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A Comparison of the Pectoral Spines in Virginia Catfishes

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A comparison of the pectoral spines in Virginia catfishes

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Abstract

Catfish pectoral spines are an anti-predator defense mechanism. They can be bound or locked, making the fish harder to swallow, or used to produce distress calls by rubbing ridges on the dorsal process against a channel in the wall of the pectoral girdle. Growth of the pectoral spine and girdle were examined in relation to fish size within and across species that occur throughout central and eastern Virginia. These included blue catfish (*Ictalurus furcatus),* channel catfish (*Ictalurus punctatus),* white catfish (*Ameiurus catus),* brown bullheads *(Ameiurus nebulosus),* yellow bullheads (*Ameiurus natalis),* flathead catfish (*Pylodictis olivaris),* margined madtom (*Noturus insignis),* and tadpole madtom (*Noturus gyrinus).*

Pectoral spines and girdles grow as catfish increase in size. In larger species spine length and weight increase nonlinearly with fish size, suggesting that maintaining spine dimensions becomes less important in bigger individuals less likely to suffer predation. The incidence of spine breakage also increases in larger fish. In smaller species spine length increases linearly in our samples (brown and yellow bullheads and margined and tadpole madtoms). In all species spine width increases linearly with total length. The spine base (dorsal process width and depth and dorsal-ventral length) grows linearly with total length in most species. However, measurements of the spine base increase nonlinearly in white catfishes, and dorsal process width increases nonlinearly in wild channel catfish although the increase was linear in cultured channel catfish.

Girdle depth increased linearly with total length in all species except for wild channel catfish, and the ratio of coracoid to cleithrum depth varied among species. Pectoral girdle weight increased linearly with fish weight in blue catfish, cultured channel catfish, brown bullheads, and margined and tadpole madtoms. However, girdle weight, a major component of the body, increased nonlinearly in wild channel, white, yellow bullheads, and flathead catfishes. Cultured channel catfish had smaller pectoral spines and girdles than wild channels, a likely epigenetic response to predators.

Catfish spines were identified to species, allowing determination of catfishes eaten by bald eagles *(Haliaeetus leucocephalus)* using spines collected near their nests. Bald eagles ate blue catfish (60%), channel catfish (27%), white catfish (9%), brown bullheads (4%) and yellow bullheads (0.5%). Madtom and flathead catfish were not consumed. Mean sizes captured were: Blue catfish (366 mm, 414 g), channel catfish (417 mm, 618 g), white catfish (320 mm, 591 g), brown bullheads (278 mm, 277 g) and yellow bullhead (203 mm, 192 g).

Introduction

Ictalurids are known for the "sting" their pectoral and dorsal spines produce (Jenkins & Burkhead 1993). The spines can be bound, locked and used to produce stridulation sounds (Tavolga 1962; Pfeiffer & Eisenberg 1965; Abu-Gideiri & Nasr 1973; Schachner 1977; Ladich & Fine 1994; Kaatz 1999; Heyd & Pfeiffer 2000). Stridulation sounds are produced when ridges on the dorsal process rub against the cleithrum. The sounds produced are used for social communication, anti-predation, and distress calls (Fine et al 1997; Fine & Ladich 2003; Bosher et al. 2006).

The function of the pectoral spine and girdle as a weapon is a major factor in the success of catfish species (Ladich & Fine 2003). Utilizing processes on the spine base and the pectoral girdle, the spine can be bound and locked (Fine et al. 1997). The resistance between these opposing processes, stabilizes the spine making it difficult for a gape-limited predators to swallow catfishes. Recher & Recher (1968) "observed increased escapes by prey with spines from herons." In other reports catfish spines were found within largemouth bass, water snakes, egrets, and brown pelicans causing wounds and/or death (Krummrich 1969; Burr & Stoeckel 1999; Werner et al. 2001; Bunkley-Williams et al. 1994). Bosher et al. (2006) experimentally determined that spines in channel catfish decreased successful predation but not attack by largemouth bass.

By studying the pectoral spines of eight Virginia catfish species, blue catfish (*Ictalurus furcatus),* channel catfish (*Ictalurus punctatus),* white catfish (*Ameiurus*

catus), brown bullhead catfish *(Ameiurus nebulosus),* yellow bullhead (*Ameiurus natalis),* flathead catfish (*Pylodictis olivaris),* margined madtom (*Noturus insignis),* and tadpole madtom (*Noturus gyrinus),* we developed a species specific identification key, examined the spine growth and development, determine morphological differences between blue and wild channel catfishes, cultured and wild channel catfish, and *Ameiurus spp.* (white, brown and yellow bullhead catfishes), and estimated TL and Wt for pectoral spines collected at bald eagle nesting sites throughout eastern Virginia.

Materials and Methods

Catfishes collected throughout central and eastern Virginia (Table 1) included blue catfish (*Ictalurus furcatus),* channel catfish (*Ictalurus punctatus),* white catfish *(Ameiurus catus),* brown bullhead *(Ameiurus nebulosus),* yellow bullhead catfish *(Ameiurus natalis),* flathead catfish *(Pylodictis olivaris)*, margined madtoms *(Noturus insignis),* and tadpole madtoms (*Noturus gyrinus*). Additionally, cultured channel catfish were obtained from aquaculture ponds associated with Virginia State University. Finally, a number of spines collected among nests of bald eagles were supplied by Bryan Watts of William and Mary. Fishes were measured for total length in millimeters (TL) and weighed.

Pectoral girdles and spines were boiled in water, cleaned, and oven dried at 55C. Girdles were weighed, and girdle, cleithrum and coracoid depths were measured along the ventral midline. Spine dimensions were measured with a micrometer to the nearest 10 µm, and spines were weighed in milligrams. Spine length and weight (Wt) were recorded for left and right spines, and spine width was measured immediately lateral to the dorsal process (spine viewed laterally with the dorsal process upright). Measurements were also made of the spine base, particularly the dorsal process, which is not subject to breakage common in tips of large spines. Measurements included dorsal process width (DP width) (Fig.1-A), dorsal process depth (DP depth) with the micrometer placed just lateral to a protrusion on the anterior-posterior midpoint (Fig. 1-B), dorsal-ventral length (DV length) was measured from tip of the dorsal process to the

tip of the proximal lobe of the ventral processes (Fig. 1-C), and finally spine width (Fig. 1-D) measured from anterior to posterior sides of the pectoral spine. Measurements of the pectoral girdle included the total girdle, coracoid, and cleithrum depths.

Statistical Analysis

Analyses were preformed using Microsoft Excel, SAS 8.02 TS Level 02M0, and Graph Pad PRISM 5.0 software. Regressions of spine dimensions against TL or Wt were calculated to describe spine and girdle growth. Ratios of spine base dimensions were also used to categorize species differences. Data were fit with linear and non-linear regressions. Analysis of covariance (ANCOVA) was run to calculate the differences among and between species. Non-linear data and regressions were either fit with an exponential growth, log-log transformed, or one phase exponential decay curves. Transformations were taken of both the dependent and independent variables and fit on the original linear scale so comparisons could be made within and across species. Catfish spines collected from bald eagle nests were identified by qualitative and quantitative morphometrics across species, and regressions of spine growth were used to estimate the TL and Wt of fishes consumed by eagles.

Results

Catfish spine morphology has been described in detail by Hubbs and Hibbard (1951), Paloumpis (1963), and Fine et al. (1997). I include some basic terms to facilitate understanding of spine morphology (Fig. 2). *Trabeculations* are raised ridges that run along the pectoral spine from base to tip. *Anterior dentations* are typically small teeth that run along the anterior edge of the spine. In the genus *Ameiurus,* anterior dentations give way to a*nterior notches* near the tip of the spine. These notches have a broad horizontal profile terminating in a medially directed point, adjacent to the diagonal trabeculations. The *posterior groove* is a channel that runs down the posterior edge of the spine that opens near the spine base into the *posterior recess*. Internally the posterior recess closes into a narrow channel that runs internally through the spine. *Posterior dentations* are teeth like projections emanating from the posterior groove. Simple dentations are individual structures with a single point, and complex dentations fuse together forming teeth with two or more points. Complex teeth are more common in larger fish. The dorsal, anterior, and ventral processes are located on the spine base. The d*orsal process* projects dorsolaterally from the spine base and fits into a fossa in the cleithrum of the pectoral girdle. The *anterior process* projects medially from the spine base, and is the anterior most process. The *locking tubercle* is located on the ventral edge of the anterior process and is shaped like an apron. The v*entral process* is located under the anterior process and points ventromedially.

Key to non-madtom Ictalurids of Central and Eastern Virginia based on morphology of the pectoral spine

1a Trabeculations on dorsal and ventral surface of spine parallel from base to tip; base of posterior dentations in central groove 2

1b Trabeculations turn diagonally forward approximately ¾ of the way to the spine tip; anterior notches present on anterior edge of spine tip; posterior dentations are located on the dorsal edge of posterior groove 3

1c Well developed posterior and anterior dentations . . . . *Pylodictis olivaris*
Flathead Catfish

2a Anterior edge forms a ridge that protrudes notably beyond the trabeculations; anterior process typically curves anteriorly; anterior dentations absent or developed minimally for the first quarter near the spine base; surface feels smooth. . . . . *Ictalurus furcatus*
Blue Catfish

2b Anterior ridge not prominent; anterior process typically curves posteriorly; anterior dentations usually present and small from base to tip; surface feels rough . . . . *Ictalurus punctatus*
Channel Catfish

3a Posterior dentations form dorsal to the posterior groove giving the dorsal surface of the spine a relatively flat appearance; the tip of the anterior process tends to points slightly anterior or be somewhat straight and is relatively blunt . . . . *Ameiurus nebulosus*
Brown Bullhead

3b Posterior dentations form dorsal to the midline of the posterior groove near the spine base and further laterally within the groove; the locking tubercle on the anterior process protrudes posteriorly; the tip of the anterior process may curve posteriorly or be relatively straight 4

4a Locking tubercle on posterior edge of anterior process is highly developed and exhibits a notable posterior protrusion; anterior most region of anterior edge occurs half way from the spine base . . . . *Ameiurus catus*
White Catfish

4b Anterior dentations are lacking along the anterior edge of spine; anterior process relatively pointed; locking tubercle poorly developed or somewhat straight . . . . *Ameiurus natalis*
Yellow Bullhead

Blue Catfish - *Ictalurus furcatus*

Blue catfish spines are slightly bowed. The forward most region of the anterior edge is located approximately one-fourth out from the spine base. Trabeculations on the dorsal and ventral surface run parallel from the base to the tip of the spine. The anterior edge forms a ridge that protrudes notably beyond the trabeculations. Its edge on the first quarter of the spine is smooth, but some individuals have small dentations further laterally. Posterior dentations are located within the center of the posterior groove extending from the base to near the tip of the spine. In smaller and medium fish (< 400 mm TL, 47 mm spine length) dentations are large and triangular in shape and point medially. In larger fish they tend to be smaller (likely from wear), more complex and variable; there are often two or more points per dentation. Dentations tend to point posteriorly near the spine base and medially near the tip of the spine. The lateral edge of the dorsal process tends to be thicker then in channel catfish, and the anterior process is relatively straight and typically points anteriorly.

Pectoral spines and girdles were sampled from 92 fish that ranged from 63 to 1,008 mm in TL and from 3.4 g to 22 kg in Wt (Table 1). Spine length and Wt increased nonlinearly from 8.61 mm and 2 mg to 96.52 mm and 10.22 g (Table 4, Fig. 5-A, B). Pectoral spines were intact in small fish, but tended to break in large animals. Spine width however, which is not affected by breaking, increased linearly from 0.84 mm to 14.99 mm (Table 4, Fig. 5-C). Similarly, the spine base, including dorsal process width and depth and dorsal-ventral length, increased linearly with fish size (Table 4, Fig. 5-D, E, F).

Midline pectoral girdle depth, including the cleithrum and the coracoid, increased linearly with fish TL. Girdle depth increased from 4.38 mm to 62.38 mm. (Table 4, Fig. 6 A). The ratio of coracoid to cleithrum depth was 1.76 ± 0.03 (Table 16). Similarly, girdle weight increased linearly with fish Wt from 12 mg to 130.4 g (Table 4, Fig. 6-B). Since the girdle grew isometrically and spine growth was nonlinear, it is not surprising that the relationship between spine dimensions and girdle dimensions was nonlinear (Table 4, Fig. C, D). Spine width, which grew linearly, was slightly nonlinear when compared against girdle depth (Table 4, Fig. 6-E). Spine density, mg/mm, also increased nonlinearly (Table 4, Fig. 6-F). The ratio of spine length to girdle depth decreased linearly with TL, meaning girdle depth increased at a faster rate than spine length (Table 4, Fig. 7-A). The ratio of spine Wt to girdle Wt decreased rapidly with fish Wt and then stabilized at about 10% (Table 4, Fig. 7-B).

Channel Catfish - *Ictalurus punctatus*

Spines are slightly bowed, with the forward most region of the anterior edge located approximately half way on the spine. Trabeculations, on the dorsal and ventral surface run parallel from the base to the tip of the spine. Small anterior dentations run from about a quarter of the spine's length to near the spine tip. Posterior dentations are located centrally within the posterior groove and run from the base to near the tip of the spine. Posterior dentations are generally simple and point medially although complex dentations can occur. The anterior process is relatively straight and typically points posteriorly.

Cultured Channel Catfish

Pectoral spines and girdles were sampled from 61 cultured channel catfish that ranged from 82 to 491 mm in TL and 4.2 to 1362 g in Wt (Table 1). Spine length and Wt increased nonlinearly from 14.09 mm and 13 mg to 45 mm and 0.791 g (Table 5, Fig. 8-A, B). Spine width increased linearly from 1.38 mm to 6.34 mm (Table 5, Fig.8-C). Dorsal process width and depth and dorsal ventral length also increased linearly with fish size (Table 5, Fig. 8-D, E, F).

Pectoral girdle depth increased linearly with fish TL. Girdle depth increased from 6.03 mm to 27.60 mm (Table 5, Fig. 9 A). The ratio of coracoid to cleithrum depth was 1.48 $\pm$ 0.03. Girdle Wt increased linearly with fish Wt from 55 mg to 7.5 g (Table 5, Fig. 9-B). Spine length and spine width also increased linearly with girdle depth (Table 5, Fig. 9-C, E). Spine Wt against girdle Wt (Table 5, Fig. 9-D) and spine density increased nonlinearly (Table 5, Fig. 9-F). The ratio of spine length to girdle depth decreased linearly with total length (Table 5, Fig. 10-A), but the ratio of spine weight to girdle weight decreased nonlinearly with fish weight and stabilized at about 12% (Table 5, Fig. 10-B).

Wild Channel Catfish

Pectoral spines and girdles were sampled from 42 wild channel catfish that ranged from 102 to 823 mm in TL and 8.9 to 1890 g in Wt (Table 1). Spine length and Wt increased nonlinearly from 16.36 mm and 20 mg to 58.48 mm and 1.449 g (Table 6, Fig. 11-A, B). Spine width increased linearly from 1.61 mm to 7.07 mm (Table 6,

Fig.11-C). Dorsal process width increased nonlinearly with TL (Table 6, Fig. 11-D). Dorsal process depth and dorsal ventral length increased linearly with TL (Table 6, Fig. 11-E, F).

Pectoral girdle depth, including the cleithrum and the coracoid, increased nonlinearly with fish TL. Girdle depth increased from 7.44 mm to 28.84 mm (Table 6, Fig. 12-A). The ratio of the coracoid and cleithrum was 1.50 ± 0.03 (Table 16). Girdle Wt increased nonlinearly with fish Wt from 80 mg to 10.50 g (Table 6, Fig. 12-B). Spine length and width against girdle depth increased linearly (Table 6, Fig. 12-C, E), but spine Wt against girdle Wt was nonlinear (Table 6, Fig. 12-D). Spine density also increased nonlinearly (Table 6, Fig. 12-F). The ratio of spine length to girdle depth decreased linearly with TL (Table 6, Fig. 13-A). The ratio of spine weight to girdle weight decreased with fish Wt and then stabilized at about 14% (Table 6, Fig. 13-B).

Ameiurus spp.

Spines exhibit several similarities in the genus *Ameiurus*, (white catfish and brown and yellow bullheads). Trabeculations on the dorsal and ventral surface run parallel, turning diagonally forward at approximately three-fourths of the spine length. Lateral to the anterior dentations notches continue along the anterior edge to the tip of the spine and mark terminations of the diagonal trabeculations. Notches have a flat anterior edge that ends in a sharp medially directed point. These notches can be worn down in large specimens. Small pointed dentations extend forward along the anterior edge from one-forth to three fourth of the spine length, The posterior dentations form

dorsal to midline of the posterior groove near the spine base and within the groove further laterally, i.e. the groove appears to close. The locking tubercle on the anterior process points posteriorly. It is typically highly developed, often with a posterior-lateral point. The ventral process curves posteriorly and is considerably posterior to the anterior process.

White Catfish - *Ameiurus catus*

Spines are bowed, with the forward most region of the anterior edge located approximately half way from the spine base. In small and medium size fish posterior dentations are mostly simple, small, and pointy in shape. In larger fish (> 400 mm TL, 45 mm spine length) dentations become more complex and variable; there are often two or more points per dentation. The first few proximal dentations point laterally, the next few point straight back, and the remaining dentations, the largest group, point medially. The anterior and ventral processes curve considerably in the posterior direction.

Pectoral spines and girdles of 45 white catfish ranged in TL from 103 to 442 mm and in Wt from 232 to 1520 g (Table 1). Spine length and Wt increased nonlinearly from 21.22 mm and 50 mg to 47.80 mm and 0.816 g in a 442 mm (Table 7, Fig. 14-A, B). Spine width increased linearly from 2.02 mm to 6.25 mm with TL (Table 7, Fig.14-C). Dorsal process width and depth were nonlinear (Table 7, Fig. 14-D, E). Dorsal-ventral length also increased nonlinearly with fish length (Table 7, Fig. 14-F).

Pectoral girdle depth increased linearly with TL. Girdle depth increased from 9.86 mm to 33.36 mm (Table 7, Fig. 15-A). The ratio of coracoid to cleithrum depth was, 1.50 ± 0.02 (Table 16). Girdle Wt increased nonlinearly with fish Wt from 0.22 g to 8.50 g (Table 7, Fig. 15-B). Spine length and width against girdle depth increased nonlinearly (Table 7, Fig. 15-C, E), as did spine Wt against girdle Wt (Table 7, Fig. 15-D). Spine density to TL was slightly nonlinear (Table 7, Fig. 15-F). The ratio of spine length to girdle depth decreased linearly with TL (Table 7, Fig. 16-A), but the ratio of spine weight to girdle weight decreased rapidly with fish size and then stabilized at about 14% (Table 7, Fig. 16-B).

Brown Bullhead - *Ameiurus nebulosus*

Spines are bowed, with the forward most region of the anterior edge located approximately one-quarter out from the spine base. Small pointed dentations extend forward along the anterior edge from one-forth to three fourth of the spine length. The posterior dentations protrude just dorsal to the closed posterior groove. In small and medium size fish dentations are mostly simple, small, and pointy in shape. In larger fish (> 400 mm TL, 45 mm spine length) dentations become more complex and variable; there are often two or more points per dentation. The first few proximal dentations point laterally, the next few point straight back, and the remaining dentations, the largest group, point medially.

Pectoral spines and girdles of 30 brown bullheads ranged from 50 mm to 291 mm in TL and 1.5 to 370 g in Wt (Table 1). Spine length increased linearly and spine

Wt increased nonlinearly from 8.71 mm and 3.5 mg to 29.18 mm and 0.269 g (Table 8, Fig. 17-A, B). Spine width increased linearly from 0.85 mm to 3.37 mm (Table 8, Fig.17-C). Dorsal process width and depth and dorsal-ventral length increased linearly with TL (Table 8, Fig. 17-D, E, F).

Pectoral girdle depth increased linearly with TL from 4.69 mm to 23.07 mm (Table 8, Fig. 18-A). The ratio of coracoid to cleithrum depth was 1.44 ± 0.04 (Table 16). Girdle Wt increased linearly from, 6 mg to 2.37 g (Table 8, Fig. 18-B). Spine length and spine width increased linearly with girdle depth (Table 8, Fig. 18-C, E). Spine Wt against girdle Wt was slightly nonlinear (Table 8, Fig. 18-D), and spine density increased nonlinearly (Table 8, Fig. 18-F). The ratio of spine length to girdle depth decreased linearly with TL (Table 8, Fig. 19-A), and the ratio of spine weight to girdle weight decreased rapidly with fish weight and then stabilized at about 12% (Table 8, Fig. 19-B).

Yellow Bullhead - *Ameiurus natalis*

Spines are bowed, with the forward most region of the anterior edge located approximately one-quarter out from the spine base. The anterior edge is smooth, lacking dentations. The posterior dentations form dorsal to the posterior groove near the spine base and within the groove further laterally, i.e. the groove appears to close. The locking tubercle on the anterior process protrudes posteriorly and is smaller than in white catfish and brown bullheads. The anterior process points anteriorly, and the ventral process curves posteriorly and is posterior to the anterior process.

Pectoral spines and girdles of 24 yellow catfish ranged from 61 to 205 mm in TL and 3.1 g to 140.2 g in Wt (Table 1). Spine length increased linearly and spine Wt increased nonlinearly from 7.41 mm and 1 mg to 26.69 mm and 0.126 g (Table 9, Fig. 20-A, B). Spine width increased linearly from 0.88 mm to 2.89 mm (Table 9, Fig. 20-C). Dorsal process width and depth and dorsal-ventral length also increased linearly with fish size (Table 9, Fig. 20-D, E, F).

Pectoral girdle depth increased linearly with fish TL. Girdle depth increased from 4.79 mm to 14.87 mm (Table 9, Fig. 21-A). The ratio of coracoid to cleithrum depth was 1.39 ± 0.04 (Table 16). Girdle Wt increased nonlinearly with fish Wt from 11 mg to 0.762 g (Table 9, Fig. 21-B). Spine length and spine width slightly increased linearly against girdle depth (Table 9, Fig. 21-C, E), but spine Wt against girdle Wt was nonlinear (Table 9, Fig. 21-D). Spine density also increased nonlinearly (Table 9, Fig. 21-F). The ratio of spine length to girdle depth decreased linearly with TL (Table 9, Fig. 22-A). The ratio of spine weight to girdle weight decreased nonlinearly with fish weight and stabilized at about 14% (Table 9, Fig. 22-B).

Flathead Catfish - *Pylodictis olivaris*

Spines are relatively straight. The forward most region of the anterior edge is located approximately one-quarter out from the spine base. Spine tips are almost always broken and have a jagged profile. Of the 53 flathead spines only the smallest fish (136 mm, 24 g) had one intact spine. The pectoral girdle and spines appeared to be oilier than in other species. The tips of broken spines had long extensions of "epithelial" tissue in

the process of forming anterior and posterior dentations, suggesting spine regeneration. Similar but less developed structures were present in other species, but they typically came off during cleaning. Trabeculations on the dorsal and ventral surface run parallel from the base to the tip of the spine beyond the break. Large simple and complex dentations on the anterior edge run from about a quarter of the spine length to the tip of the spine, again beyond the break. The first few proximal dentations point forward and the remaining dentations, the largest group, point medially. However, anterior dentations are quite variable. Large simple and complex posterior dentations are located within the center of the posterior groove extending from the base to the tip of the spine. In smaller and medium fish (< 500 mm TL, 45 mm spine length) the first few proximal dentations point laterally and the remaining dentations, the largest group, point medially. In larger fish the directions of the dentations reverse and all point laterally. The anterior process is large and relatively straight. The ventral process is considerably posterior of the anterior process.

Pectoral spines and girdles were sampled from 53 flathead catfish that ranged from 136 to 935 mm in TL and 24 to 11,300 g in WT were measured (Table 1). Spine length and Wt increased nonlinearly from 12.78 mm and 20 mg to 80.02 mm and 5.28 g (Table 10, Fig. 23-A, B). Spine width increased linearly with TL from 2.30 mm to 15.52 mm (Table 10, Fig.23-C). Dorsal process width and depth and dorsal-ventral length increased linearly with fish length (Table 10, Fig. 23-D, E, F).

Pectoral girdle depth increased linearly with TL. Girdle depth increased from 6.59 mm to 43.61 mm (Table 10, Fig. 24-A). The ratio of coracoid to cleithrum depth

was 1.31 ± 0.02 (Table 16). Girdle Wt increased nonlinearly with weight from, 0.12 g to 56.60 g (Table 10, Fig. 24-B). Spine length and spine width increased linearly with girdle depth (Table 10, Fig. 24-C, E). Spine Wt increased nonlinearly with girdle Wt (Table 10, Fig. 24-D), and spine density increased nonlinearly with TL (Table 10, Fig. 24-F). The ratio of spine length to girdle depth decreased linearly with TL (Table 10, Fig. 25-A), but the ratio of spine weight to girdle weight decreased rapidly with weight and then stabilized at about 8% (Table 10, Fig. 25-B).

Margined Madtoms – *Noturus insignis*

Spines are straight. Trabeculations on the dorsal and ventral surface run parallel, turning diagonally forward at approximately one-fourth of spine length. The anterior edge is smooth, lacking dentations. Anterior notches start at approximately one-fourth out from the spine base and continue along the anterior edge to the tip of the spine marking terminations of the diagonal trabeculations. Notches have a flat anterior edge that ends in a sharp medially directed point. The posterior groove appears closed. The posterior dentations run just dorsal to the posterior groove and occur in the middle half of the spine, i.e. not at the base or the tip. Dentations are generally simple although a few are complex, and they point straight back. The anterior process points anteriorly and the ventral process is considerably posterior of the anterior process.

Pectoral spines and girdles were sampled from 12 margined madtoms that ranged from 67 to 169 mm in TL and 1.7 to 43.1 g in Wt (Table 1). Spine length increased linearly and Wt increased nonlinearly from 9.42 mm and 3 mg to 19.54 mm

and 46 mg (Table 11, Fig. 26-A, B). Spine width increased linearly from 0.85 mm to 2.43 mm with TL (Table 11, Fig.26-C). Dorsal process width and depth and dorsal-ventral length all increased linearly (Table 11, Fig. 26-D, E, F).

Pectoral girdle depth increased linearly against TL. Girdle depth increased from 3.32 mm to 8.55 mm (Table 11, Fig. 27-A). The ratio of coracoid to cleithrum depth was 2.13 $\pm$ 0.09. Girdle Wt increased linearly with fish Wt from 10 to 270 mg (Table 11, Fig. 27-B). Spine length and spine width increased linearly with girdle depth (Table 11, Fig. 27-C, E), but spine Wt against girdle Wt increased slightly nonlinearly (Table 11, Fig. 27-D). Spine density increased nonlinearly with TL (Table 11, Fig. 27-F). The ratio of spine length to girdle depth did not change with TL (Table 11, Fig. 28-A). The ratio of spine weight to girdle weight against fish weight decreased nonlinearly with fish size (Table 11, Fig. 28-B).

Tadpole Madtoms – *Noturus gyinus*

Spines are straight. Trabeculations on the dorsal and ventral surface run diagonally forward from the base to the tip of the spine. The anterior edge is smooth, lacking dentations and anterior notches. The posterior groove appears closed and dentations are absent. The anterior process points medially. The ventral process is posterior of the anterior process.

Pectoral spines and girdles of 7 tadpole madtoms ranged from 42 to 68 mm in TL and 0.7 to 2.6 g in Wt (Table 1). Spine length increased linearly and Wt increased nonlinearly from 6.89 mm and 1 mg to 10.82 mm and 8 mg (Table 12, Fig. 30-A, B).

Unlike in other species, spine Wt growth appeared to accelerate. Spine width increased linearly from 0.72 mm to 1.08 mm with TL (Table 12, Fig. 30-C). Dorsal process width and depth and dorsal-ventral length all increased linearly (Table 12, Fig. 30-D, E, F).

Pectoral girdle depth increased linearly against TL. Girdle depth increased from 3.47 mm to 5.4 mm (Table 12, Fig. 31-A). The ratio of coracoid to cleithrum depth was 1.64 $\pm$ 0.10. Girdle Wt increased linearly from 7 mg to 26 mg (Table 12, Fig. 31-B). Spine length increased nonlinearly with girdle depth (Table 12, Fig. 31-C). However, spine Wt increased linearly with girdle Wt (Table 12, Fig. 31-D). Spine width increased linearly with girdle depth (Table 12, Fig. 31-E). Spine density compared to TL was nonlinear (Table 12, Fig. 31-F). The ratio of spine length to girdle depth slightly increased linearly with TL (Table 12, Fig. 32-A), and the ratio of spine weight to girdle weight increased with fish weight (Table 12, Fig. 32-B).

Comparisons between species

Blue and wild channel catfish

Blue and wild channel catfish data were compared to determine the characteristics *Ictalurids* have in common and if final size affects spine demensions. Blue catfish grow larger, and their spines grow to a larger size than in channel catfish. An ANCOVA was used to compare regressions between species. Although the data are plotted on the original axes, ANCOVA utilized log-log transforms to linearize the data (Table 13). Interestingly, channel catfish spines tended to be larger than blue spines in smaller fish. Around 300 - 400 mm TL the regressions tended to cross, and blue catfish

spines became larger for the equitantly sized fish (Fig. 32, 33). Spine length compared to TL was slightly larger in blue catfish, but spine Wt against Wt was similar (Table 13 Fig 32-A, B). Spine width, dorsal process width and depth and dorsal-ventral length were different among blue and channel catfish (Table 13, Fig. 32-C, D, E, F).

Pectoral girdle and coracoid depths were larger in channel than in blue catfish. However, the slope of the cleithrum depth was not different between species, but the elevation was higher in channel catfish (Table 13, Fig. 33-A, B, C). The slope of girdle Wt against Wt was similar between blue and channel catfish, but the elevation was greater in channel catfish (Table 13, Fig. 33-D). Spine length and spine width against girdle depth and spine Wt compared to girdle Wt were all similar between species (Table 13, Fig. 33-E, F, G). Spine density was greater in blue catfish (Table 13, Fig. 33-H). The spine length girdle depth ratio against TL was greater in blue catfish (Table 13, Fig. 34-A). Finally, the slope of the Wt and girdle Wt ratio was the same in both species, but blue catfish were larger because of a higher elevation (Table 13, Fig. 34-B).

Wild and cultured channel catfish

Spine dimensions were greater in wild than cultured channel catfish from juveniles to adults (Fig. 35, 36). Slopes were usually parallel, however intercepts were significantly different. Spine length had similar slopes in wild and cultured fish, but the elevation was higher in wild channels (Table 14, Fig. 35-A). Wild channel catfish spines were heavier than cultured channel catfish (Table 14, Fig. 35-B). The slope of spine width was greater in wild channel catfish (Table 14, Fig. 35-C). Dorsal process

width, dorsal process depth and dorsal-ventral length compared against TL were different, again wild channel catfish had higher elevations although the slopes were different (Table 14, Fig. 35-D, E, F).

The slope of the girdle, coracoid, and cleithrum depths were not significantly different, however the elevation was higher in the wild channels (Table 14, Fig. 36-A, B, C). The girdle Wt against Wt and spine length with girdle Wt varied between groups (Table 14, Fig. 36-D, E). The relationship of spine Wt to girdle Wt, spine width against girdle depth, and spine density with TL were similar (Table 14, Fig. 36-F, G, H). The spine length and girdle depth ratio against TL varied between species (Table 14, Fig. 37-A). Finally, the spine Wt and girdle Wt ratio was the same between species (Table 14, Fig. 37-B).

Ameiurus spp.

White catfish grew larger, and their spines developed to a greater size than in brown and yellow bullheads. Brown and yellow bullhead's growth was similar across spine dimensions (Fig. 38, 39). Spine length against TL was significantly different between species with white catfish having an elevation (Table 15, Fig. 38-A). The slope of spine Wt against Wt varied across catfish (Table 15, Fig. 38-B). The slope of the spine width was similar in brown and yellow bullheads, but differed in brown bullheads and white catfish, and yellow bullheads and white catfish to TL (Table 15, Fig. 38-C). Dorsal process width and depth were different among species when compared to TL (Table 15, Fig. 38-D, E). Dorsal-ventral length was similar in the brown and yellow

bullheads, but differed in brown bullheads and white catfish, and yellow bullheads and white catfish (Table 15, Fig. 38-F).

Girdle and coracoid depth slopes were similar across species. Brown and yellow bullheads intercepts were also significant (Table 15, Fig. 39-A, B). Cleithrum depth to TL and girdle Wt compared to Wt was significantly different between species (Table 15, Fig. 39-C, B). The slope of spine length against girdle depth was similar between brown and yellow bullheads, however differed between brown bullheads and white catfish, and yellow bullheads and white catfish (Table 15, Fig. 39-E). Spine Wt was different among fishes (Table 15, Fig. 39-F). Spine width was similar between brown and yellow bullheads, though it differed between brown bullhead and white and yellow bullhead and white catfish compared to girdle depth (Table 15, Fig. 39-G). Spine density was significantly different to TL (Table 15, Fig. 39-H). The spine length and girdle depth ratio was similar across species (Table 15, Fig. 40-A). The yellow bullhead was slightly elevated over the brown bullhead. Lastly, spine Wt and girdle Wt ratio was different in brown and yellow bullheads, but was slightly similar between brown bullheads and white catfish and yellow bullheads and white catfish (Table 15, Fig. 40-B).

Comparisons of all species

Regressions were plotted on the same graphs to visualize difference among species (Fig. 41, 42). Genera do not cluster together across all dimensions; however there are groupings for certain characteristics. The *Ictalurus* and *Noturus* genera are

often grouped together; however we saw separation within the *Ameiurus* genus. White catfish separate from brown and yellow bullheads and are located at a higher elevation; for example, spine length and spine width to TL and spine Wt and girdle Wt against Wt (Fig. 41-B, D, F, Fig. 42-B). The *Ameiurus spp.* share similar girdle depths.

One-way ANOVAs conducted to test relationships of spine dimension ratios across all species (blue, channel, white, brown and yellow bullheads, and flathead catfish) were significantly different (Fig. 43, 44). The spine length and TL ratio was similar in channel, white, and brown and yellow bullhead, yet blue and flathead catfish varied from other species (Table 16, Fig. 43-A). Spine Wt and Wt ratio was alike in blue, channel, and white, however yellow bullheads and flathead catfishes were different (Table 16, Fig. 43-B). The dorsal process width and dorsal process depth ratio was similar in blue catfish and brown and yellow bullheads. Channel, white, and flathead catfishes also shared similarities (Table 16, Fig. 43-C). The dorsal process width and spine width ratio was similar in all species, except yellow bullheads (Table 16, Fig. 43-D). The dorsal process depth and spine width ratio was similar in blue, white, brown and yellow bullheads, and flathead catfishes (Table 16, Fig. 43-E). Also, channel catfish were similar to white and flathead catfishes. The coracoid and cleithrum ratio was similar in channel, white, brown and yellow bullhead catfishes. Brown and yellow bullheads and flatheads were also similar; however blue catfish were different (Table 16, Fig. 43-F). Dorsal ventral length and spine with ratio was similar in the blue, channel and white catfishes. Channel, white, and brown bullhead catfishes were also shared similarities, though yellow bullheads and flathead catfishes were

different (Table 16, Fig. 44-A). The dorsal-ventral length and dorsal process width was similar in blue, channel, white, brown and yellow bullhead catfishes, however flatheads were different (Table 16, Fig. 44-B). The dorsal-ventral length and dorsal process depth ratio was similar across species (Table 16, Fig. 44-C). Finally, the adjusted means were taken at 200 mm to calculate spine density showing it varied tremendously between species (Table 16, Fig. 44-D), with larger species having a greater density.

Bald Eagles

Six hundred and one pectoral spines collected at bald eagle nesting sites throughout eastern Virginia (Fig. 49) were cleaned, dried and measured for length and weight. A large collection of spines from central and eastern Virginia catfishes were used to provide spine identifications of individual catfish species, and to estimate fish length and weight from spine length, spine weight using nonlinear regressions (Table 17, Fig. 45). If spines were badly broken I used the length between the dorsal and ventral process of the spine base to estimate fish size (Fig. 45).

Three hundred and sixty one (60%) blue, 161 (26.7%) channel, 52 (8.6%) white catfishes, 23 (3.8%) brown and 3 (0.49%) yellow bullheads, and 1 (0.16%) unknown spines were found (Table 18). Spines from flathead catfish and madtoms were not present in these collections. Estimated fish size varied for the different catfish species for total length ($F_{4,574} = 43.88$, $p < 0.0001$) and weight ($F_{4,574} = 12.09$, $p < 0.0001$), which relates to the size distribution for each species. Samples of species that grow to a larger size (blue, channel and white catfish) were larger than spines sampled from

smaller species, e.g. brown and yellow bullheads (Table 21, Fig. 46). Channel catfish had the largest mean weight although there was no difference in total length between channel and blue catfish (channels 417 mm, 618 g; blues 366 mm, 414 g) (Table 20, Fig. 46). These were followed by white catfish (320 mm, 591 g), and brown (278 mm, 277 g) and yellow bullheads (203 mm, 192 g) (Table 20, Fig. 47). The average catfish across all species was 317 mm, 418 g (Table 19). Histograms of catfish consumed by eagles indicate that they take fish over a large range in size (Fig. 46, 47) with modes ranging from about 230 to 540 mm TL. Eagles do not eat the smallest individuals of any species, and they do not capture the largest channel and blue catfishes. Note there was one outlier in the blue catfish data that was 834 mm TL and 6878 g Wt; the next largest fish consumed, also a blue catfish, was 606 mm TL and 1818 g Wt. For smaller species including brown and yellow bullheads and large white catfish, eagles take a higher percentage of large individuals and are more likely to have a detrimental effect on populations of these species already under stress from nonnative blue and flathead catfishes.

Discussion

Pectoral spines of catfishes have been interpreted as anti-predator adaptations based on anecdotal (Recher & Recher 1968; Werner et al. 2001; Bunkley-Williams et al. 1994) and experimental evidence (Bosher et al. 2006). Given the large range in size, habitats and predators of catfishes, numerous constraints are likely to affect spine development within and across species. In this study we collected catfish species that ranged in size from small tadpole madtoms (maximum size) 68 mm TL, 2.6 g Wt, margined madtoms, yellow and brown bullheads, white, cultured channel, wild channel and flathead catfish to blue catfish, 1008 mm TL, 22,000 g Wt. Specimens were collected within the Mattaponi, James, Potomac, Poquoson, and Rappahannock rivers, Lake Chesdin, and Virginia State University aquaculture farms. Individual species were originally plotted based on the collection area; however the points overlapped so they were combined.

Spine size is affected by various factors including selection for appropriate size to survive attacks by aquatic and aerial predators, use in locomotion (primarily breaking and turning), and as a signaling device to produce acoustic signals (Fine & Ladich 2003). These considerations suggest several hypotheses for pectoral spine and girdle development as fish growth occurs.

1. Spine morphology, adapted for locomotion binding, locking, and stridulatory sound production is imprisioned by convergent evolution so that the major features of the spines in different species are likely to be conservative.

2. Spine dimensions (length and weight) will increase with fish size within each species.
3. Since chances of predation decrease with fish size, it may not be necessary for spine dimensions to increase linearly with body dimensions (isometric growth).
4. The pectoral girdle is a major component of the fish's girth and would be expected to grow isometrically.
5. The spine base, with dorsal, anterior and ventral processes that articulate with, and are therefore matched to the pectoral girdle, should grow isometrically.
6. Spine width, adjacent to the base, would also grow isometrically even if the spine's length and width increase allometrically.
7. Spines are more likely to grow allometrically in larger than in smaller species.
8. Growth functions are likely to be more similar in closely related species.

Spine morphology

Pectoral spine anatomy varies slightly within and across catfish species making it difficult to distinguish species. Minor characteristics, however, allow individual species to be identified. Within the *Ictalurus* genus blue catfish spines have a well defined anterior edge and anterior dentations that are absent or minimally developed; the anterior edge is usually smooth. Channel catfish lack a defined anterior edge, though dentations are often present. The *Ameiurus* genus has anterior notches found near the spine tip and has a well defined locking tubercle encompassing the entire anterior processes. Within the *Noturus* genus anterior notches are present, margined

madtom spines are straight and the tadpole madtoms lack anterior dentations. *Pylodictis olivaris* (flathead catfish) have well developed anterior and posterior dentations, and spine breakage does not seem to be size related, because it occurs independent to fish size.

Pectoral spine and girdle growth

Spine length and Wt generally grow allometrically whereas dimensions of the spine base and girdle depth increase isometrically. Girdle weight grows both allometrically and isometrically. Spine length increases nonlinearly in blue, channel, white, and flathead catfishes, but it increases linearly in brown and yellow bullheads and margined and tadpole madtoms, all smaller species. Spine Wt increases nonlinearly across species. Allometric growth in spine Wt suggests spines may not be as important in larger fish due to decreased predation although part of the decrease results from tip breakage. The spine base (dorsal process width and depth and dorsal-ventral length) grows isometrically in most species. However, dorsal process width in wild channel and white catfishes, and dorsal process depth and dorsal-ventral length also decreases in white catfish. Spine width grows isometrically across species. Girdle depth, including the coracoid and cleithrum, grows isometrically in all species except wild channel catfish. Girdle Wt grows isometrically in blue, cultured channel, brown bullheads, and margined and tadpole madtom catfishes. Surprisingly, it grows allometrically in wild channel, white, yellow bullheads, and flathead catfishes.

Slopes of cultured and wild channel catfish spine regressions were similar, however wild channel catfish spines and pectoral girdle elevations were greater. There are many possibilities for this differentiation including differences in diet, genetic variation in the founding populations, and potential inbreeding. Previous studies have demonstrated that predators induce a change in body depth in crusian carp, (Brönmark & Miner 1992) perch, and roach (Eklöv & Jonsson 2007).

The pectoral spines identified from bald eagle nesting sites were mainly nonnative blue and channel catfishes followed by native white, brown and yellow bullhead catfishes. Eagles are consuming large channel catfish (modal range 379 – 475 mm TL, 531 – 770 g Wt), blue (240 – 437 mm TL, 81 – 700 g Wt), and white (261 – 379 mm TL, 247 – 1135 g Wt) catfishes and smaller brown (241 – 315 mm TL, 192 – 364 g Wt) and yellow bullheads (179 – 248 mm TL, 142 – 252 g Wt). No flathead catfishes were consumed although their range is partially sympatric with the eagles. We suspect their absence reflects a behavioral response of the flatheads not to feed in shallow water rather than rejection by the eagles. In line with the optimal foraging theory it appears that eagles do not select fish much less than 200 mm TL, likely because they contain insufficient calories. For blue catfish large individuals above 1200 g Wt are rarely taken although fish of this size range occur in eagle feeding areas. Large fish are likely too heavy to be carried by eagles that weigh approximately 5454 g, indicating that eagles can carry about 22% of their body weight. Although occasional large blue, channel, and white catfishes caught may exceed eagle capabilities.

Densely populated bald eagle nesting sites are found throughout tidal fresh waters of the east coast. Eagle studies originally focused on habitat location, but research suggests the need to include diet patterns. Markhan's (2004) study identified that catfish make up 33.6% of the prey consumed by bald eagles. Catfishes were recognized by their spines, but they were not identified to species. By understanding the diet of eagles, including fish consumption, we will be better able to manage fishery resources and track contaminate consumption. A Polychlorinated Biphenyl (PCB) advisory for the James River states (VDH 2006) that humans should consume only two blue catfish (< 820 mm TL) per month. Eagles are eating large amounts of blue catfish although most of them are smaller than specified in the advisory. A study by Garman et al. (1998) concluded that as blue catfish size increases, PCB biomagnification increases exponentially. This research will help gain a better insight on catfish consumption by eagles and allow us to better manage fish resources to further protect piscivores.

Table 1. Sample size, total length, weight, and capture location for catfish species.

Common Name	Scientific Name	n	TL, mm	Wt, g	Location
Blue	*Ictalurus furcatus*	92	63 – 1008	3.4 – 22,000	Mattaponi R. and James R.
Cultured Channel	*Ictalurus punctatus*	61	87 – 455	4.2 – 1362	Aquaculture
Wild Channel	*Ictalurus punctatus*	42	102 – 562	8.9 – 1890	Mattaponi R., James R., Lake Chesdin
White	*Ameiurus catus*	45	103 – 442	23.2 – 1520	Mattaponi R. and Dogue Creek - Potomac R.
Brown Bullhead	*Ameiurus nebulosus*	30	50 – 291	1.5 – 370	Poquoson R., Mattaponi R., and Dogue Creek -Potomac R.
Yellow Bullhead	*Ameiurus natalis*	24	61 – 205	3.1 – 140.2	Rappahannock R.
Flathead	*Pylodictis olivaris*	53	136 – 935	24 – 11,300	James R.
Margined Madtoms	*Noturus insignis*	12	67 – 169	1.7 – 43.1	Preddy Creek - James R.
Tadpole Madtoms	*Noturus gyrinus*	7	42 – 68	0.7 – 2.6	Kimages Creek -, James R.

Table 2: Adjusted mean weights calculated for various total lengths in catfish species. Dashes indicate lengths that were smaller or larger than sampled.

	Total Length, mm										
Common Name	**75**	**150**	**200**	**300**	**400**	**500**	**600**	**700**	**800**	**900**	**1000**
Blue	5.4	26.4	55.4	318	605	1219	2468	4350	6542	11 483	18 971
Cultured Channel	-	26.8	57.8	227	715	-	-	-	-	-	-
Wild Channel	-	23.4	128	282	545	-	-	-	-	-	-
White	-	97.3	145	337	903	-	-	-	-	-	-
Brown Bullhead	12.3	39	95	459	-	-	-	-	-	-	-
Yellow Bullhead	7.63	40.1	124	-	-	-	-	-	-	-	-
Flathead	-	250	330	570	930	1450	2530	4090	6690	10 950	-
Margined Madtom	3.88	26.4	-	-	-	-	-	-	-	-	-
Tadpole Madtom	1.16	-	-	-	-	-	-	-	-	-	-

Table 3: Exponential growth equations and coefficients of determination (R^2) for length weight regressions in various catfish species.

Common Name	Exponential Equation	R^2
Blue	$Wt = 109.9\ e^{0.005129\ TL}$	0.975
Cultured Channel	$Wt = 22.52\ e^{0.008572\ TL}$	0.956
Wild Channel	$Wt = 26.80\ e^{0.007609\ TL}$	0.917
White	$Wt = 16.95\ e^{0.009956\ TL}$	0.980
Brown Bullhead	$Wt = 3.571\ e^{0.01617\ TL}$	0.983
Yellow Bullhead	$Wt = 1.336\ e^{0.02265\ TL}$	0.988
Flathead	$Wt = 148.6\ e^{0.004743\ TL}$	0.983
Margined Madtoms	$Wt = 0.6017\ e^{0.0206\ TL}$	0.951
Tadpole Madtoms	$Wt = 0.1170\ e^{0.04608\ TL}$	0.975

Table 4: Regression equations, coefficients of determination (R^2), p-value, and adjusted means ± 1 SE for the spine and pectoral girdle dimensions in blue catfish.

Regression Equation	**R^2**	**P***	**Mean ± 1 SE**
Log Spine L = -0.377 + 0.789 Log TL	0.963	-	48.45 ± 2.75 mm
Log Spine Wt = -1.855 + 0.663 Log Wt	0.982	-	1.97 ± 0.27 g
Spine Width = 0.000772 + 0.0149 TL	0.991	< 0.0001	6.47 ± 0.42 mm
DP Width = -0.0559 + 0.0189 TL	0.990	<0.0001	8.16 ± 0.54 mm
DP Depth = 0.156 + 0.00490 TL	0.960	<0.0001	2.28 ± 0.14 mm
DV L = 0.189 + 0.0278 TL	0.991	<0.0001	12.27 ± 0.80 mm
Girdle Depth = -1.477 + 0.0601 TL	0.989	<0.0001	24.67 ± 1.73 mm
Coracoid Depth = -0.997 + 0.0388 TL	0.970	<0.0001	15.84 ± 1.12 mm
Cleithrum Depth = -0.156 + 0.0209 TL	0.966	<0.0001	8.94 ± 0.61 mm
Girdle Wt = 0.994 + 0.00586 Wt	0.981	<0.0001	16.68 ± 2.85 g
Log Spine L = 0.709 + 0.719Log Girdle Depth	0.947	-	48.62 ± 2.77 mm
Log Spine Wt = -0.480 + 0.716 Girdle Wt	0.988	-	1.97 ± 0.27 g
Log Spine Width = -0.411 + 0.887 Log Girdle Depth	0.976	-	6.47 ± 0.42 mm
Log Spine Density = -3.98 + 1.99 Log TL	0.982	-	26.81 ± 3.03 mg/mm
Spine L/Girdle Depth = 2.553 + (-0.0009359) TL	0.404	<0.0001	2.14 ± 0.03
Spine Wt/Girdle Wt = $0.2529 - 0.1114\, e^{(-0.0007\ \mathrm{Wt}) + 0.1114}$	0.693	-	0.19 ± 0.00

* P values are not given for nonlinear regressions.

Table 5: Regression equations, coefficients of determination (R^2), p-value, and adjusted means ± 1 SE for the spine and pectoral girdle dimensions in cultured channel catfish.

Regression Equation	**R^2**	**P***	**Mean ± 1 SE**
Log Spine L = -0.0561 + 0.639 Log TL	0.962	-	31.68 ± 1.35 mm
Log Spine Wt = 1.984 + 0.588 Log Wt	0.956	-	0.30 ± 0.03 g
Spine Width = 0.364 + 0.0123 TL	0.970	< 0.0001	3.63 ± 0.21 mm
DP Width = 0.822 + 0.013 TL	0.962	<0.0001	4.52 ± 0.24 mm
DP Depth = 0.407 + 0.003069 TL	0.879	<0.0001	1.23 ± 0.05 mm
DV L = 0.9983 + 0.02343 TL	0.987	<0.0001	7.24 ± 0.40 mm
Girdle Depth = 10.12 + 0.02386 TL	0.257	<0.0001	16.28 ± 0.80 mm
Cleithrum Depth = 5.815 + 0.01448 TL	0.279	<0.0001	9.56 ± 0.47 mm
Coracoid Depth = 4.256 + 0.009332 TL	0.207	<0.0001	6.63 ± 0.34 mm
Girdle Wt = 0.2893 + 0.005171 Wt	0.964	<0.0001	2.55 ± 0.29 g
Spine L = 5.677 + 1.573 Girdle Depth	0.939	-	29.45 ± 1.30 mm
Log Spine Wt = -0.7421 + 0.7175 Log Girdle Wt	0.981	-	0.26 ± 0.02 g
Spine Width = -0.1668 + 0.2478 Girdle Depth	0.960	-	3.64 ± 0.20 mm
Log Spine Density = -3.010 + 1.577 Log TL	0.966	-	8.00 ± 0.66 mg/mm
Spine L/Girdle Depth = 2.428 + (-0.001507) TL	0.539	<0.0001	1.99 ± 0.03
Spine Wt/Girdle Wt = 0.2423 – 0.1172 $e^{(-0.004\ Wt) + 0.1172}$	0.802	-	0.16 ± 0.00

* P values are not given for nonlinear regressions.

Table 6: Regression equations, coefficients of determination (R^2), p-value, and adjusted means ± 1 SE for the spine and pectoral girdle dimensions in wild channel catfish.

Regression Equation	**R^2**	**P***	**Mean ± 1 SE**
Log Spine L = 0.001654 + 0.6518 Log TL	0.919	-	46.67 ± 1.57mm
Log Spine Wt = -1.928 + 0.6480 Log Wt	0.890	-	0.67 ± 0.06 g
Spine Width = 1.122 + 0.01143 TL	0.905	<0.0001	5.33 ± 0.20 mm
Log DP Width = -1.399 + 0.4067 Log TL	0.717	-	1.70 ± 0.05 mm
DP Depth = 0.7589 + 0.0025 TL	0.703	<0.0001	1.70 ± 0.05 mm
DV L = 3.108 + 0.0198 TL	0.903	<0.0001	10.26 ± 0.36
Log Girdle Depth = 0.1088 + 0.04183 Log TL	0.892	-	23.09 ± 0.81 mm
Log Coracoid Depth = 0.1365 + 0.0524 Log TL	0.847	-	13.94 ± 0.51 mm
Log Cleithrum Depth = 0.2129 + 0.08186 Log TL	0.683	-	9.43 ± 0.38 mm
Log Girdle Wt = -1.284 + 0.7197 Log Wt	0.865	-	4.85 ± 0.48 g
Spine L = 4.029 + 1.846 Girdle Depth	0.915	< 0.0001	46.67 ± 1.57 mm
Log Spine Wt = -0.7183 + 0.8328 Girdle Wt	0.972	-	0.67 ± 0.06 g
Spine Width = -0.1959 + 0.2393 Girdle Depth	0.894	<0.0001	5.33 ± 0.20 mm
Log Spine Density = -3.039 + 1.265 Log TL	0.913	-	13.36 ± 0.90 mg/mm
Spine L/Girdle Depth = 2.141 + (-0.0002873) TL	0.425	0.1899	2.03 ± 0.02
Spine Wt/Girdle Wt = 0.2458 – 0.1339 $e^{(-0.004\ Wt) + 0.1339}$	0.749	-	0.15 ± 0.00

* P values are not given for nonlinear regressions.

Table 7: Regression equations, coefficients of determination (R^2), p-value, and adjusted means ± 1 SE for the spine and pectoral girdle dimensions in white catfish.

Regression Equation	**R^2**	**P***	**Mean ± 1 SE**
Log Spine L = 0.1369 + 0.5866 Log TL	0.895	-	36.03 ± 0.96 mm
Log Spine Wt = -1.736 + 0.5193Log Wt	0.924	-	0.33 ± 0.02 g
Spine Width = 1.078 + 0.01158 TL	0.903	<0.0001	4.17 ± 0.14 mm
Log DP Width = -0.7540 + 0.6124 Log TL	0.796	-	5.35 ± 0.15 mm
Log DP Depth = -1.462 + 0.6644 TL	0.817	-	1.40 ± 0.04 mm
Log DV L = -0.653 + 0.6475 TL	0.868	-	8.20 ± 0.24 mm
Girdle Depth = 0.1655 + 0.07547 TL	0.952	< 0.0001	20.37 ± 6.03 mm
Coracoid Depth = 1.090 + 0.04272 TL	0.914	< 0.0001	12.53 ± 3.48 mm
Cleithrum Depth = -1.363 + 0.03705 TL	0.925	< 0.0001	8.55 ± 3.00 mm
Log Girdle Wt = -1.523 + 0.7692 Log Wt	0.965	-	2.41 ± 0.31 g
Log Spine L = 0.8168 + 0.5687 Log Girdle Depth	0.867	-	36.03 ± 0.96 mm
Log Spine Wt = -0.6938 + 0.6546 Log Girdle Wt	0.962	-	0.33 ± 0.02 g
Log Spine Width = -0.3370 + 0.7348 Log Girdle Depth	0.909	-	4.17 ± 0.141 mm
Log Spine Density = -2.282 + 1.324 Log TL	0.949	-	8.64 ± 0.53 mg/mm
Spine L/Girdle Depth = 2.454 + (-0.002340) TL	0.604	<0.0001	1.82 ± 0.03
Spine Wt/Girdle Wt = 0.2273 – 0.1343 e $^{(-0.004\ Wt) + 0.1343}$	0.607	-	0.16 ± 0.00

* P values are not given for nonlinear regressions.

Table 8: Regression equations, coefficients of determination (R^2), p-value, and adjusted means ± 1 SE for the spine and pectoral girdle dimensions in brown bullheads.

Regression Equation	**R^2**	**P***	**Mean ± 1 SE**
Spine L = 3.592 + 0.1062 TL	0.957	<0.0001	16.65 ± 1.33 mm
Log Spine Wt = -2.545 + 0.8015 Log Wt	0.957	-	0.04 ± 0.01 g
Spine Width = 0.0920 + 0.0147 TL	0.964	<0.0001	1.84 ± 0.17 mm
DP Width = 0.1781 + 0.01804 TL	0.987	<0.0001	2.39 ± 0.22 mm
DP Depth = 0.1484 + 0.0042 TL	0.914	<0.0001	0.67 ± 0.05 mm
DV L = 0.6984 + 0.02676 TL	0.975	<0.0001	4.00 ± 0.34 mm
Girdle Depth = 0.5904 + 0.08093 TL	0.983	<0.0001	10.17 ± 0.96 mm
Coracoid Depth = 1.133 + 0.04135 TL	0.924	<0.0001	6.02 ± 0.50 mm
Cleithrum Depth = -0.6453 + 0.04293 TL	0.960	<0.0001	4.43 ± 0.51 mm
Girdle Wt = 0.02277 + 0.007279 Wt	0.977	<0.0001	0.33 ± 0.13 g
Spine L = 2.916 + 1.302 Girdle Depth	0.953	<0.0001	16.65 ± 1.33 mm
Log Spine Wt = -0.8735 + 0.9125 Log Girdle Wt	0.994	-	0.04 ± 0.01 g
Spine Width = -0.02502 + 0.1835 G Depth	0.953	<0.0001	1.84 ± 0.17 mm
Log Spine Density = -3.92 + 1.991 Log TL	0.987	-	2.09 ± 0.47 mg/mm
Spine L/Girdle Depth = 1.814 + (-0.001495) TL	0.301	0.0025	1.63 ± 0.03
Spine Wt/Girdle Wt = 0.1933 – 0.1204 $e^{(-0.014\ Wt) + 0.1204}$	0.765	-	0.17 ± 0.00

* P values are not given for nonlinear regressions.

Table 9: Regression equations, coefficients of determination (R^2), p-value, and adjusted means ± 1 SE for the spine and pectoral girdle dimensions in yellow bullheads.

Regression Equation	R^2	P*	Mean ± 1 SE
Spine L = -0.7039 + 0.9149 TL	0.981	<0.0001	17.28 ± 1.25 mm
Log Spine Wt = -2.718 + 0.8506 Log Wt	0.965	-	0.04 ± 0.00 g
Spine Width = -0.1540 + 0.01545 TL	0.929	<0.0001	1.91 ± 0.15 mm
DP Width = -0.1558 + 0.02051 TL	0.979	<0.0001	2.62 ± 0.21 mm
DP Depth = -0.05503 + 0.0048 TL	0.946	<0.0001	0.77 ± 0.05 mm
DV L = 0.09854 + 0.02976 TL	0.960	<0.0001	4.08 ± 0.30 mm
Girdle Depth = -0.5903 + 0.07301 TL	0.952	<0.0001	9.14 ± 0.77 mm
Coracoid Depth = 0.4005 + 0.04401 TL	0.884	<0.0001	5.31 ± 0.48 mm
Cleithrum Depth = 0.2077 + 0.03103 TL	0.854	<0.0001	3.82 ± 0.34 mm
Log Girdle Wt = -2.718 + 0.8506 Log Girdle Wt	0.965	-	0.04 ± 0.00 g
Spine L = 2.708 + 1.579 Girdle Depth	0.937	<0.0001	17.28 ± 1.25 mm
Log Spine Wt = -0.7967 + 0.9289 Log Girdle Wt	0.991	-	0.04 ± 0.00 g
Spine Width = -0.0010 + 0.2085 Girdle Depth	0.925	<0.0001	1.91 ± 0.15 mm
Log Spine Density = -4.291 + 2.150 Log TL	0.966	-	2.21 ± 0.32 mg/mm
Spine L/Girdle Depth = 2.024 + (-0.001110) TL	0.0.95	0.0958	1.87 ± 0.03
Spine Wt/Girdle Wt = 0.2021 – 0.1536 $e^{(-0.014\,Wt) + 0.1536}$	0.605	-	0.18 ± 0.00

* P values are not given for nonlinear regressions.

Table 10: Regression equations, coefficients of determination (R^2), p-value, and adjusted means ± 1 SE for the spine and pectoral girdle dimensions in flathead catfish.

Regression Equation	R^2	**P***	**Mean ± 1 SE**
Log Spine L = -0.7917 + 0.8966 Log TL	0.956	-	49.74 ± 2.05 mm
Log Spine Wt = -2.343 + 0.7390 Log Wt	0.950	-	1.74 ± 0.18 g
Spine Width = 0.2383 + 0.01647 TL	0.957	<0.0001	10.10 ± 0.45 mm
DP Width = 0.2383 + 0.01647 TL	0.957	<0.0001	10.10 ± 0.45 mm
DP Depth = 0.5876 + 0.003497 TL	0.865	<0.0001	2.68 ± 0.1 mm
DV L = 1.228 + 0.02130 TL	0.976	<0.0001	4.09 ± 0.58 mm
Girdle Depth = 0.7150 + 0.04526 TL	0.961	<0.0001	27.83 ± 1.23 mm
Coracoid Depth = 0.8279 + 0.02509 TL	0.920	<0.0001	15.86 ± 0.70 mm
Cleithrum Depth = -0.1122 + 0.02049 TL	0.945	<0.0001	12.16 ± 0.56 mm
Log Girdle Wt = -1.770 + 0.8577 Log Wt	0.977	-	17.69 ± 2.17 g
Spine L = 4.822 + 1.614 Girdle Depth	0.940	<0.0001	49.74 ± 2.05 mm
Log Spine Wt = -0.8557 + 0.8864 Log Girdle Wt	0.989	-	1.74 ± 0.19 g
Spine Width = 0.1878 + 0.3563 Girdle Depth	0.954	<0.0001	10.10 ± 0.45 mm
Log Spine Density = -3.367 + 1.740 Log TL	0.927	-	30.89 ± 2.40 mg/mm
Spine L/Girdle Depth = 1.974 + (-0.0002796) TL	0.160	0.0057	1.80 ± 0.01
Spine Wt/Girdle Wt = 0.1526 – 0.0922 $e^{(-0.006\ Wt) + 0.0922}$	0.843	-	0.10 ± 0.00

* P values are not given for nonlinear regressions.

Table 11: Regression equations, coefficients of determination (R^2), p-value, and adjusted means ± 1 SE for the spine and pectoral girdle dimensions in margined madtoms.

Regression Equation	**R^2**	**P***	**Mean ± 1 SE**
Spine L = 1.831 + 0.1076 TL	0.894	<0.0001	14.91 ± 1.07 mm
Log Spine Wt = -2.753 + 0.9168 Log Wt	0.903	-	0.02 ± 0.00 g
Spine Width = 0.2493 + 0.01175 TL	0.779	0.0001	1.67 ± 0.12 mm
DP Width = -0.1385 + 0.01840 TL	0.925	<0.0001	2.09 ± 0.18 mm
DP Depth = 0.1998 + 0.003943 TL	0.651	0.0015	0.67 ± 0.04 mm
DV Length = 0.2381 + 0.02321 TL	0.967	<0.0001	3.06 ± 0.22 mm
Girdle Depth = 0.8139 + 0.04300 TL	0.942	<0.0001	6.04 ± 0.41 mm
Coracoid Depth = 0.1317 + 0.03296 TL	0.944	<0.0001	4.13 ± 0.32 mm
Cleithrum Depth = -0.3125 + 0.01905 TL	0.856	<0.0001	2.00 ± 0.19 mm
Girdle Wt = -0.002 + 0.006 Wt	0.974	<0.0001	0.10 ± 0.02 g
Log Spine L = 0.4460 + 0.9319 Log Girdle Depth	0.786	-	14.91 ± 1.07 mm
Log Spine Wt = -0.7642 + 0.8817 Log Girdle Wt	0.959	-	0.02 ± 0.00 g
Spine Width = -0.4902 + 0.9171 Girdle Depth	0.774	-	1.67 ± 0.12 mm
Log Spine Density = -4.759 + 2.331 Log TL	0.983	-	1.41 ± 0.25 mg/mm
Spine L/Girdle Depth =1.939 + (-0.001145) TL	0.063	0.4287	1.80 ± 0.04
Spine Wt/Girdle Wt = 0.2421 + 26.12 $e^{(-0.014 \wedge 0.005 Wt) + (-26.12)}$	0.447	-	0.18 ± 0.00

* P values are not given for nonlinear regressions.

Table 12: Regression equations, coefficients of determination (R^2), p-value, and adjusted means ± 1 SE for the spine and pectoral girdle dimensions in tadpole madtoms.

Regression Equation	**R^2**	**P***	**Mean ± 1 SE**
Spine L = -0.6678 + 0.9264 TL	0.943	-	8.85 ± 0.54 mm
Log Spine Wt = -2.769 + 1.592 Log Wt	0.993	-	0.00 ± 0.00 g
Spine Width = 0.1156 + 0.01395 TL	0.956	0.0001	0.88 ± 0.05 mm
DP Width = 0.350 + 0.01576 TL	0.933	0.0004	1.22 ± 0.05 mm
DP Depth = 0.2292 + 0.002927 TL	0.411	0.1206	0.39 ± 0.01 mm
DV L = 0.6300 + 0.02088 TL	0.794	0.0070	1.78 ± 0.08 mm
Girdle Depth = 0.4249 + 0.06862 TL	0.881	0.0017	4.22 ± 0.26 mm
Coracoid Depth = 1.223 + 0.02428 TL	0.586	0.0447	2.56 ± 0.11 mm
Cleithrum Depth = -0.2635 + 0.03396 TL	0.881	0.0017	1.61 ± 0.12 mm
Girdle Wt = -0.001637 + 0.01074 Wt	0.963	<0.0001	0.01 ± 0.00 g
Log Spine L = 0.3487 + 0.9563 Log Girdle Depth	0.938	-	8.85 ± 0.54 mm
Spine Wt = 0.3326 + (-0.001274) Girdle Wt	0.967	-	0.00 ± 0.00 g
Spine Width = 0.1395 + 0.1772 Girdle Depth	0.824	0.0047	0.88 ± 0.05 mm
Log Spine Density = -6.161 + 3.296 Log TL	0.994	-	0.42 ± 0.08 mg/mm
Spine L/Girdle Depth =2.002 + 0.001656 TL	0.033	0.6965	2.09 ± 0.03
Spine Wt/Girdle Wt = -0.0065 – 0.3158 $e^{(-0.963\ Wt) + 0.3158}$	0.811	-	0.23 ± 0.02

* P values are not given for nonlinear regressions.

Table 13: Comparison of regressions of spine growth in blue and wild channel catfish including analysis of covariance and p-value.

Regression Equation	**Slope F**	**P**	**Intercept F**	**P**
Spine L and TL	$_{1,\,127} = 26.00$	<0.0001	-	-
Spine Wt and Wt	$_{1,\,122} = 2.47$	0.188	$_{1,\,123} = 2.08$	0.1512
Spine Width and TL	$_{1,\,126} = 50.15$	<0.0001	-	-
DP Width and TL	$_{1,\,126} = 114.11$	<0.0001	-	-
DP Depth and TL	$_{1,\,126} = 49.10$	<0.0001	-	-
DV Length and TL	$_{1,\,122} = 86.09$	<0.0001	-	-
Girdle Depth and TL	$_{1,\,126} = 71.84$	<0.0001	-	-
Coracoid Depth and TL	$_{1,\,126} = 21.53$	<0.0001	-	-
Cleithrum Depth and TL	$_{1,\,126} = 2.72$	0.1015	$_{1,\,127} = 69.78$	<0.001
Girdle Wt and Wt	$_{1,\,122} = 0.90$	0.3425	$_{1,\,123} = 23.97$	<0.0001
Spine L and Girdle Depth	$_{1,\,128} = 0.26$	0.6089	$_{1,\,129} = 0.99$	0.3201
Spine Wt and Girdle Wt	$_{1,\,124} = 0.87$	0.3519	$_{1,\,125} = 13.98$	0.00027
Spine Width and Girdle Depth	$_{1,\,128} = 0.33$	0.5634	$_{1,\,129} = 65.14$	<0.0001
Spine Density and TL	$_{1,\,123} = 7.54$	0.006938	-	-
Spine L/Girdle Depth and TL	$_{1,\,126} = 5.56$	0.01987	-	-
Spine Wt/Girdle Wt and Wt	$_{1,\,121} = 0.43$	0.5118	$_{1,\,122} = 30.08$	<0.0001

Intercept F: "Since the slopes differ so much, it is not possible to test whether the intercepts differ significantly."

Table 14: Comparison of regressions of spine growth in cultured and wild channel catfish including analysis of covariance and p-value.

Regression Equation	Slope F	P	Intercept F	P
Spine L and TL	$_{1, 91}$ = 1.23	0.2669	$_{1, 92}$ = 219.61	<0.0001
Spine Wt and Wt	$_{1, 91}$ = 10.70	0.001509	-	-
Spine Width and TL	$_{1, 82}$ = 3.18	0.07815	$_{1, 83}$ = 37.40	<0.0001
DP Width and TL	$_{1, 83}$ = 8.36	0.004884	-	-
DP Depth and TL	$_{1, 83}$ = 4.36	0.03973	-	-
DV Length and TL	$_{1, 78}$ = 9.94	0.002293	-	-
Girdle Depth and TL	$_{1, 96}$ = 0.39	0.3935	$_{1, 97}$ = 29.65	<0.0001
Coracoid Depth and TL	$_{1, 95}$ = 0.29	0.5876	$_{1, 96}$ = 25.85	<0.0001
Cleithrum Depth and TL	1, 95 = 0.23	0.6304	$_{1, 96}$ = 12.67	0.000577
Girdle Wt and Wt	$_{1, 86}$ = 8.10	0.005529	-	-
Spine L and Girdle Depth	$_{1, 90}$ = 8.74	0.009372	-	-
Spine Wt and Girdle Wt	$_{1, 97}$ = 1.56	0.2142	$_{1, 98}$ = 47.98	<0.0001
Spine Width and Girdle Depth	$_{1, 86}$ = 0.73	0.3923	$_{1, 87}$ = 5.11	0.02628
Spine Density and TL	$_{1, 89}$ = 0.06	0.8024	$_{1, 90}$ = 51.99	<0.0001
Spine L/Girdle Depth and TL	$_{1, 96}$ = 17.69	<0.0001	-	-
Spine Wt/Girdle Wt and Wt	$_{1, 94}$ = 0.34	0.5593	$_{1, 95}$ = 20.05	<0.0001

Intercept F: "Since the slopes differ so much, it is not possible to test whether the intercepts differ significantly."

Table 15: Comparison of regressions of spine growth in *Ameiurus* species (white, brown and yellow bullhead) including analysis of covariance and p-value.

Regression Equation	Species	Slope F	P	Intercept F	P
Spine L and TL	Brown and Yellow	1, 48 = 8.34	0.005	-	-
	Brown and White	1, 70 = 17.28	<0.0001	-	-
	Yellow and White	1, 64 = 52.96	<0.0001	-	-
Spine Wt and Wt	Brown and Yellow	1, 47 = 17.20	0.0001	-	-
	Brown and White	1, 69 = 28.14	<0.0001	-	-
	Yellow and White	1, 64 = 55.75	<0.0001	-	-
Spine Width and TL	Brown and Yellow	1, 46 = 0.46	0.4967	1, 47 = 7.93	0.00707
	Brown and White	1, 67 = 9.85	0.002516	-	-
	Yellow and White	1, 65 = 9.03	0.003767	-	-
DP Width and TL	Brown and Yellow	1, 48 = 11.26	0.0015	-	-
	Brown and White	1, 70 = 18.39	<0.0001	-	-
	Yellow and White	1, 64 = 17.68	<0.0001	-	-
DP Depth and TL	Brown and Yellow	1, 48 = 8.18	0.006	-	-
	Brown and White	1, 70 = 4.36	0.04034	-	-
	Yellow and White	1, 64 = 13.71	0.0004	-	-
DV Length and TL	Brown and Yellow	1, 48 = 3.83	0.05605	1, 49 = 5.98	0.01805
	Brown and White	1, 69 = 14.3	0.00031	-	-
	Yellow and White	1, 65 = 14.8	0.0002	-	-
Girdle Depth and TL	Brown and Yellow	1, 46 = 3.93	0.05322	1, 47 = 101.75	<0.0001
	Brown and White	1, 69 = 1.76	0.1887	1, 70 = 11.12	0.001
	Yellow and White	1, 63 = 0.17	0.6753	1, 64 = 7.30	0.008
Coracoid Depth and TL	Brown and Yellow	1, 46 = 11.28	0.935	1, 47 = 11.28	0.001
	Brown and White	1, 69 = 0.16	0.689	1, 70 = 0.30	0.581
	Yellow and White	1, 64 = 0.10	0.7476	1, 64 = 8.17	0.005
Cleithrum Depth and TL	Brown and Yellow	1, 46 = 9.96	0.002	-	-
	Brown and White	1, 69 = 4.78	0.032	-	-
	Yellow and White	1, 63 = 3.50	0.065	-	-
Girdle Wt and Wt	Brown and Yellow	1, 46 = 5.52	0.023	-	-
	Brown and White	1, 68 = 2.36	0.128	-	-
	Yellow and White	1, 64 = 10.36	0.002	-	-
Spine L and Girdle Depth	Brown and Yellow	1, 45 = 0.14	0.7087	1, 46 = 25.84	<0.0001
	Brown and White	1, 69 = 21.24	<0.0001	-	-
	Yellow and White	1, 62 = 18.28	<0.0001	-	-
Spine Wt and Girdle Wt	Brown and Yellow	1, 46 = 11.69	0.0013	-	-
	Brown and White	1, 68 = 35.07	<0.0001	-	-
	Yellow and White	1, 64 = 52.47	<0.0001	-	-
Spine Width and Girdle Depth	Brown and Yellow	1, 43 = 0.01	0.914	1, 44 = 17.56	0.0001
	Brown and White	1, 66 = 12.90	0.000624	-	-
	Yellow and White	1, 63 = 10.37	0.002026	-	-

Spine Density and TL	Brown and Yellow	$_{1,46}$ = 13.65	0.0005835	-	-
	Brown and White	$_{1,68}$ = 28.54	<0.0001	-	-
	Yellow and White	$_{1,64}$ = 48.60	<0.0001	-	-
Spine L/Girdle Depth and TL	Brown and Yellow	$_{1,44}$ = 0.24	0.6223	$_{1,45}$ = 38.68	<0.0001
	Brown and White	$_{1,69}$ = 2.45	0.122	$_{1,70}$ = 97.23	<0.0001
	Yellow and White	$_{1,61}$ = 2.91	0.09311	$_{1,62}$ = 20.16	<0.0001
Spine Wt/Girdle Wt and Wt	Brown and Yellow	$_{1,45}$ = 5.12	0.028	-	-
	Brown and White	$_{1,62}$ = 3.79	0.05583	$_{1,63}$ = 3.55	0.06409
	Yellow and White	$_{1,67}$ = 1.75	0.1892	$_{1,68}$ = 16.84	0.0001

Intercept F: "Since the slopes differ so much, it is not possible to test whether the intercepts differ significantly."

Table 16: Comparison of spine growth across species, analysis of variance, and p-value.

Ratio	**F***	**P**	**Species**	**Mean ± 1 SE***
Spine L/TL	$_{5,\,273}$ = 73.74	<0.0001	Blue	0.11 ± 0.00
			Channel	0.13 ± 0.00
			White	0.13 ± 0.00
			Brown Bullhead	0.14 ± 0.00
			Yellow Bullhead	0.12 ± 0.00
			Flathead	0.08 ± 0.00
Spine Wt/Wt	$_{5,\,272}$ = 28.45	<0.0001	Blue	$0.001 \pm 5.74^{0.0005}$
			Channel	$0.001 \pm 6.19^{0.0005}$
			White	$0.001 \pm 6.49^{0.0005}$
			Brown Bullhead	$0.001 \pm 9.11^{0.0005}$
			Yellow Bullhead	$0.001 \pm 6.59^{0.0005}$
			Flathead	$0.0005 \pm 1.95^{0.0005}$
DP Width/ DP Depth	$_{5,\,274}$ = 11.57	<0.0001	Blue	0.29 ± 0.00
			Channel	0.26 ± 0.00
			White	0.26 ± 0.00
			Brown Bullhead	0.28 ± 0.00
			Yellow Bullhead	0.29 ± 0.00
			Flathead	0.26 ± 0.00
DP Width/Spine Width	$_{5,\,270}$ = 5.53	0.0005	Blue	0.37 ± 0.00
			Channel	0.32 ± 0.00
			White	0.33 ± 0.00
			Brown Bullhead	0.37 ± 0.00
			Yellow Bullhead	0.39 ± 0.02
			Flathead	0.35 ± 0.00
DP Depth/Spine Width	$_{5,\,271}$ = 7.06	<0.0001	Blue	0.37 ± 0.00
			Channel	0.32 ± 0.00
			White	0.33 ± 0.00
			Brown Bullhead	0.37 ± 0.00
			Yellow Bullhead	0.39 ± 0.02
			Flathead	0.35 ± 0.00
Coracoid/Cleithrum	$_{5,\,272}$ = 23.94	<0.0001	Blue	1.76 ± 0.03
			Wild Channel	1.50 ± 0.03
			Cultured Channel	1.48 ± 0.03
			White	1.50 ± 0.02
			Brown Bullhead	1.44 ± 0.04
			Yellow Bullhead	1.39 ± 0.04
			Margined Madtom	2.13 ± 0.09
			Tadpole Madtom	1.64 ± 0.10
			Flathead	1.31 ± 0.02

DV Length/Spine Width	$_{5, 267} = 33.90$	0.0063	Blue	1.91 ± 0.01
			Channel	1.95 ± 0.02
			White	1.97 ± 0.01
			Brown Bullhead	2.17 ± 0.03
			Yellow Bullhead	2.18 ± 0.04
			Flathead	1.81 ± 0.02
DV Length/DP Width	$_{5, 273} = 6.77$	<0.0001	Blue	1.52 ± 0.00
			Channel	1.43 ± 0.06
			White	1.53 ± 0.01
			Brown Bullhead	1.63 ± 0.06
			Yellow Bullhead	1.58 ± 0.02
			Flathead	1.39 ± 0.01
DV Length/DP Depth	$_{5, 273} = 4.00$	<0.0001	Blue	5.25 ± 0.06
			Channel	5.57 ± 0.25
			White	5.86 ± 0.06
			Brown Bullhead	5.69 ± 0.22
			Yellow Bullhead	5.24 ± 0.10
			Flathead	5.20 ± 0.07
Spine Density			Blue	4.69
			Channel	5.33
			White	5.85
			Brown Bullhead	4.54
			Yellow Bullhead	4.55
			Flathead	4.38

* F - Analysis of variance, and p-value was not calculated from spine density across species due to total length and weight differences.
* Mean ± 1 SE – Adjusted means were taken to calculate spine density across species at 200 mm due to total length and weight differences.

Table 17: Power series and liner equations comparing spine length to total length and spine weight to weight in the pectoral spines of blue and channel catfish and white catfish, and brown and yellow bullheads to estimate total length and weight.

	Total Length, mm		**Weight, g**	
Common Name	**Regression Equation**	**R^2**	**Regression Equation**	**R^2**
Blue	$TL = 0.67\ (Spine\ L)^{1.563} + 30.18\ (Spine\ L)^{0.3308}$	0.958	$Wt = 327.4\ (Spine\ Wt)^{1.526} + 316.1\ (Spine\ Wt)^{1.430}$	0.976
	$TL = -3.277 + 35.68\ (DV\ L)$	0.991	$Wt = -1.559\ (DV\ L)^{2.547} + 0.2753\ (DV\ L)^{3.434}$	0.962
Wild Channel	$TL = (-0.211)\ (Spine\ L)\ 2.363 + 0.4778(Spine\ L)^{2.198}$	0.908	$Wt = 557.1\ (Spine\ Wt)^{2.176} + 309.7\ (Spine\ Wt)^{0.484}$	0.885
	$TL = -152.7 + 51.13\ (DV\ L)$	0.792	$Wt = 0.08487\ (DV\ L)^{4.126} + -0.07297\ (DV\ L)^{4.023}$	0.848
White	$TL = 9.452\ (Spine\ L)^{0.8914} + 3.394(Spine\ L)^{6.320}$	0.915	$Wt = 2395\ (Spine\ Wt)^{2.306} + 37.32\ (Spine\ Wt)^{-0.215}$	0.945
	$TL = 0.02423\ (DV\ L)^{3.632} + 45.98\ (DV\ L)^{0.7173}$	0.872	$Wt = -0.5505\ (DV\ L)^{5.252} + 0.5539\ (DV\ L)^{5.252}$	0.797
Brown Bullhead	$TL = 2.216\ (Spine\ L)^{1.182} + 2.139(Spine\ L)^{1.183}$	0.956	$Wt = 602.4\ (Spine\ Wt)^{1.072} +539.5\ (Spine\ Wt)^{1.070}$	0.947
	$TL = 9.235\ (DV\ L)^{1.148} + 15.59\ (DV\ L)^{1.147}$	0.973	$Wt = 0.327\ (DV\ L)^{2.995} + 0.2195\ (DV\ L)^{2.995}$	0.885
Yellow Bullhead	$TL = 17.29\ (Spine\ L)^{1.105} + 4.14^{0.006}\ (Spine\ L)^{-6.484}$	0.982	$Wt = 532.7\ (Spine\ Wt)^{1.071} + 671.1\ (Spine\ Wt)^{1.068}$	0.960
	$TL = 17.29\ (DV\ L)^{0.963} + 17.35\ (DV\ L)^{0.964}$	0.960	$Wt = 0.4888\ (DV\ L)^{2.638} + 0.4357\ (DV\ L)^{2.638}$	0.883

Table 18: Number and percent of identified catfish pectoral spines collected at Bald Eagle nesting sites throughout various locations along the Chesapeake Bay and its tributaries.

Number and Percent of Catfishes per Location							
Location	**Blue**	**Channel**	**White**	**Brown**	**Yellow**	**Unknown**	**Total**
Charles City	**18** (79.2)	**5** (20.8)	**0** (0)	**0** (0)	**0** (0)	**0** (0)	**23**
Essex	**24** (67.8)	**7** (25.8)	**3** (3.8)	**2** (2.6)	**0** (0)	**0** (0)	**36**
Isle of Wight	**5** (71.4)	**0** (0)	**1** (14.3)	**0** (0)	**0** (0)	**1** (14.3)	**7**
James City	**80** (51.9)	**48** (33.9)	**23** (13.0)	**0** (0)	**1** (1.3)	**0** (0)	**152**
King William	**1** (33.3)	**0** (0)	**2** (66.7)	**0** (0)	**0** (0)	**0** (0)	**3**
Lancaster	**7** (70.0)	**1** (10.0)	**2** (20.0)	**0** (0)	**0** (0)	**0** (0)	**10**
Middlesex	**1** (25.0)	**3** (75.0)	**0** (0)	**0** (0)	**0** (0)	**0** (0)	**4**
New Kent	**52** (75.4)	**4** (5.8)	**2** (2.9)	**10** (14.5)	**1** (1.4)	**0** (0)	**69**
Newport News	**6** (54.5)	**1** (9.1)	**2** (18.2)	**2** (18.2)	**0** (0)	**0** (0)	**11**
Richmond	**88** (80)	**18** (16.4)	**4** (3.6)	**0** (0)	**0** (0)	**0** (0)	**110**
Surry	**55** (46.6)	**48** (40.7)	**7** (5.9)	**8** (6.8)	**0** (0)	**0** (0)	**118**
Misc. 1999-2000	**24** (41.1)	**26** (44.8)	**6** (10.3)	**1** (1.7)	**1** (1.7)	**0** (0)	**58**
Total	**361 (60)**	**161 (26.7)**	**52 (8.6)**	**23 (3.8)**	**3 (0.49)**	**1 (0.16)**	**601**

Table 19: Estimated average of total length and fish weight using identified catfish pectoral spines collected at Bald Eagle nesting sites throughout various locations along the Chesapeake Bay and its tributaries.

Estimated Average of Total Length (mm) and Weight (g) of Catfishes per Location						
Location	**Blue**	**Channel**	**White**	**Brown**	**Yellow**	**Average**
Charles City	**395** - 494	**402** - 558	-	**315** - 184	-	**371** – 412
Essex	**386** - 463	**423** - 616	**264** - 290	**241** - 192	-	**329** – 781
Isle of Wight	**353** - 223	-	**289** - 439	-	-	**321** - 331
James City	**400** - 471	**422** - 770	**340** - 647	-	**183** - 184	**336** – 518
King William	**284** - 81	-	**379** - 1135	-	-	**332** - 608
Lancaster	**409** - 495	**459** - 724	**346** - 640	-	-	**405** – 620
Middlesex	**315** - 176	**415** - 531	-	-	-	**365** – 354
New Kent	**240** - 305	**379** - 520	**335** - 376	**286** - 364	**248** - 252	**298** – 363
Newport News	**437** - 678	**475** - 686	**261** - 247	**254** - 280	-	**357** – 473
Richmond	**425** - 700	**411** - 544	**335** - 704	-	-	**390** – 649
Surry	**400** - 446	**397** - 639	**322** - 835	**284** - 333	-	**351** - 563
Misc. 1999-2000	**353** - 436	**390** - 590	**329** - 601	**286** - 314	**179** - 142	**307** - 417
Average	**366** - 414	**417** - 618	**320** - 591	**278** - 277	**203** - 192	**317 - 418**

Table 20: Estimated total length and weight for various catfish species derived from regressions run on the catfish pectoral spines collected at Bald Eagle nesting sites. Note: The largest blue catfish (TL 834, Wt 6878) collected was taken out of this analysis.

		Total Length, mm			**Weight, g**		
Common Name	**n**	**Mean**	**SD**	**SE**	**Mean**	**SD**	**SE**
Blue	354	394.46	59.36	3.38	479.79	279.87	23.43
Channel	142	401.12	58.66	4.92	616.35	257.39	21.59
White	53	322.52	69.90	9.60	590.66	59.36	59.36
Brown	24	282.37	30.72	6.27	314.08	106.77	21.79
Yellow	3	203.33	38.73	22.36	192.66	55.50	32.04

Table 21: Comparison of estimated total length and weight across various species including analysis of covariance, and p-value from catfish pectoral spines collected at Bald Eagle nesting sites.

Ratio	**F**	**P**	**Species**	**Mean ± 1 SE**
Total Length	4, 574 = 43.88	<0.0001	Blue	393.5 ± 3.15
			Channel	401.1 ± 4.92
			White	322.5 ± 9.60
			Brown Bullhead	282.4 ± 6.27
			Yellow Bullhead	203.3 ± 22.36
Weight	4, 574 = 12.09	<0.0001	Blue	461.7 ± 14.90
			Channel	616.4 ± 21.60
			White	590.7 ± 59.36
			Brown Bullhead	314.10 ± 21.79
			Yellow Bullhead	192.7 ± 32.05

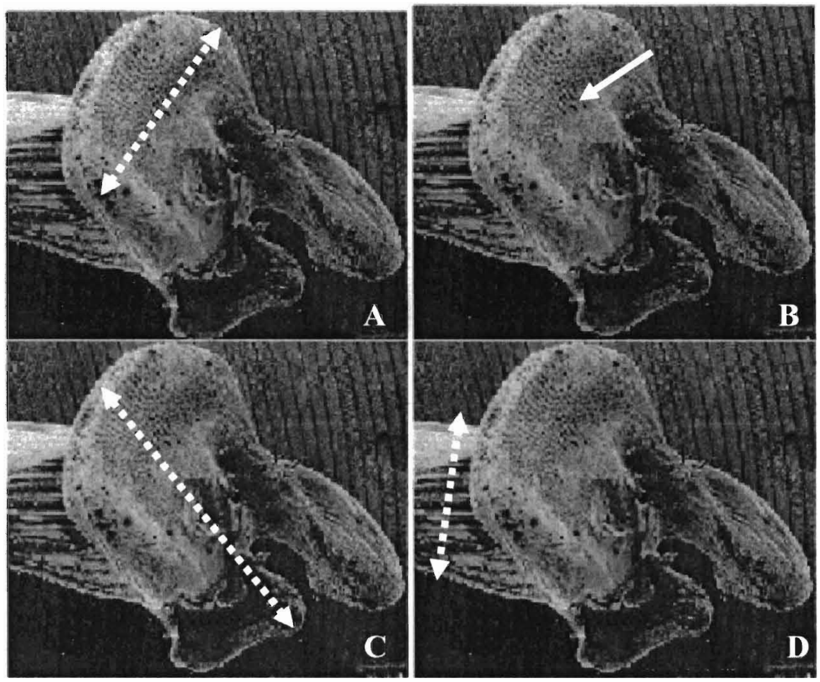

Fig 1. Scanning electron micrographs of the pectoral spine from a channel catfish from a posteriomedial view of the spine base and its processes. (A) Dorsal process width measurements from the anterior to posterior sides. (B) Dorsal process depth measurements from the proximal to distal width. (C) Dorsal – ventral tip depth measurements from the dorsal to ventral midline. (D) Spine width measurements from the anterior to posterior sides.

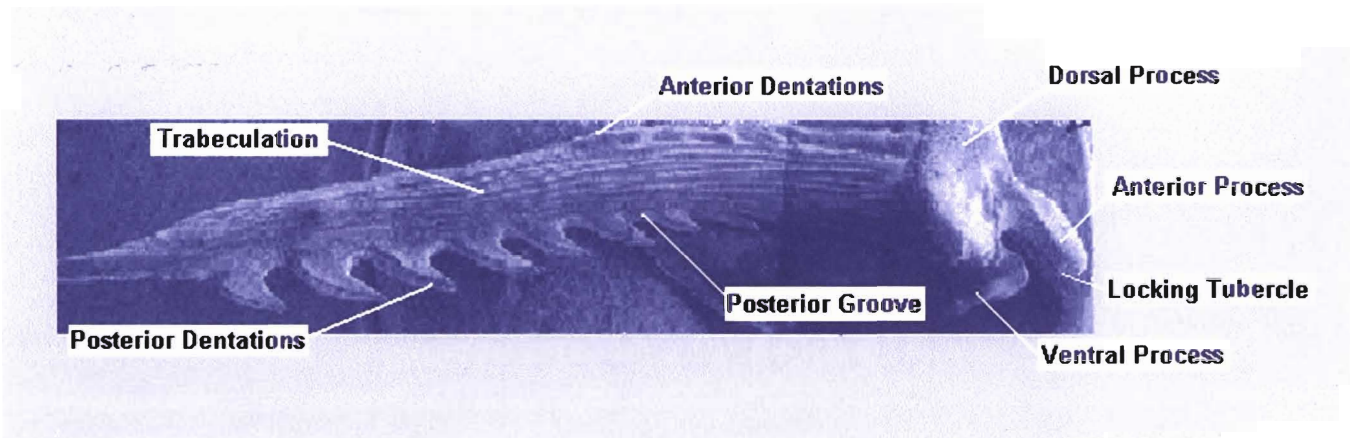

Fig 2. Scanning electron micrograph of the pectoral spine from a channel catfish, viewed dorsally describing the trabeculations, anterior dentations, posterior groove, posterior dentations, dorsal, anterior, and ventral processes and the locking tubercle.

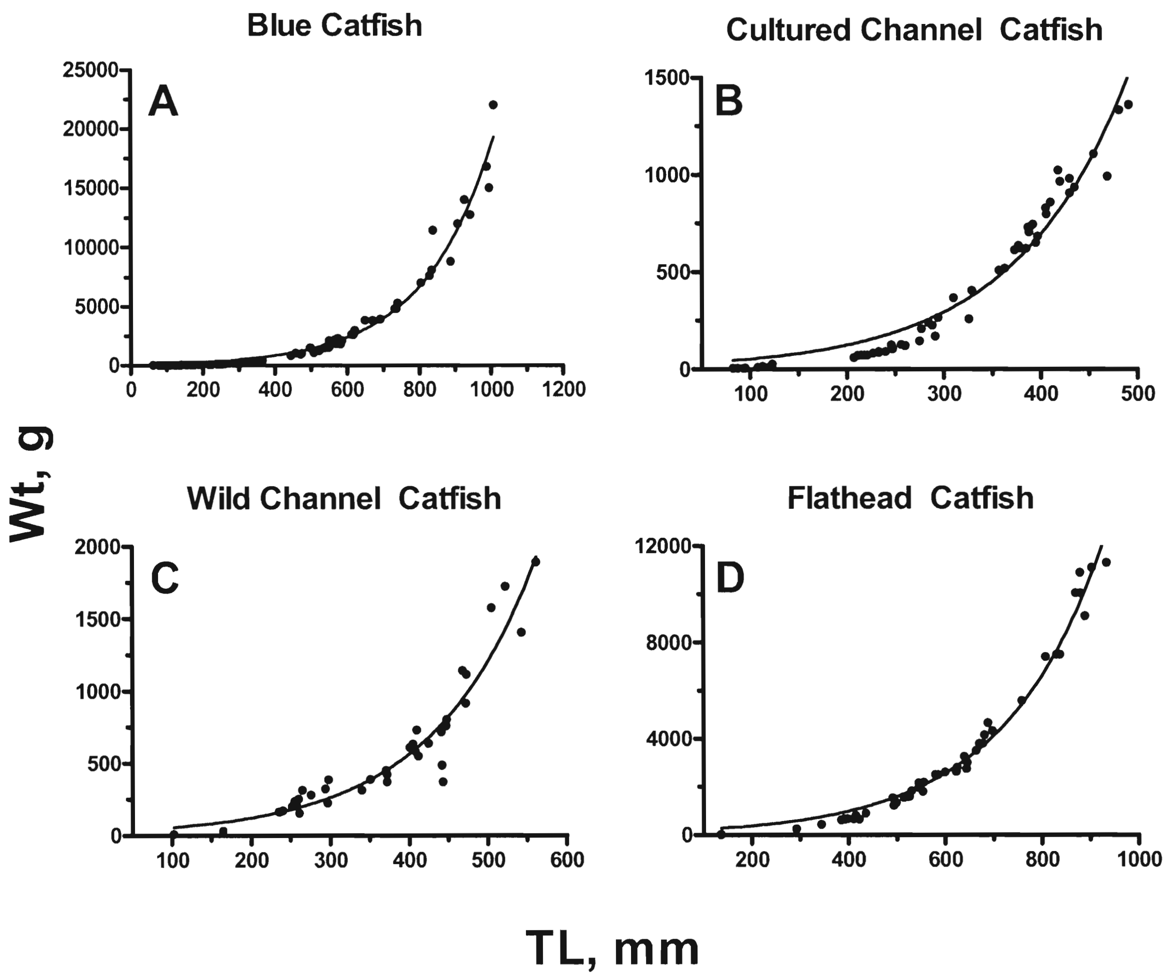

Fig. 3. Relationship of weight to total length in the blue, channel, and flathead catfish.

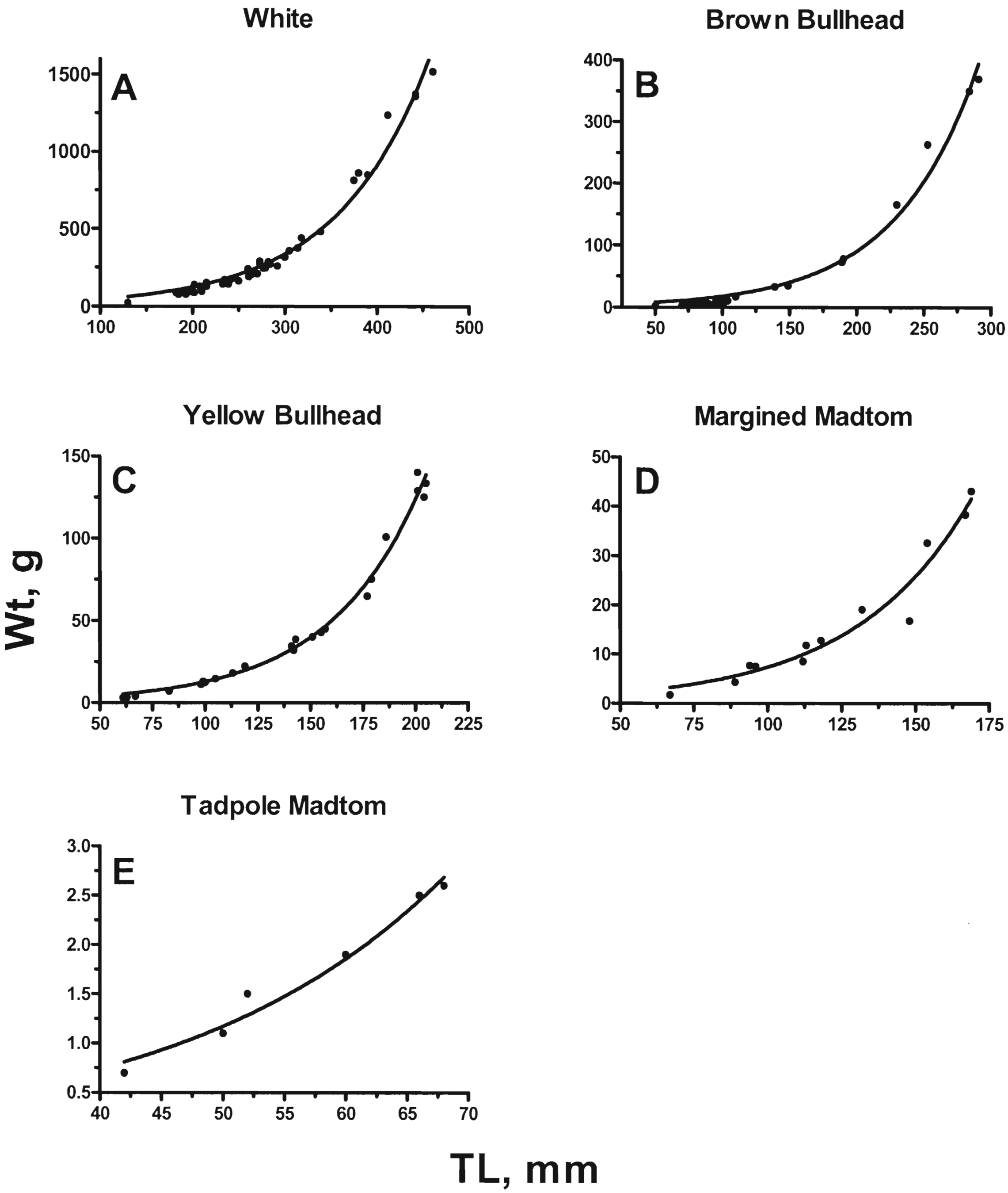

Fig. 4. Relationship of weight to total length in the white, brown bullhead, yellow bullhead, margined madtom, and tadpole madtom catfish.

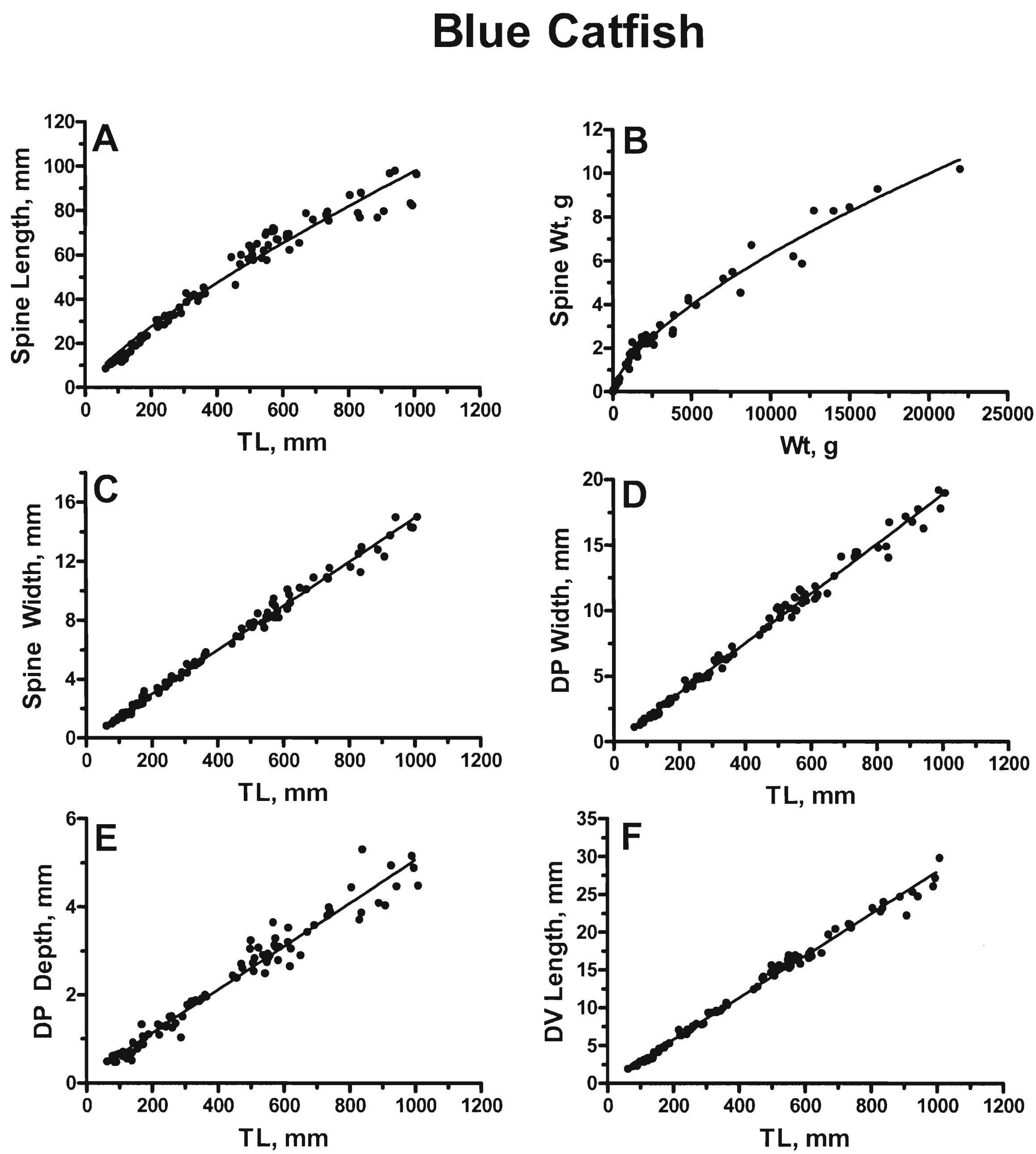

Fig. 5. Relationship of pectoral spine length, spine width, dorsal process width, dorsal process depth, dorsal-ventral length to total length and spine weight to weight in the blue catfish, *Ictalurus furcatus.*

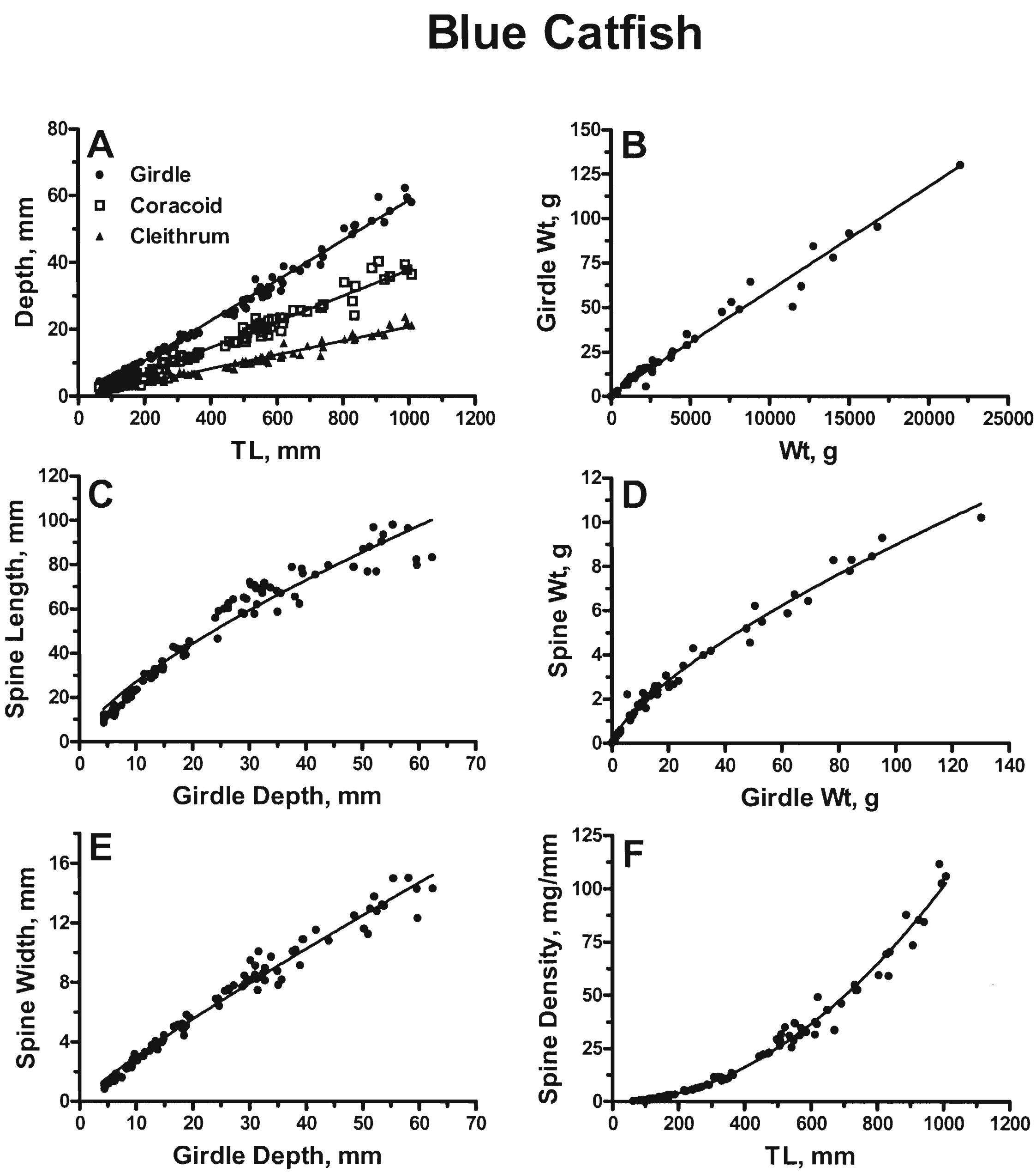

Fig. 6. Relationship of pectoral girdle, coracoid, and cleithrum depth and spine density to total length, girdle weight to weight, spine length and spine width to girdle depth, and spine weight to girdle weight in the blue catfish.

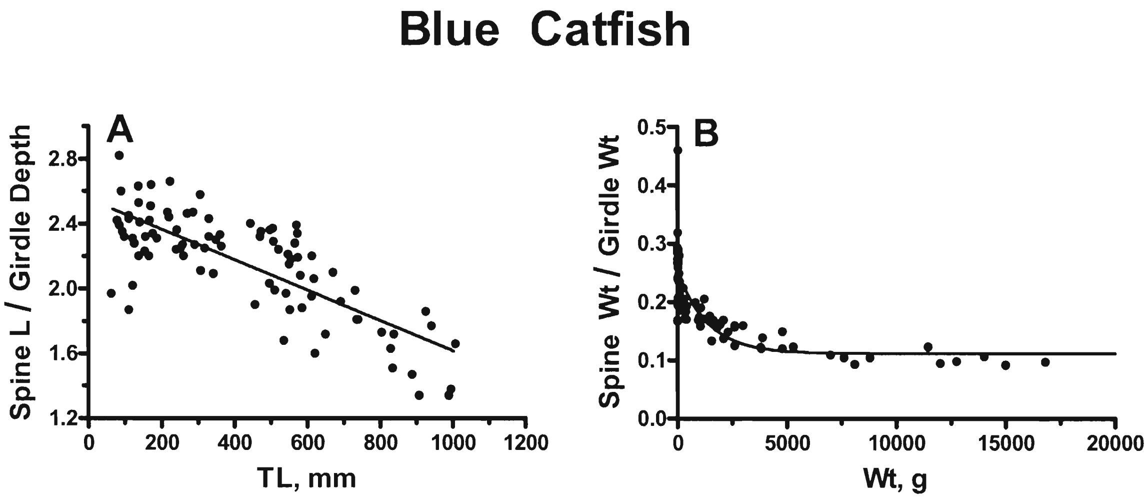

Fig. 7. Relationship of pectoral spine length and girdle depth ratio to total length and spine weight and girdle weight ratio to weight in the blue catfish.

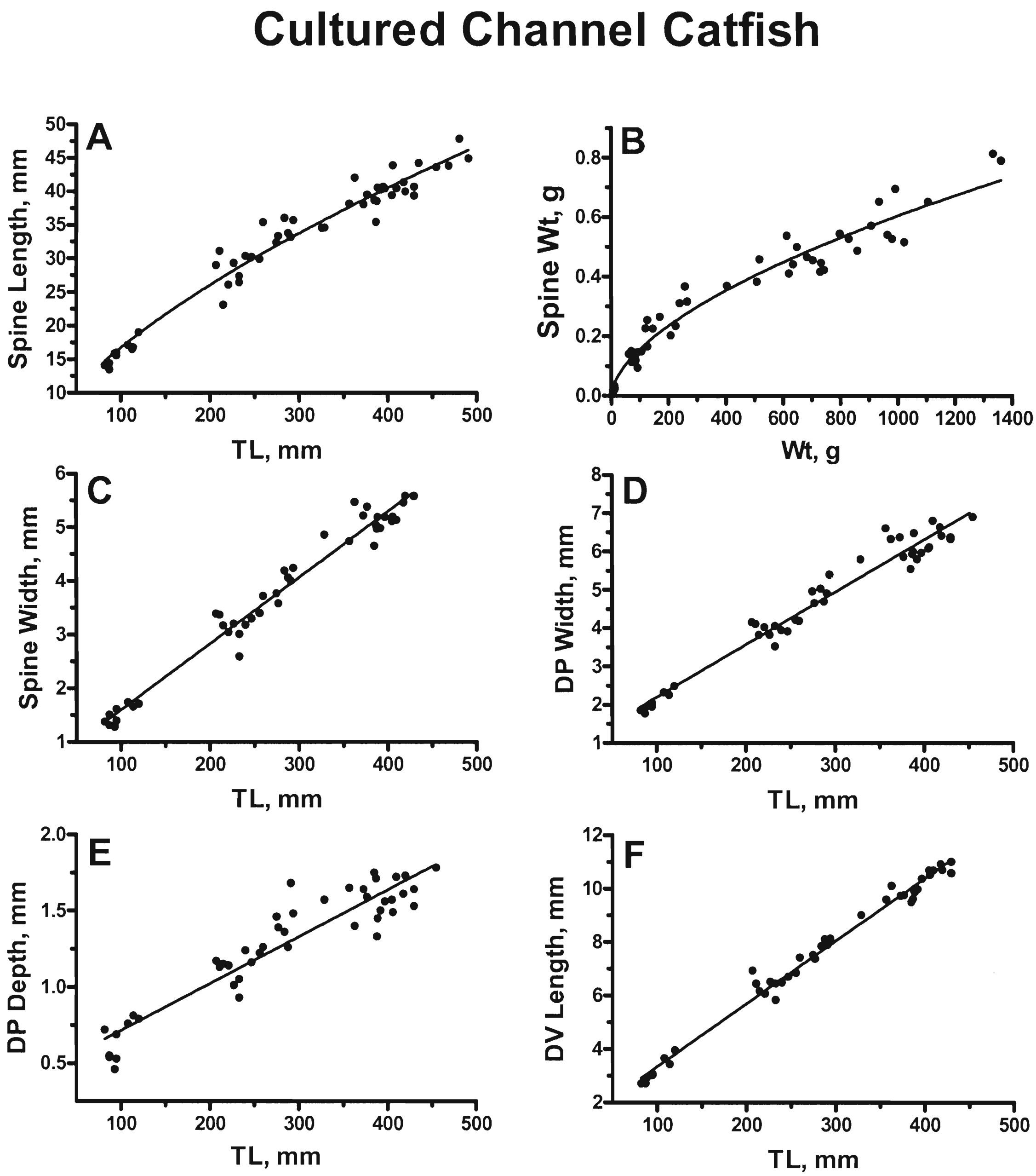

Fig. 8. Relationship of pectoral spine length, spine width, dorsal process width, dorsal process depth, dorsal-ventral length to total length and spine weight to weight in the cultured channel catfish *Ictalurus punctatus.*

Cultured Channel Catfish

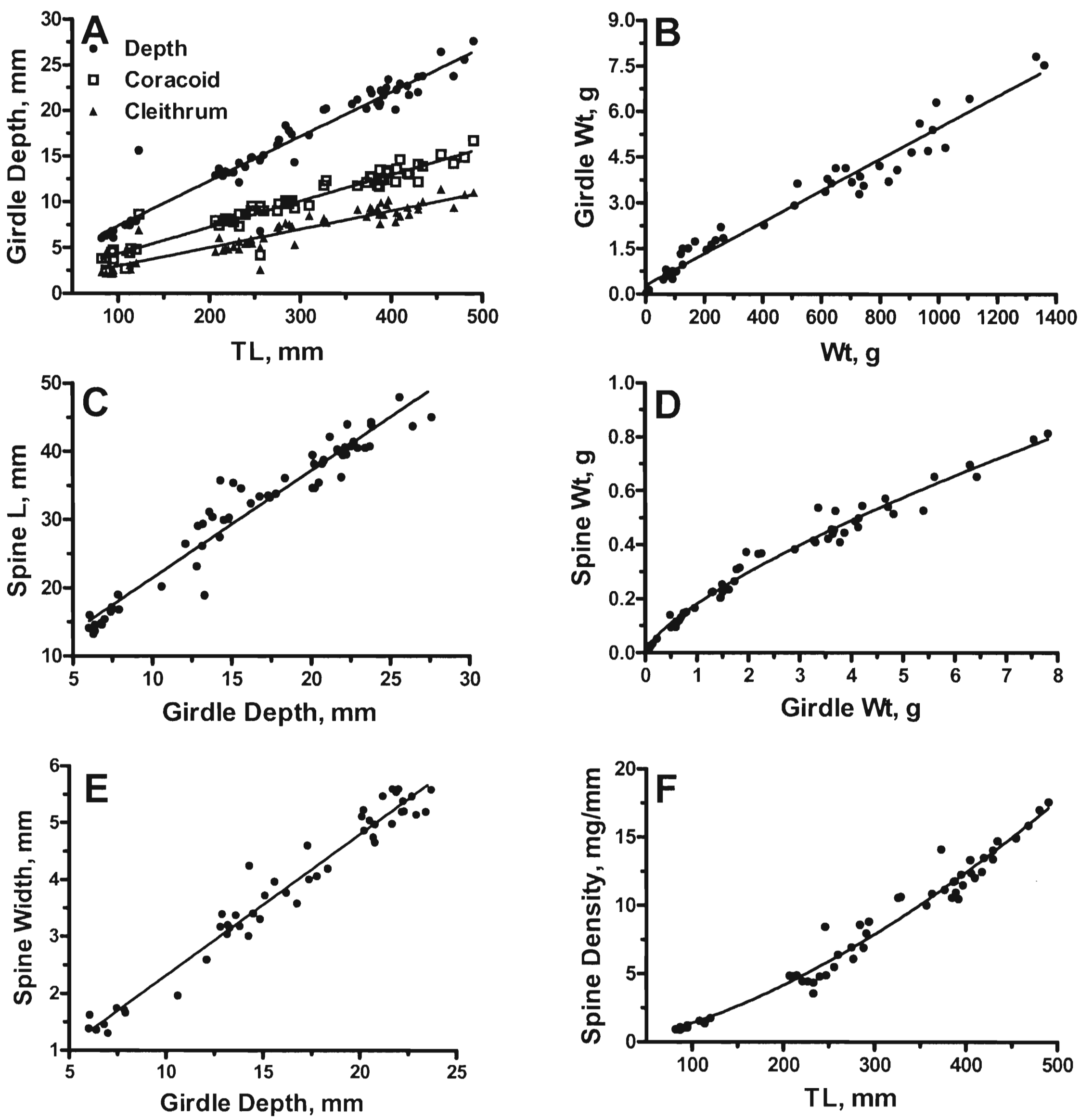

Fig. 9. Relationship of pectoral girdle, coracoid, and clethrum depth and spine density to total length, girdle weight to weight, spine length and spine width to girdle depth, and spine weight to girdle weight in the cultured channel catfish.

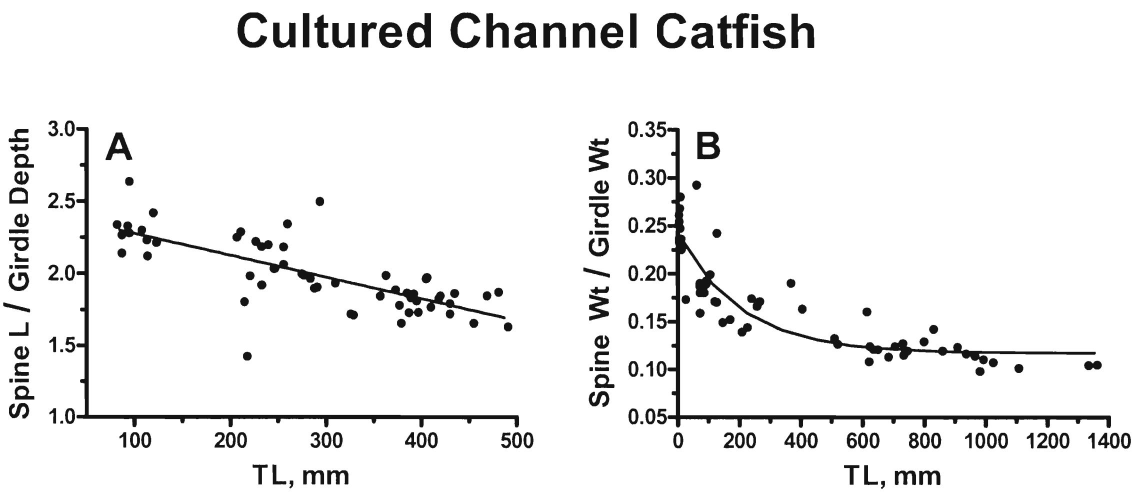

Fig. 10. Relationship of pectoral spine length and girdle depth ratio to total length and spine weight and girdle weight ratio to weight in the cultured channel catfish.

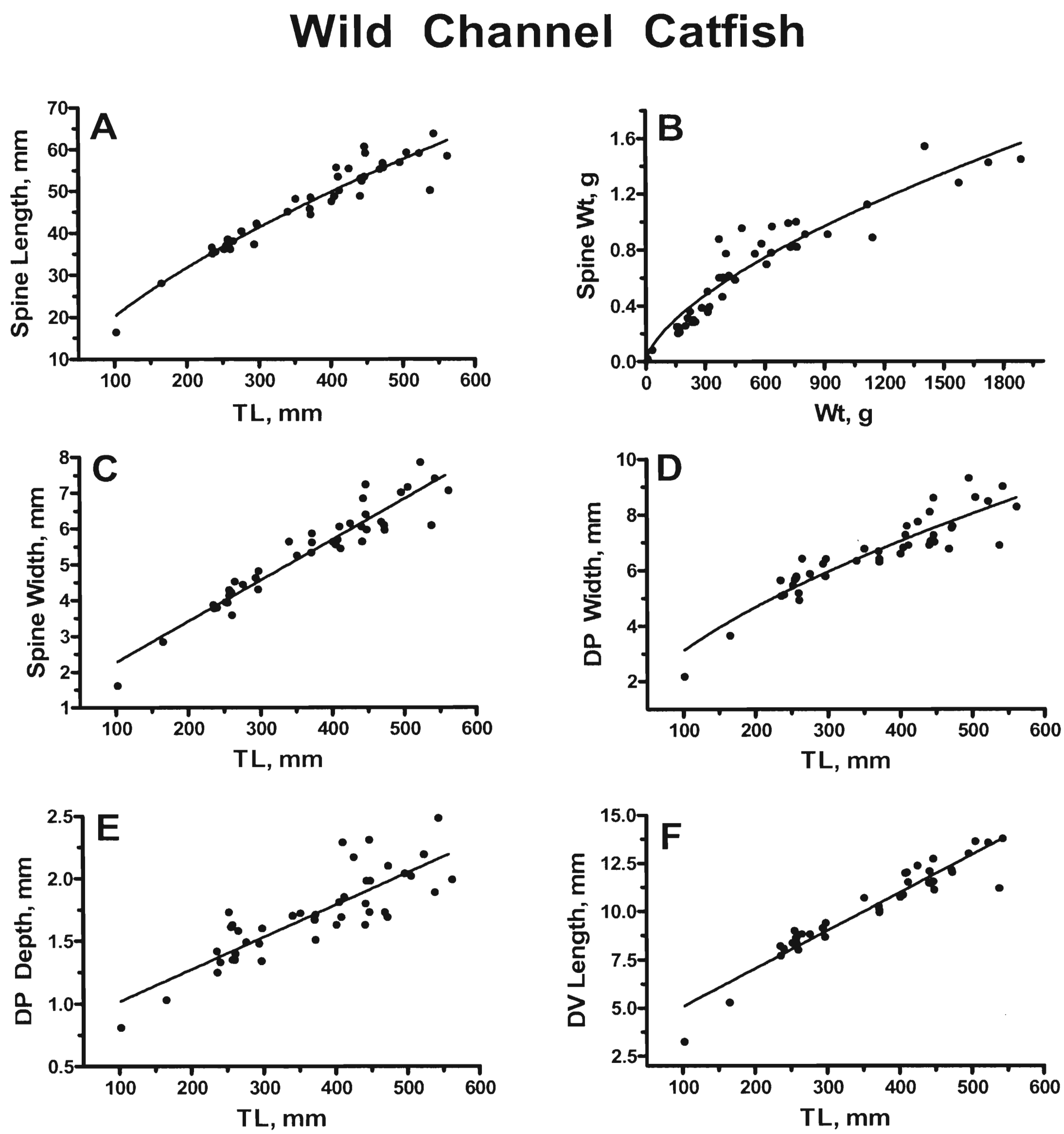

Fig. 11. Relationship of pectoral spine length, spine width, dorsal process width, dorsal process depth, dorsal-ventral length to total length and spine weight to weight in the wild channel catfish *Ictalurus punctatus*.

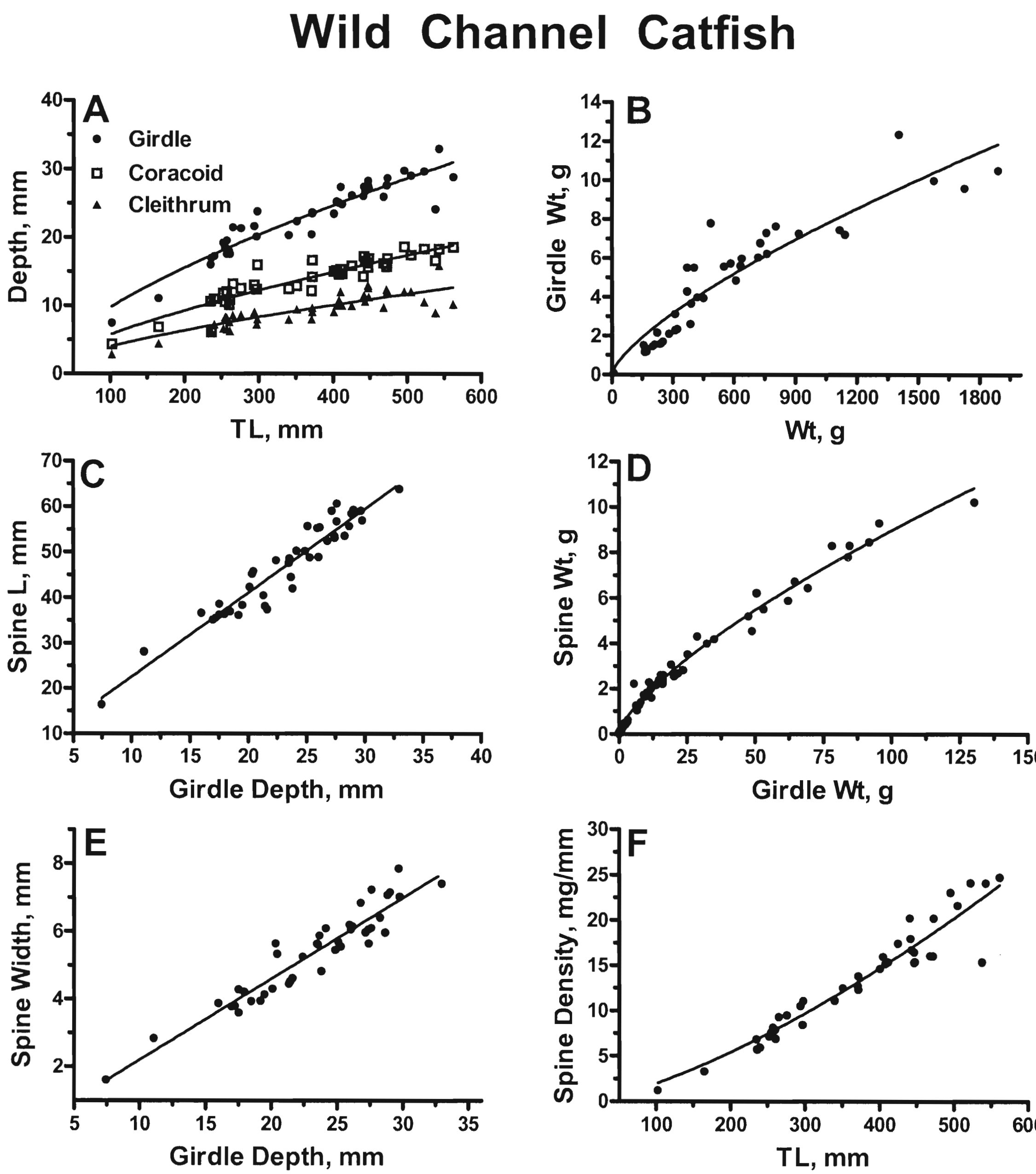

Fig. 12. Relationship of pectoral girdle, coracoid, and clethrum depth and spine density to total length, girdle weight to weight, spine length and spine width to girdle depth, and spine weight to girdle weight in the wild channel catfish.

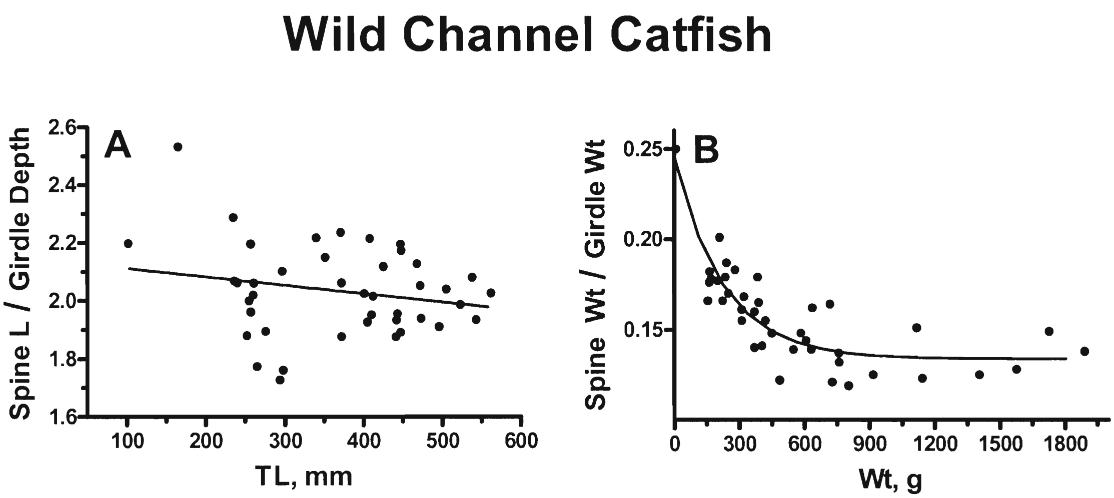

Fig. 13. Relationship of pectoral spine length and girdle depth ratio to total length and spine weight and girdle weight ratio to weight in the wild channel catfish.

White Catfish

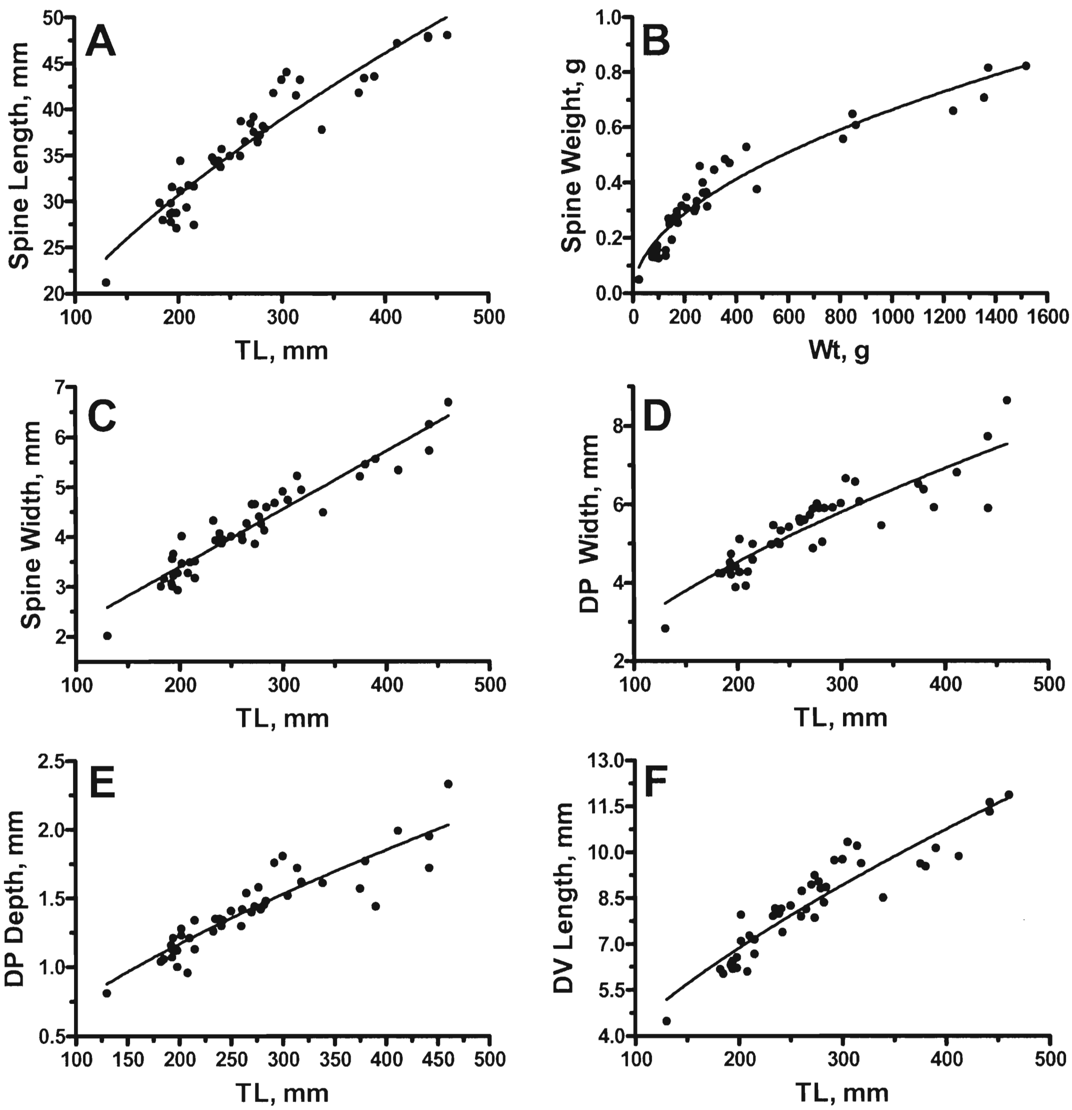

Fig. 14. Relationship of pectoral spine length, spine width, dorsal process width, dorsal process depth, dorsal-ventral length to total length and spine weight to weight in the white catfish *Ameiurus catus*.

White Catfish

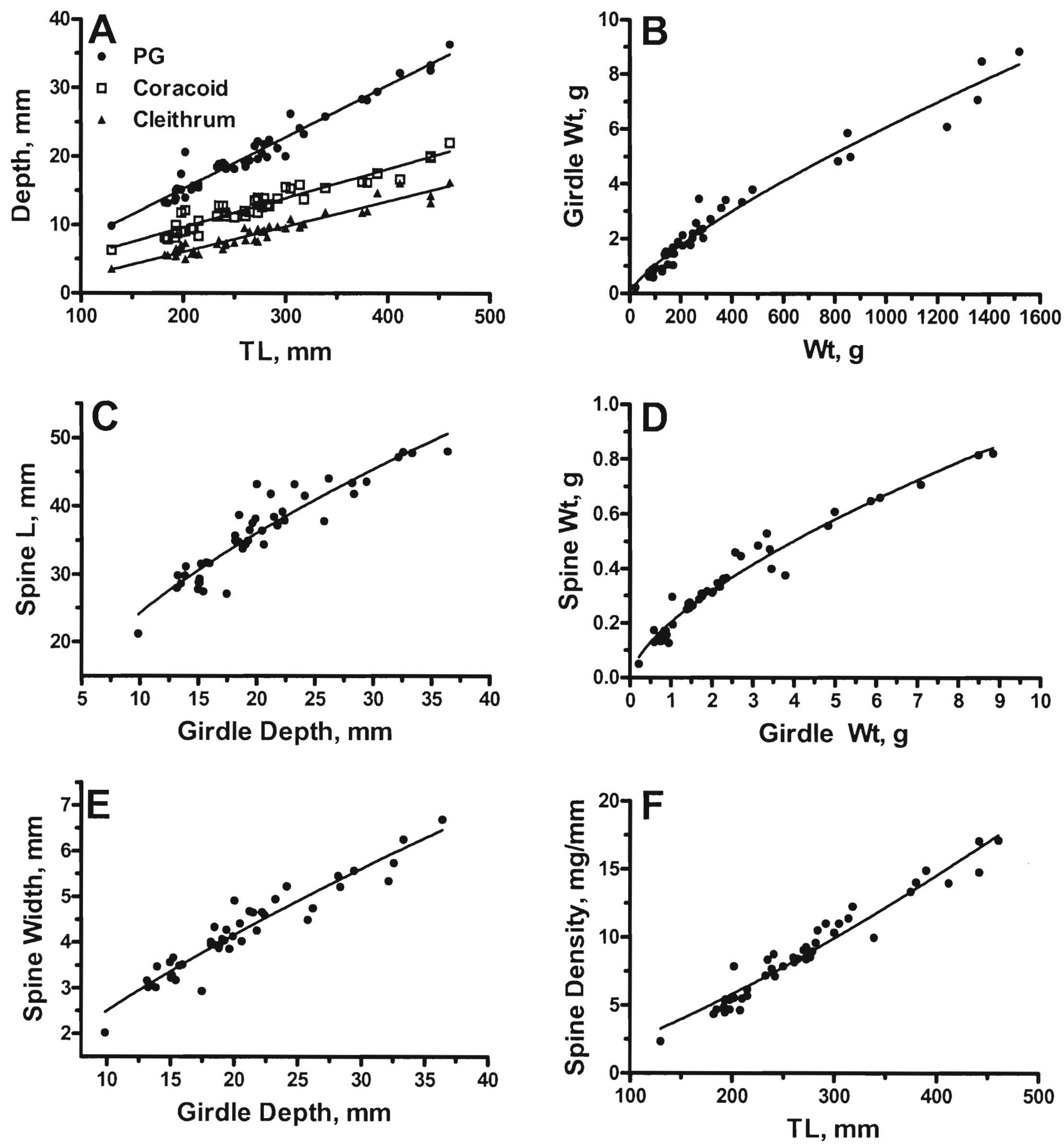

Fig. 15. Relationship of pectoral girdle, coracoid, and clethrum depth and spine density to total length, girdle weight to weight, spine length and spine width to girdle depth, and spine weight to girdle weight in the white catfish.

White Catfish

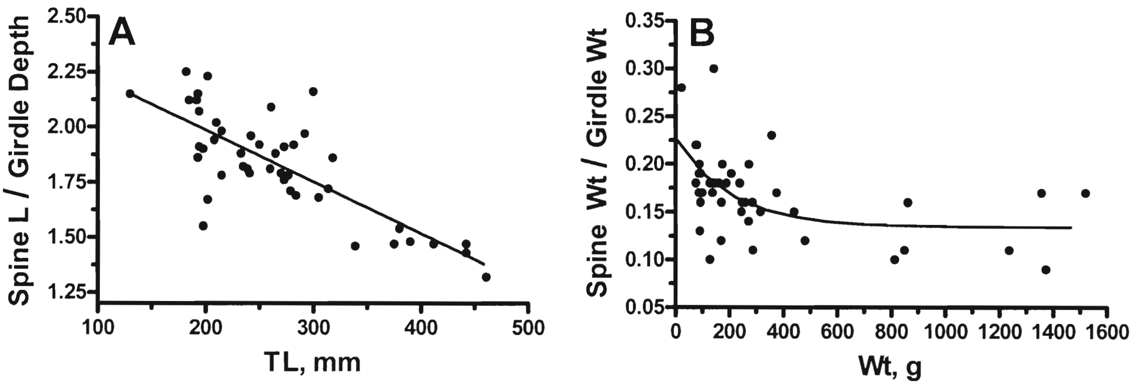

Fig. 16. Relationship of pectoral spine length and girdle depth ratio to total length and spine weight and girdle weight ratio to weight in the white catfish.

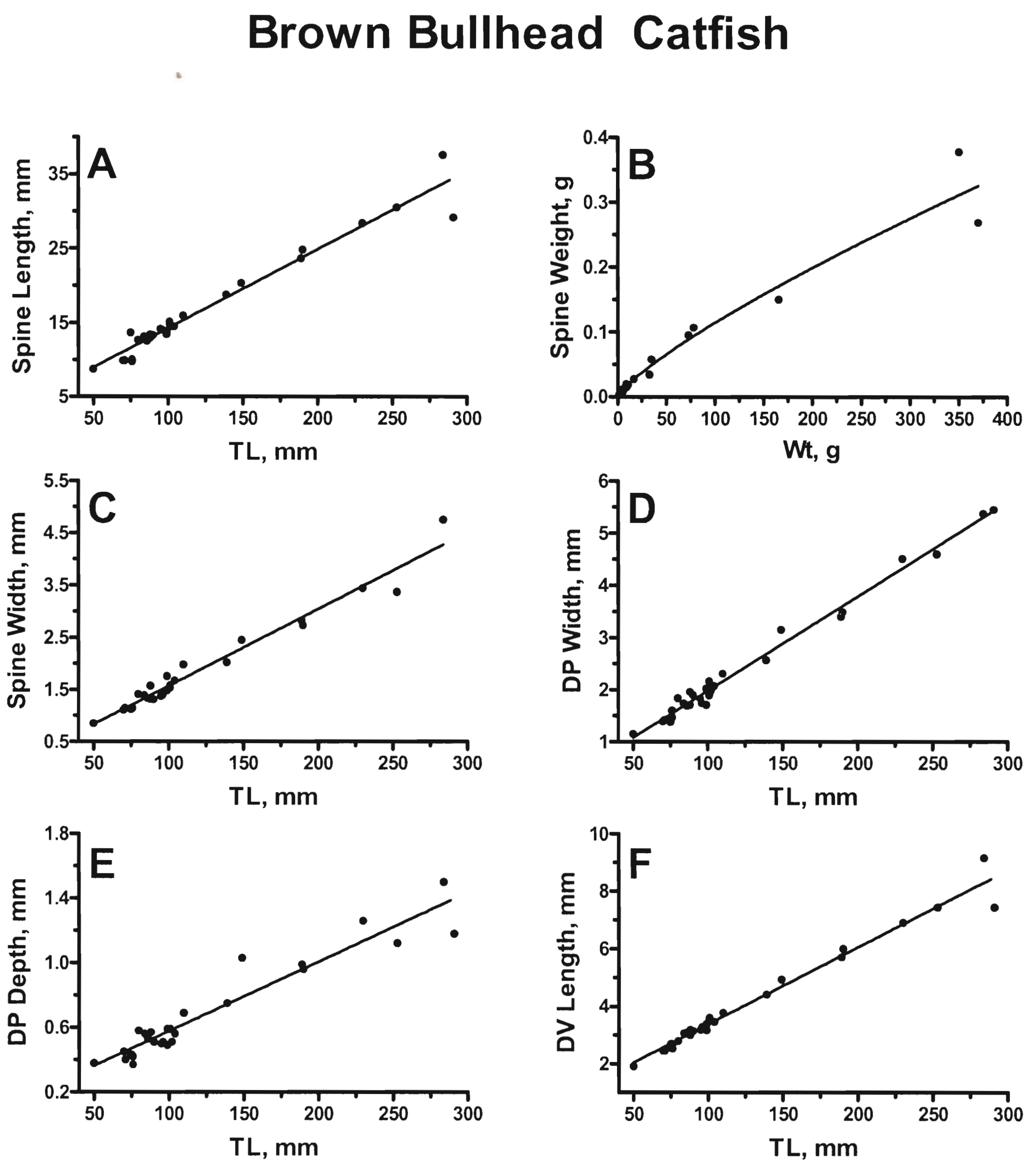

Fig. 17. Relationship of pectoral spine length, spine width, dorsal process width, dorsal process depth, dorsal-ventral length to total length and spine weight to weight in the brown bullheads *Ameiurus nebulosus*.

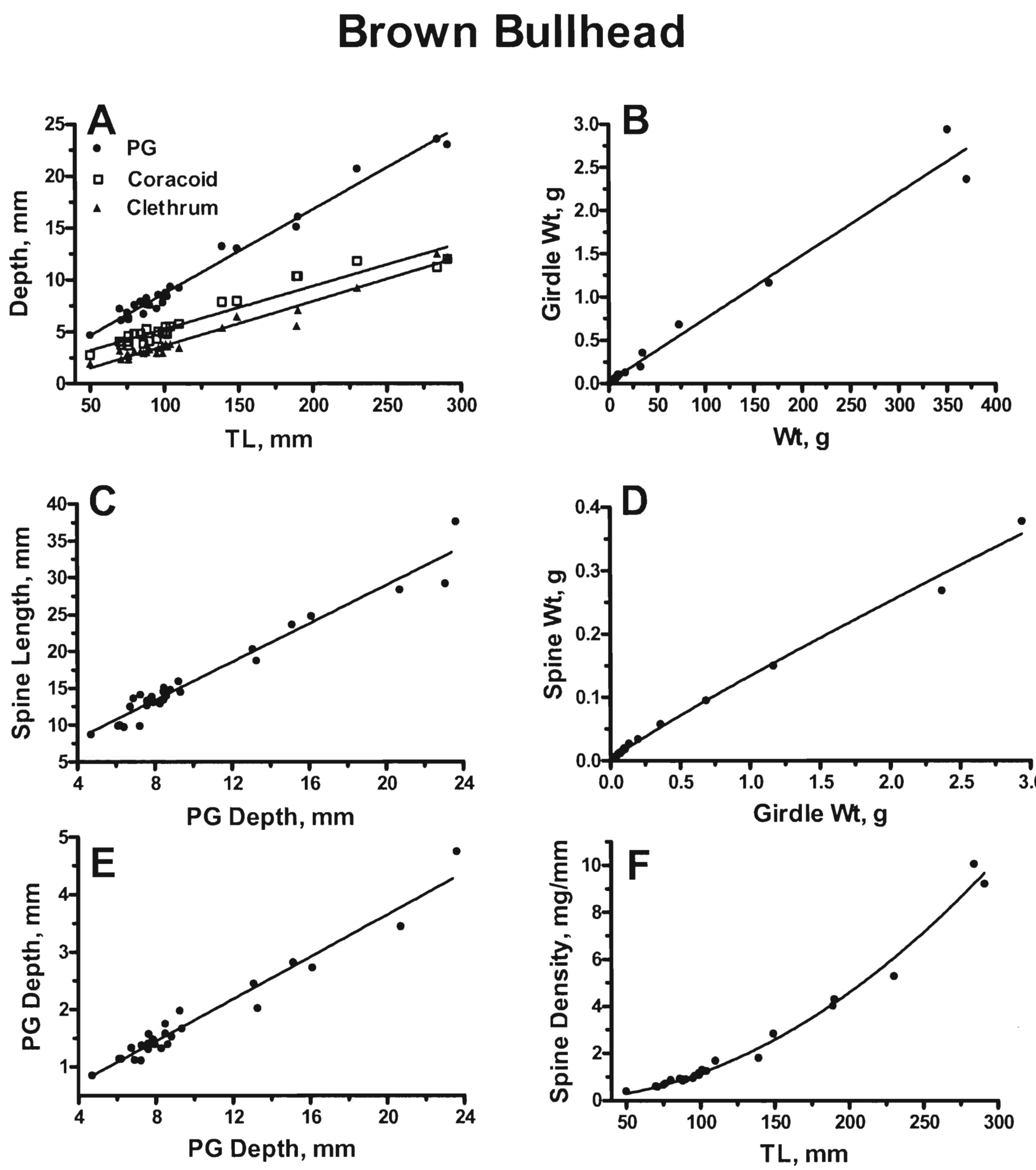

Fig. 18. Relationship of pectoral girdle, coracoid, and clethrum depth and spine density to total length, girdle weight to weight, spine length and spine width to girdle depth, and spine weight to girdle weight in the brown bullheads.

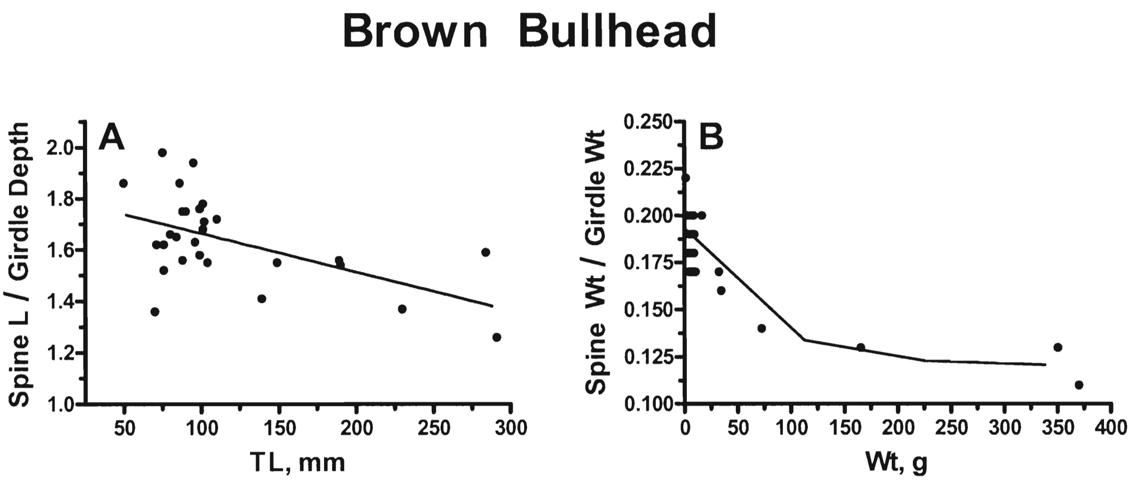

Fig. 19. Relationship of pectoral spine length and girdle depth ratio to total length and spine weight and girdle weight ratio to weight in the brown bullheads.

Yellow Bullhead

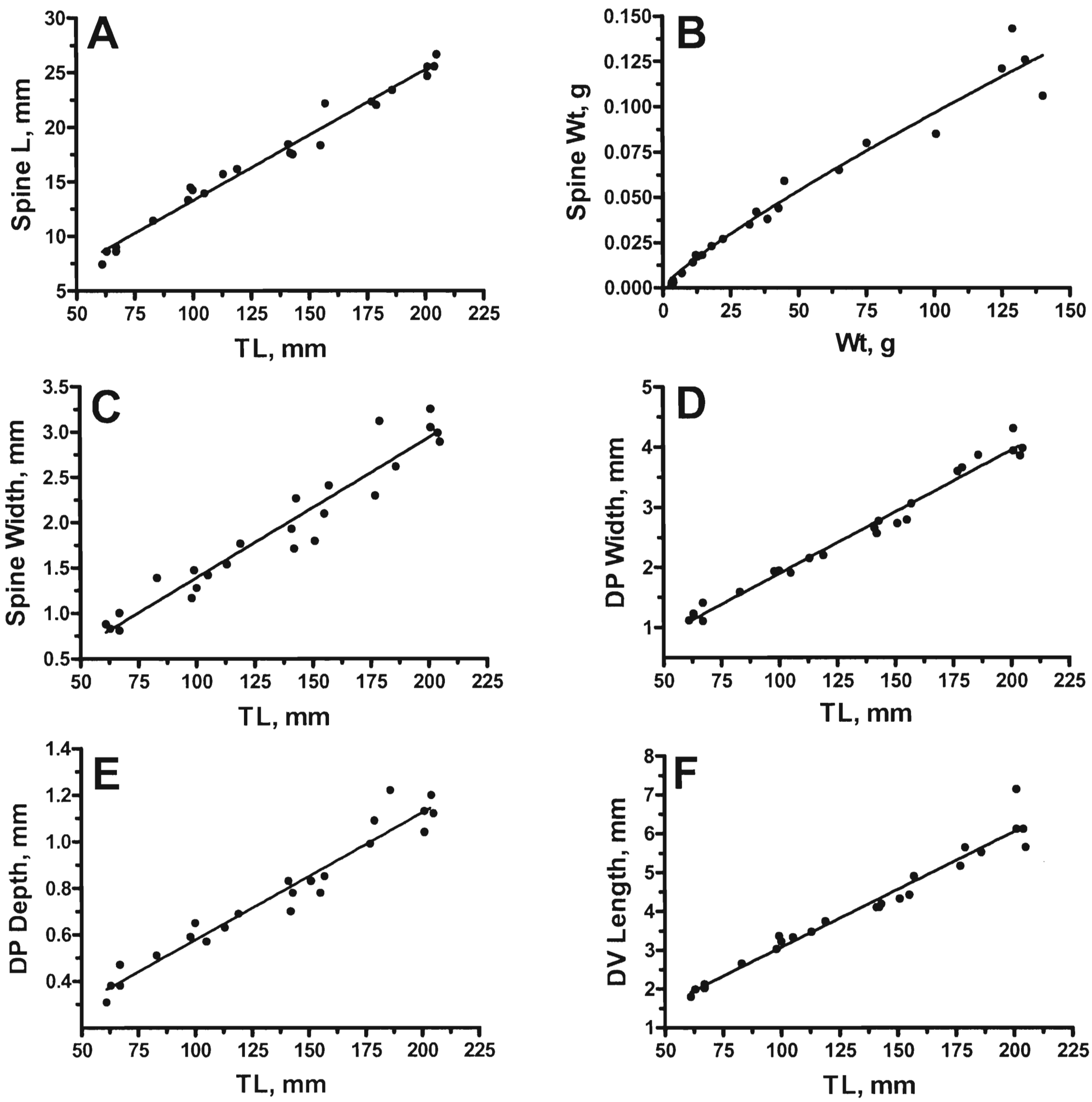

Fig. 20. Relationship of pectoral spine length, spine width, dorsal process width, dorsal process depth, dorsal-ventral length to total length and spine weight to weight in the yellow bullheads *Ameiurus natalis.*

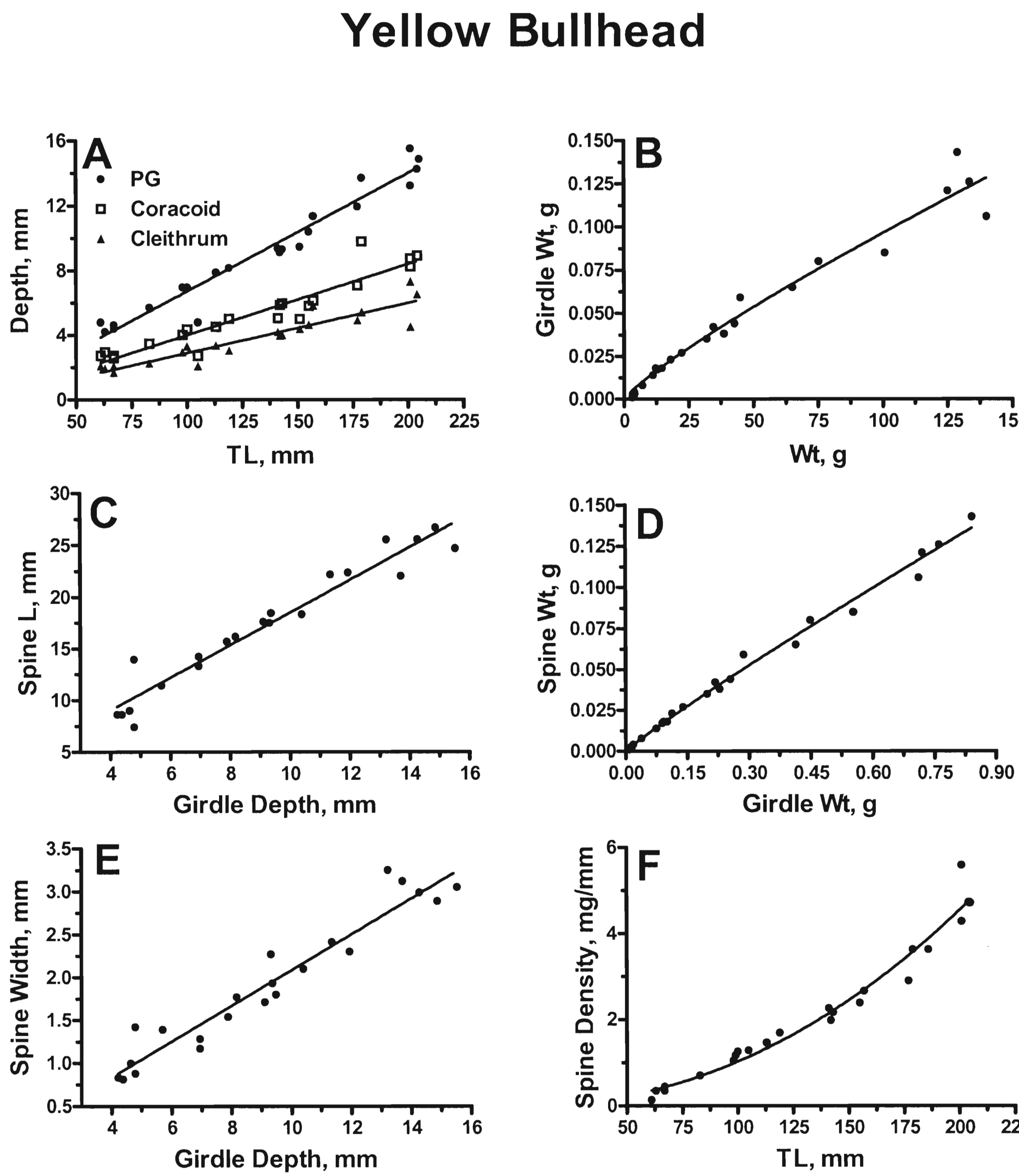

Fig. 21. Relationship of pectoral girdle, coracoid, and clethrum depth and spine density to total length, girdle weight to weight, spine length and spine width to girdle depth, and spine weight to girdle weight in the yellow bullheads.

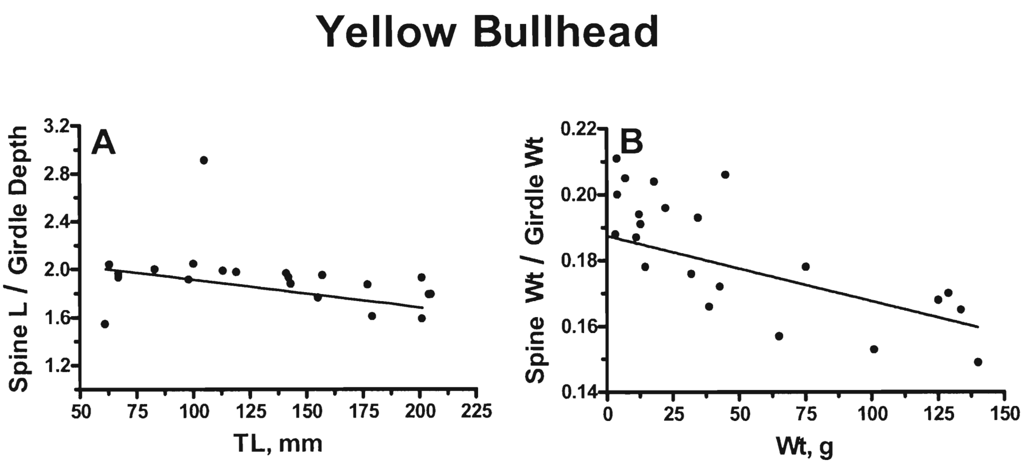

Fig. 22. Relationship of pectoral spine length and girdle depth ratio to total length and spine weight and girdle weight ratio to weight in the yellow bullheads.

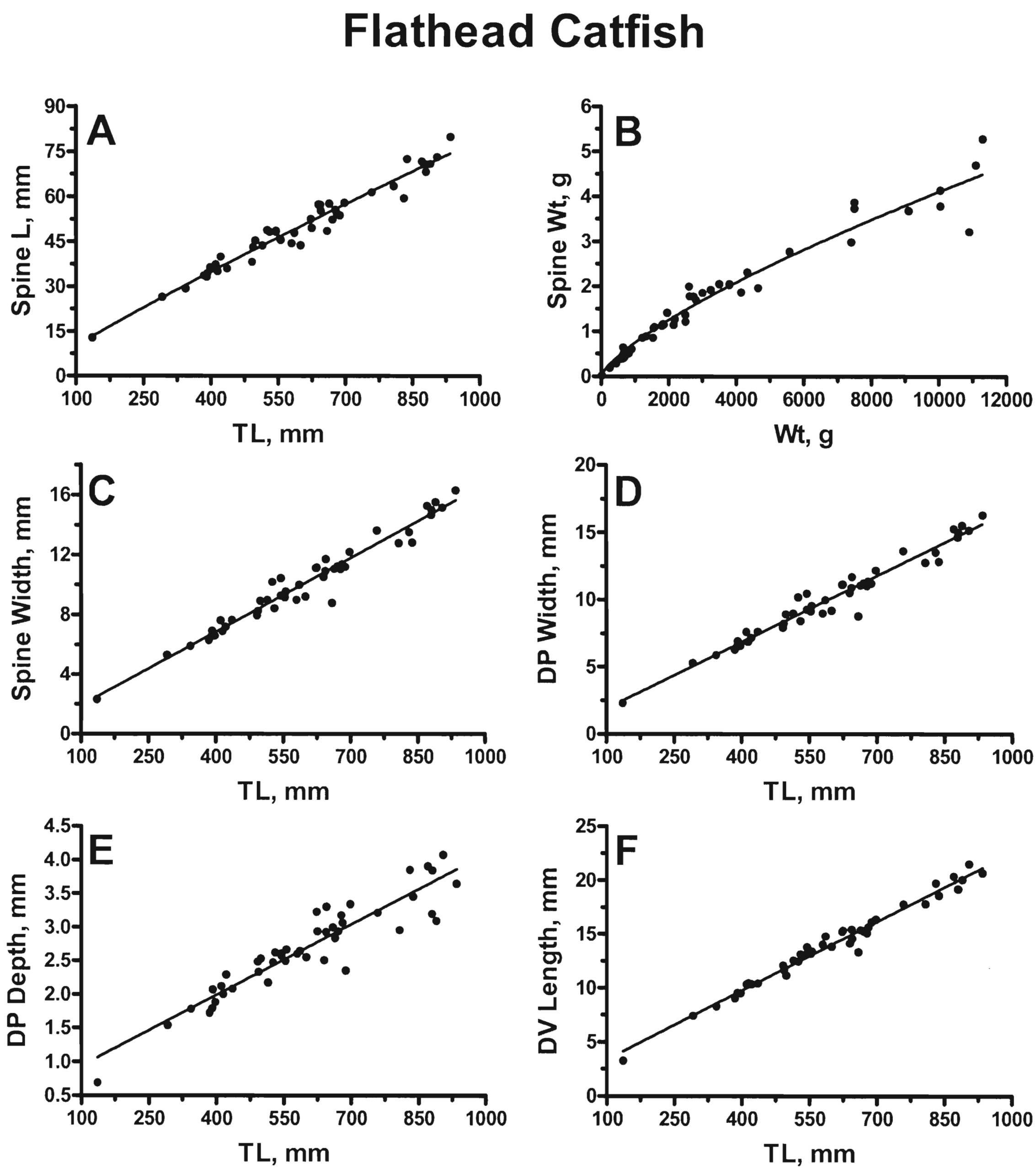

Fig. 23. Relationship of pectoral spine length, spine width, dorsal process width, dorsal process depth, dorsal-ventral length to total length and spine weight to weight in the flathead catfish *Pylodictis olivaris.*

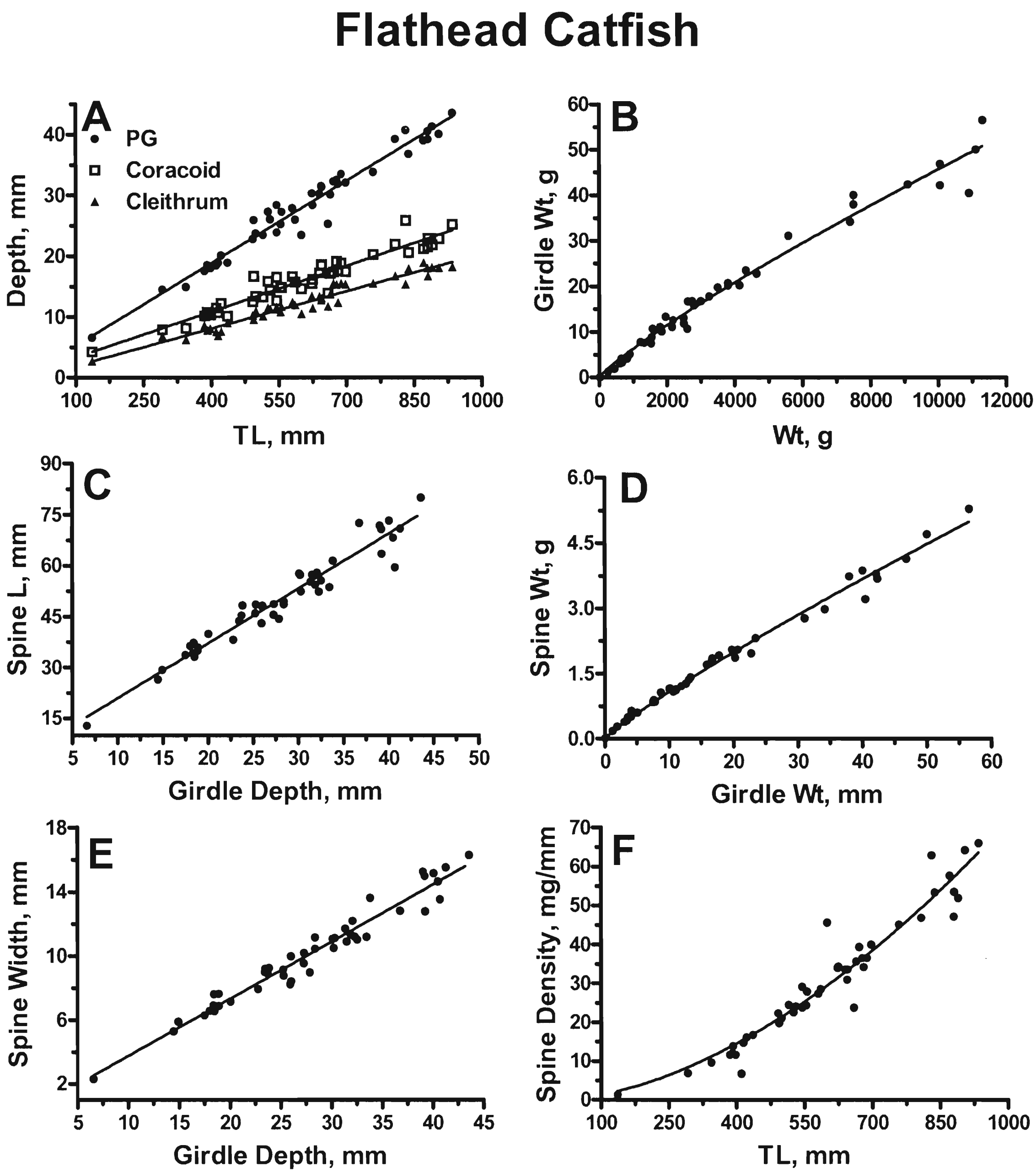

Fig. 24. Relationship of pectoral girdle, coracoid, and clethrum depth and spine density to total length, girdle weight to weight, spine length and spine width to girdle depth, and spine weight to girdle weight in the flathead catfish.

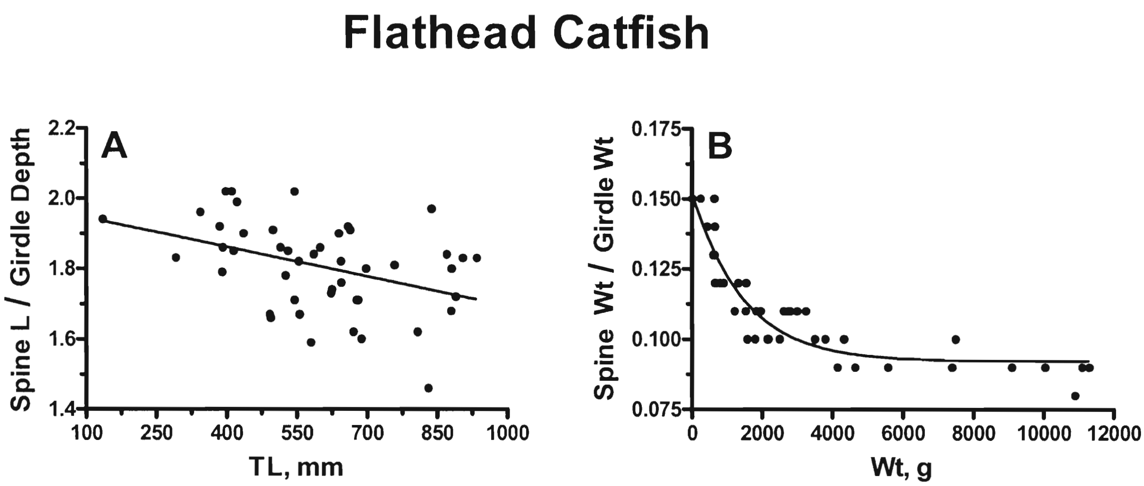

Fig. 25. Spine length and pectoral girdle depth ratio to total length and spine weight and girdle weight ratio to weight in the flathead catfish.

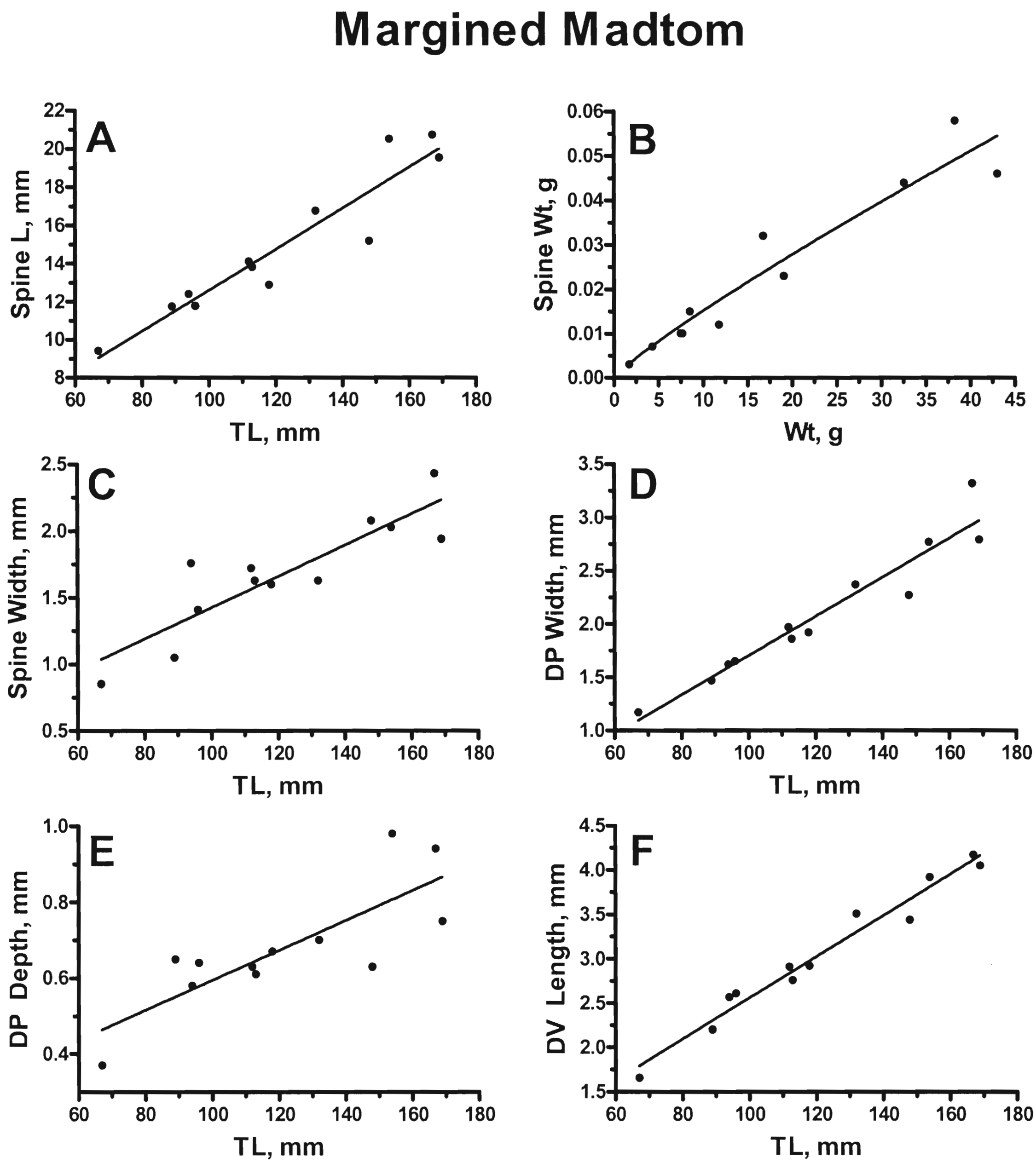

Fig. 26. Relationship of pectoral spine length, spine width, dorsal process width, dorsal process depth, dorsal-ventral length to total length and spine weight to weight in the margined madtoms *Noturus insignis*.

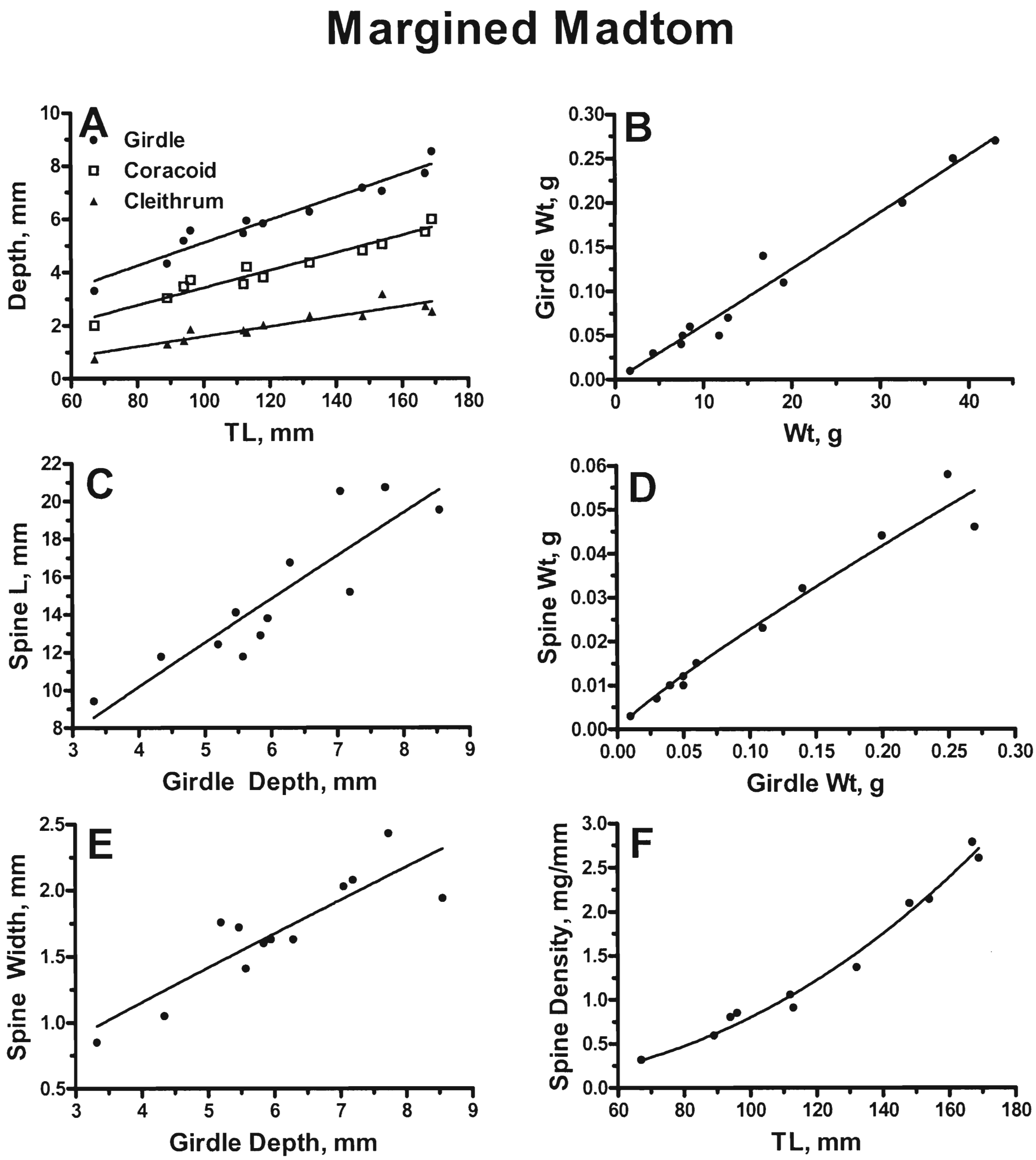

Fig. 27. Relationship of pectoral girdle, coracoid, and clethrum depth and spine density to total length, girdle weight to weight, spine length and spine width to girdle depth, and spine weight to girdle weight in the margined madtoms.

Margined Madtom

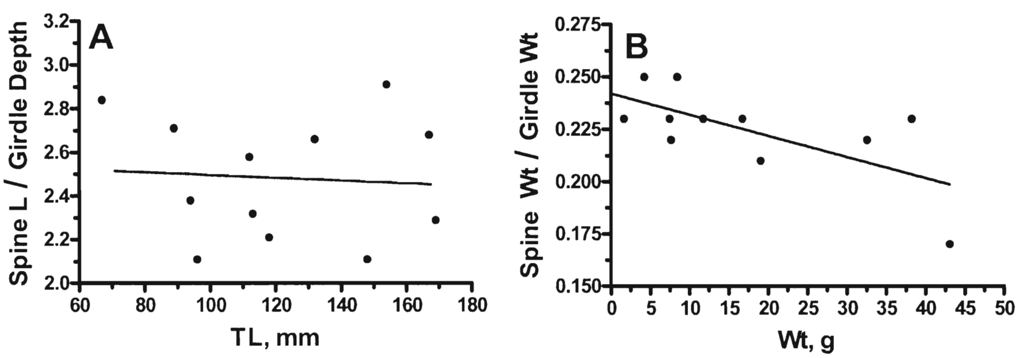

Fig. 28. Relationship of pectoral spine length and girdle depth ratio to total length and spine weight and girdle weight ratio to weight in the margined madtoms.

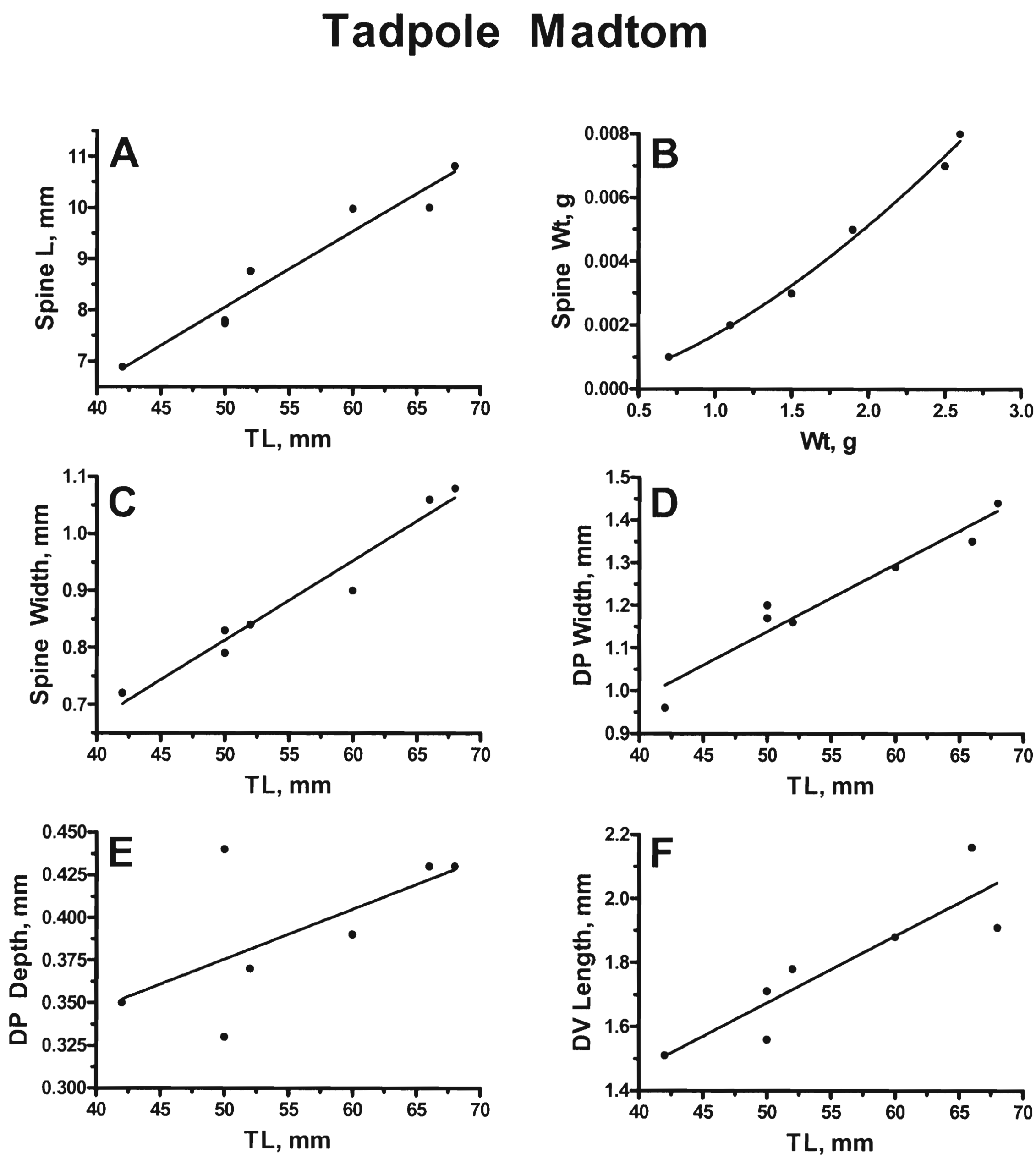

Fig. 29. Relationship of pectoral spine length, spine width, dorsal process width, dorsal process depth, dorsal-ventral length to total length and spine weight to weight in the tadpole madtoms *Noturus gyrinus*.

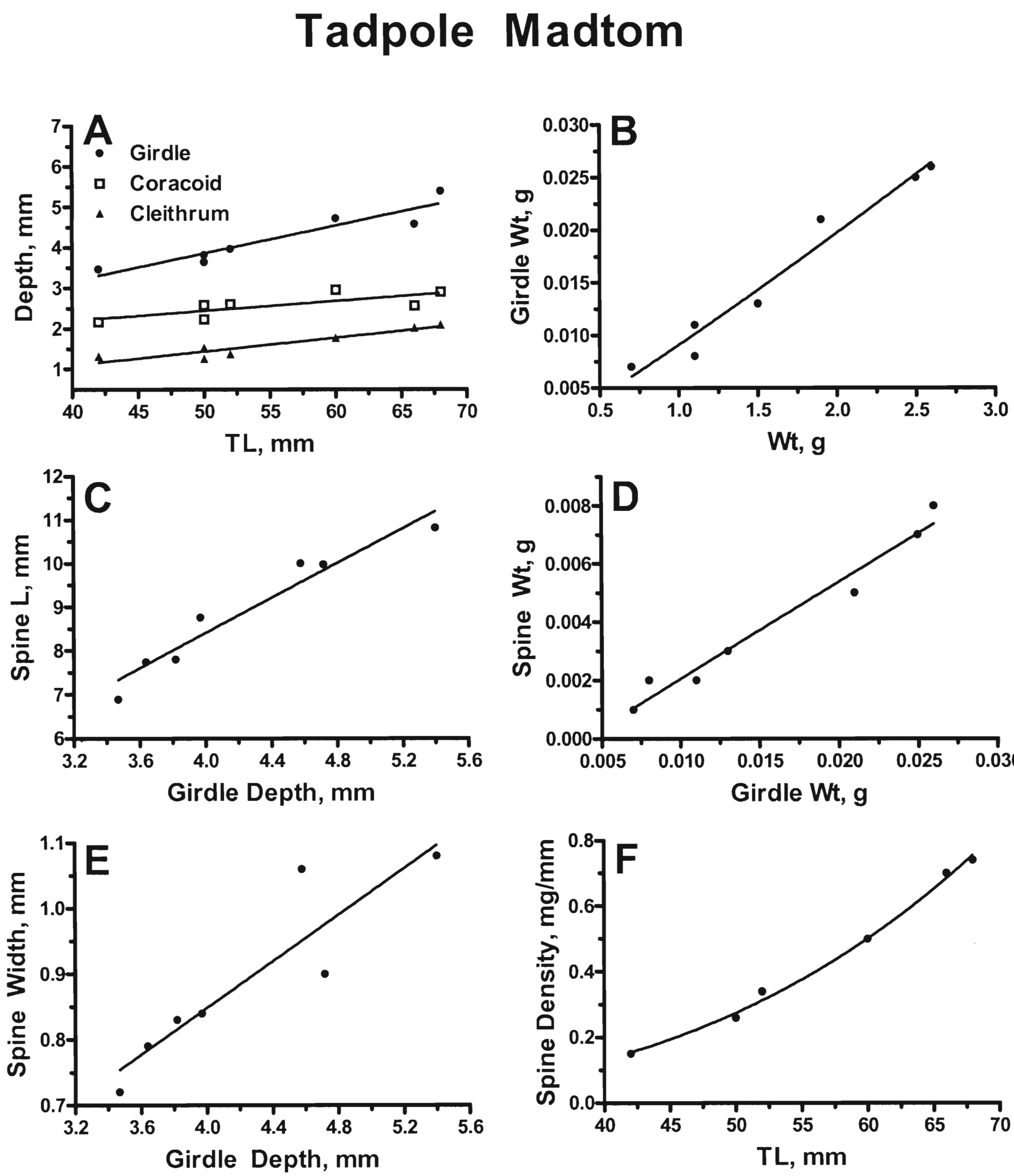

Fig. 30. Relationship of pectoral girdle, coracoid, and clethrum depth and spine density to total length, girdle weight to weight, spine length and spine width to girdle depth, and spine weight to girdle weight in the tadpole madtoms.

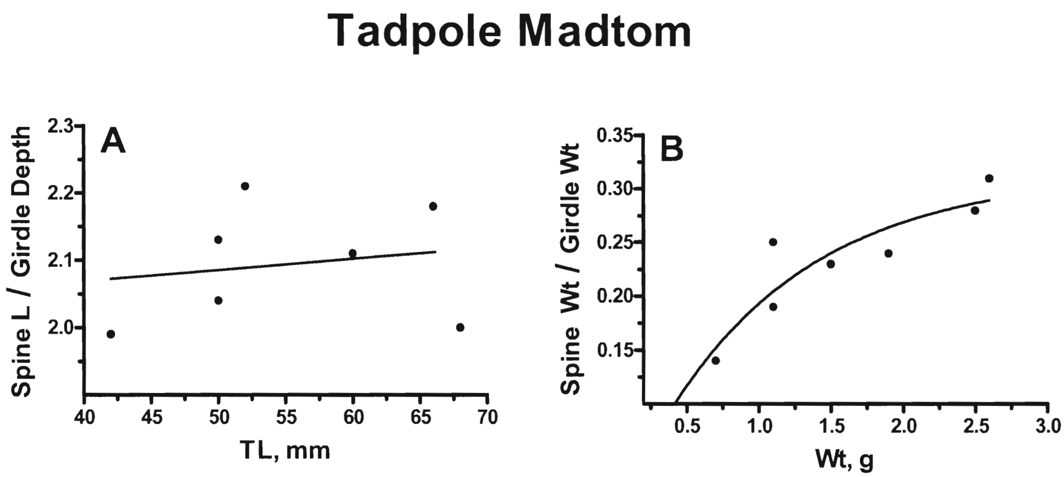

Fig. 31. Relationship of pectoral spine length and girdle depth ratio to total length and spine weight and girdle weight ratio to weight in the tadpole madtoms.

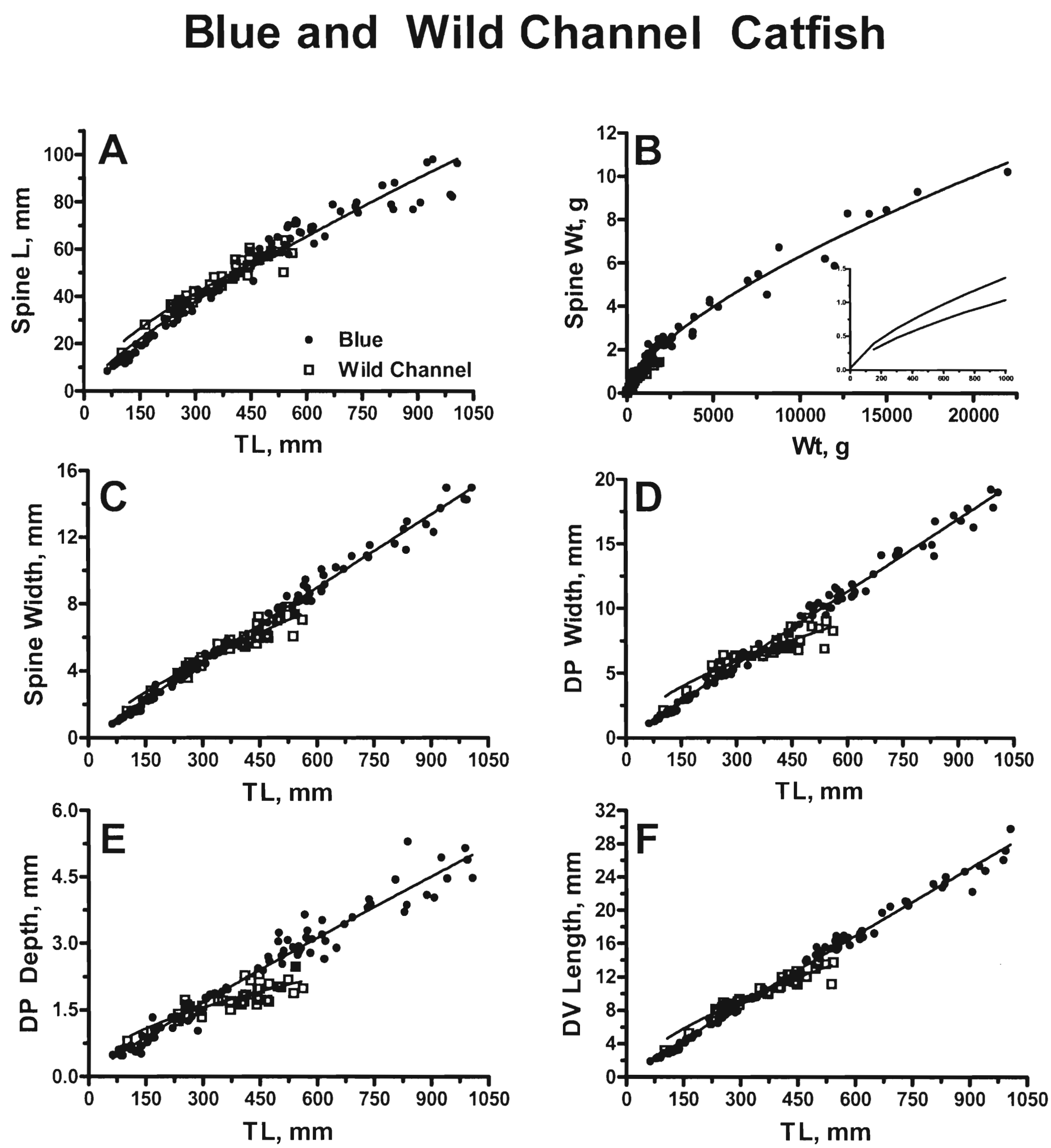

Fig. 32. Comparisons of spine length and width, dorsal process width, dorsal process depth, dorsal-ventral length to total length and spine weight to weight between blue and wild channel catfish's pectoral spine.

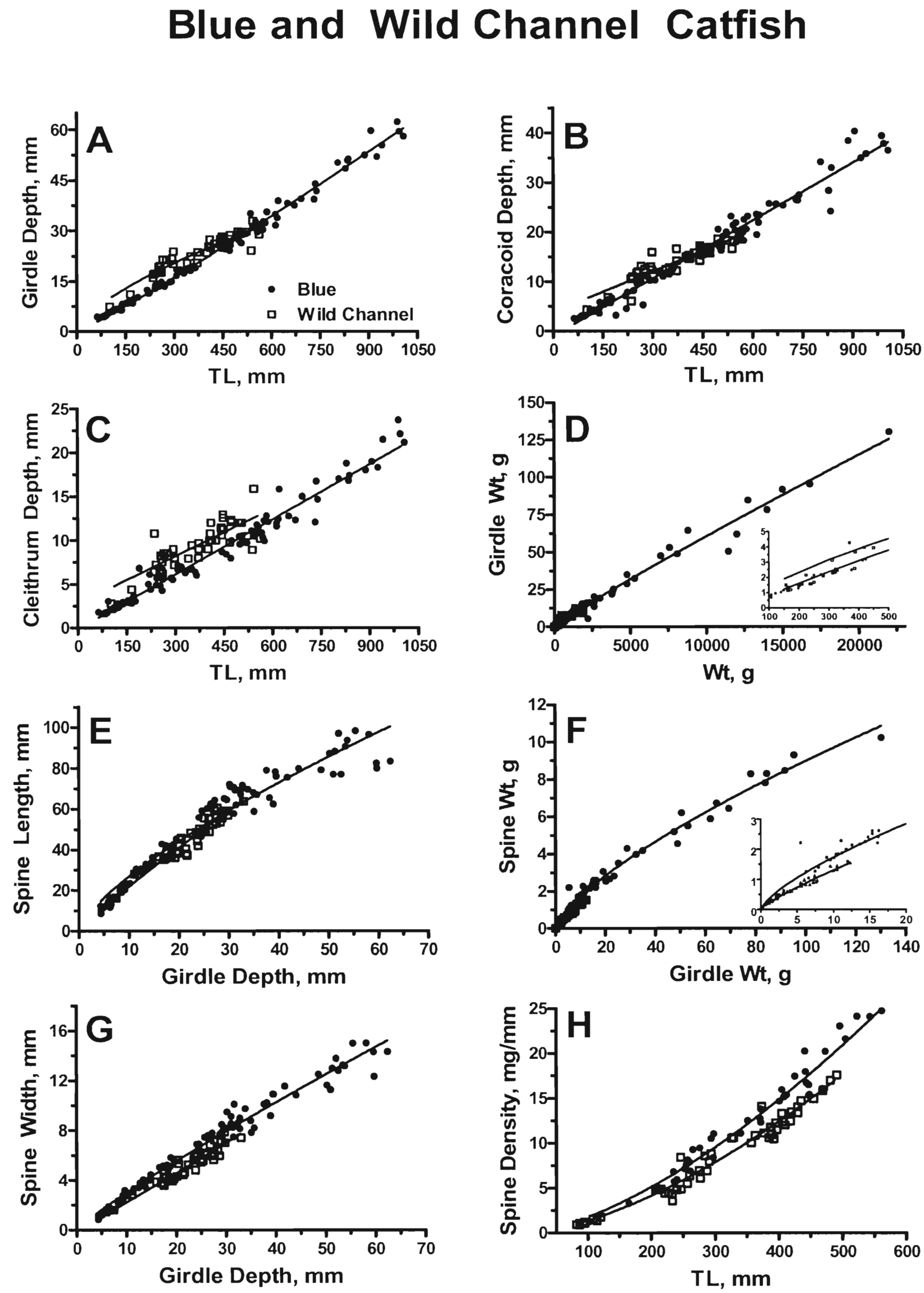

Fig. 33. Comparisons of pectoral girdle, coracoid, and cleithrum depth to total length, girdle weight to weight, spine length and spine width to girdle depth, and spine weight to girdle weight between blue and wild channel catfish's pectoral spine.

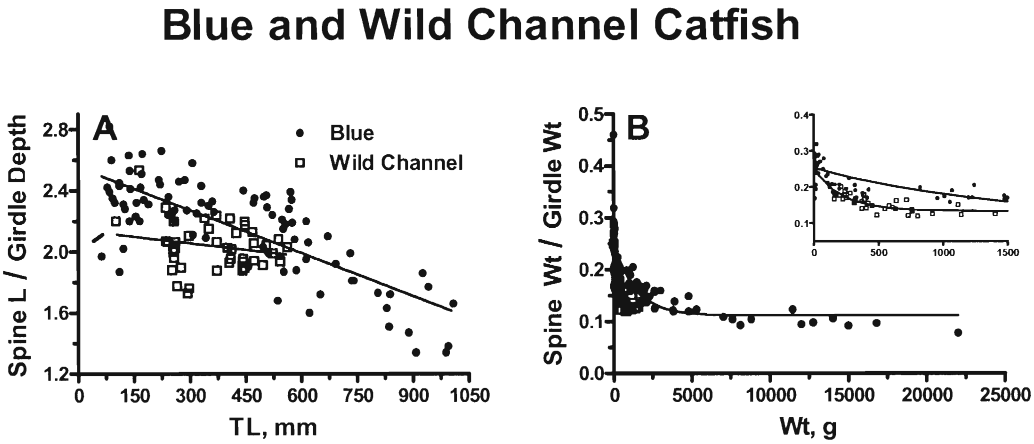

Fig. 34. Relationship of spine length and girdle depth ratio to total length and spine weight and girdle weight ratio to weight between blue and wild channel catfish's pectoral spine.

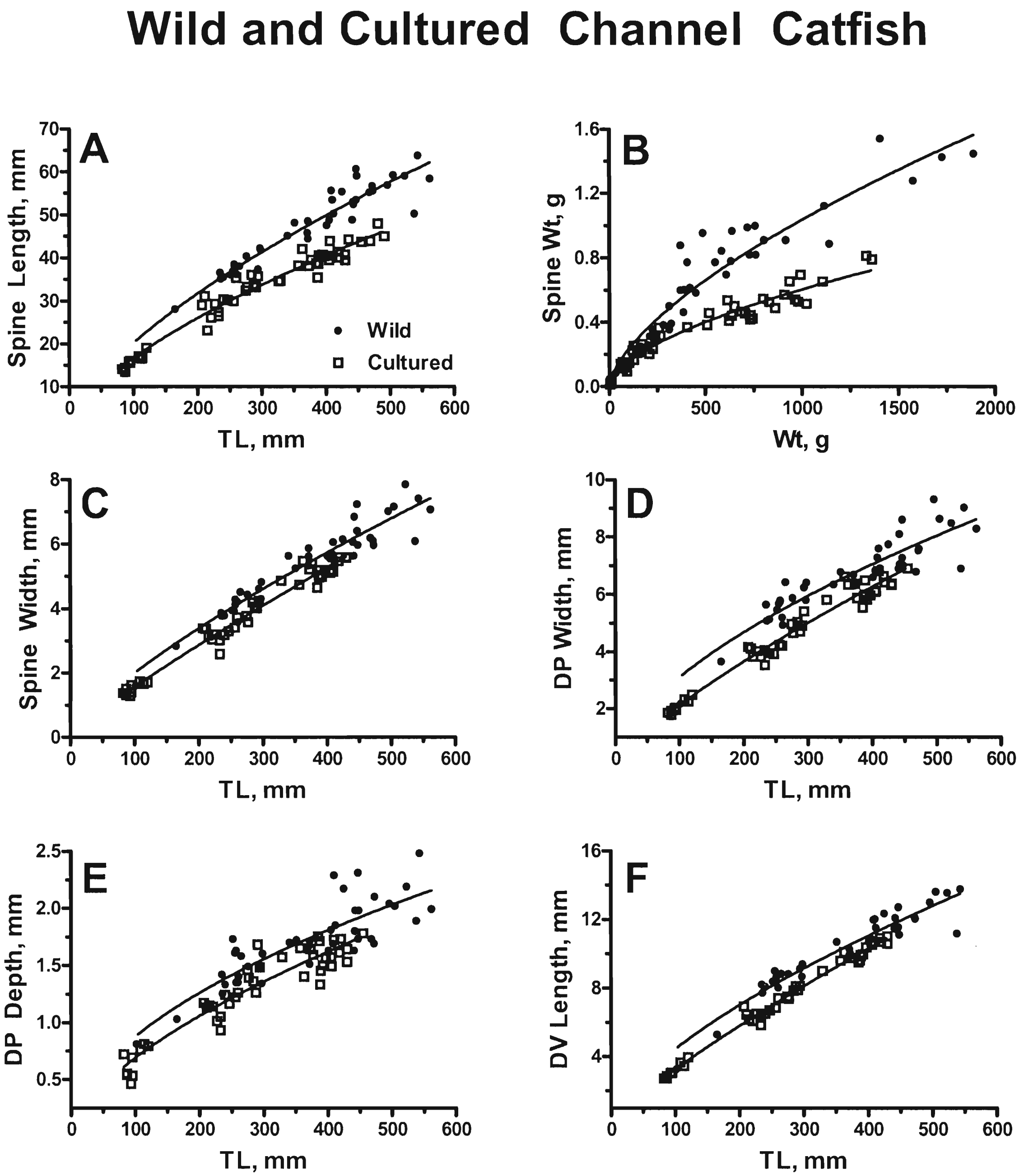

Fig. 35. Comparisons of spine length, spine width, dorsal process width, dorsal process depth, dorsal-ventral length to total length and spine weight to weight between wild and cultured channel catfish's pectoral spines.

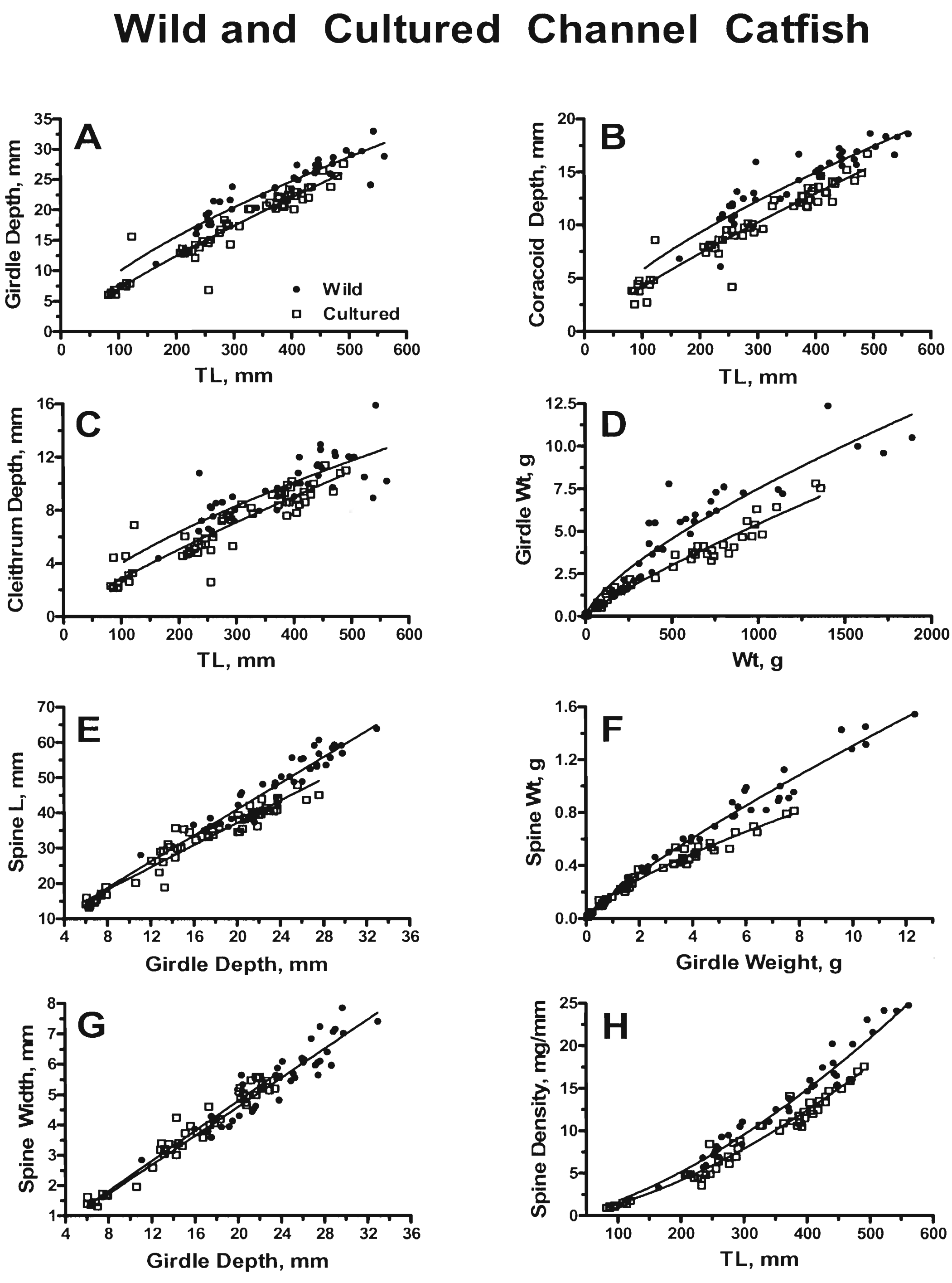

Fig. 36. Comparisons of pectoral girdle, coracoid, and cleithrum depth to total length, girdle weight to weight, spine length and spine width to girdle depth, and spine weight to girdle weight between cultured and wild channel catfish's pectoral spine.

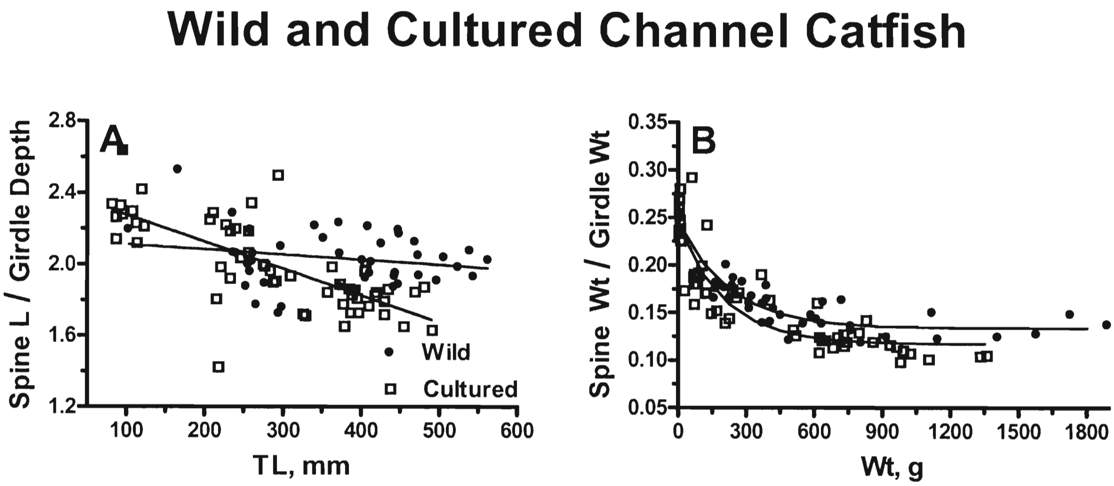

Fig. 37. Relationship of spine length and girdle depth ratio to total length and spine weight and girdle weight ratio to weight between cultured and wild channel catfish's pectoral spine.

Ameiurus sp.

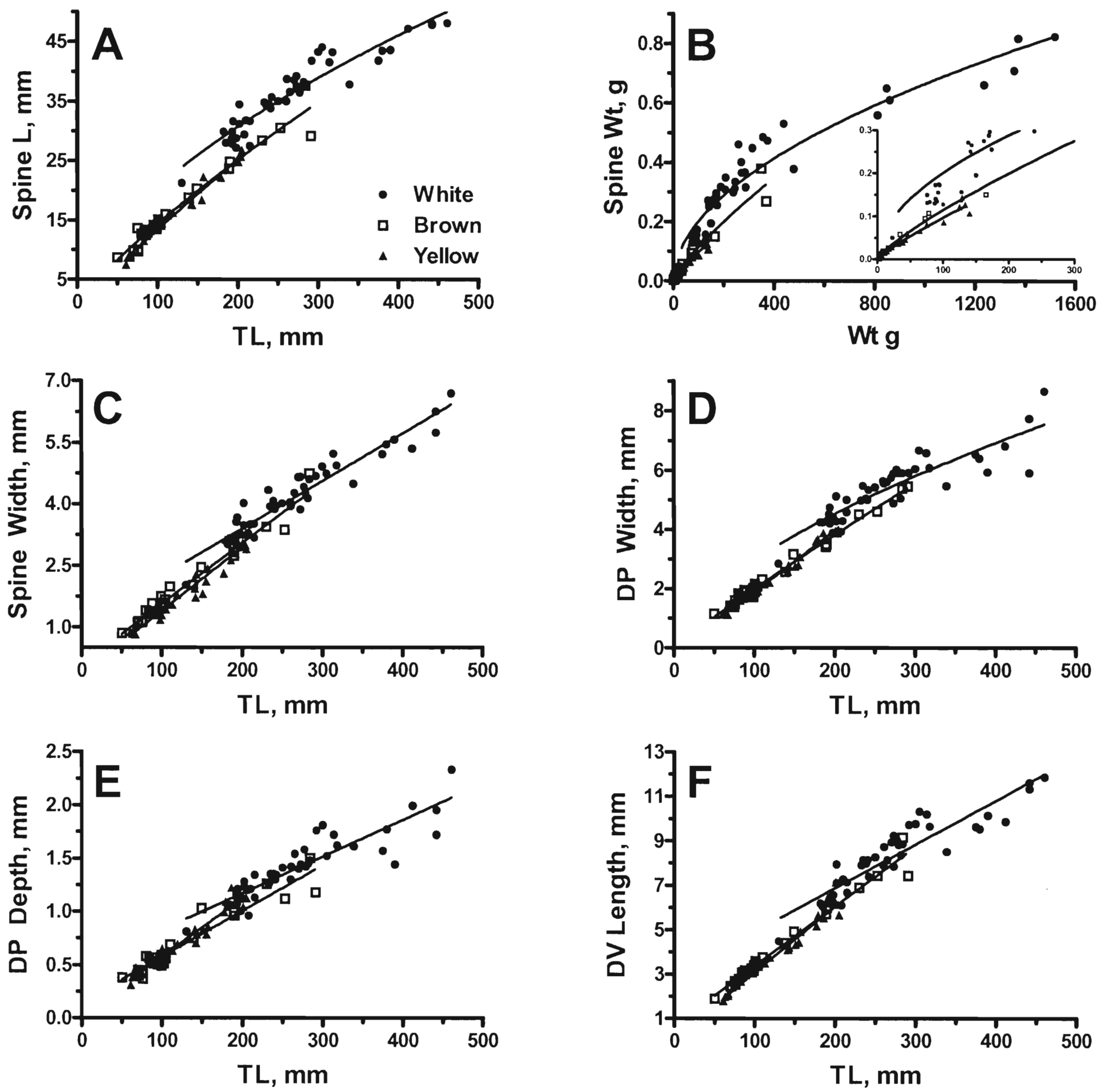

Fig. 38. Comparisons of spine length, spine width, dorsal process width, dorsal process depth, dorsal-ventral length to total length and spine weight to weight for white catfish and brown and yellow bullhead pectoral spines.

Ameiurus sp.

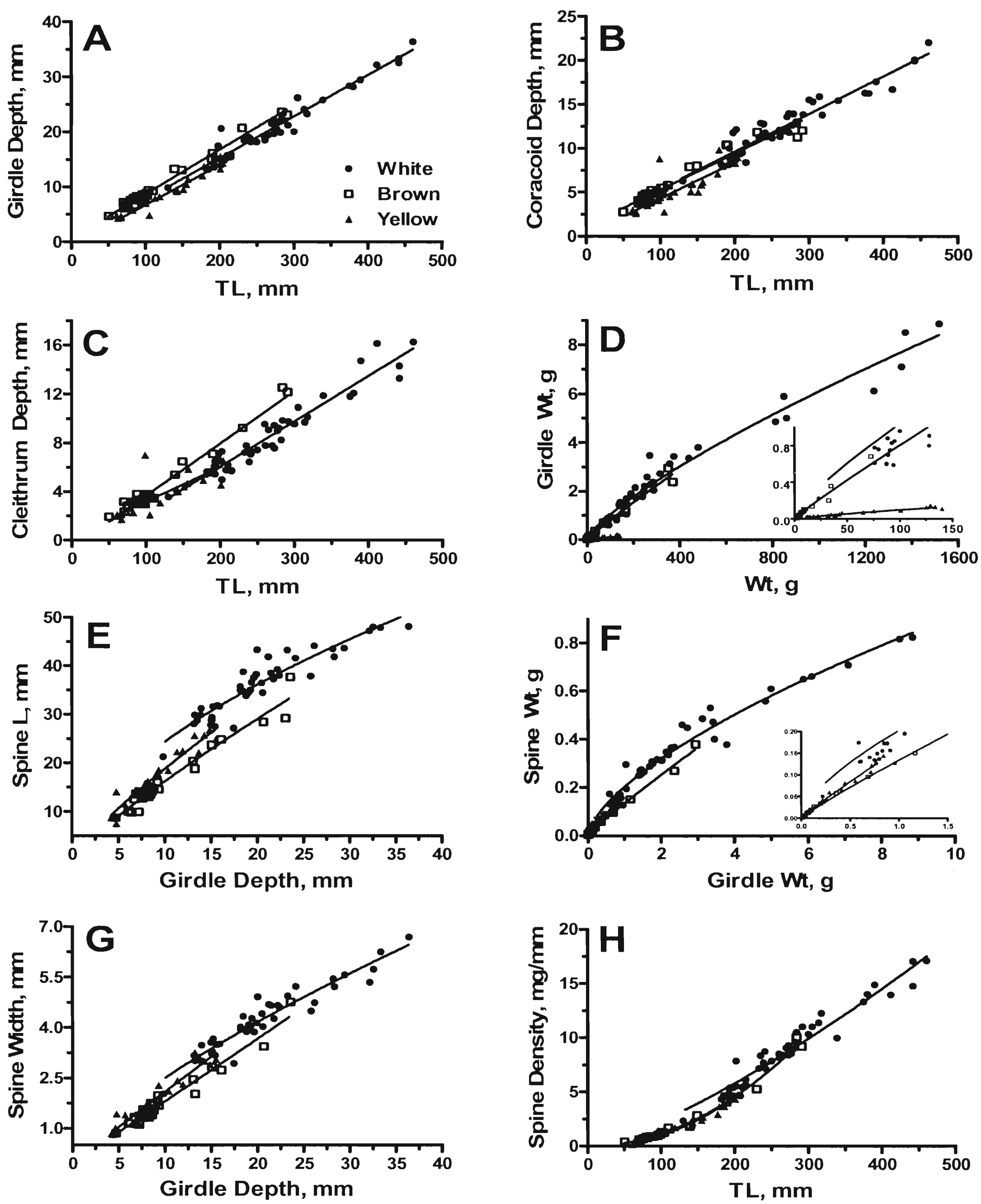

Fig. 39. Comparisons of pectoral girdle, coracoid, and clethrum depth to total length, girdle weight to weight, spine length and spine width to girdle depth, and spine weight to girdle weight for the white catfish and brown and yellow bullhead pectoral spines.

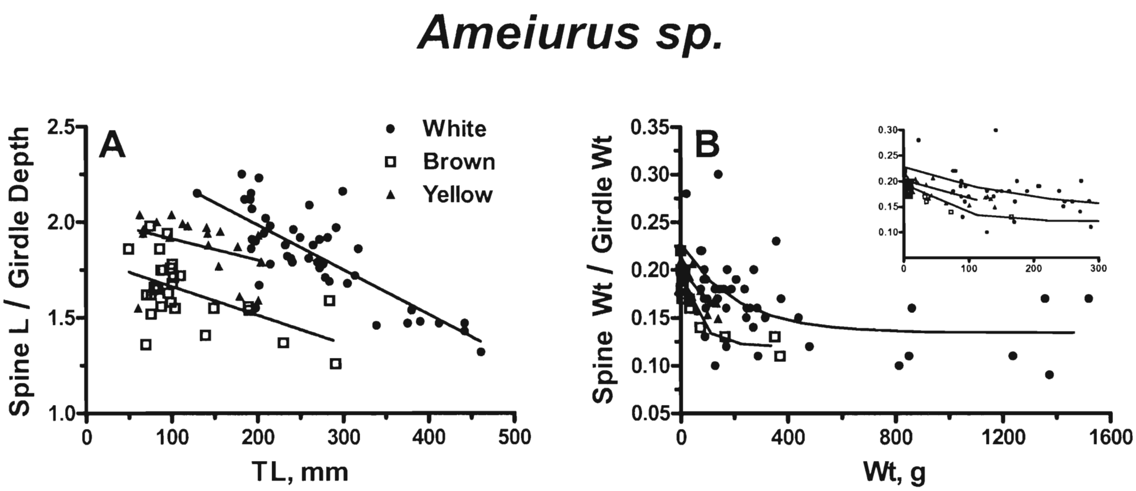

Fig. 40. Relationship of spine length and girdle depth ratio to total length and spine weight and girdle weight ratio to weight for white catfish and brown and yellow bullhead pectoral spines.

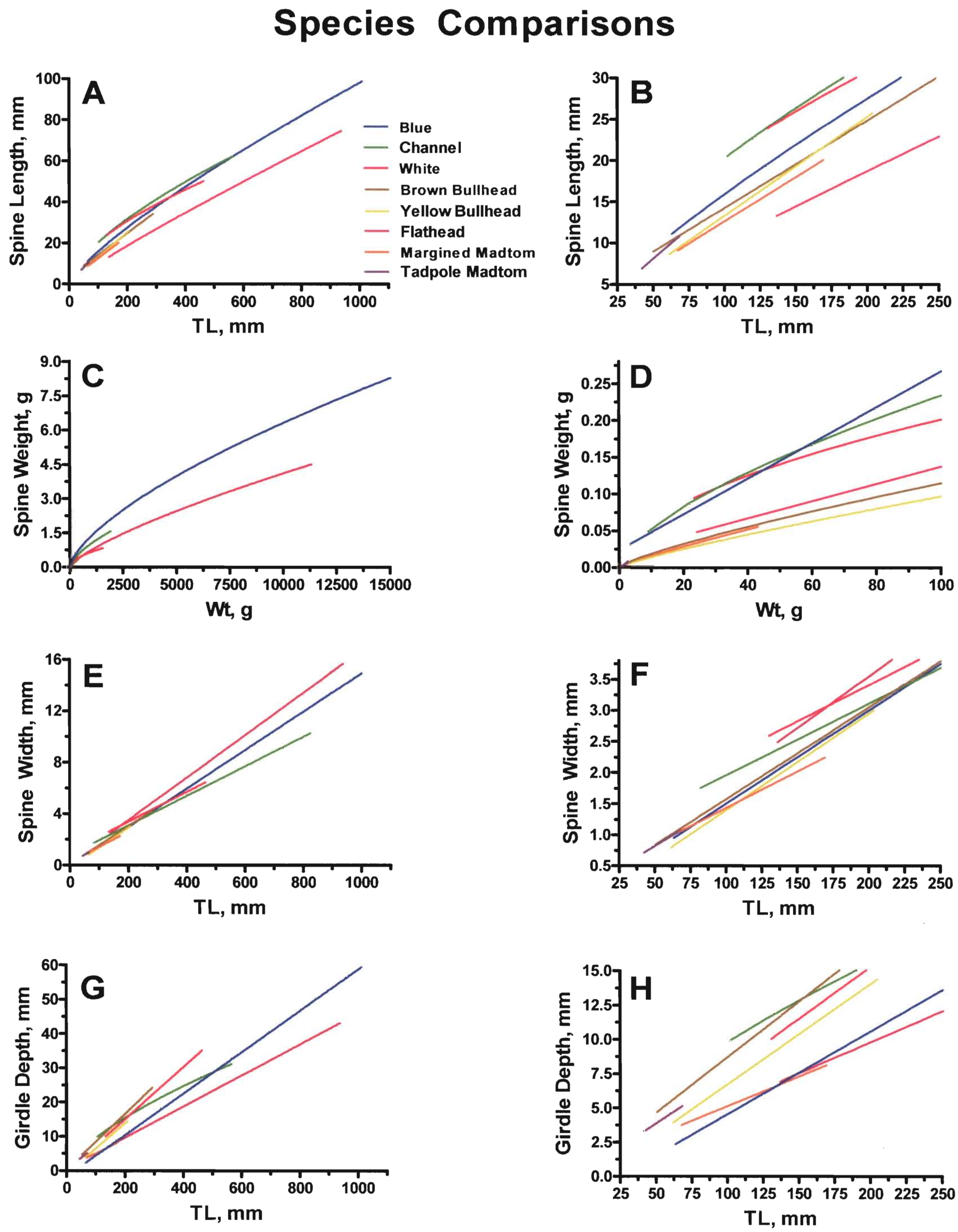

Fig. 41. Comparisons of spine length, spine width and girdle depth to total length and spine weight to weight in blue, channel, white, brown bullhead, yellow bullhead, and flathead catfishes.

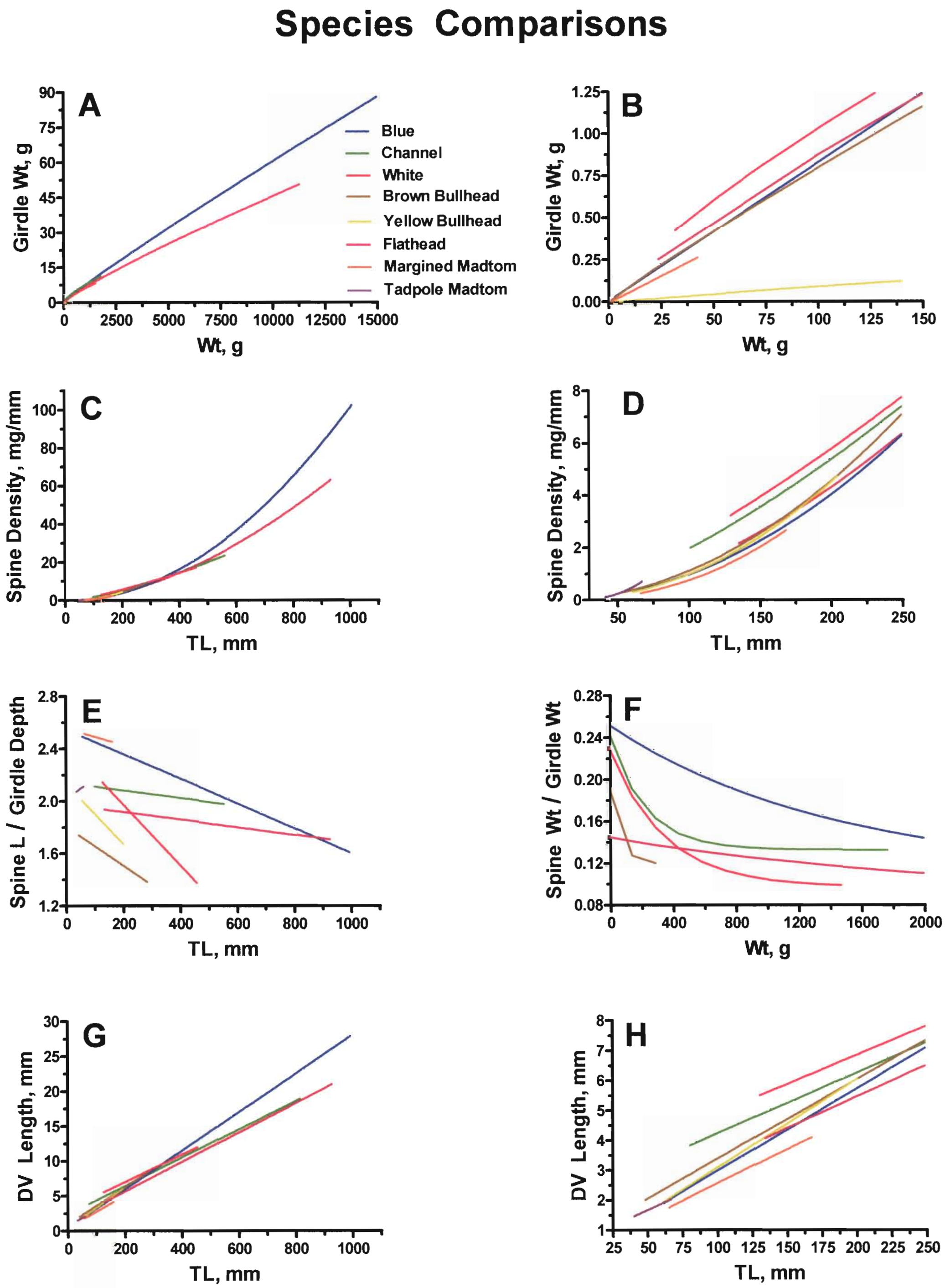

Fig. 42. Comparisons of girdle weight and spine length and girdle depth ratio to weight and spine density, spine length and girdle depth ratio, and dorsal-ventral length to length in the blue, channel, white, brown bullhead, yellow bullhead, and flathead catfishes.

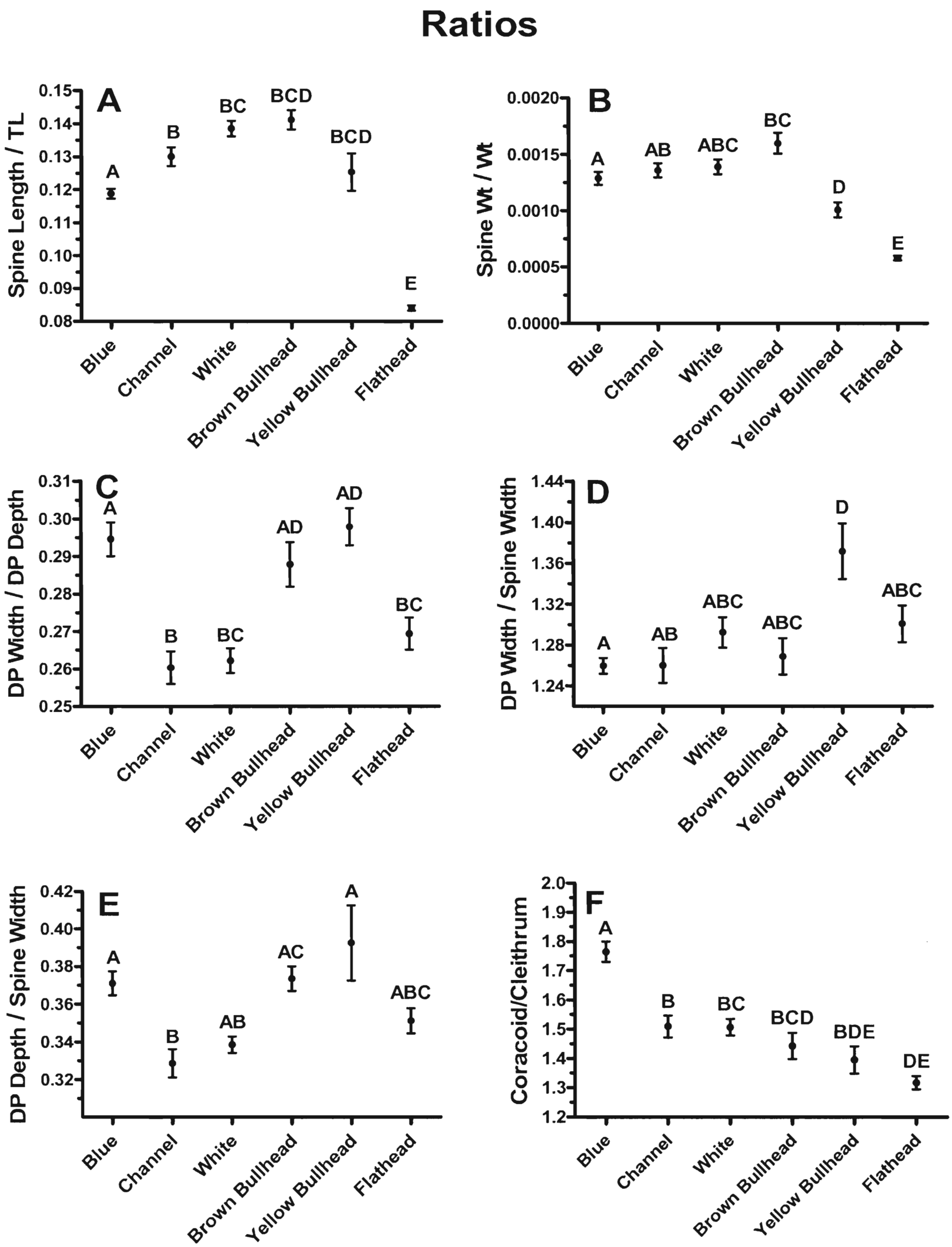

Fig. 43. Ratios of spine length and total length, spine weight and weight, dorsal process width and depth, dorsal process width and spine width, dorsal process depth and spine width, and coracoid and cleithrum compared across blue, channel, white, brown bullhead, yellow bullhead, and flathead catfishes.

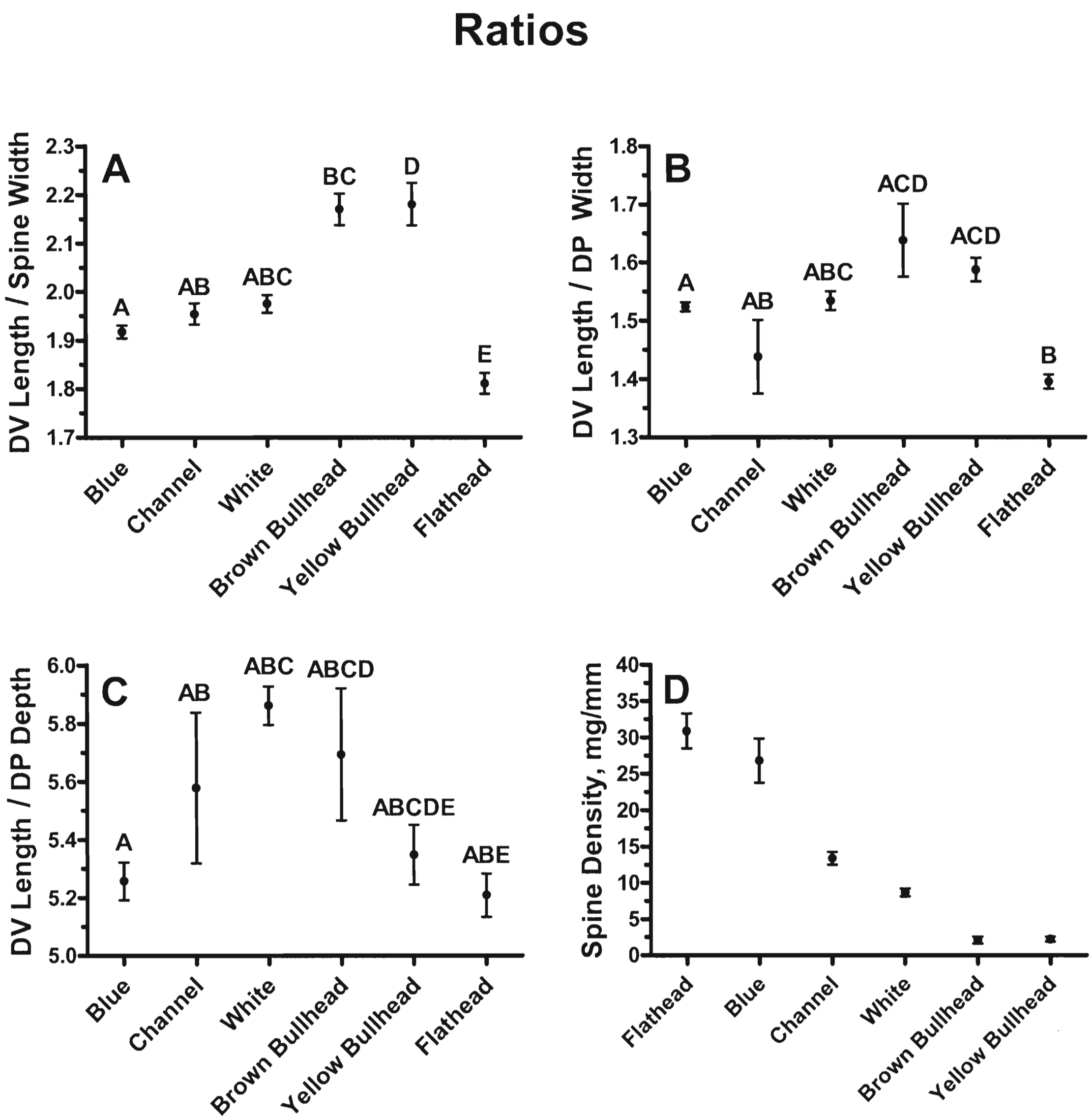

Fig. 44. Ratios of dorsal-ventral length and spine width, dorsal-ventral length and dorsal process width, dorsal-ventral length and dorsal process depth, and spine density compared across blue, channel, white, brown bullhead, yellow bullhead, and flathead catfishes.

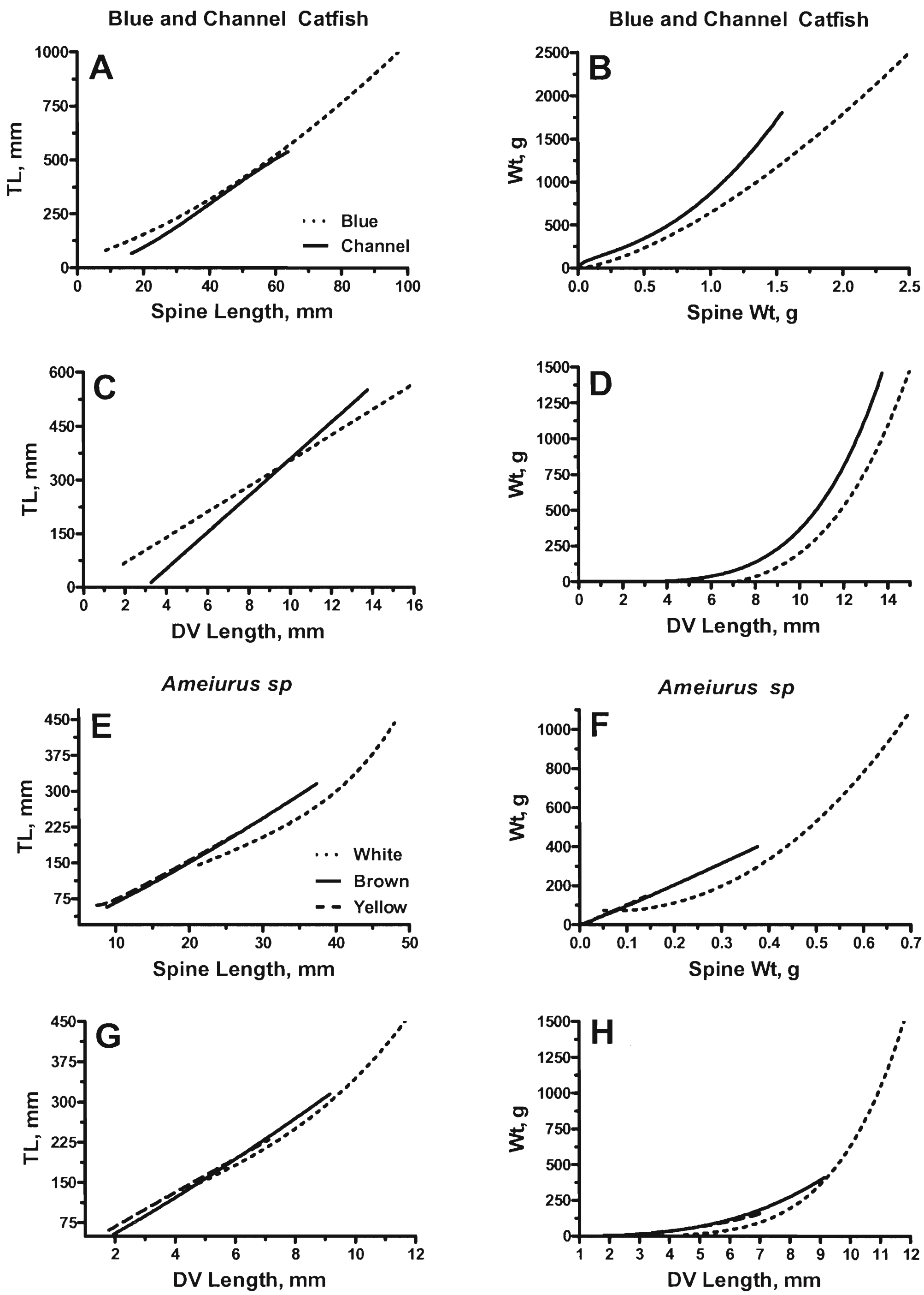

Fig. 45. Relationship of spine length to total length, spine weight to weight, and dorsal-ventral length to total length and weight in the pectoral spines of blue, channel, and white catfish, brown and yellow bullheads. Regressions used to estimate total length and weight of catfish.

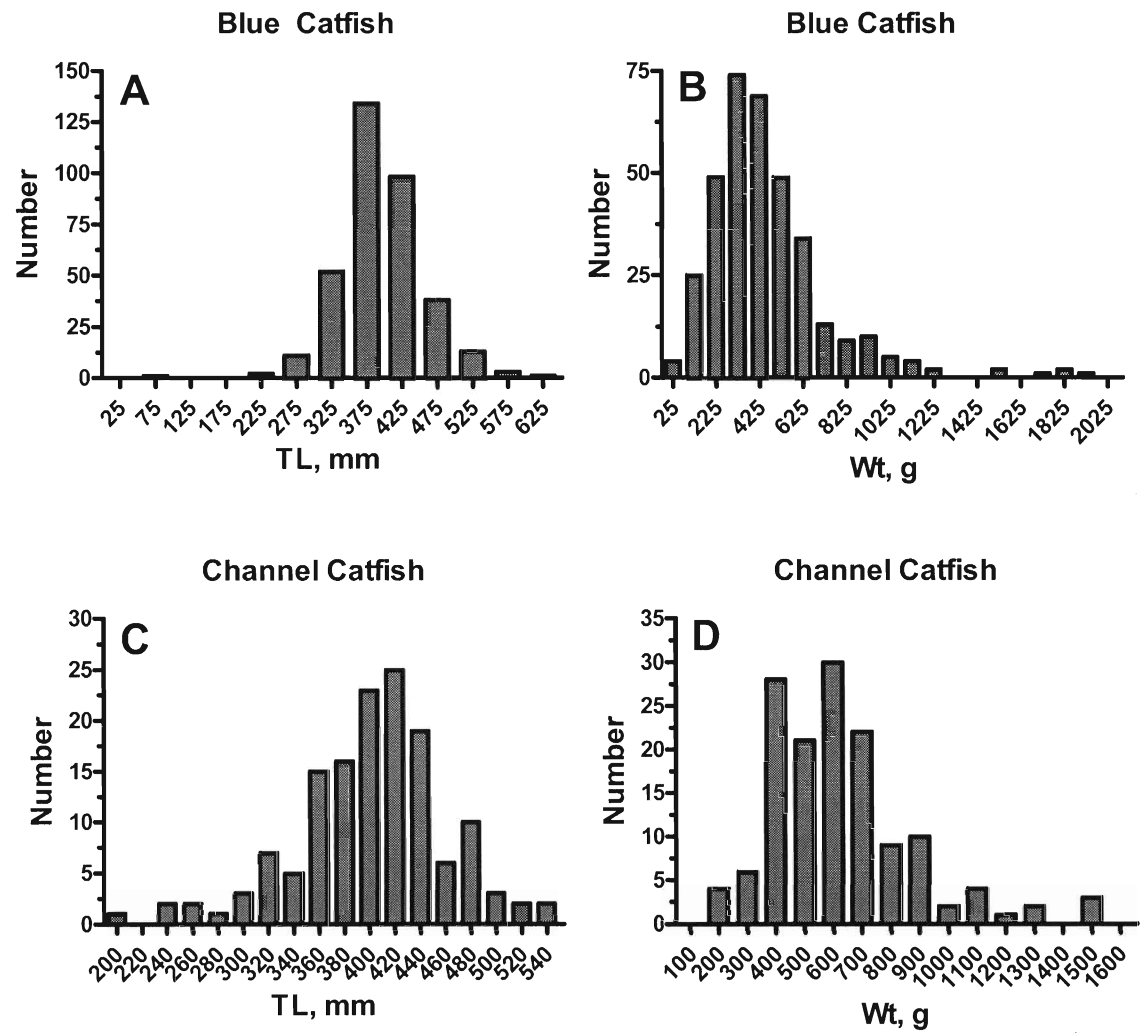

Fig. 46. Frequency distribution of estimated total length and weight of blue and channel catfish derived from catfish pectoral spines collected at eagle nesting sites. Note: Largest blue catfish (834 mm TL, 6878 g Wt) was not included in the blue catfish histograms.

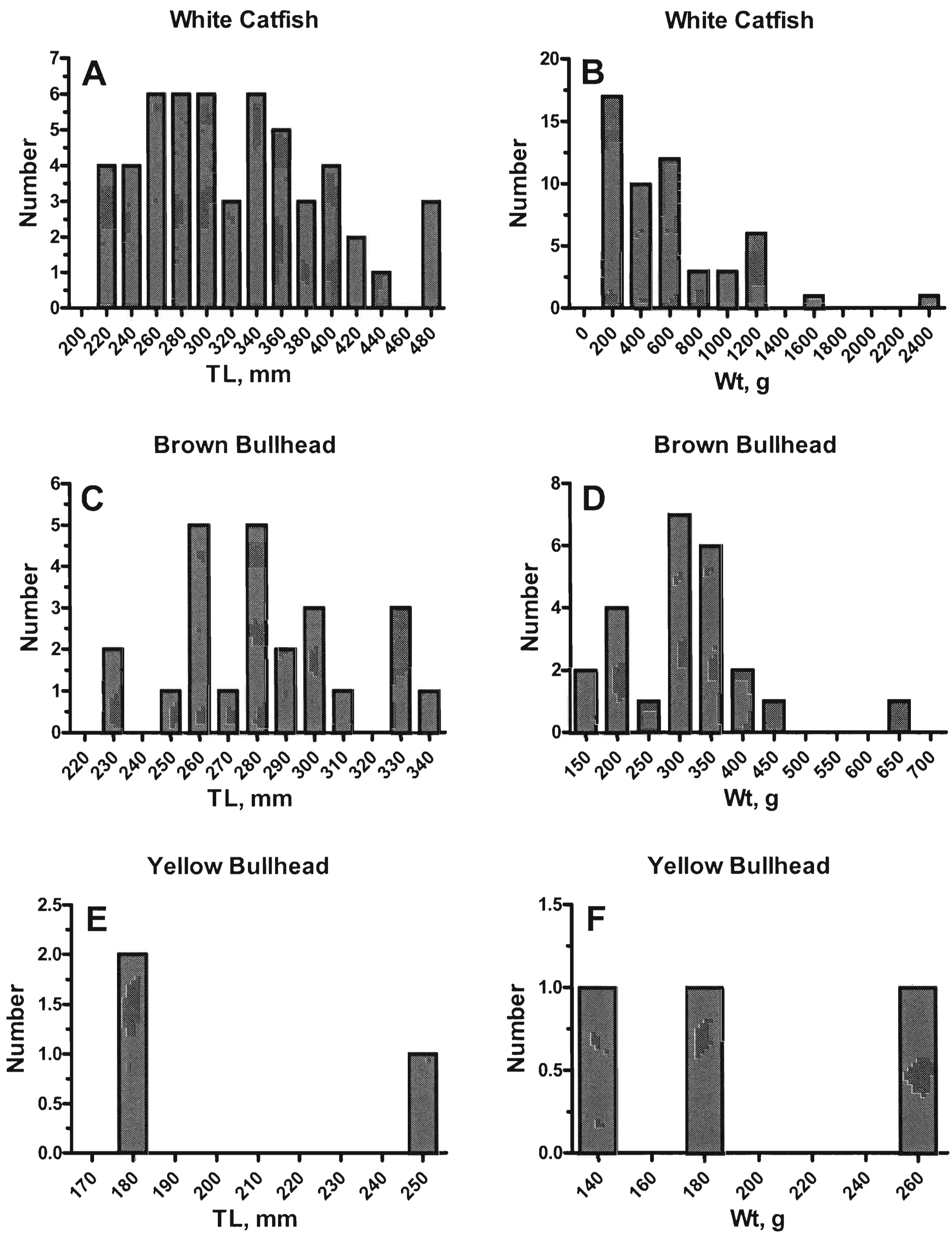

Fig. 47. Frequency distribution of estimated total length and weight of white, brown, and yellow catfish derived from catfish pectoral spines collected at eagle nesting sites.

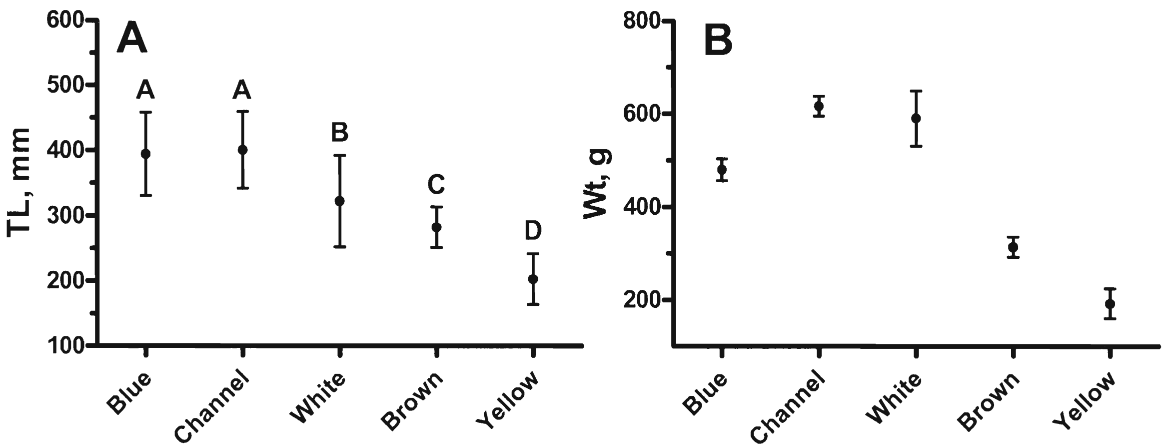

Fig. 48. Estimated total length and weight (mean ± SE) of blue, channel, and white catfish, brown and yellow bullhead derived from catfish pectoral spines collected at Bald Eagle nesting sites.

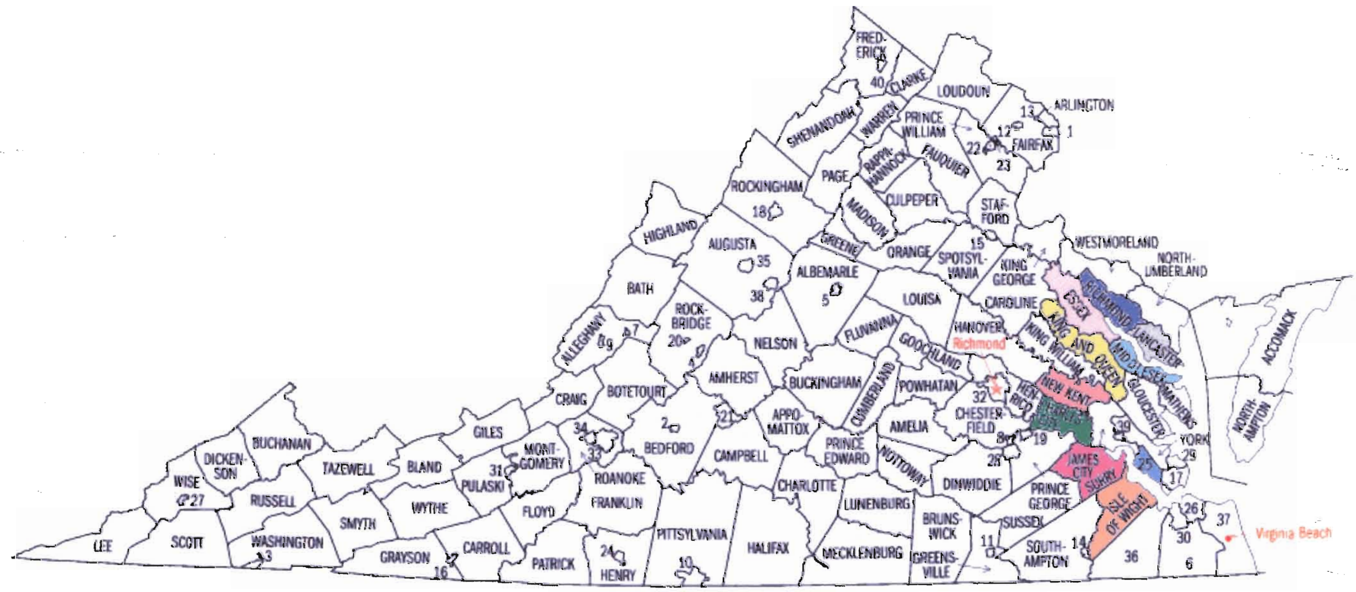

Fig. 49. Bald Eagle nesting and catfish pectoral sampling site locations, including Essex, King William, Middlesex, Richmond, Lancaster, Charles City, Isle of Wight, Surry, James City, Newport News, New Kent, and Charles City counties.

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Appendix 1

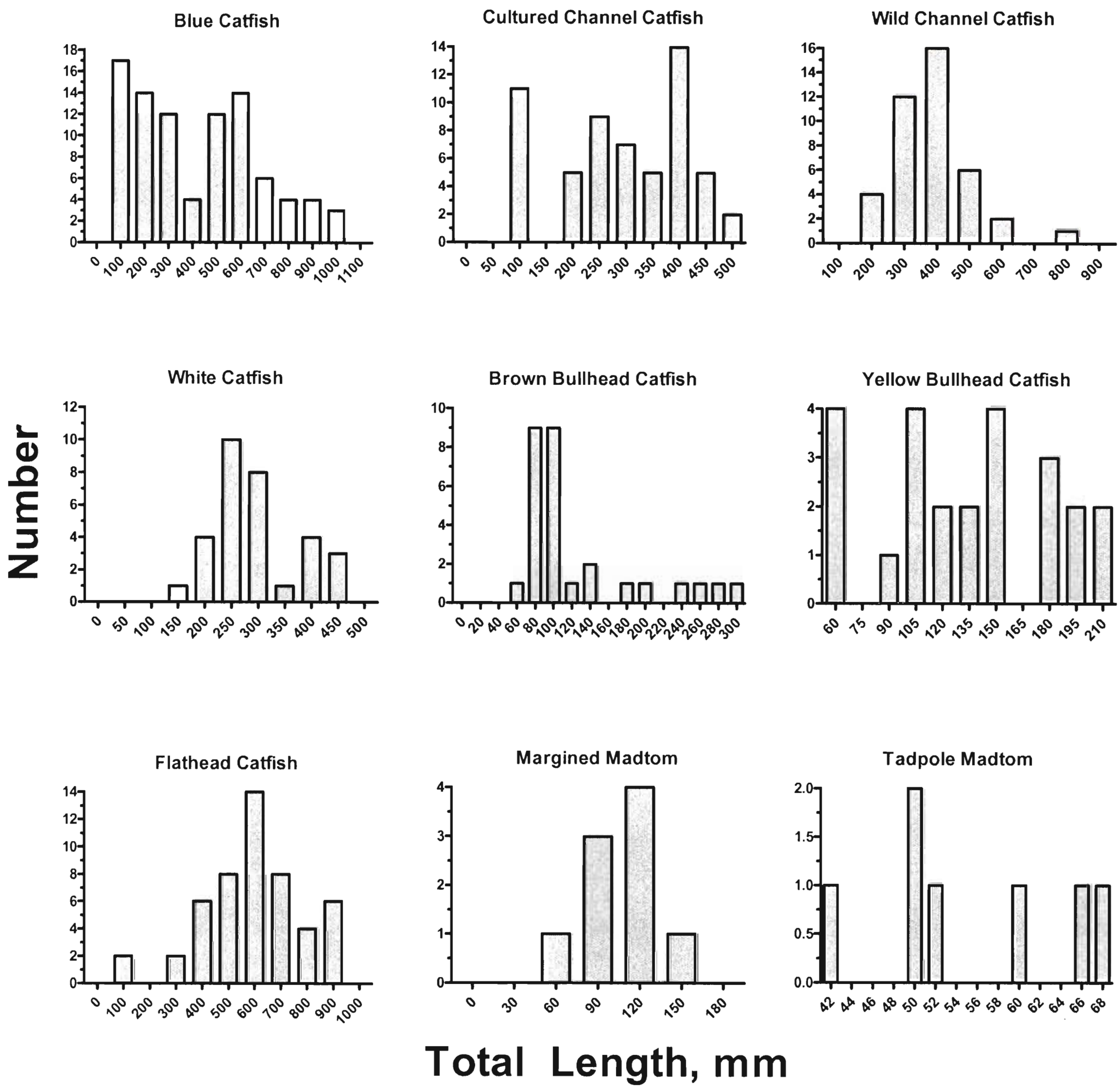

Fig 1. Sizes of catfishes used in this study.

VITA

Amanda D. Duvall was born in Newburg, West Virginia on November 17, 1978. She received her B.A. degrees in environmental science and biology and art from Davis and Elkins College in December 2000. Mrs. Duvall was awarded the Inger and Walter Rice Center - Environmental Science Research Grant, Center for Environmental Studies Research Grant, and the Jesse Hibbs and Marion Waller Scholarship in 2006 to support her graduate research. Mrs. Duvall is employed as a life and earth science middle school teacher at Seven Hills School from December 2002 to present.