assume that relationships between residual growth increments and the variables of interest are linearly related and allow for only simple interactions between variables.

Regression trees are an exploratory alternative to linear regression and correlation-based techniques. Rather than estimating beta weights to determine the importance of variables, regression trees use only those variables that effectively split the response data into several small, homogenous groups. Regression trees have several advantages over linear regression for exploratory analyses, including rapid assessment of variables from multivariable datasets, more flexibility in the types of interactions allowed between predictors, and straightforward interpretations when numeric and categorical variables are used (Clark and Pregibon 1997).

**Study Objectives**

All the ecological information recorded by the otoliths of fish has seldom been examined fully and robustly. Chapter Two details the third and fourth objectives of this study. Growth patterns are examined across species, sexes, and rivers, and growth curves are then fit to the most homogeneous unit possible. The residuals from this final step are examined using relatively robust methods in an attempt to understand the extrinsic factors that influence the growth of blue, channel, and white catfishes.
Methods

To understand interannual variations in the growth of each species, other sources of variation must be identified and removed from the data. Somatic growth patterns were investigated first to identify any patterns that might be recorded in the otoliths of each species. Differences in growth patterns between sexes and between rivers were examined by coding for sex or river, fitting an appropriate curve to each respective group, and checking for overlap of the 95% confidence intervals for the expected size-at-age for the curve fitted to each group of data (SAS 1989, PROC NLIN). Estimated growth curves were then compared across rivers and species. This process was then repeated for the otolith growth curves of each species so that the residuals from the final growth curves for each species could be analyzed for temporal trends.

Due to the unusual relationship between blue catfish otolith radius and fork length, a similar process was applied to the otolith radius/fork length data of each species to provide insights into the possible causes for the slope change in the otolith radius/fork length relationship.

Once all identifiable sources of variation were described for the otolith growth curves, studentized residuals from the regression for the final, appropriate level of data grouping (by species level, sex, river, etc.) were plotted by year using boxplots to display any existing temporal patterns. Studentized residuals
were used to create a common scale for residuals from points of differing statistical leverage or for residuals from regressions of data of differing variation (Fox 1984; Hoaglin et al. 1983). Boxplots show location, spread, and skewness of the data and are an efficient method of exploratory data analysis that are useful for revealing the relationships between different groups of data, which are growth years in this case (Hoaglin et al. 1983).
Results

Patterns in Somatic Growth

If Figure 43 is plotted and coded for sex, the 95% confidence intervals for the expected lengths-at-age for both males and females of each species overlap to a large degree for most ages, indicating no significant differences between males and females of each species (Figure 45). Attempts at modeling the blue catfish data with a von Bertalanffy growth curve resulted in either nonsensical results or failure of the parameter estimating algorithm to converge on parameter estimates. Instead, a logistical growth curve,

\[ L_t = L_\infty / (1 + be^{ct}) \]

where:

- \( L_t \) = length at age \( t \)
- \( L_\infty \) = hypothetical maximum mean length
- \( b \) = x value (age in years) of the inflection point of the curve
- \( c \) = a growth coefficient (different definition than k for the von Bertalanffy growth curve)
- \( t \) = age in years

was fitted to the blue catfish data with more suitable results (Figure 45).

Parameter estimates for each species by sex are shown in Table 15.
Comparison of Growth Curves by Sex for Blue, Channel, and White Catfishes

**Blue Catfish**
- Males: $n = 203$, $R^2 = 72.58\%$
- Females: $n = 250$, $R^2 = 78.27\%$

**Channel Catfish**
- Males: $n = 73$, $R^2 = 53.58\%$
- Females: $n = 124$, $R^2 = 60.01\%$

**White Catfish**
- Males: $n = 90$, $R^2 = 75.09\%$
- Females: $n = 115$, $R^2 = 65.55\%$

Figure 45. Somatic growth curves by sex for each species. The dashed lines surrounding each curve represent the 95% confidence interval around the expected value.
Table 15. Estimated somatic growth curve parameters for each species by sex. A logistic growth curve was used for the blue catfish data while a von Bertalanffy growth curve was used for the other two species. Therefore, von Bertalanffy parameter estimates are unavailable for blue catfish, and logistic growth curve parameter estimates are likewise unavailable for channel and white catfishes. Note that the growth coefficient for the von Bertalanffy and logistic growth curves are not equivalent.

<table>
<thead>
<tr>
<th>Regression Information</th>
<th>Blue Catfish</th>
<th>Channel Catfish</th>
<th>White Catfish</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Males</td>
<td>Females</td>
<td>Males</td>
</tr>
<tr>
<td>n</td>
<td>203</td>
<td>250</td>
<td>73</td>
</tr>
<tr>
<td>L_∞</td>
<td>789.40</td>
<td>815.30</td>
<td>443.88</td>
</tr>
<tr>
<td>Growth Coeff.</td>
<td>0.37</td>
<td>0.29</td>
<td>0.20</td>
</tr>
<tr>
<td>t_0</td>
<td>NA</td>
<td>NA</td>
<td>-1.28</td>
</tr>
<tr>
<td>b (Inflect pt.)</td>
<td>5.82</td>
<td>4.80</td>
<td>NA</td>
</tr>
<tr>
<td>p-value</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>r²</td>
<td>0.7258</td>
<td>0.7827</td>
<td>0.5358</td>
</tr>
</tbody>
</table>
If Figure 43 is plotted and coded for river, some patterns become apparent (Figure 46). For all three species (Figure 46), data for fish from the York River System generally fall above the regression line (positive residuals) while data from Rappahannock River fish tend to fall below the regression line (negative residuals). Data from the James River was intermediate for all three species (Figure 46). Growth curves for each species for each river and coded for gear are shown in Figures 47-49 and parameter estimates are given in Table 16. Once again, a logistical growth curve was fitted to the blue catfish data instead of a von Bertalanffy growth curve because the logistical growth curve resulted in a better fit (Figure 47). Several outliers were present in the length-at-age data for blue catfish from the James River that prevented every attempted curve from fitting adequately. These fish were caught by the USFWS Sturgeon Restoration Project using a large-mesh gill net and represent the majority of large fish caught in the James River (Figure 47). Once these seven outliers were removed, a logistic growth curve represented these data satisfactorily; however, the parameter estimates from this data should be viewed with caution due to insufficient representation of large fish (Figure 47, Table 16). Von Bertalanffy growth curves were used for both channel and white catfishes (Figures 48-49).

The use of logistic growth curves to model somatic growth of blue catfish is rather unusual since the growth of many fishes typically follow a von Bertalanffy growth curve; therefore, further investigation is required to determine the robustness and validity of the logistic growth of blue catfish. The data shown in Figure 47 were plotted, coded by sampling year, and modeled with logistic
Figure 46. Length-at-age data for each species coded for river. Growth rates for each species may vary by river based on the patterns present in the length-at-age data cloud for each species.
Figure 47. Blue catfish somatic growth curves for each river coded for gear. The dashed lines surrounding each curve represent the 95% confidence interval around the expected value. The seven highlighted points from the James River were not included in the analysis.
Table 16. Estimated somatic growth curve parameters for each species by river. A logistic growth curve was used for the blue catfish data while a von Bertalanffy growth curve was used for the other two species. Therefore, von Bertalanffy parameter estimates are unavailable for blue catfish, and logistic growth curve parameter estimates are likewise unavailable for channel and white catfishes. Note that the growth coefficient for the von Bertalanffy and logistic growth curves are not equivalent.

<table>
<thead>
<tr>
<th>Species</th>
<th>River</th>
<th>n</th>
<th>$L_\infty$</th>
<th>Growth Coeff.</th>
<th>$t_0$</th>
<th>b (Inflect. pt.)</th>
<th>p-value</th>
<th>r2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blue Catfish</td>
<td>James</td>
<td>258</td>
<td>754.3</td>
<td>0.25</td>
<td>NA</td>
<td>4.11</td>
<td>&lt;0.0001</td>
<td>0.6941</td>
</tr>
<tr>
<td></td>
<td>Rappahannock</td>
<td>222</td>
<td>881.6</td>
<td>0.27</td>
<td>NA</td>
<td>5.90</td>
<td>&lt;0.0001</td>
<td>0.8356</td>
</tr>
<tr>
<td></td>
<td>York System</td>
<td>75</td>
<td>741.3</td>
<td>0.47</td>
<td>NA</td>
<td>4.29</td>
<td>&lt;0.0001</td>
<td>0.6506</td>
</tr>
<tr>
<td>Channel Catfish</td>
<td>James</td>
<td>114</td>
<td>451.7</td>
<td>0.23</td>
<td>-0.39</td>
<td>NA</td>
<td>&lt;0.0001</td>
<td>0.7466</td>
</tr>
<tr>
<td></td>
<td>Rappahannock</td>
<td>75</td>
<td>457.0</td>
<td>0.12</td>
<td>-1.96</td>
<td>NA</td>
<td>&lt;0.0001</td>
<td>0.6096</td>
</tr>
<tr>
<td></td>
<td>York System</td>
<td>49</td>
<td>400.4</td>
<td>0.54</td>
<td>0.27</td>
<td>NA</td>
<td>&lt;0.0001</td>
<td>0.6383</td>
</tr>
<tr>
<td>White Catfish</td>
<td>James</td>
<td>67</td>
<td>382.3</td>
<td>0.11</td>
<td>-4.14</td>
<td>NA</td>
<td>&lt;0.0001</td>
<td>0.6532</td>
</tr>
<tr>
<td></td>
<td>Rappahannock</td>
<td>59</td>
<td>341.4</td>
<td>0.17</td>
<td>-2.72</td>
<td>NA</td>
<td>&lt;0.0001</td>
<td>0.5071</td>
</tr>
<tr>
<td></td>
<td>York System</td>
<td>91</td>
<td>412.2</td>
<td>0.19</td>
<td>-0.67</td>
<td>NA</td>
<td>&lt;0.0001</td>
<td>0.8413</td>
</tr>
</tbody>
</table>
Figure 48. Channel catfish somatic growth curves for each river coded for gear. The dashed lines surrounding each curve represent the 95% confidence interval around the expected value.
Figure 49. White catfish somatic growth curves for each river coded for gear. The dashed lines surrounding each curve represent the 95% confidence interval around the expected value.
growth curves if there were sufficient data (Figure 50). As shown in Figure 50, the pattern exists for blue catfish collected from the James River in 1999 and the Rappahannock River in 1999 and 2000. The data from the York River System must be interpreted with caution due to the small sample size (Figure 50).

When somatic growth curves were compared across species by river, blue catfish were larger than both channel and white catfishes after age five in all three rivers (Figure 51). Channel catfish were larger than white catfish after age two in both the James and York rivers, but growth curves for channel and white catfishes in the Rappahannock overlapped throughout the entire life span of both species (Figure 51). Comparing somatic growth curves across rivers by species revealed that all three species tended to reach a larger size earlier in the York River System (Figure 52). By age two, blue catfish from the York River System were larger than blue catfish from both the James and Rappahannock; however, blue catfish from all three rivers were similar in size by age ten (Figure 52). It is emphasized that the growth curve for James River blue catfish may underestimate the true growth rate due to the lack of large fish in the samples. Channel catfish from the York River system were larger than channel catfish from the other two rivers by age two, but fish from all three rivers were similar in size again by age eight (Figure 52). The greatest differences in growth occurred between channel catfish populations of the James and Rappahannock rivers. James River channel catfish were larger than Rappahannock River channel catfish from about age three until age ten (Figure 52). White catfish exhibited a somewhat different pattern than that noted for the other species (Figure 52).
Figure 50. Blue catfish somatic growth curves for each river coded for year. The dashed lines surrounding each curve represent the 95% confidence interval around the expected value. The seven highlighted points from the James River were not included in the analysis.
Figure 51. Comparison of somatic growth curves across species by river. The dashed lines surrounding each curve represent the 95% confidence interval around the expected value.
Figure 52. Comparison of somatic growth curves across rivers by species. The dashed lines surrounding each curve represent the 95% confidence interval around the expected value.
White catfish from the York River system were just slightly larger than Rappahannock or James River fish from age six to age ten, when fish from all three rivers were approximately equal in length (Figure 52).

Figure 53 compares the growth curves for each species from each river with growth curves for each species reported by other studies. However, the comparisons are intended to be casual because there are several caveats that must be mentioned. First, large blue catfish from the James River and large channel catfish are underrepresented in this study, as mentioned earlier. Second, many of the studies shown in Figure 53 used pectoral spine sections to age the catfishes. Third, many of those studies that used pectoral spines for aging made no mention of correcting for early annuli that may have been eroded (Appelgate and Smith 1951; Sneed 1951; Jenkins 1956; Conder and Hoffarth 1965; Kelley, Jr. and Carver 1966; Porter 1969; Hughes and Carlson 1986; Hale and Timmons 1990). Therefore, it is possible that the growth curves presented by the other studies may be overestimated if the ages of the catfishes were underestimated, which was shown in Chapter One to be likely. Finally, all of the studies shown used back-calculated lengths-at-age in their determinations of mean length-at-age (Appelgate and Smith 1951; Sneed 1951; Marzolf 1955; Jenkins 1956; Conder and Hoffarth 1965; Gray 1965; Kelley, Jr. and Carver 1966; Schwartz and Jachowski 1965; Borgeson and McCammon 1967; Porter 1969; Freeze 1977; Hughes and Carlson 1986; Hale and Timmons 1990). Since the relationship between pectoral spine radius and total length may not necessarily be isometric throughout the entire life span of each fish, back-
Comparison of Growth Curves Across Studies by Species

Blue Catfish

Channel Catfish

White Catfish

Publication | Location | Years          | Sample Size
---         | ---      | ---            | ---
1. Jenkins 1956 | Lake Texoma, OK 1948-1955 | 192
2. Conder and Hoffarth 1965 | Kentucky Lake, TN 1961 | 135
3. Gray 1965 | Arkansas River, AK 1964 | 126
5. Hale and Timmons 1990 | Kentucky Lake, TN, Riverine Section 1985 | 369
6. Hale and Timmons 1990 | Kentucky Lake, TN, Lacustrine Section 1985 | 467
7. Appelgate and Smith 1951 | Mississippi River, IA 1945-1946 | 535
8. Sneed 1951 | Grand Lake, OK 1949 | 188
9. Marzolf 1955 | Lake of the Ozarks, MO 1951 | 434
10. Conder and Hoffarth 1965 | Kentucky Lake, TN 1961 | 134
13. Schwartz and Jachowski 1965 | Patuxent River, MD 1963 | 470

Figure 53. Comparison of somatic growth curves observed in this study and those reported in other studies.
calculations can often introduce unexpected and unpredictable biases in the
estimated mean lengths-at-age.

Patterns in Otolith Growth

Otolith growth curves for each species exhibited patterns very similar to
the somatic growth curves for each species. Otolith growth curves for both sexes
for each species were well described by von Bertalanffy growth curves, and
parameter estimates for both sexes for each species are shown in Table 17.
Growth curves for males and females of each species overlapped almost
completely for all ages (Figure 54).

Otolith growth curves for each species in each river were also well
described by von Bertalanffy growth curves, and all regressions had R² values
greater than 95% (Figures 55-57). Otolith growth curve parameter estimates are
given in Table 18. The seven outliers from the length-at-age data for blue catfish
from the James River are not readily apparent in the otolith radius/age data, but
fish caught with the sturgeon gill net tended to lie above the regression line for
the data (Figure 55). No other gear-related patterns are readily noticeable in the
blue catfish data (Figure 55) or in the data for the other two species (Figures 56
and 57).

Differences in otolith growth rates among species are less apparent than
differences in somatic growth rates when comparing across species by river
(Figure 58). Growth curves for channel and white catfishes from the James River
overlapped for all observed ages, as did growth curves for blue and channel
<table>
<thead>
<tr>
<th>Regression Information</th>
<th>Blue Catfish Males</th>
<th>Blue Catfish Females</th>
<th>Channel Catfish Males</th>
<th>Channel Catfish Females</th>
<th>White Catfish Males</th>
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<tr>
<td>n</td>
<td>820</td>
<td>853</td>
<td>598</td>
<td>673</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$L_0$</td>
<td>789.40</td>
<td>815.30</td>
<td>365.40</td>
<td>384.10</td>
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<td></td>
</tr>
<tr>
<td>k</td>
<td>0.37</td>
<td>0.26</td>
<td>0.20</td>
<td>0.15</td>
<td>-1.24</td>
<td>-2.12</td>
</tr>
<tr>
<td>$t_0$</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>p-value</td>
<td>&lt;0.0001</td>
<td>0.9637</td>
<td>&lt;0.0001</td>
<td>0.9642</td>
<td>0.9602</td>
<td>0.9631</td>
</tr>
<tr>
<td>$r^2$</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>
Comparison of Otolith Growth Curves by Sex for Blue, Channel, and White Catfishes

Blue Catfish
Males n = 820, $R^2$ = 96.02%
Females n = 853, $R^2$ = 96.63%

Channel Catfish
Males n = 371, $R^2$ = 96.37%
Females n = 598, $R^2$ = 96.42%

White Catfish
Males n = 457, $R^2$ = 96.07%
Females n = 673, $R^2$ = 96.31%

Figure 54. Otolith growth curves by sex for each species. The dashed lines surrounding each curve represent the 95% confidence interval around the expected value.
Figure 55. Blue catfish somatic growth curves for each river coded for gear. The dashed lines surrounding each curve represent the 95% confidence interval around the expected value.
Figure 56. Channel catfish otolith growth curves for each river coded for gear. The dashed lines surrounding each curve represent the 95% confidence interval around the expected value.
Figure 57. White catfish otolith growth curves for each river coded for gear. The dashed lines surrounding each curve represent the 95% confidence interval around the expected value.
Table 18. Estimated otolith growth curve parameters for each species by river. Sample sizes (n) are the total number of increments used for each regression.

<table>
<thead>
<tr>
<th>Species</th>
<th>River</th>
<th>n</th>
<th>$L_\infty$</th>
<th>Growth Coeff.</th>
<th>$t_0$</th>
<th>p-value</th>
<th>r2</th>
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<tr>
<td>Blue Catfish</td>
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<td>Rappahannock</td>
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<td>York System</td>
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<td>-0.51</td>
<td>&lt;0.0001</td>
<td>0.9744</td>
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</tbody>
</table>
Comparison of Otolith Growth Curves across Species by River

Figure 58. Comparison of growth curves across species by river. The dashed lines surrounding each curve represent the 95% confidence interval around the expected value.
catfishes from the James River (Figure 58). Growth curves for blue and white catfishes did not overlap after age seven, with blue catfish otoliths growing larger than white catfish otoliths (Figure 58). Channel catfish and white catfish growth curves also overlapped for all observed ages for fish from the Rappahannock River, but the otoliths of blue catfish were larger than the other two species’ otoliths after age six (Figure 58). Growth curves for all three species overlapped completely for fish from the York River System (Figure 58).

Fish from the Rappahannock River appear to have smaller otoliths than fish from the other two rivers, regardless of species (Figure 59). For blue catfish, otolith growth curves for fish from the James River and York River system overlap completely; however, overlap with the otolith growth curve for Rappahannock River fish occurs only before age three and after age ten (Figure 59). Growth curves for channel catfish from the James River and York River system overlap for all observed ages, while channel catfish from the Rappahannock River have smaller otoliths than fish from the other two rivers after age two (Figure 59). White catfish growth curves for fish from the James River and York River system overlapped until age six (Figure 59). Rappahannock River otolith growth curves for white catfish ceased overlapping with those from the other rivers after age two (Figure 59).

Patterns in Otolith Radius/Fork Length Relationships

The nonlinear relationship between otolith radius and fork length of blue catfish persisted even at the river level with no obvious connection to gear type
Comparison of Otolith Growth Curves across Rivers by Species

Blue Catfish

Regression --- 95% CI-----

Channel Catfish

White Catfish

Figure 59. Comparison of otolith growth curves across rivers by species. The dashed lines surrounding each curve represent the 95% confidence interval around the expected value.
with which fish were caught (Figure 60). The outlying blue catfish caught with the sturgeon gill net in the James River deviate strongly from the relatively linear cloud reflecting the data from the other blue catfish caught in the James River (Figure 60), which suggests that the change in relationship between otolith radius and fork length is particularly strong for fast growing fish. For the sturgeon gill net fish, otolith radius increased little despite an almost 400mm increase in fork length (Figure 60). This nonlinear behavior is present in the data for blue catfish from the Rappahannock River and York River system, as well (Figure 60).

The otolith radius/fork length data cloud for channel catfish in each tributary also appears approximately linear; however, the data cloud is almost circular for fish 250-350mm fork length (Figure 61). A similar phenomenon occurs for white catfish (Figure 62). In both cases, many of the fish were caught by the VIMS Trawl Survey (Figures 61 and 62).

**Interannual Variations in Otolith Growth**

Boxplots of the studentized residuals from the river-based otolith growth curves for each species are shown in Figures 63-65. Intra-annual variations in growth appear far greater than interannual variations for all three species in all three rivers (Figures 63-65), indicating that interannual variations in growth for each species in each river may occur at the individual level. No further analyses were performed due to the lack of any meaningful temporal patterns in the data.
Figure 60. Otolith radius versus fork length for blue catfish coded by gear.
Channel Catfish Otolith Radius vs. Fork Length by River and Gear

James River
n = 111

Rappahannock River
n = 50

York River System
n = 46

Figure 61. Otolith radius versus fork length for channel catfish coded by gear.
Figure 62. Otolith radius versus fork length for white catfish coded by gear.
Figure 63. Boxplots of studentized residuals for blue catfish by year for each river.
Figure 64. Boxplots of studentized residuals for channel catfish by year for each river.
Figure 65. Boxplots of studentized residuals for white catfish by year for each river.
Discussion

Somatic growth curves and otolith growth curves largely overlapped for males and females for each of the three catfish species. Other age and growth studies of blue and channel catfishes also failed to find differences in growth rates between males and females (Hubert 1999; Hale and Timmons 1990; Hale 1987). No direct comparisons of male and female growth rates for white catfish were found, but length-at-maturity for white catfish from the Sacramento-San Joaquin Delta, California, were similar for males and females in that study (Borgeson and McCammon 1967).

Except for blue catfish from the James River, somatic and otolith growth curves showed that all three catfish species grew slowest in the Rappahannock River (Figures 52 and 59). Growth rates for each species tended to be highest in the York River system (Figures 52 and 59). Growth curves for James River catfishes were intermediate between those observed in catfishes from the York River system and Rappahannock River, or overlapped with York River system growth rates (Figures 52 and 59). The somatic growth curve for James River blue catfish may not truly reflect somatic growth rates of the James River population because seven of the fastest growing fish were excluded from the regression analysis (Figure 47). While the otolith growth rates of these fish tended to fall above the regression curve for James River blue catfish, the
deviation from the otolith growth curve was not as great as the deviation from the somatic growth curve (Figures 47 and 55). These fish may have represented a faster growing portion of the blue catfish population in the James River, and this part of the population was poorly sampled since few large blue catfish were caught in the James River. When compared with blue catfish from the York River system, which had the fastest growth rates of the three tributaries, the James River outliers appear less extreme (Figure 47). Thus, somatic growth rate for James River blue catfish may be more similar to that of blue catfish in the York River system than the James River blue catfish data imply.

According to Owenby et al. (1993), the majority of the drainage area for each river falls mainly in the same climatic zone. If climate is the sole determinant of catfish growth, the growth rates of each species should be relatively similar in all three rivers. Latitude, as an indirect measure of climate, often has an impact on the growth rates of many species; however, the growth rates of blue, channel, and white catfishes in this study appear unaffected by latitude because the York River system is north of the James River. Primary productivity or catfish density may vary in a fashion similar to the observed growth rates. Density-dependent impacts on growth rates of blue and channel catfishes have been implicated in several studies of Kentucky Lake (Hale and Timmons 1990; Freeze 1977; Conder and Hoffarth 1965). The order of otolith growth rates from slowest to fastest does match the temporal order of the first blue catfish introductions into the Virginia tributaries of the Chesapeake Bay, which suggests density dependence as a possible constraint. Blue catfish were
first introduced into the Rappahannock River in 1974, into the James River in 
1975, and into the York River system in 1985 (VDGIF 1974; VDGIF 1977; VDGIF 
1985; VDGIF 1989; Jenkins and Burkhead 1994). Additional introductions 
occurred in 1975 and 1977 in the Rappahannock River and in 1985 and 1989 in 
the James River (VDGIF 1977; VDGIF 1985; VDGIF 1989; Jenkins and 
Burkhead 1994). Information on food webs and catfish densities in each river is 
necessary to understand the forces that influence growth rates in each river. 

When compared to length-at-age data from other studies, blue, channel, 
and white catfishes from the James, Rappahannock, and York rivers appear to 
be among the slowest growing (Figure 53); however, such comparisons must be 
made with caution for several reasons. First, all the previously published studies 
included back-calculated lengths-at-age in their calculations of mean lengths-at-
age (Appelgate and Smith 1951; Sneed 1951; Marzolf 1955; Jenkins 1956; 
Conder and Hoffarth 1965; Gray 1965; Kelley, Jr. and Carver 1966; Schwartz 
and Jachowski 1965; Borgeson and McCammon 1967; Porter 1969; Freeze 
1977; Hughes and Carlson 1986; Hale and Timmons 1990), which may introduce 
error depending on the assumptions made and back-calculating technique used. 
Second, basal recess sections were used for age estimation in many of these 
studies, but no mention was made concerning corrections for annuli eroded by 
the lumen (Appelgate and Smith 1951; Sneed 1951; Jenkins 1956; Conder and 
Hoffarth 1965; Kelley, Jr. and Carver 1966; Porter 1969; Hughes and Carlson 
1986; Hale and Timmons 1990). Therefore, length-at-age estimates reported by 
these studies may be overestimated if the true ages of the fish were
underestimated. In those studies where corrections were made, or the fishes were aged using vertebrae, growth rates were comparable to those observed in this study up to age six for blue catfish and channel catfish and ages six to nine for white catfish (Figure 53) (Marzolf 1955; Gray 1965; Schwartz and Jachowski 1965; Freeze 1977). When compared to other studies conducted in estuarine settings and assuming reported length-at-age estimates are correct, blue catfish collected during this study had considerably slower growth rates than blue catfish from the Recent Delta of the Mississippi River, and white catfish from the Patuxent River, MD, and the Hudson River estuary, NY, were larger after ages nine and five, respectively, than white catfish collected during this study (Figure 53). Maximum ages observed in this study for each species were often two to three years older than those reported in previous studies (Figure 53). Another item worth noting is that this study is the only one to date in which blue, channel, and white catfishes existed sympatrically (Figure 53).

When the blue catfish data from all the rivers are combined, a von Bertalanffy growth curves fits the data reasonably well (Figure 43); however, a logistic growth curve appears more appropriate for the length-at-age data for each river (Figures 47 and 50). The use of logistic growth curves to model length-at-age data for fishes has rarely, if ever, been reported, which suggests that the use of logistic growth curves to describe the blue catfish length-at-age data collected during this study should be further explored. As Figure 50 shows, the logistic growth curve adequately models the blue catfish length-at-age data from one year of data from the James River, two years of data from the
Rappahannock River, and two years of data from the York River System. During 1998 in the James, Rappahannock, and York rivers, and 2000 in the James River, sample sizes were insufficient for modeling purposes. Since the logistic growth curve adequately models the blue catfish length-at-age data from more than one river in more than one year, two alternate conclusions may be reached. First, the somatic growth of blue catfish as a species, or at least in the area sampled during this study, truly follows the logistic growth curve. If this is the case, it is interesting to note that the inflection points of the logistic growth curves for male and female blue catfish and for blue catfish from each river occurred between four and six years of age, corresponding to ages when blue catfish mature (Table 16; Graham 1999, Jenkins and Burkhead 1994). This relationship may just be a mathematical convenience, but it is not unreasonable to believe that increases in length may slow after maturity since more energy is directed toward development and maintenance of reproductive tissues, spawning activities, and reduced feeding during parental care. An alternative conclusion is that the apparent logistic growth of blue catfish is an artifact of inadequate sampling. Underrepresentation of fish 200mm FL and shorter (slow-growing one and two year-olds) would result in the data for the fish under six years old appearing more level than expected if growth truly followed the von Bertalanffy growth curve. Underrepresentation of fast growing fish between the ages of four and six years old would further favor a logistic curve over a von Bertalanffy growth curve for describing the blue catfish length-at-age data. Since the combined data shown in Figure 43 were adequately described by a von
Bertalanffy growth curve, any gear-biased biases from one river maybe 
“cancelled out” by complementary data from another river, which would de-
emphasize the sigmoid shape of the data cloud from each river. Additionally,
carefully planned sampling of blue catfish from each river would provide more 
insight into the nature of blue catfish somatic growth.

When otolith radius/fork length data for each species is plotted by river 
and coded for gear, the data appears relatively linear for channel and white 
catfishes (Figures 61 and 62) but remains nonlinear for blue catfish (Figure 60). 
The blue catfish caught with the sturgeon gill net from the James River, along 
with a few fish caught with the low-frequency electrofisher, fall on a much 
different line than the rest of the James River blue catfish (Figure 60). However, 
the line these large fish fall on does not appear dramatically different than that for 
the large blue catfish in the other two rivers, suggesting this may be a 
phenomenon intrinsic to Virginia blue catfish. Several studies have documented 
otolith growth being faster than somatic growth during periods of slow somatic 
growth and slower than somatic growth during periods of rapid somatic growth 
(Casselman 1990; Secor and Dean 1989; Mosegaard et al. 1988; Neilson et al. 
1985; Penny and Evans 1985; and Marshall and Parker 1982); however, only 
one of these studies was conducted on post-juvenile fish (Casselman 1990). 
Data from this study suggest that somatic growth outpaces otolith growth once 
blue catfish attain a certain size (Figure 60). As mentioned earlier, the otolith 
radius/fork length relationship for channel and white catfishes was relatively 
linear (Figures 61 and 62), except for white catfish from the Rappahannock River
(Figure 62), but the variability of the relationship increased suddenly between 300-400mm fork length for both species. Visual inspection of Figures 61 and 62 reveals that many of the 300-400mm fish were caught by the VIMS Trawl Survey. Fish of this size may represent the size class for which this gear has the highest selectivity; as a result, most fishes caught are 300-400mm long but vary in age. This effect is reflected to some degree in the somatic growth curves for channel and white catfishes (Figures 48 and 49).

Given that the Chesapeake Bay area has one of the most dynamic climate regimes in the world, it is rather surprising that blue, channel, and white catfishes do not experience equally large interannual variations in growth (Figures 63-65). This interannual stability of growth rates is even more striking considering that the numbers of blue catfish have increased dramatically (Figure 3). Theoretically, growth rates should decline due to density dependent factors, such as intra- and inter-specific competition for food; however, there is no indication of such changes in the residuals of the growth curves for each species in each river (Figures 63-65). The concurrent decline of channel and white catfish populations (Figure 4) may offset density dependent impacts caused by the increasing blue catfish population in each river. Alternatively, resources utilized by blue, channel, and white catfishes may not yet be limiting in the tributaries of the Chesapeake Bay, and the decline of channel and white catfishes may be altogether unrelated to the growth of the blue catfish population in each river. Finally, species are typically most sensitive to environmental conditions at the edges of their range; however, the Chesapeake Bay is at a latitude similar to that of the center of the
native range for each species (Murdy et al. 1997; Jenkins and Burkhead 1994). Thus, neither environmental conditions nor resource limitation appear to be a limiting factor for the growth of blue, channel, or white catfishes in Virginia tributaries of the Chesapeake Bay.
Study Conclusions

Otoliths proved to be a superior method for aging blue, channel, and white catfish compared to traditional methods. Annulus formation on the otoliths of each species was complete by August for each year of the study. Within- and between-reader precision for otolith sections of each species were substantially higher than within- and between-reader precision for two different pectoral spine sections. Otolith growth rates were much more similar in size and shape across species than somatic growth rates, but otolith growth rates still reflected patterns comparable to somatic growth rates. The growth curves for males and females of each species overlapped to a large degree. Growth rates were highest for fish from the York River system, lowest for Rappahannock River fish, and intermediate for James River fish. The gear with which fishes were caught may impact growth rate estimates. The relationship between otolith radius and fork length for blue catfish exhibited a change in slope around 400mm FL, such that the total length of fish over 400mm FL increased faster than their otolith radius. Despite the dynamic environmental conditions of the Chesapeake Bay region, no interannual variations in the growth rates of blue, channel, or white catfishes were observed.
Literature Cited


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Porter, M. E. 1969. Comparative age, growth, and condition studies on the blue catfish, Ictalurus furcatus (LeSueur), and the channel catfish, Ictalurus punctatus (Rafinesque), within the Kentucky waters of Kentucky Lake. Master's thesis. Murray State University, Murray, Kentucky.


Weisberg, S. 1997. On growth, growth models, and linear growth models: what does it all mean anyway? 

Appendix

A1. Plate 1 taken from Warburton (1978) showing a whole otolith from Galeichthys caerulescens. The author states that the otoliths used were sagittae.

A2. Figure 2 from Reis (1986) showing cross-section from a lapillus of Netuma barba.

A3. Figure 2 from Crumpton et al. (1987) illustrating the appearance of whole otoliths and two otolith sections. The authors refer to the otoliths as “sagittae.”

A4. Figures 1 and 2 from Nash and Irwin (1999) showing cross-sections taken from the otoliths and pectoral spines of flathead catfish.

A5. Figure 1 from Thompson and Beckman (1995) illustrating the section from a lapillus of a white sucker.
Vita

It all started in 1976. William John Connelly was born on September 19, 1976 in Manassas, Virginia, around the same time the blue catfish he would study two decades later were being introduced into Virginia’s tributaries of the Chesapeake Bay. At the age of seven and at the suggestion of his mother (and much to her later chagrin), Bill and his father went fishing for the first time. Despite their initial lack of success, Bill was forever hooked on all things aquatic. His long relationship with the Virginia Institute of Marine Science began with a summer Governor’s School mentorship with Herbert M. Austin in 1993. In 1994, he graduated third in his class from Stonewall Jackson High School in Manassas, Virginia. Bill returned to VIMS again in 1996 as a humble summer technician collecting data on fishes caught in pound nets in the Potomac River. In 1997, he was awarded a summer fellowship with the Virginia Water Resources Research Center and subsequently published a paper entitled “Habitat of the riverweed darter, Etheostoma podostemone Jordan, and the decline of riverweed, podostemum ceratophyllum, in the tributaries of the Roanoke River, Virginia.” He received a B.S., summa cum laude, in Fisheries and Wildlife Science from Virginia Polytechnic Institute and State University in 1998. Bill returned to VIMS for the third time in 1998 as a fellowship student and entered the School of Marine Science. He still looks for minnows near the water’s edge.