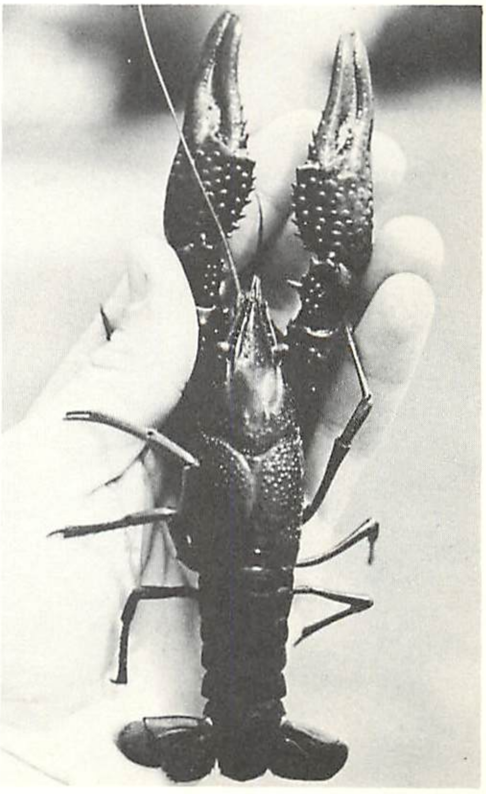
RED SWAMP CRAWFISH:

BIOLOGY AND EXPLOITATION



J. V. HUNER
J. E. BARR

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SEA GRANT PUBL. NO. LSU-T-80-001

LOUISIANA STATE UNIVERSITY CENTER FOR WETLAND RESOURCES, BATON ROUGE, LA 70803.

This research was supported by the Louisiana Sea Grant College Program, a part of the National Sea Grant Program maintained by the National Oceanic and Atmospheric Administration, U.S. Department of Commerce. The LSU program is administered by the Center for Wetland Resources, Louisiana State University, Baton Rouge, LA 70803.

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ERRATA

RED SWAMP CRAWFISH
Biology and Exploitation

by J. V. Huner and J. E. Barr

1. P. 47, Fig. 21. Labeling for Bourchardina robisoni should be changed as follows: "a" = "e"; "b" = "d"; "d" = "a"; "e" = "b"; and "f" = "c".

2. P. 73, paragraph 2, line 4. "50,000 acres" should be "55,000 acres".

3. P. 73, paragraph 2, line 9. After the word "general," insert the following phrase: "recreational harvest from".

4. P. 93, paragraph 1, line 5. Insert the word "winter" after the word "late".

5. P. 110, Fig. 53. The photograph is upside down. The two larger insects are Lethocerus; the two smaller ones are Belostoma.

6. P. 143, column 1, line 2. The word "affinia" should be "affinis".

7. P. 86, paragraph 3. The term "flash freezing" means rapid freezing, less than 15 minutes, and should not be misconstrued to mean a particular method of freezing.

ACKNOWLEDGMENTS

We appreciate the reviews of: J. W. Avault, Jr.; Joe B. Black; J. T. Davis; H. H. Hobbs, Jr.; J. F. Payne, J. Wright, and K. Wright; and the benefit of experience from the industry: J. Boyce, Jr.; D. Duchamp, Jr.; D. Gooch; J. Hurst; F. B. Kyle; J. McCahill; J. Thibaut; and A. Warinner. Illustrations are courtesy of: Carolina Biological Supply, Figs. 1, 6, 11; H. H. Hobbs, Jr., Figs. 7, 14, 21, 22, 23, 24; B. Huner, Figs. 8, 29, 51, 59; K. Lyle, Figs. 10, 52, 53, 54, 55, 56, 57; W. Hayes, III, Fig. 13; Louisiana Agricultural Experiment Station, Figs. 15, 17, 31, 32, 34, 36, 38, 39, 40, 45, 46, 47, 48, 49, 50; J. Witzig, Figs. 18, 33, 58, 61; S. K. Johnson, Fig. 20; D. Klarberg, Fig. 35; G. Warren, U.S. Soil Conservation Service, Figs. 43, 44.

The crawfish depicted in Figures 3, 4, 5, and 20 is taken from the original print of the red crawfish in Huxley's 1868 publication, The Crayfish. It was the only cambarid crawfish illustrated in that work.

Our special thanks to the support staff of the Louisiana Sea Grant College Program, Celia Harrod, Susan Lynch, and Jean Gazaway. We wish to dedicate this effort to Ronald E. Becker, Associate Director of the Louisiana Sea Grant College Program, whose concern and support are acknowledged with thanks.

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INTRODUCTION

I Freshwater crawfishes have had a close association with western man for centuries. Huxley's magnificent 1868 work entitled The Crayfish assured that virtually every high school and college biology student would study these small decapod crustaceans as part of their comprehensive education. The didactic value of these creatures is difficult to question, and physiologists, ecologists, ethologists, and many other natural scientists have found them to be excellent subjects for their studies.

Crawfishes have played a major role in the history of western man. For centuries they have been an important food resource in Europe, assuming a unique cultural role. Their value has been greatly magnified in recent decades when habitat destruction and the crawfish plague reduced supplies and restricted access to the catch from the general public. When Europeans came to North America, they found vast numbers of crawfish in the lower Mississippi River Valley, the Great Lakes region, and the West Coast area. These had long been exploited by the Indians. The Swedes and Frenchmen, who had come from regions of Europe where crawfish were highly prized, quickly took advantage of the new found bonanza.

Over the years, food fisheries have developed into a successful business with up to 45,000,000 lbs of crawfish harvested annually. However, most of this activity has been centered in Louisiana where the unique topography of the land results in huge overflow swamps. These are formed by the flooding Mississippi River as it reaches the Gulf of Mexico from the continent's heartlands. Such swamps provide virtually unlimited habitats for crawfishes. The West Coast catch approaches 1,000,000 lbs per year, but the resource is largely under-exploited. Most production is shipped to Europe where native species have been decimated by pollution and disease. Production in the Great Lakes area exceeds 50,000 lbs per year.

In North America crawfishes are most commonly used for fish bait. Their unique trophic status as detritivores establishes them as important food resources for carnivorous fishes. North Americans have long depended upon such fishes for food and recreational use. Therefore, it is not at all surprising that crawfish, which play such an important role as fish foods, have also become popular fish baits. In fact, several popular artificial fish lures are designed to simulate crawfish.

This volume is devoted to a survey of the biology and exploitation (fishery management and culture) of the most cosmopolitan of the crawfish species, Procambarus clarkii (P. clarkii) (Girard, 1852), more commonly called the red or red swamp crawfish. Thirty to sixty million pounds are harvested annually from swamps and marshes and cultivated ponds, primarily in Louisiana. The catch may exceed forty million pounds in years when excessive flooding generates a more favorable habitat. The red crawfish is native to northern Mexico and the

Mississippi Valley into southern Illinois. It has been successfully introduced on both the East and West coasts of the United States. It is a hardy, adaptable species that has also been introduced in Central America (Costa Rica), Europe (Spain and France), Africa (Kenya and Uganda), Hawaii, and Japan. Figs. 1, 2, 3.

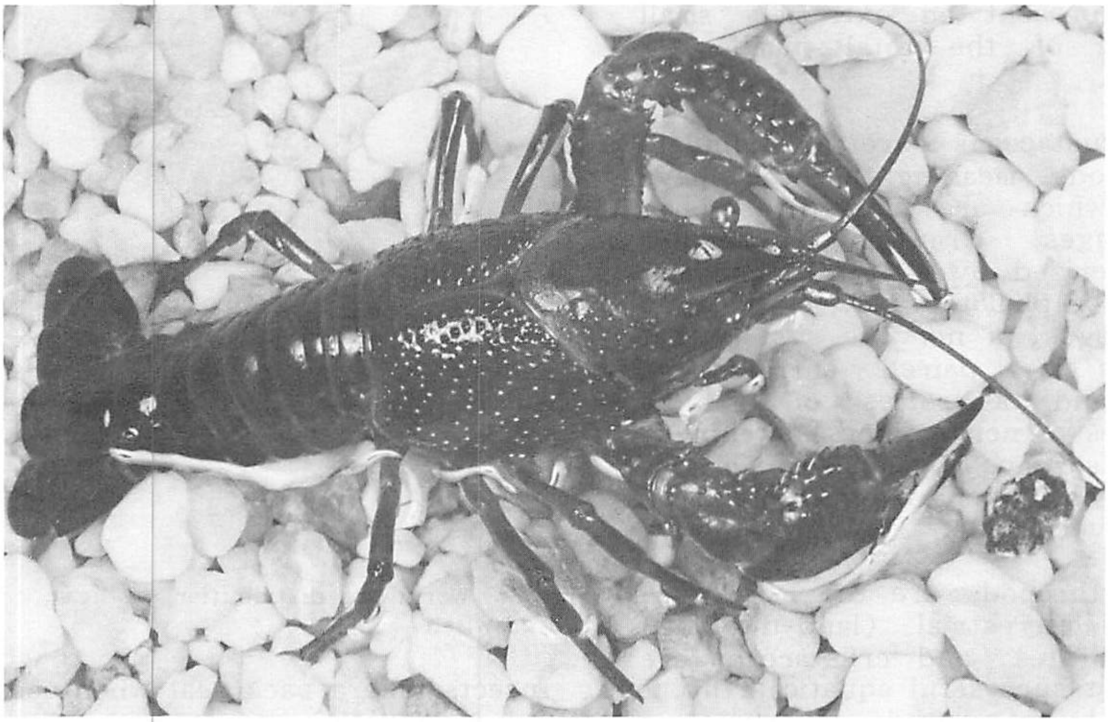


Fig. 1. Adult male red crawfish.

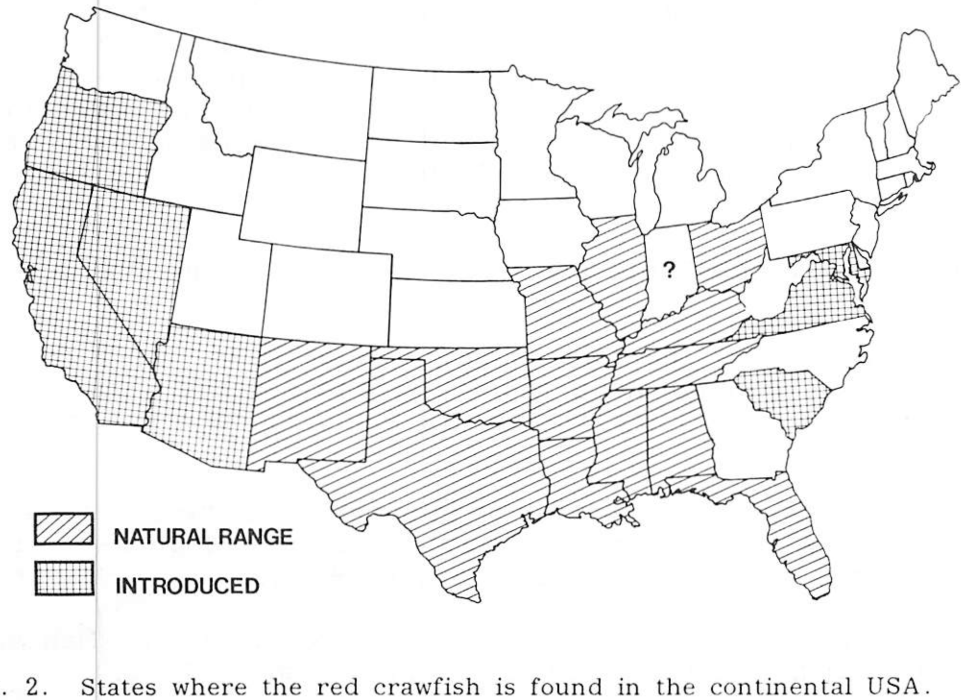


Fig. 2. States where the red crawfish is found in the continental USA.

II[1] Crawfish[2] are crustaceans, a class of arthropods that has radiated into more marine and freshwater environments than any of its insect relatives. Yet, of the 1.1 million arthropods, crustaceans, which number about 26,000 species, still represent an extremely small segment of the total number of species.

Crustaceans are mandibulate arthropods, meaning that they have jaws, which are classed as head appendages. Crawfish are further characterized by a fused head and thorax (cephalothorax), joint-legged appendages, a nervous system that consists of a paired ventral nerve cord and a series of ganglia (bundles of nerve fibers) swellings. They also have specialized excretory glands and a characteristic embryonic development. Fig. 4.

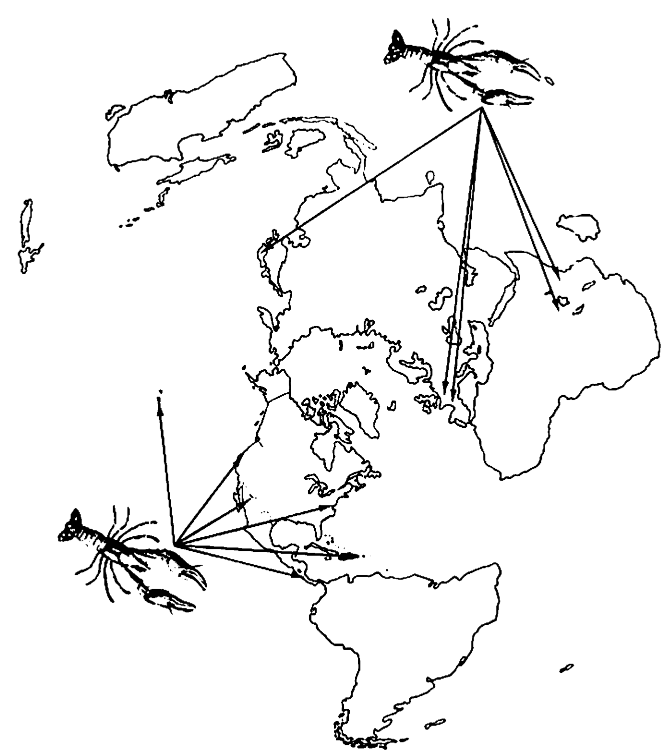


Fig. 3. Worldwide distribution of the red crawfish.

Arthropods are the most successful terrestrial (land-dwelling) invertebrates, and crustaceans are the most successful aquatic arthropods. Insects take a back seat when compared to the huge numbers of crustaceans found in aquatic ecosystems. It appears that insects are isolated in the fresh and brackish water near land, while crustaceans have done quite well in both the salty oceans and freshwater lakes high in the mountains. However, most crustaceans are mainly marine and live in the open ocean, shores of bays and estuaries, or in the brackish waters of marshes. Crawfish are freshwater crustaceans isolated in freshwater systems. In North America, crawfishes and several other crustaceans have long dominated freshwater ponds, lakes, and rivers. Caves and underground rivers contain these hardy creatures. There are even species that live in wet earth, rarely seeing bodies of water.

Crustaceans are divided into two major groups: entomostracans and malacostracans. Fig. 5.

Entomostracans include the fairy shrimp, water fleas, copepods, and barnacles. Barnacles are common along the shores and beaches of many coastlines. Copepods, water fleas, and fairy shrimp are found in open waters. They are

1. We do not credit specific sources of information in the traditional scientific format because we view this biology as a compendium of well-published material. Various specialists are recognized for their expertise where we feel appropriate.

2. In this biology the term "crawfish" refers to cambarid crawfish in general. The term "Red Crawfish" refers specifically to Procambarus clarkii.

very small and are unable to fight currents. Thus, they are referred to as planktonic creatures. Water fleas and fairy shrimp are typically freshwater creatures, although the brine shrimp is a fairy shrimp that is adapted to life in briny lakes.

Malacostracans, the other subclass, includes isopods and decapods (crawfish, shrimp, crabs, and lobsters). Of these, crawfish are the only freshwater crustaceans in North America of major economic importance to man.

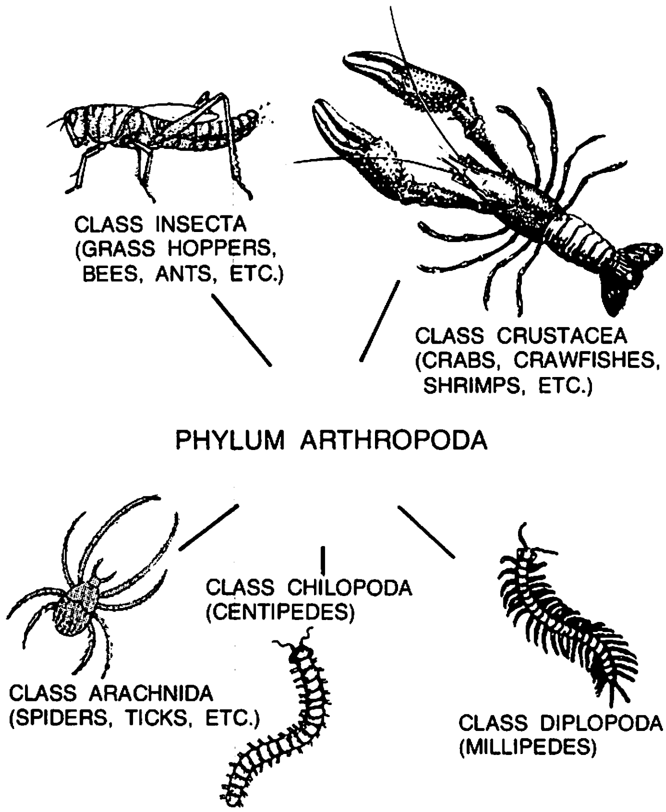


Fig. 4. Phylum Arthropoda--various classes.

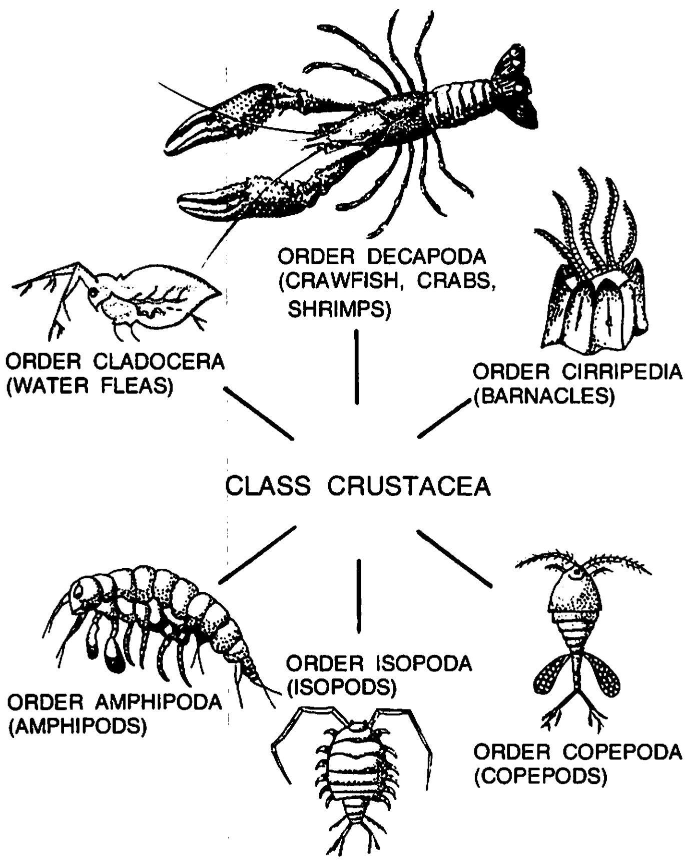


Fig. 5. Class Crustacea.

GENERAL BIOLOGY

EXTERNAL ANATOMY

The characteristic exoskelton of the crawfish can be divided into the three body regions. The head and thorax are combined into a head-thorax or cephalothorax. The abdomen is highly segmented. The entire length of the body is composed of somites (3 in the head, 10 in the thorax, and 6 clearly defined ones in the abdomen). The somites of the head and thorax (cephalothorax) are covered by a carapace that encloses the back and sides. A cervical groove divides the head from the thorax. The abdominal somites contain a transverse back or dorsal plate called a tergum. A lower or ventral sternum is joined to the tergum by the pleuron. Figs. 1, 6, 7, 8.

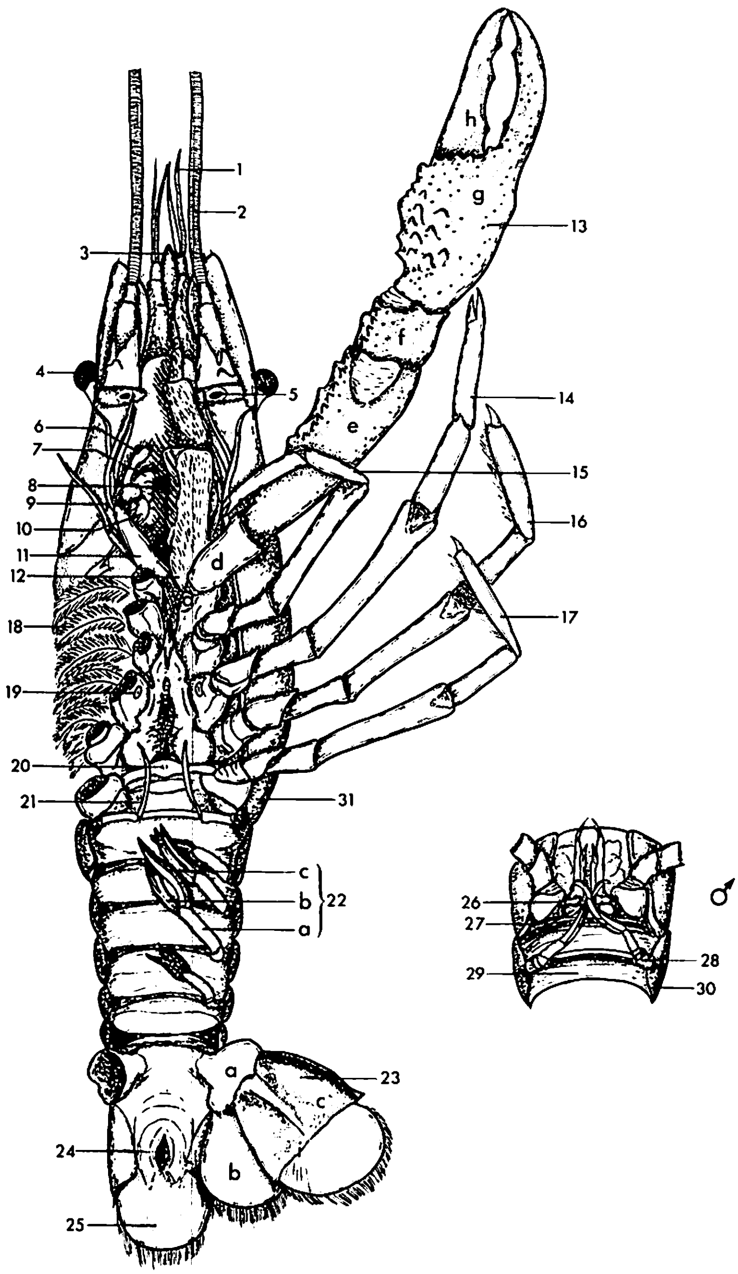
The compound eyes are stalked and movable and are set in front of (anterior to) the carapace. The mouth is on the the head, between the mandibles. The anus opens ventrally from the large "tail" or telson at the end of the abdomen. On each side of the body is a large gill chamber. The anterior end of the carapace is elongated into a platelike shelf (rostrum) with a short or long spine (acumen).

Appendages

Crawfish have a single pair of appendages attached to each somite. All of the appendages are jointed and possess internal muscles.

Each pair of appendages functions differently yet has similar homologous parts. All have a protopodite, which is made up of two joints, the coxopodite and the basiopodite. The general pattern is to have two branches arising from the protopodite, which are the endopodite and the exopodite. This is the biramous (branching) condition. However, the expodite is frequently missing. In the case of the second and third maxillipeds (jaw legs) and the pereipods (walking legs) the endopodite is composed of five segments, named in order from the protopodite (1) ischipodite, (2) meropodite, (3) carpopodite, (4) propodite, and (5) dactylpodite. Additionally, there may be other outgrowths of the protopodite called epipodites. These are not to be confused with either the endopodites or exopodites. Fig. 9.

There are six groups of appendages. Each group functions according to its origin. The sensory appendages are made up of the antennae and the shorter antennules. These structures receive and transmit the sensory stimuli of the environment. The mouth-parts consist of the chewing mandibles that crush the food and two other groups of appendages, maxillae and maxillipeds, which handle the food. The large characteristic claw or pincer (chelae) is used to grasp food. An offensive and defensive appendage, it is often lost in combat. It is classified as a pereipod, or walking leg. The following four pairs of pereipods are summarily used for locomotion; however they handle food and act as cleaning wands for the body. The second and third pairs of maxillipeds and the five pairs of pereipods have gills, podobranchs, attached to the protopodites. The pleopods, or swimmerets, are important in transporting the glair-covered eggs. Their movement circulates the water in and around the eggs to promote respiration. The first two pairs of pleopods of males are modified to transfer sperm to females. Sperm is stored in the annulus ventralis of the female, located between the fourth and fifth pairs of pereipods. Sexually active males will also have prominent "hooks" on the ischipodites of the third and fourth pairs of pereipods. These assist in grasping the female during the mating act. The uropods are paddle-shaped appendages to the fifth abdominal somite. They along with the flattened, sixth abdominal somite, the telson, form a tail fan used for the characteristic backward swimming behavior of the crawfishes. Table 1 provides a detailed summary of the parts and functions of the various appendages.



1. Antennule
2. Antenna
3. Rostrum
4. Eye
5. Nephridiopore
6. 1st maxilla
7. Mandible
8. Mouth
9. 1st maxilliped
10. 2nd maxilla
11. 2nd maxilliped
12. 3rd maxilliped
13. Chela
14. 3rd walking leg
15. 2nd walking leg
16. 4th walking leg
17. 5th walking leg
18. Gills
19. Oviduct opening
20. Seminal receptacle
21. 1st pleopod
22. 4th pleopod
23. Uropod
24. Anus
25. Telson
26. Genital opening (male)
27. 1st pleopod
28. 2nd pleopod
29. Sternum
30. Pleuron
31. Tergum

a. Protopodite
b. Endopodite
c. Exopodite
d. Ischipodite
e. Meropodite
f. Carpopodite
g. Propodite
h. Dactylpodite
i. Transverse hinge

Fig. 6. Crawfish external anatomy, ventral view.

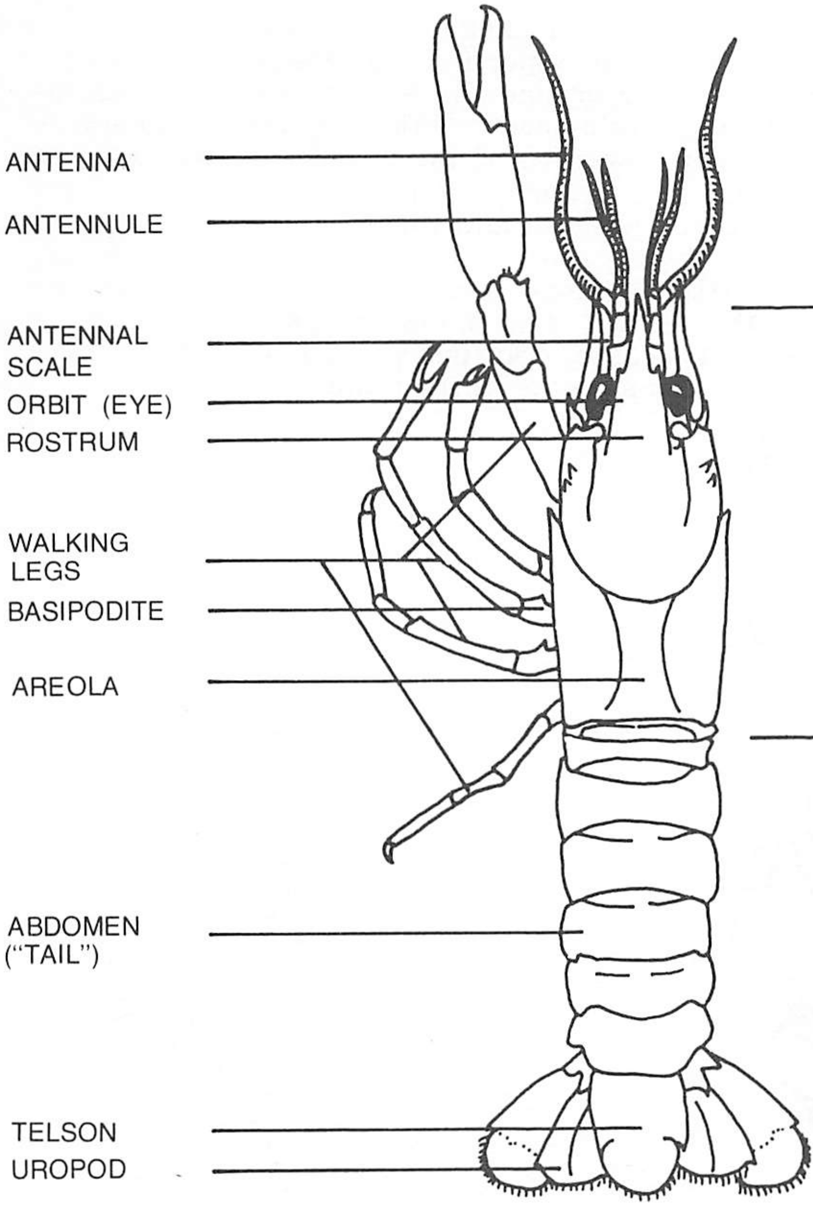


Fig. 7. Dorsal view of generalized crawfish, showing various body parts.

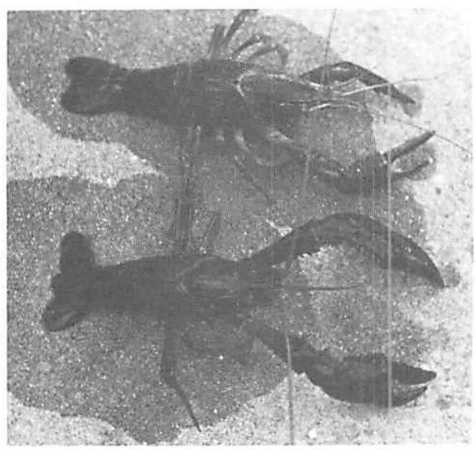


Fig. 8. Adult male (lower) and adult female (upper) red crawfish. Note the male's enlarged claws.

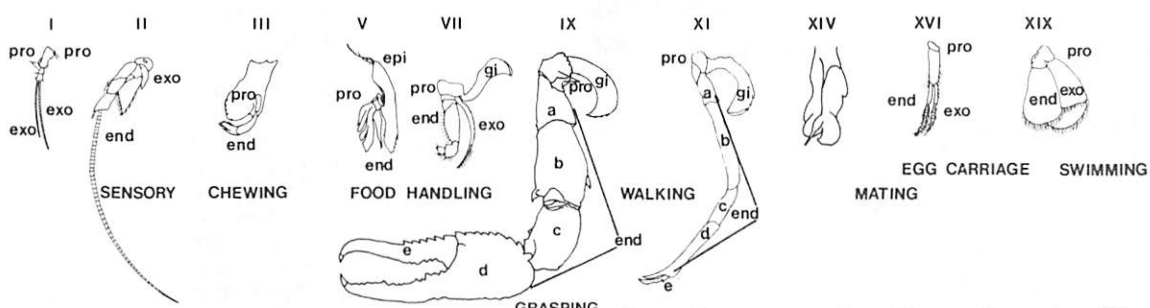


Fig. 9. Appendages of the red crawfish.

Legend: pro, protopodite; end, endopodite; exo, exopodite; gi, gill; a. ischipodite; b. meropodite; c. carpopodite; d. propodite; e. dactylopodite.

TABLE 1. Crawfish limbs.

	BODY SEGMENT & NAME OF LIMB	STRUCTURE OF PARTS/NUMBER			USE
		PROTOPODITE	ENDOPODITE	EXOPODITE	
HEAD	I Antennule	Statocyst in dorsal base/3	Short, jointed feeler	Short, jointed feeler	Taste, touch, & equilibrium
HEAD	II Antenna	Excretory opening in ventral base/2	Multijointed, long feeler	Thin, pointed blade	Taste & touch
HEAD	III Mandible	Robust jaw & base of palp/2	Distal sections of palp/2	-	Tearing, crushing, & biting food
THORAX	IV First Maxilla	Thin, medial plate/2	Unjointed & small/1	-	Food manipulation & filter feeding
THORAX	V Second Maxilla	Bilobed plates/2	Slender exopodite & epipodite form "gillbailer" to move water over gills/1		Filter feeding, food manipulation, touch, & taste
THORAX	VI First Maxilliped	Broad medial plate & epipodite/2	Small & narrow/2	Narrow & very small/2	
THORAX	VII Second Maxilliped	Short & has gill/2	Short & stout/5	Narrow/2	
THORAX	VIII Third Maxilliped	Has gill/2	Longer/5	Narrow/2	
THORAX	IX First Walking Leg	Has gill/2	Robust with heavy claw at tip/5	-	Combat & protection
THORAX	X Second Walking Leg	Has gill/2	Slender with small claw at tip/5	-	Ambulatory (walking) movements & grasping
THORAX	XI Third Walking Leg	Has gill & in female has sex opening/2	Slender with small claw at tip & in mature male <u>P. clarkii</u> has grasping hook on ischipodite/5	-	
THORAX	XII Fourth Walking Leg	Has gill/2	Slender & in mature male <u>P. clarkii</u> has grasping hook on ischipodite/5	-	Ambulatory movements; dactylopodites at tips of endopodites juxtaposted on limbs XII & XIII to permit clinging, leaving other 3 legs free
THORAX	XIII Fifth Walking Leg	Has gill & in male has sex opening/2	Slender/5	-	
ABDOMEN	XIV First Swimmeret	Reduced greatly in female; protopodite/endopodite fused in males to form a "tube"			Sperm transfer from male to female
ABDOMEN	XV Second Swimmeret	Two joints in male; short in female/2	Conical & rolled in males; segmented filament in females	Filamentous; jointed filament in females	Accessory to XIV in males; water movement & carry eggs/young in females
ABDOMEN	XVI Third Swimmeret	Short/2	Segmented filament	Filamentous	Water movement in both sexes; carry eggs/young in females
ABDOMEN	XVII Fourth Swimmeret	Short/2	Segmented filament	Filamentous	
ABDOMEN	XVIII Fifth Swimmeret	Short/2	Segmented filament	Filamentous	
ABDOMEN	XIX Uropod	Short & broad/1	Flat & oval/1	Flat & oval with a hinge/1	Swimming; egg protection in females

*Some specialists feel that a segment lacking "limbs" is present in front of the segment bearing the antennules. This would mean that there are 20 body segments (4 in head) rather than 19.

†Some specialists prefer to consider the head to consist of the first 5 body segments rather than the first 3.

Exoskeleton

The red crawfish shell or exoskeleton is made up primarily of inorganic calcium carbonate ($CaCO_3$) in the form of calcite. Calcite is supported by an organic matrix made up of a compound called chitin and various protein molecules. The percentage of calcium carbonate remains fairly constant during the intermolt stage, regardless of age, but the thickness of the shell increases as the crawfish grows older. This compound maintains structural integrity of the shell as the animal grows. The exoskeleton of all crawfish consists of four layers. These are the outer, uncalcified epicuticle, the calcified exocuticle, the calcified endocuticle, and the inner, uncalcified membranous layer. The dominant layer is the endocuticle accounting for more than 80 percent of the total thickness. In order for growth to occur, the old exoskeleton must be periodically shed and a new exoskeleton must be synthesized. Details about the changes that take place in the exoskeleton during the molt cycle may be found in the section on molting. When molting ceases temporarily at maturity, additional layers of endocuticle are laid down, causing a thickening of the shell. This deposition of endocuticle continues until the next premolt period begins, normally following the completion of reproductive activity. In rapidly molting crawfish the intermolt phase soon gives way to the premolt phase and the inner endocuticle is destroyed. This limits the absolute thickness of the shell.

Color

Color patterns of crawfish are generally determined by the distribution and relative concentrations of cells that contain pigments, called chromatophores. Each chromatophore is branched and lies beneath the cuticle of the epidermis. The color of the crawfish depends upon the dispersion of the pigment within the chromatophores. If the pigment is concentrated, the crawfish will appear lighter than if the pigment is completely dispersed throughout each chromatophore. Chromatophores of particular colors or aggregation can produce patterns of stripes or spots.

Most crawfish have transparent shells through which the chromatophores may be seen. However, in some species such as the red crawfish, patterns occur within the material making up the shell. This pattern is superimposed on the color-laden chromatophores. Deposition of shell cuticle increases the thickness of the shell and changes the color of the older adult red crawfish.

There are two types of pigment molecules deposited in the endocuticle. These include carotenoids and carotenoproteins, which influence the color. Carotenoproteins are actually protein molecules bound to carotenoid molecules. The basic colors found in adults are derived from purple, blue, and red carotenoproteins. Unbound carotenoids also influence color. The red carotenoproteins are most concentrated on the sides of the carapace and on the claws and walking legs. The blue and purple carotenoproteins dominate the dorsal region of the carapace and abdomen. These carotenoproteins produce the blue-black appearance found in many crawfish. There is some evidence that the red carotenoprotein is actually produced by a chemical reaction in which the blue and purple carotenoproteins combine. When crawfish are boiled, the blue and purple carotenoproteins change, or denature, and turn red. This explains why boiled crawfish are always reddish-orange.

Young red crawfish have a characteristic greenish-brown tint. A faint brown band, bordered laterally by thin, darker lines, extends from the rear of the carapace to the telson. Adults generally are dark purple-black on the top of the carapace. The sides and claws become dark red as the animal grows older. Often, other color variations occur, such as when the red is replaced by a purplish or tan-orange color. Crawfish from clear, acid stained waters are usually very dark or even black, whereas crawfish from very murky waters with little green vegetation are pale or often tinted with a reddish-pink hue.

Occasionally blue crawfish appear in the catch. The blue is the result of a genetic mutation and has been reported in many crawfish species, including the red crawfish. There are two types of "blue" red crawfish. One has been characterized as French blue and the other is a relatively pale blue. The French blue is believed to be sex-limited because it appears only in females. The pigment is actually incorporated into the shell. The light blue appears in both males and females. The light blue mutation is said to be recessive because it only occurs when both contributing genes (all genes are paired with offspring receiving one gene from the mother and one gene from the father for each characteristic) are for the blue pattern.

The true light blue mutation should not be confused with the light blue crawfish produced when grown in alkaline waters and fed artificial diets. After two to four molts, red crawfish will become light blue as a result of dietary deficiencies, a process that can be reversed.

Eye Color. The normal eye color among crawfish is black. One very rare mutation involves eye color. Since 1969 more than 30 specimens of red crawfish have been collected with eyes that lack the black pigment, melanin. The eyes have been variously described as yellow-colored, white-colored, silver-colored, and platinum-colored. This condition is caused by a recessive mutation. Dr. Joe Black of Louisiana College in Pineville, La., has been able to cross such crawfish with his stocks of blue mutants and produce blue, yellow-eyed, "red crawfish." Fig. 10.

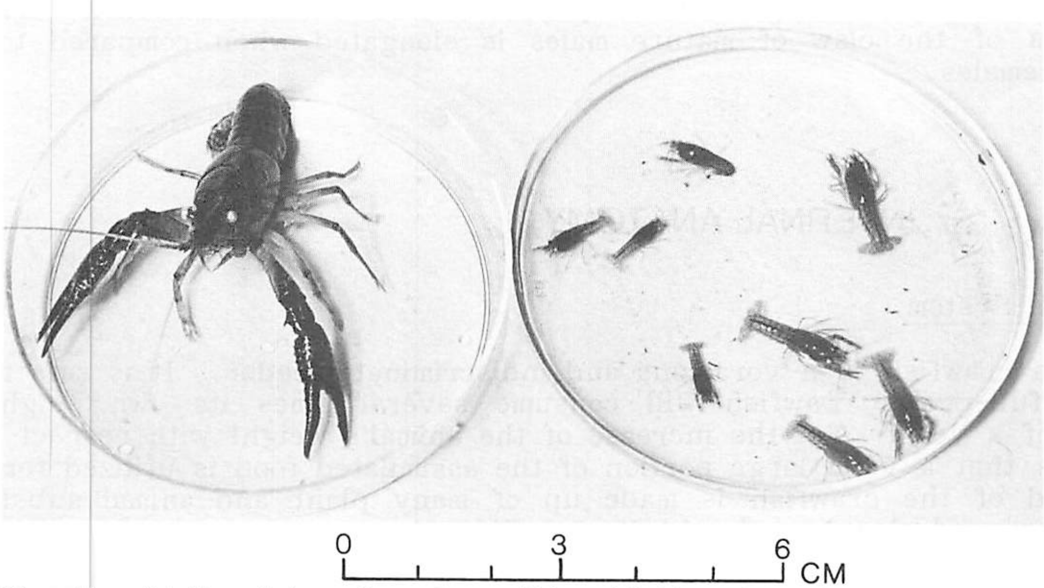


Fig. 10. Adult and juvenile red crawfish exhibiting the white eye mutation.

Black pigment in the eye serves the same purpose as the iris of the mammalian eye; it controls the amount of light that can enter the crawfish's eye. At night the pigment contracts permitting all available light to enter. When a light is directed on the eye a luminescent circle can be seen. During the day the pigment expands to cover most of the eye, thus reducing the luminescent circle. The change from full expansion to contraction of the black pigment is endogenous; that is, it is an automatic phenomenon that takes place even when the crawfish is held under conditions of total darkness. Since the yellow-eyed crawfish has no pigment in its eyes, it can effectively be blinded if its eyes are flooded by light during the day. At night its eyes function quite well.

Physical Variations

One unusual variation among crawfish is the occurrence of male secondary sexual characteristics in mature females. The presence of hooks on the walking legs and the development of the first pair of swimmerets to resemble the corresponding male swimmerets (gonopods) cause some females to look like males. Some have referred to such variations erroneously as hermaphroditism, the presence of both sexes in the same animal. They are really pseudo (false) hermaphrodites because such animals are invariably functional females; however, a case of true hermaphroditism has been observed in the red crawfish. It is not clear if these conditions are genetic or hormonal. Pseudohermaphrodites have seldom been seen. Literally hundreds of thousands of red crawfish have been examined by scientists and qualified laymen, but fewer than a dozen of the pseudohermaphrodites have been reported. This is unusual because the pseudohermaphroditic phenomenon is relatively common in other cambarid crawfish.

Anyone examining large numbers of red crawfish will frequently find animals with disfigured bodies. This can take the form of a grotesque claw, an awkwardly bent carapace, or a broken carapace exposing the gills. These anomalies are the result of mechanical damage and subsequent regeneration of damaged or missing body parts. Another noticeable variation in red crawfish is the width of the palm of the claw. It may be spatulate (shovel shaped) or narrow (needle nosed); however, the spatulate shape is the most common situation. Then, too, the palm of the claw of mature males is elongated when compared to that of mature females.

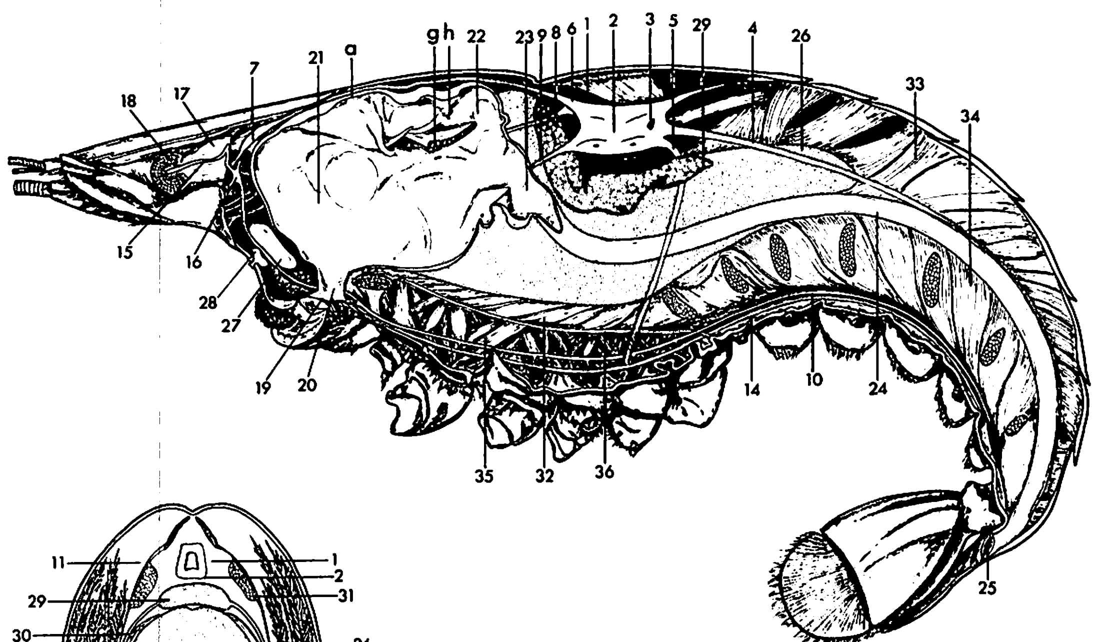
INTERNAL ANATOMY

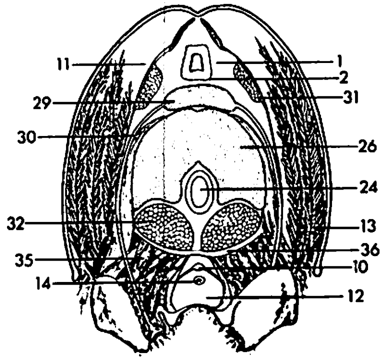
Digestive System

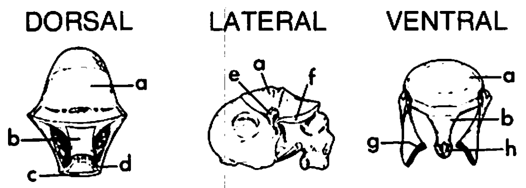
The crawfish is a voracious and indiscriminate feeder. It is safe to assume that a full-grown crawfish will consume several times its own weight in the course of a year. Yet the increase of the animal's weight with respect to intake indicates that a very large portion of the assimilated food is utilized for energy. The food of the crawfish is made up of many plant and animal substances, a topic discussed elsewhere in this text. Fig. 11.

The first step in the process of feeding is to separate the nutritive parts of the food matter from its undigestible parts. This preliminary operation is the subdivision of the food into a convenient size for introduction into the digestive tract. Food may be seized by the pincers or by the anterior ambulatory appendages and transferred to the first or second cephalic appendages. These appendages grasp the food and thrust it between the mandibles. The latter crush and divide the food brought to them as it passes between their toothed edges at the opening of the mouth.

The alimentary canal stretches from the mouth at the anterior end to the anus at the posterior. The canal is continuous with the body wall, making the crawfish's digestive tract appear to be a small, hollow cylinder within another cylinder. A short esophagus leads upwards from the mouth into a large stomach. The stomach is divided into a large cardiac chamber and a small pyloric chamber. In the cardiac chamber the food particles are ground and crushed by the gastric mill. The mill contains three chitinous teeth. The teeth







1. Pericardial sinus
2. Heart
3. Ostium
4. Superior abdominal artery
5. Sternal artery
6. Opthalmic artery
7. Cor frontale
8. Antennary artery
9. Hepatic artery
10. Ventral nerve cord
11. Brachiocardiac sinus
12. Ventral sinus
13. Gills
14. Ventral thoracic artery
15. Optic nerve
16. Cerebral ganglion
17. Eyestalk
18. Eye
19. Mouth
20. Esophagus
21. Cardiac stomach
22. Pyloric stomach
23. Midgut
24. Intestine
25. Anus
26. Liver
27. Green gland
28. Bladder
29. Ovary
30. Oviduct
31. Extensor of thorax
32. Flexor of thorax
33. Extensor of abdomen
34. Flexor of abdomen
35. Proximal claw muscle
36. Endophragmal shelf

Gastric mill
a. Cardiac ossicle
b. Urocardiac ossicle
c. Pyloric ossicle
d. Prepyloric ossicle
e. Zygocardiac ossicle
f. Pterocardiac ossicle
g. Lateral tooth
h. Median tooth

Fig. 11. Crawfish internal anatomy.

are controlled by muscles that triturate the food as it moves into the stomach. A fibrous strainer permits only the smallest particles to pass into the stomach's pyloric chamber. The pouched midgut region contains glands that secrete enzymes and adsorb food matter, while the major digestive gland is the hepatopancreas. It is a trilobed structure with two lobes projecting forward on either side of the stomach and the third lobe projecting to the rear of the carapace. The hepatopancreas is the so-called "fat," "liver," or "honey" of the crawfish. The midgut is not lined with chitin and is very short. Most of the digested food passes into the hepatopancreas through tubes from the midgut and is absorbed there. The hindgut (proctodeum) ends with the anus.

Gastroliths are the so-called "stomach stones." These are calcium carbonate stones found on either side of the cardiac stomach. As the molt approaches, some of the calcium carbonate extracted from the old exoskeleton is stored in the gastroliths. During molting, the joined lining of the esophagus and stomach, including the gastric mill, passes forward through the mouth. The gastroliths come to lie in the cavity of the stomach where they are dissolved. The body absorbs the calcium carbonate from the gastroliths for the initial hardening of the exoskeleton and mouth parts. There is enough calcium carbonate in the gastroliths, hepatopancreas, and blood to harden the new exoskeleton to about one-third the normal level. Scientists have been able to determine the molt stage of various species of crawfish by taking x-rays of the developing gastroliths.

Muscular System

Crawfish muscles are all contained within the exoskeleton and are not external to the skeleton as in vertebrate animals. They are arranged in opposed pairs with a flexor muscle to draw the part of the body to a point of articulation (connection) and an extensor muscle to straighten the part. Since most muscles have at least one connection with the exoskeleton, a soft crawfish is a considerable disadvantage. Fig. 11.

In the abdomen and above the intestines there are two pairs of extensor muscles, which originate at the sides of the thorax and fill the upper part of the abdomen. The massive abdominal flexor muscles, which provide the driving power for the tail fan, are located below the intestine. They also originate in the thorax with connections throughout the abdomen ending at the telson. Other important muscles include those of the claws, the mandibles, the stomach, and the various limbs. All crawfish muscles are excellent for eating, but, because of their relatively large size, normally only the claw and abdominal muscles are eaten.

The meat removed from the abdomen is called "tail" meat by most laymen. This is technically incorrect since the telson and uropods are the true tail of the crawfish. It should be called, more correctly, abdominal meat.

Respiratory System

Crawfishes obtain oxygen and eliminate carbon dioxide through gills. The gills contain blood sinuses and are located on both sides of the thorax in <u>gill</u> or branchial chambers. The branchial chamber is formed by the lateral sections of the carapace, and external to (outside of) the body. A paddle-shaped projection, called the scaphognathite, of the second maxilla beats back and forth below the mouth and draws water into the branchial chamber. The water circulates from beneath the pereipod and from the rear of the chamber passing forward to the upper portion of the chamber and exiting below the mouth. Fig. 11.

In crawfishes there are two types of gills--the podobranchs and the arthrobranchs. In the red crawfish the podobranchs arise from the protopodites of the second and third maxillipeds and the first four pairs of pereiopods (one per appendage). The paired arthrobranchs arise from the body wall adjacent to the second (one pair only) and third maxillipeds and the first four pairs of pereipods. Thus the total number of gills is 34, 17 on each side.

As long as a crawfish's branchial chamber is moist, it can obtain oxygen. The oxygen diffuses from the atmosphere into the water where it saturates the gills and moves into the blood. The red crawfish can survive for several months out of water as long as its branchial chamber is damp. This is one reason for its living in damp, humid burrows where the water in the lower portions of the burrows is often very low in dissolved oxygen. This ability permits them to live in surface waters when oxygen depletion takes place due to the rapid decomposition of vegetation in the water. Crawfish will simply climb to the surface and raise one side of the carapace out of the water so that atmospheric oxygen can then enter the branchial chamber on that side.

On the dorsal side, the red crawfish has a small separation between the two halves of the carapace. This separation is referred to as the aerola. Anatomically, this means that there is a larger branchial chamber and more space for gill filaments. This increases the red crawfish's ability to obtain oxygen from the water. In general, crawfish from habitats with little or no problems with low oxygen have wide aerolas, while crawfish from oxygen-poor habitats generally have very narrow aerolas.

The Circulatory System

Circulation in crawfish is similar to that in most other arthropods in which an open system consists of a heart, arteries, and sinus cavities. The compact heart, located dorsally and to the rear of the cephalothoracic region, is an elastic, muscular sac enclosed within a thin membrane (pericardium). A small space between the heart and the membrane is called the pericardial sinus. Hemolymph (blood) enters from the pericardial sinus through the three pairs of openings called ostia. The heart walls have three pairs of ostia, two on the dorsal, two on the ventral, and two on the lateral sides of the heart. Valves are located in each of the ostia to prevent the outflow of hemolymph. Fig. 11.

Arteries branch into the vital organs. Hemolymph is pumped to the head through a single artery (median ophthalmic artery). After passing above the stomach, the hemolymph flows into a pair of arteries that supply the optic region. It is pumped to the abdominal region by the dorsal abdominal artery, which runs above the intestine. This artery forms many small branchings that supply hemolymph to the dorsal muscles of the abdomen. At its origin near the heart, the dorsal abdominal artery divides into a second branch, the ventral abdominal artery. This artery further divides into two additional branches that pass through the thoracic canal. These arteries carry hemolymph to the anterior and abdominal regions. Several other arteries supply the antennae, the hepatic system, digestive gland, and reproductive system.

Once hemolymph reaches the various body regions and tissues, it enters open sinuses where it bathes those tissues in these open areas, and an exchange of food, waste products, and oxygen/carbon dioxide takes place. The hemolymph then returns to the heart by gradually flowing through and around body organs. No veins are involved. This is why the crawfish's circulatory system is said to be open. This open system circulates oxygenated blood to the many organs of the crawfish. The gills resupply the deoxygenated hemolymph with oxygen. From the gills it circulates to the heart and is pumped throughout the body.

Crawfish hemolymph consists of a colorless fluid (plasma) and "blood" corpuscles resembling vertebrate white cells. A compound known as hemocyanin (similar to hemoglobin in higher animals) contains a copper porphyrin molecule that responds to oxygen as does iron by binding the free oxygen from the water. One major reason a crawfish is able to live at relatively low oxygen levels is the ability of copper to bind the oxygen. One gram of copper in crawfish blood can fix more than 176 cubic centimeters (1 oz = 28g; 1 in. = 2.54 cm) of oxygen. This is more than ten times greater than the binding ability of iron in mammals. Oxygenated hemocyanin has a faint blue color so that crawfish may be said to be "blue blooded."

The hemolymph contains a high percentage of soluble salts (about 1.2 percent NaCl), which results in absorption of fresh water through the body wall. The body wall of crustaceans contains many semi-permeable membranes such as the membranes of the joints, the cuticle of the gills, and the ventral abdominal wall. To offset this osmotic pressure, it is necessary for the special excretory system to eliminate excess water from the body. (See the section on the excretory system for more information.)

Hemolymph corpuscles (amebocytes) function similarly to phagocytic white cells found in vertebrates. Some of the corpuscles release substances that act to clot the hemolymph.

The Nervous System

The ability of any organism to survive in its environment requires a characteristic irritability of the cells. Specialized cells called neurons make up the nervous systems of most multicellular animals. As in all arthropods, the nervous system of the crawfish consists of a central bundle of nerves with many single branching neurons (the central nervous system) and many smaller nerve bundles branching throughout the body (the peripheral nervous system). Concentrations of neuron cell bodies called ganglia form coordination centers. These major nerve bundles run along the ventral side in arthropods, not along the dorsal or back side as in vertebrates. Each embryonic body segment contains paired ganglia. Those of the first three segments fuse above the esophagus. This fused mass is referred to as the supraesophageal ganglion. The supraesophageal ganglion found at the anterior, or front, end of the nerve cord is larger than the other ganglia, and is often considered the brain. The crawfish brain is not physically separated into specialized regions as is the brain of man, but some have given names to the three pairs of fused ganglia. The anterior region is called the protocerebrum, the mid-region is called the deuterocerebrum, and the hindmost is called the tritocerebrum. Small nerves branch from it and innervate the optic (eye) region, the antennules, and the antennae.

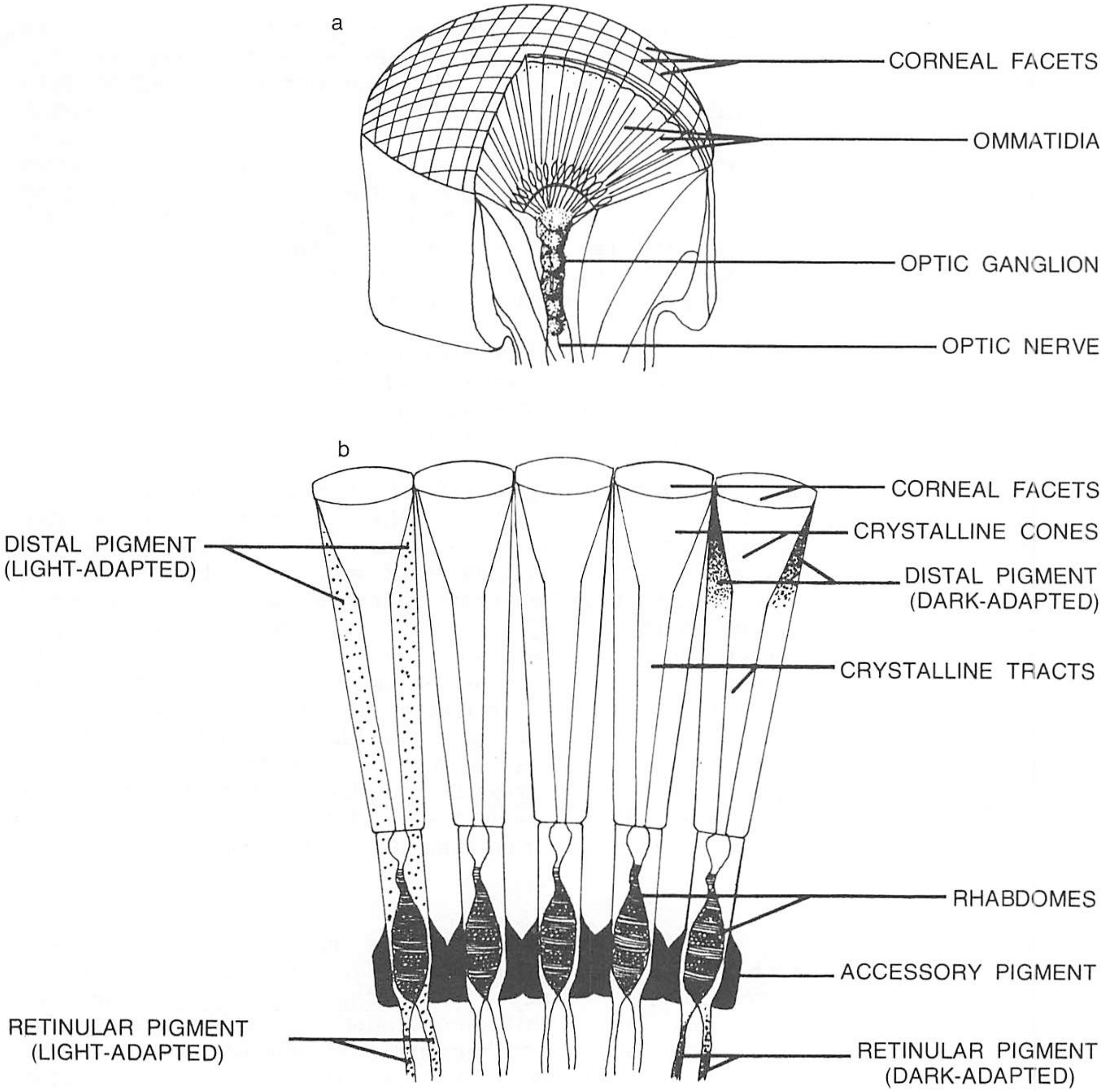
A pair of neural bands, the circumesophageal connectives, pass backward from the brain around the esophagus, and join a large ganglion, the subesophageal ganglion below the esophagus. The subesophageal ganglion represents the five or six pairs of ganglia for embryonic segments four through nine. Branches from this huge composite ganglion innervate the mouth appendages, the green gland, the esophagus, and various muscles in the anterior region. A large ventral nerve cord originates from the subesophageal ganglion and passes through the abdomen. A pair of fused segmental ganglia in each segment are found along the ventral nerve cord and send fibers to the appendages, muscles, and organs. The various ganglia of the brain and ventral nerve cord of the nervous system are called the central nervous system.

Some of the nerve fibers found in the central nervous system of crustaceans are among the largest neural fibers known. Neurophysiologists use them to learn more about the function of nervous systems. Of the crustaceans, *P. clarkii* is probably the most commonly used in such research.

The peripheral nervous system consists of all nerves connecting to the central nervous system. It has two subdivisions, the voluntary nervous system and the involuntary, or sympathetic nervous system. The voluntary nervous system controls voluntary movements of various limbs and the abdominal muscles through the ganglia of the "brain" and the ventral nerve cord. The sympathetic nervous system regulates involuntary body functions such as heart beat, digestive gland function, stomach movements, and similar processes. That is, it controls systems that must continue to function at all times. The sympathetic nervous system arises from ganglia in the circumesophageal connectives (one in each). These send off a single nerve and these two single nerves fuse into an anterior ganglion. A single nerve passes from the anterior ganglion to the dorsal wall of the stomach to a stomatogastric ganglion. Branches from the stomatogastric ganglion lead to the stomach walls, digestive gland, and the heart. An unpaired nerve also connects the sympathetic system directly to the supraesophageal ganglion.

Sensory Receptors. Crawfish have one of the most extensive sensory systems of all the arthropods. They have well developed sensory receptors for vision, chemicals (chemoreceptors), balance, touch (tactile receptors), and internal muscle tension (proprioceptors). All senses must be highly developed if the crawfish is to survive in its constantly changing environment, and they are. On land the crawfish is slow and clumsy so it must be able to rapidly detect enemies. It does so with excellent vision (including color) and tactile receptors. In the aquatic environment, the eyes are used as long as the water is relatively clear, yet much of the time turbid water reduces the efficiency of the eyes. Crawfish also receive appropriate information from chemoreceptors, which detect food, potential enemies, and other crawfish and tactile receptors, which detect vibrations and water movements.

The compound eyes of crawfish are similar to those found in insects. They are covered by a transparent membrane called the cornea. The compound eye is composed of many smaller units or facets called ommatidia; as many as 2,500 ommatidia make up one eye. Each ommatidium is composed of several different cells that serve to collect light from objects and translate the information to the brain. This produces a mosaic image. Fig. 12.



Legend: a. eye cut to reveal structure; b. ommatidia drawn to show light adaptation (left ommatidium) and dark adaptation (right ommatidium). In strong light, pigment distributes in such a way to isolate each ommatidium from adjacent ommatidia. As a result, an opposition, or mosaic, image is formed. In weak light, pigment concentrates at extreme ends of each ommatidium so that light rays are able to spread to adjacent ommatidia. As a result, a superposition, or continuous, image is formed.

Fig. 12. Compound crawfish eye with detailed section through ommatidia.

Each ommatidium consists of a corneal facet or lens; two corneagen cells (cells that secrete the cornea); four cells that together form a crystalline cone; several distal pigment cells about the cone; a central rhabdom formed by the junction of a long tapering retinula of eight cells; basal pigment cells surrounding the internal retinula; and tapetum cells between the internal bases of the retinular cells. The rhabdom is a translucent element that is universally found in compound eyes and is chemically made up of alternating layers of lipids (fat molecules) and proteins. It has been suggested that this may be the photoreception element of the eye. The sensory nerve fibers are attached to the eye via the retinular cells. These fibers form the optic nerve and pass through the optic ganglia to the brain.

The movement of the pigment cells allows the crawfish to have two types of vision. Surrounding each ommatidium are three groups of pigment cells arranged to form a sleeve. In bright daylight, the pigment is extended to isolate each ommatidium. This produces a mosaic (composite) image, as each ommatidium has its own sensory neuron. In dim light, the pigment recedes to increase the amount of light that enters the ommatidium. This forms a continuous, less precise image. The daily migration patterns of pigments is discussed in external anatomy.

Other Sensory Receptors. Chemoreceptors are located on the antennules, antennae, and other anterior appendages. Most are hairlike structures with thin cuticles and stand exposed to the environment. Leydig's apparatus, located on the outer branch of the antennules, is a pitlike structure with sensory hairs projecting into the center of the pit. Various chemicals in the water enter the pit and stimulate the sensory hairs.

Thigmoreceptors (mechanoreceptors) respond to pressure changes in the surrounding environment and to physical touch. A number of these tend to be concentrated in the anterior portion of the crawfish's cephalothorax behind the eye and along the cervical groove. It is thought that this may represent a sort of acoustic (sound) receiving system. It is clear that the system can detect low frequency vibrations and may, in fact, "hear" sounds in the surrounding waters. Certainly, this system can detect variations in currents flowing over a crawfish as well as other environmental vibrations.

Tactile hairs are distributed all over the body but are concentrated in the claws, mouth parts, under the abdomen, and at the edge of the telson. Proprioceptors are located within the body proper and function to inform the central nervous system as to the relative positions of the various muscles.

Balance is maintained by the statocysts. These are located at the bases of the antennules. The hollow, hair-lined statocysts are open to the exterior and maintain the animal's balance. The openings are guarded by hairs that prevent the escape of fine grains of sand. These grains exert pressure on the sides of the statocysts in accordance with the body's orientation, a phenomenon that provides the crawfish with information on the body's position relative to the center of gravity. Statocyst grains must be replaced at each molt, as the inner lining of the statocyst is shed at each molt. If iron filings are placed in a container with a crawfish as it molts, they will collect inside the statocyst. The crawfish can then be induced to turn in the direction of a magnet placed next to the statocyst.

Finally, there is a caudal photoreceptor in the sixth abdominal somite. Its exact function is not clearly understood.

Endocrine System

Endocrine tissues produce hormones, which mediate body functions. Circulating to all parts of the body, these hormones help regulate certain body functions over sustained periods of time ranging from a few hours to months. This type of body regulation is in sharp contrast to the instantaneous electrochemical regulation typical of the nervous system.

The nervous system is in close communication with the endocrine system. Many of the essential hormones are actually produced by neural tissue in the eyestalk, supraesophageal ganglion, the circumesophageal connectives, and the subesophageal ganglion. Such hormones are called neurohormones.

Eyestalk neurohormones are produced by the so-called X-organs, the medulla terminalis X-organ and the sensory papilla X-organ. These communicate with a sac nearby, called the sinus gland, which serves as a storage center for secretions of the X-organs. Neurohormones from the eyestalk include chromatophoretrophic hormones (regulate pigment dispersions in the epidermis), hyperglycemic hormones (regulate blood sugar), molt-inhibiting hormone (MIH), cardio-accelerator hormones (accelerate heart beat), antidiuretic hormones (regulate body water levels), metabolic hormones, and ovary-inhibiting hormones. Related neurohormones are produced by the supra-, circum-, and sub-esophageal complex. It is thought that the neurohormones are polypeptides composed of several amino acid units (building blocks of proteins).

Removal of eyestalks accelerates the next molt by eliminating the MIH, but many critical hormones are also lost. Thus, crawfish without eyestalks will normally die after one molt; however, a few can survive more than three molts.

Other critical endocrine organs are the Y-organs paired and found near the bases of the maxillae. They have no direct connection with the nervous system. Their principal function is the production of molt-stimulating hormones (MSH). The chemical name for these hormones is ecdysones. Ecdysones are the natural molt-stimulating hormones found in all arthropods. They were first isolated from plant tissues where they serve as natural insecticides by killing arthropods if too much is consumed.

The crawfish Y-organ produces alpha ecdysone, an inactive form of MSH. This is converted by the body into the active form called beta ecdysone. Beta ecdysone has also been called crustecdysone, 20-hydroxyecdysone, and ecdysterone. All ecdysones are steroid molecules and are derived from cholesterol. Cholesterol must be obtained from food as crawfish cannot manufacture it. Molt-inhibiting hormones inhibit the production of molt stimulating hormones. MIH rises to the highest levels during the intermolt period. Gradually it declines followed by a rise in MSH at the molt period. Adverse conditions can lead to prolonged dominance of MIH presumably because of the direct control that the central nervous system has over secretion of MIH.

Initial experiments with beta ecdysone has revealed that doses high enough to induce molting result in abnormal molts fatal to most crawfish. During the normal molt cycle, levels of MSH increase only gradually. Slow release forms of beta ecdysone have been developed, eliminating the problem of abnormal molt acceleration.

One interesting approach used to speed up a molt is the removal of claws and walking legs. This involves the crawfish's ability to regenerate lost parts. Each walking leg and claw has a constriction at its base, and crawfish can break one or more of these limbs at these points at will (a process called autotomy). This is especially advantageous when a predator has the crawfish in its grasp. Once it has lost limbs, it must be able to replace them quickly. Development at the stump is very slight during the period preceding the next molt, but the "nub" will increase four or five times in size at that molt. Three molts are usually sufficient to regenerate lost parts. Study has shown that when limbs are removed, the actual stimulus to hasten molt is loss of nervous connection to the limbs. Severing the nerves while leaving the limbs intact has the same effect as limb removal.

The Y-organs are also necessary for the development of ovaries. The ovaries and testes, as in vertebrates, produce steriod sex hormones that are important in proper functioning of the reproductive cycle. Male crawfish are also known to have glands called the androgenic glands located on the sperm tubes, or vasa deferentia, near the testes. These are believed to be responsible for producing the change from the juvenile or quasi-juvenile (Form II) conditions to the sexually active (Form I) condition (see Reproduction section).

Insects are known to secrete juvenile hormones. During their development, the amount of juvenile hormones gradually declines. At very low levels, the insects molt into the adult body form. Juvenile hormones are apparently present in crustaceans and probably have the same general function, although few studies exist of this area of crustacean endocrinology. Juvenile hormones are now in use as "third generation" insecticides. They are thought to be safer than chlorinated hydrocarbons or organic phosphate because they are not persistent in the environment. Yet, no one knows how they could affect crustacean populations.

Pheromones. Animals may communicate with each other through self-generated chemicals called pheromones. The best studied pheromone in the red crawfish is the brood pheromone. It is first released at the beginning of the incubation period and is most effective when the eggs hatch. Following the third molt of the hatchlings the pheromone becomes less potent, and the young become less responsive to their mothers. Interaction of young crawfish and their mothers maintains her brooding behavior. A mother will normally not undergo the post reproductive period molt until the young leave.

There is some controversy currently as to whether adult crawfishes, especially the red crawfish, communicate via pheromones. In early studies, male and female test crawfish showed antagonistic or sexual responses after being held in static water several days. In later studies water flowing continuously from chambers with males or females failed to generate similar results. Further studies will be needed to clarify this matter.

Behavior

Behavior is a complex series of responses an organism may perform in its environment. Behavior patterns that are preprogrammed genetically are called innate behavior. Behavior patterns that develop as a result of past experiences are called learned behavior. Most of the behavior of crawfish is innate, as its central nervous system is less developed than that of vertebrates. Simple responses to stimuli such as environmental changes are normally referred to as simple reflexes, and the brain does not become involved. Complex responses to stimuli are called complex reflexes or instincts. Although arthropods are not normally thought of as intelligent, they do develop learned behavior. They can be taught to come for food or to retreat from certain stimuli.

Simple Reflex--Instinctive Behavior. Several simple reflex reactions in crawfish are fairly well known. These include eyestalk withdrawal, claw closing, and autotomy. Crawfish have movable eyestalks that retract into a space beneath the rostrum. If the eye is touched, it will automatically retract into this space.

Another simple reflex, claw closing, is triggered if the inside of the propodite (fourth segment of the cheliped) is touched. The response is caused by the stimulation of a ganglion in the claw.

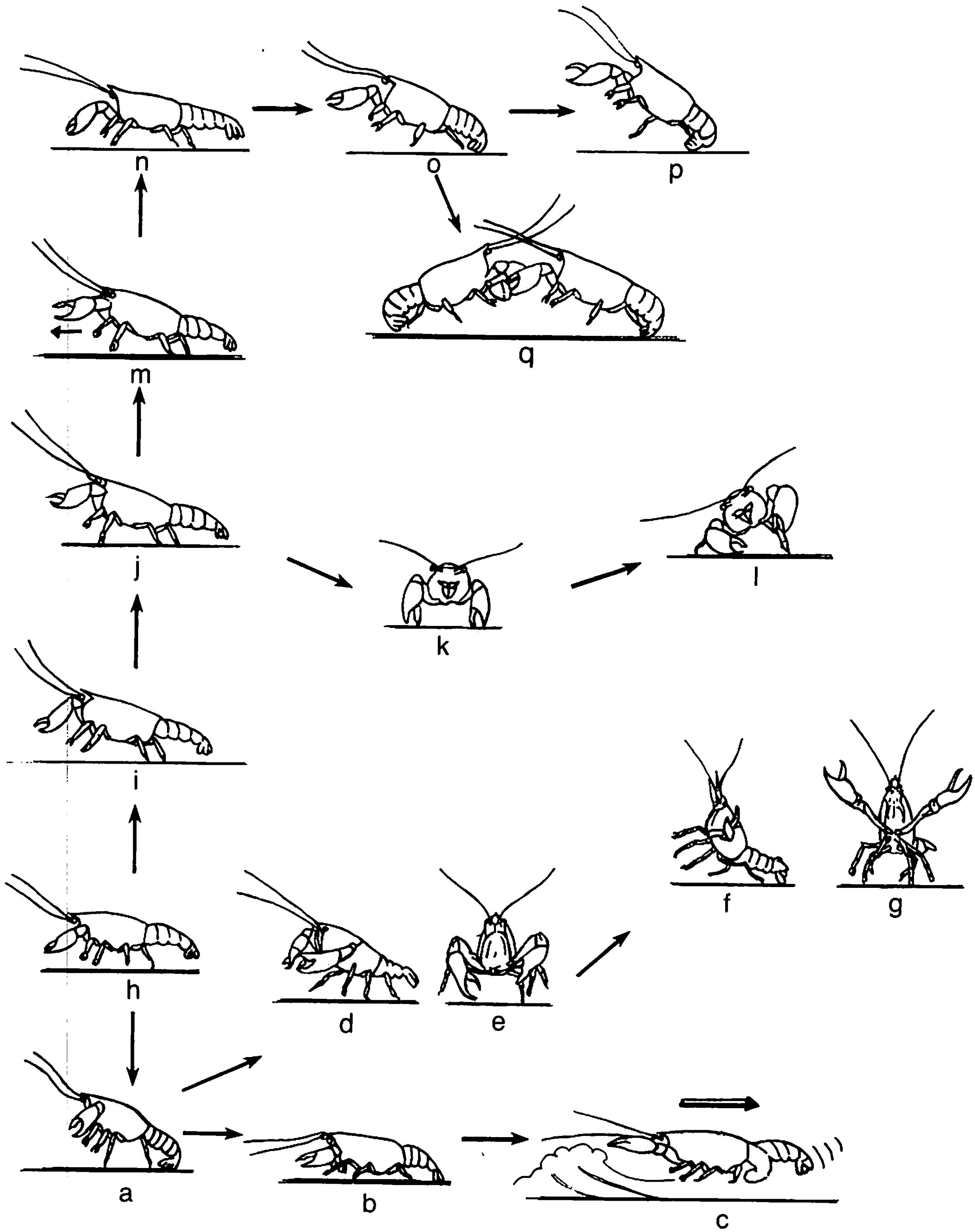
One unique reflex is autotomy. Autotomy in crustaceans is the casting off of a limb at the level of a joint between the protopodite and ischiopodite when strong stimulation occurs. Muscles contracting in the joint are capable of forcing the joint apart. This reflex is characteristic of a similar defense mechanism in some reptiles that lose their tails if held tightly by a predator. The crawfish will regenerate a new appendage in several months (see Molting).

Complex Reflex--Instinctive Behavior. In complex reflex, the "brain" is always involved, and a series of events may take place. That is, an initial stimulus causes a crawfish to do one characteristic thing. It will raise its claws in a defense posture, for example, if the stimulus is another aggressive crawfish. The actions of the aggressor will then determine the course of action of the other crawfish (attack, fight, or flee). The following discussion analyzes the behavior component of social interactions in *P. clarkii*.

Many behavioral patterns of *P. clarkii* show close similarity to those of crabs. Visual and tactile senses are important during social contact. Crawfish have a 360° range of sight along with a high sensitivity to visible light. In normal crawfish, touch and vision are coordinated to give well-organized responses. Without vision, touch is sufficient; however, the absence of both results in behavioral disintegration. *P. clarkii* uses visual presentation, touch, and sound production during social interactions.

Visual presentation involves changes in body postures and chelae positions. Touch is involved in both aggressive and sexual activities. Sound is produced by air bubble emission from efferent branchial channels as in fiddler crabs. This appears to be a signal, but its purpose is unknown.

Eight behavioral components have been observed and described by Dr. William Hayes of Murray State College, in Tishomingo, Okla., for the activities of crawfish during social interaction: alert, approach, threat, combat, submission, avoidance, escape, and courtship. Only slight variations in these components have been observed. The normal stance is described for each, and, according to Dr. Hayes, each applies to the red crawfish. Fig. 13.



Legend: a. avoidance; b. submission; c. escape; d. low intensity predator response, side view; e. low intensity predator response, front view; f. high intensity predator response, side view; g. high intensity predator response, front view; h. alert; i. approach; j. low intensity threat; k. courtship; l. courtship turning; m. high intensity threat; n. low intensity combat; o. high intensity (ritualized) combat; p. maximum intensity combat; and q. opponents engaged in ritualized combat.

Fig. 13. Red crawfish behavior patterns.

The alert posture is assumed by the crawfish during normal activity when not affected by any specific external stimulus. The body is held horizontally, usually raised slightly above the substrate and supported by the walking legs. The abdomen is held with the distal (hind) end below horizontal. Chelae are held close to the body, moderately flexed, with fingers slightly below horizontal and separated slightly. Tips of chelae are directed medially (toward the middle) well below horizontal.

The approach posture is assumed when an individual moves toward another. The body, supported by the walking legs with the front of the carapace raised slightly, is oriented toward the other individual. The abdomen, held with the caudal end below horizontal, often touches the substrate. The chelae are held forward and laterally, moderately flexed, with fingers moderately separated. Tips of chelae are directed medially well below horizontal.

The threat posture is divisible by intensity into two subcomponents. The low intensity threat posture is assumed by a dominant individual when nearing another. The body and abdomen are held as in approach. Chelae are flexed less, with tips oriented more directly at the opponent. Fingers are widely separated. Tips of chelae are directed medially and below horizontal.

The high intensity threat posture, a modification of low intensity posture, is initiated at proximity to the opponent. The body is raised higher than in low intensity threat and readied for maximum intensity threat action--strike.

Combat follows threat with the crawfish assuming combat posture. The body is elevated on the last three pairs of walking legs with the anterior of the cephalothorax slightly above horizontal and oriented toward the other individual. The abdomen is held almost horizontally with uropods spread. Chelae are held in chelae-forward display, with fingers slightly spread. Combating individuals face each other with chelae tips touching or overlapping. Increased intensity results in each trying to grasp the other's chelae or rostrum. This usually leads to more intense combat. In such combat, the anterior portion of the body is held even higher, supported by the last two or three pairs of walking legs. The abdomen is semi-flexed. Chelae are held in a ritualized position--right chela flexed, shielding the body, left forward grasping the immovable finger of the opponent's shield chela (less often, the mirror image of this posture is displayed). Tuberculations (swellings like warts) on inner surfaces of fingers prevent maximum interlocking of chelae during normal ritualized combat. With extreme aggression in one or both combatants, chelae may slip past tuberculations and engage maximally.

Maximum intensity combat--wild fights--appears to be extremely dangerous to individuals involved, often resulting in injury or death. Evidence of wild fights are crush-marks on chelae of captured specimens. Wild fights are fairly uncommon. Most combat ends in retreat of one opponent after low or high intensity battles without severe injury.

Preceding courtship, the male approaches the female and initiates typical threat activities. If she becomes submissive or evasive he will adopt a chelae-forward courtship display similar to a low intensity threat but with chelae held almost vertically. Upon nearing the submissive female's side, he adopts a turning posture, turns her over, and mounts.

Avoidance is an interesting posture because of the combination of elements evidenced in it. The body is often held moderately high as in threat, but the chelae are strongly flexed in front of the mouth as in submission. The posture is usually combined with turning away from the stimulus that initiated it (i.e., a dominant male). It appears to result from interaction of fright and aggression. Combat, submission, or escape may result if the individual is stimulated further.

Submission is the opposite of threat. This posture occurs when a subdominant male or a female is approached by a dominant male. This apparently hides or significantly reduces threat value of display color or form, thus lowering the dominant male's aggression. In this posture, the body is held flat against the substrate with all but the last pair of walking legs pointing forward and partially appressed (held flat). The last pair of walking legs is usually held laterally. The abdomen is either spread and held flat against the substrate or folded back beneath itself. It helps to force the anterior end of the cephalothorax below horizontal. Chelae are held forward with fingers only slightly spread and pointing medially.

Escape is the family's characteristic backward swim. The posture streamlines the crawfish for rapid movement and except for tail movement is roughly the same movement used in submission.

The predator response is not actually an aspect of social interaction-behavior. There are several levels of intensity depending on the degree of threat. In low intensity predator response, the body is oriented toward the predator, held high, and supported by the walking legs and abdomen. The front of the carapace is raised at an angle of approximately 20 degrees to the ground. The abdomen may or may not be curled. The claws point forward and slightly inward with the hands held at a downward angle to the ground. The fingers are moderately separated. In high intensity predatory response, the front of the carapace is raised until it is almost vertical. The claws are held widely to the side with their fingers widely separated. In maximum intensity predator response, the crawfish quickly strikes its claws together in front of and above itself resulting in a snapping noise. Fig. 13.

The red crawfish will invariably back away from a predator when given the opportunity. The abdomen will curl at that time. It will be completely folded over on itself if the crawfish is in a corner.

Solitary Behavior

Drs. Roy Stein (Ohio State University) and John Magnuson (University of Wisconsin-Madison) have described a series of behavior patterns for Orconectes virilis, a northern species of crawfish. We have observed the same patterns in the red crawfish. These involve solitary crawfish as well as two crawfish (social behavior) or a crawfish and another organism. We present the terminology for solitary behavior patterns here. Behavior patterns involving interactions between crawfish or between a crawfish and another organism are covered above. Walking: The crawfish uses its second through fifth walking legs to move either forward or backward. Climbing: The chelipeds are placed against an object and the walking legs (principally, the third and fourth) support the body perpendicular to the object. The crawfish then uses the walking legs to climb upward.

Swimming: A crawfish swims backwards off the bottom propelled by powerful strokes of its abdomen. Motionless: A crawfish remains motionless except for rhythmic movements of the antennae. Probing: A crawfish inserts its cephalothorax into openings. Digging: A crawfish excavates a hole with its walking legs and/or chelipeds. Buried: A crawfish backs into an opening so that only the claws and/or antennae are visible. Feeding: A crawfish uses its mandibles to tear food items into small pieces while manipulating them with its third maxillipeds and second and third walking legs. Grooming: A crawfish remains stationary while using its second and third walking legs to remove materials from body surfaces.

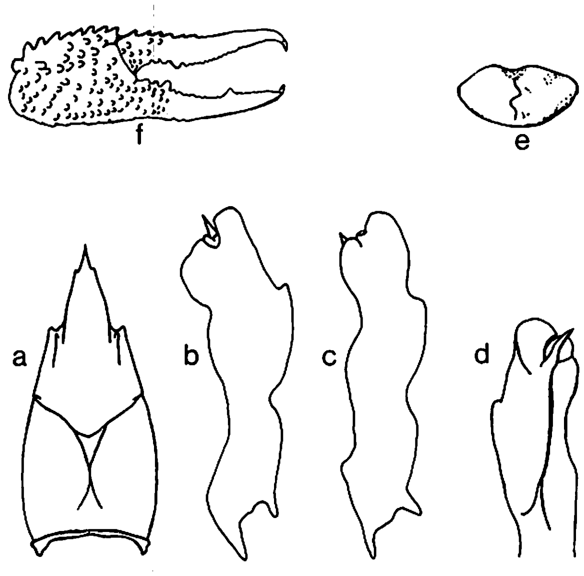
Feeding Behavior. The red crawfish is attracted to animal food or an artificial diet by its "scent." Researchers have found that certain combinations of amino acids (the building blocks of proteins) are the actual "scent" that stimulates feeding behavior. Once the scent reaches the crawfish, it quickly scurries in the general direction of the food with its claws outstretched but held at an angle such that the tips are directly in front of each eye. It does not move in a straight line but moves laterally as it progresses forward toward the food. It is not unusual for a crawfish to miss the food on the first or even the second pass. The maxillae and maxillipeds beat vigorously and create currents that conduct the scent to sensory organs in the anterior region of the body. The antennae invariably touch the food item first and they move in arcs from the side of the body to directly in front of it as the crawfish searches for the food. When contact is made, the crawfish will literally pounce on the food and draw it to the mouth with the claws and walking legs. It is then manipulated to the mouth by the maxillae and maxillipeds. The food is shredded, if necessary, by the powerful mandibles. The mandibles are formidable, and they permit the crawfish to eat even thick shelled snails. Thin shelled pond snails are dispatched with little fanfare. Heavy shelled snails like the ramshorn cannot be easily crushed. The crawfish will gradually chew up the shell, piece by piece, until it gets to the snail's soft body.

Crawfish cannot float and do not swim very well, but they can catch food items on the surface. Floating fish feeds are sometimes caught by an unusual maneuver. The crawfish will swim backwards in an arc towards the surface by vigorously flipping its tail. When it reaches the surface, it will grab floating feed with its claws as the crawfish settles back to the bottom. A naturally occurring source of food found on the surface is an assemblage of small floating animals and plants called the Neuston community. Normally the Neuston community is widely dispersed over the surface, but periodically it concentrates when the wind forces it against the bank or some other structure. At such times the crawfish will climb to the surface on any convenient object. Once there it will cling to the object with the third, fourth, and fifth pairs of walking legs. It creates currents with the rest of its anterior limbs and draws the neustonic material to its mouth. This behavior should not be confused with the surfacing of crawfish when oxygen levels are low.

Reproduction System

Crawfish are dioecious, that is the sexes are separate. Both males (testes) and females (ovaries) have trilobed gonads. Two of the three male or female lobes run anteriorly, below the heart and above and to the side of the intestine bounded laterally by the lobes of the hepatopancreas. In females, two tubes, or oviducts (one from each side of the ovary), pass to openings in the genital papillae (one on each side) located at the base of the third pair of walking legs. Before and after egg laying, the openings are covered by a very thin layer of exoskeleton. In males, two tubes, the vas deferens (one from each side of the testes), pass to openings in the phallic papillae (one on each side) at the bases of the fifth pair of walking legs. As in females, these openings are covered by a thin layer of exoskeleton. Sperm is transferred from the male to the female by way of the first pair of pleopods on the male. The second pair of pleopods also assists in the transfer. Both pairs are called gonopods. The sperm is stored in a structure located between the legs of the female called the annulus ventralis, or seminal receptacle. Figs. 11, 14.

The sexually mature crawfish, male and female, assumes distinctive secondary sexual characteristics when compared to immature crawfish. The male exhibits the most dramatic change in body proportions. The claws become elongated and greatly enlarged. Distinct hooks appear at the bases of the third and fourth pairs of walking legs. And, the first two pairs of swimmerets (called gonopods), located between the walking legs, become cornified (hardened). These will serve to transfer sperm to the female. The large claws and hooks will serve to grasp the female while mating. Physical changes in the female are not as apparent, although the claws enlarge to a degree. In red crawfish a conspicuous gap forms between the fixed and immovable fingers of the claws so that the male can grip the claws of a female during mating. The presence of hooks on the males is unique to crawfish of the family Cambaridae. Males that have distinct hooks, cornified gonopods, and enlarged claws are called Form I males. Figs. 8, 14, 15.



Legend: a. carapace; b. lateral view of male, from II, first gonopodium; c. lateral view of male, form I, first gonopodium; d. mesial view of male, form I first gonopodium; e. annulus ventralis, mature female; f. chela of male, form I.

Fig. 14. Key taxonomic features of the red crawfish.

Following production of young crawfish, a unique metamorphosis takes place in both the male and female crawfish. They begin to eat voraciously and within two to three weeks, molt. When they complete this molt, they again assume the juvenile appearance. This is referred to as the Form II state for males. The common condition for cambarid crawfish is to alternate "juvenile" (Form II) states with the sexually active (Form I) state after maturity is first reached.

<u>Reproduction, Development, Growth--Mating</u>. When a mature male red crawfish encounters a receptive female, the male seizes the female, turns her on her back, and mounts her. Sperm is transferred from openings of the sperm ducts at the bases of the fifth pair (last) of walking legs down grooves

in the first pair of swimmerets (both pairs are referred to as the gonopods) to the seminal (sperm) receptacle (annulus ventralis) located between the legs of the female. Amplexus may last several minutes or may continue for several hours. Observers of crawfish behavior have noted that a mature male will try to mate with any male or female crawfish he encounters. Non-receptive females and males will generally resist those advances successfully.

The seminal receptacle is sealed with a clear jellylike sperm plug that looks like uncooked egg white when viewed under a microscope. Sperm will remain viable in the seminal receptacle for more than eight months.

Fig. 15. Juvenile red crawfish.

Burrowing generally begins after amplexus; however, it is not absolutely necessary for females to go into a burrow to lay eggs. They will readily lay eggs in artificial pools and aquaria. As burrows contain both a male and female crawfish, the female will often drive the male out of the burrow at the time of egg laying. Typically, the male will be found near the entrance of the burrow while the female will be behind the male near the bottom of the burrow.

Egg Laying. In general, egg laying by red crawfish begins in the burrow during summer and continues into the fall. In warm climates there is some egg laying year round. Before the eggs are laid, they undergo a change both in color and size. The small (0.012 mm; 25.4 mm = 1.0 in.), pale white eggs mature dramatically as they grow, steadily changing color. A sequential change follows a pattern from white to yellow (0.4 mm), then to tan (1.0 mm), and finally to a dark brown (1.6 mm). As the eggs are laid they are fertilized by sperm stored in the seminal receptacle. Immediately following fertilization, the eggs (zygotes) are attached to the swimmerets underneath the abdomen by a sticky substance called glair. Some authors refer to glair as a type of "placenta," as torn or punctured glair will have disastrous results. The egg maturation cycle varies from six weeks to eight months. The incubation period may range from two to three weeks at summer temperatures to two to three months at late winter temperatures. The number of eggs produced in the female's ovary is directly proportional to her size. A two and one-third inch female can produce 100 eggs, a three and one-quarter inch female can produce 300 eggs, while a four inch female can produce as many as 500 eggs. The number of eggs actually laid is usually somewhat lower than the number produced in the ovary.

Egg mortality on the female's abdomen can be considerable. Eggs can be lost as a result of physical damage if the female is forced from the burrow and must move about on dry land. In the water, extreme temperature changes can permit attack by a fungal growth called Saprolegnia, which causes infertile and dead eggs to turn orange while fertile eggs turn black.

Egg Development. The fertilized crawfish egg (zygote) receives one member of each pair of chromosomes from each parent. As the genes may be identical (or homogenous) for the same characteristic, or different (heterogenous) for the same characteristic, the offspring can differ greatly from the parents when one considers the vast numbers of gene combinations possible in a single chromosome pair.

To our knowledge, the normal chromosome number (the 2N condition) has not been determined for the red crawfish, but the number for the cambarid crawfish, Orconectes virilis, is 200 (100 pairs) and that for a native Japanese crawfish of the genus Cambaroides is 196 (98 pairs). These compare with 46 (23 pairs) for man and 8 (4 pairs) for field corn.

Embryonic Development. The zygote contains all of the genetic material required to produce a new offspring. The zygote divides by a process called mitosis, producing two then four, eight, sixteen, thirty-two, sixty-four and so on until the entire yolk is filled with cells. At this point the nuclei migrate to the surface and superficial changes occur, producing the blastula stage. Once the blastula forms, a new process called gastrulation begins. Gastrulation occurs when some of the cells on the hollow ball (blastula) begin to invaginate or fold inward forming a pouch. This folding will eventually become the digestive tract of the newly developing crawfish. The opening or stomodeum of the gastrula will become the mouth. Another folding will occur later, forming the proctodeum or embryonic anus of the crawfish. Buds will form on the gastrula that will eventually become the eyes. Shortly, more buds will emerge from the mass of cells to differentiate into the many appendages of the crustacean. Fig. 16.

Growth continues as cells divide and differentiate into tissues and organs. Finally all of the major body organs and appendages are developed and the egg hatches. As in many newly hatched animals, the head and optic region are out of proportion to the rest of the body. Yet the young crawfish is fully equipped to survive. The eyes are large and the cephalothorax is exaggerated. This differs considerably from what takes place in many marine crustaceans such as penaeid shrimp and the tiny, planktonic copepods. Their eggs hatch in less than 48 hours, producing a "creature" called a nauplius that looks like an ovate ball with three sets of paired appendages. If you have ever raised brine shrimp, the larvae that hatch from the eggs are nauplii. These must undergo more than 15 different stages (nauplius, protozoeal, zoeal, and mysis) before they assume an adult appearance. The elimination of those stages complete with excellent maternal protection are adaptations that crawfish have undergone. Thus they are able to adapt and invade freshwater habitats from their ancestral homes in the sea.

While in the burrow, the female does not keep the eggs submerged. Instead she keeps them wet at all times, as the water in the burrow is normally too low in oxygen to support the needs of the developing embryos. However, as long as the eggs are wet, oxygen can diffuse from the atmosphere into them. The female fans her swimmerets, constantly exposing the eggs to the humid burrow atmosphere.

Growth. Initially the young red crawfish is connected to the swimmerets of its mother by the telson thread originating from the egg stalk. It is also able to grasp the egg stalk with its claws. It survives on food stored in the unused yolk within its body and eats parts of the old eggshell. The first molt frees it from the old eggshell, and the second molt gives it even more freedom. Yet the young crawfish will return to the mother because she produces a "brood" pheromone that attracts them to her. Fig. 17.

During the initial molts, the carapace, abdomen, and appendages grow. The size at which the young leave the mother is about 1/3 inch.

Females normally leave the burrows when fall rains raise water levels in otherwise dry habitats. The moisture probably helps the female by softening the hard mud plug at the end of the burrow. This means that young hatched in mid-summer may have to remain in the burrow for 6 to 12 weeks. Not surprisingly, these young suffer considerable mortality. Dr. Mark Konikoff of the University of Southwestern Louisiana proved conclusively what others had long suspected: the adult red crawfish in the burrow, male and female, may eat their progeny. In addition, the small crawfish will eat each other. Through the first two molts, they survive on stored yolk from the egg, but they must begin to eat within a reasonable amount of time. Although there are food items available in the burrow, many young crawfish could deplete them quickly. Finally, crawfish of all sizes will also kill each other under crowded conditions even in the presence of a great deal of food.

After the female leaves the burrow, the young will occasionally leave her as she forages about. Attracted by her pheromone, they will continue to return to her. Eventually the young are left behind as her activity increases and her production of maternal pheromone ceases.

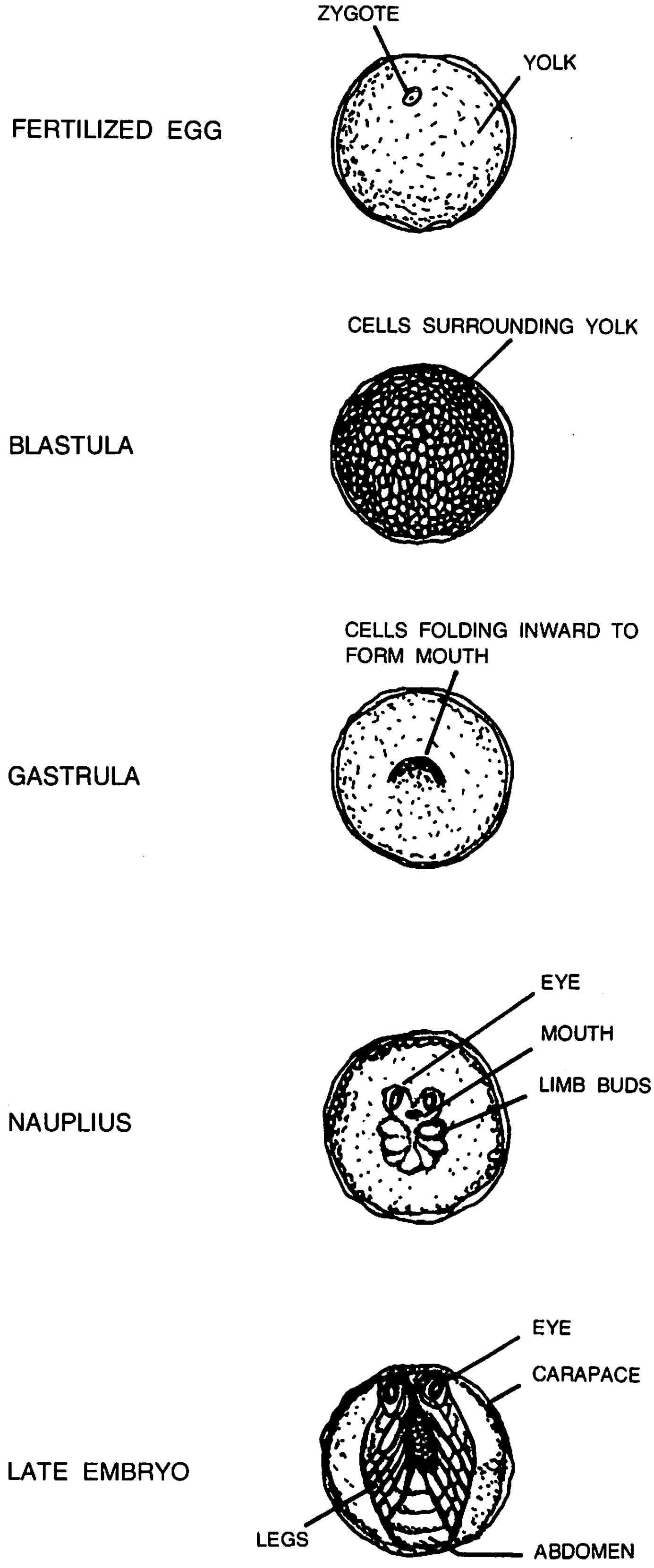


Fig. 16. Crawfish embryonic development.

Hatchery owners have observed that both hatchlings and eggs may be eaten by females, but egg eating occurs more often. Dead eggs are frequently removed and eaten before fungus can attack them and spread to viable eggs.

John and Katherine Wright, Newberry Crayfish Hatchery, Santa Barbara, CA, also observed a "baby snatcher" phenomenon. They report that some females in group situations gain first and second instar young from their mothers. Survival is not affected.

Once the young crawfish enter open water, growth can be quite rapid. Molting can occur every five to ten days if water temperatures are 70° to 80°F. Crawfish will undergo a minimum of nine molts following release from the mother before they mature. With such a growth rate, they will become mature in as little as two months. (Minimum number of molts to maturity are eleven, as there are two with the mother.)

An interesting juvenile behavior pattern observed by the Wrights is the "fetal ball." When young red crawfish are threatened they may curl up into a ball. Dr. Hayes has observed this in other species of crawfish and suggests that it may increase the size of the crawfish relative to the mouth of its predator. This would make the crawfish too big to eat.

Growth also depends on the type of habitat. In restricted habitats such as ditches and temporary ponds, normal molt growth increment is 1/4 inch with a mature size of 2 1/4 to 3 inches. In large swamp and marsh habitats or culture ponds, the molt increment can be as much as 1/2 inch per molt with a mature size of 3 1/2 to 4 1/4 inches. Exceptionally good conditions will produce a 5 inch crawfish in one growing season.

The length of time that it takes a crawfish to mature is quite variable, depending on environmental conditions. Water temperatures must be an optimum 70° to 80°F; food must be abundant; there must be sufficient oxygen in the water; and perhaps most important of all, there must be water present. Water is a critical factor in all natural habitats. In culture ponds, it can be controlled to some degree. Even though ideal conditions are not always present, growth to maturity in nature normally takes three to five months.

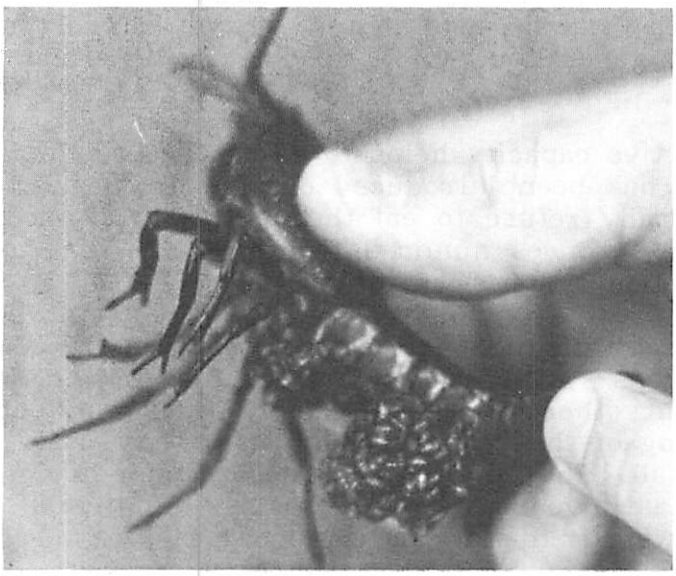


Fig. 17. Female red crawfish with newly hatched young attached to swimmerets.

During growth, the young crawfish are normally a green-brown (in murky water) or green-black (in clear acid stained swamp waters). But when they mature, they undergo drastic changes in physical appearance both in body proportions (discussed in the Reproduction section) and color. The backs of males and females turn black, their sides turn red (the darker the water, the more vivid these colors will be). Fig. 18.

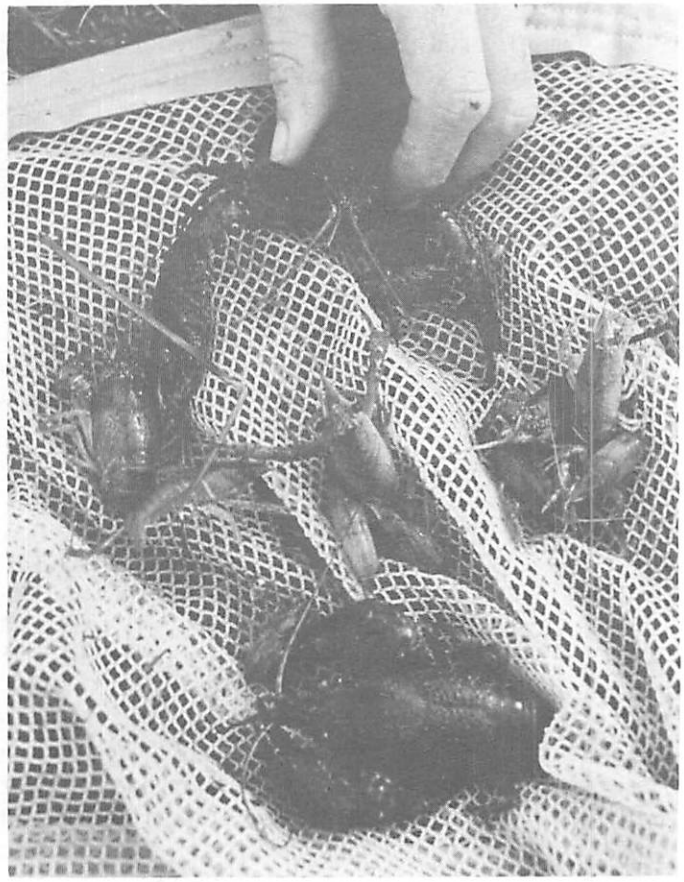


Fig. 18. Several age classes of red crawfish.

We have noted that egg production can take as few as six weeks; that incubation and maternal attachment takes three to four weeks; and that maturation can take place in as little as eight weeks. This means that under ideal conditions a generation of P. clarkii can be produced in four and one-half months. Two generations of P. clarkii have been observed in Louisiana ditches and crawfish ponds in a single year, yet the average number of generations under normal conditions is actually one and one-half generations. Natural habitats are greatly dependent on the vagaries of nature to generate rainfall and floodwaters. Young crawfish will not grow in dried up habitats. Egg maturation, egg incubation, and growth are all severely inhibited by temperatures below about 50° to 55°F. In fact, cold weather forces P. clarkii to shift from a fall-winter-spring growing animal in the deep South to a summer growing animal in the northern parts of its U.S. range and in Japan where it has been introduced. Conversely, in areas such as Costa Rica, Hawaii, and Kenya, which are warm all year long, two and one-half to three generations of P. clarkii can be produced each year.

P. clarkii's phenomenal reproductive capacity helps to explain its reputation as a troublemaker and pest where it has been introduced outside of its natural range. Residents of such areas normally refuse to eat them and natural predators are few. Constant reproduction produces hundreds of thousands of crawfish, which can wreak havoc on irrigation systems and crops.

At least in Louisiana, all young crawfish do not leave burrows at the same time; rather, there are distinct periods (at least two) during the summer and fall when more young emerge than at other times. These are referred to by fisheries biologists as waves of young-of-the-year recruitment. They seem to correlate with periods of heavy rainfall. The length-weight relationship for mature (Form I) males, immature or quasi-juvenile (Form II) males, and female P. clarkii may be obtained from the following mathematical relationships:

Form I males	$\log W = -4.885 + 3.2186 \log L$
Form II immature males	$\log W = -4.8537 + 3.1552 \log L$
Females	$\log W = -4.9659 + 3.2196 \log L$

(Log = base 10 logarithm; W = weight in grams [1 oz = 28 grams]; L = total length in millimeters [1 in. = 25.4 mm]).

The carapace is roughly one half of the total length of P. clarkii. The mathematical relationships between carapace length and total length are as follows:

$$TL = 2.6984 + 1.8581\ CL$$

$$CL = -1.4522 + 0.5382\ TL$$

(TL = total length in millimeters; CL = carapace length in millimeters.)

Excretory System

Excretion. Crawfish such as P. clarkii have water constantly flowing into the body. As their body fluids have much greater concentrations of dissolved salts than do the surrounding fresh waters, this flow increases the osmotic pressure. The body of the crawfish is covered for the most part by a heavily calcified shell that is impermeable to the osmosis of water. This reduces the amount of water that can enter the body by osmosis; however, some semipermeable cuticle is present in the branchial chambers. The elimination of the excess water that enters the crawfish is largely accomplished by the paired green glands (also called antennal glands). The green glands produce large amounts of urine that are very low in dissolved salts and other dissolved solids. One investigator found that adult P. clarkii normally produce a volume of urine equal to about 4.5 percent of their body weight in 24 hours. Naturally, when a crawfish is outside of water, whether resting in a humid burrow or crawling about on dry land, it is not absorbing much water; therefore, very little urine is produced. This conserves the water within the body.

In P. clarkii the levels of salts and water in the hemolymph (blood) and body tissues are controlled by hormones produced by neurosecretory centers in the brain and eyestalks. These hormones are stored and released by the sinus glands located in the eyestalks. By removing the eyestalks, the crawfish will undergo a very gradual weight gain because the crawfish can no longer eliminate water faster than it enters its body. By implantation of a sinus gland, the condition can be halted. This suggests that hormones stored by sinus glands may affect the osmoregulatory function of the green glands. Thus with such complex excretory organs, crawfish and other crustaceans have been able to survive in variable aquatic habitats. Changes in the salt concentrations in water alter the osmotic pressure in an environment; therefore, some animals live only in fresh water or only in salt water. Animals that are adapted to fresh water must be able to remove the excess water from their bodies, whereas those living in salt water must be able to maintain an adequate amount of water. Organisms sensitive to slight changes in dissolved salt concentration in water are said to be stenohaline. Organisms that can maintain an equilibrium over a wide range of dissolved salt concentrations are called euryhaline. P. clarkii is euryhaline and can survive in water almost completely free of dissolved salts and up to eight weeks in waters with salinities up to 20 ppt. The preferred salinity in which reproduction occurs ranges between 0.5 ppt (considered fresh water) to 4-5 ppt (mildly brackish water). Growth will continue at salinities up to 12 ppt.

Waste Elimination. Ammonia, a toxic waste produced by animals, results from the metabolic breakdown of proteins that contain nitrogen. When the protein is metabolized, the nitrogen is cleaved from it and hydrogen is combined with it, thus transforming it into ammonia (NH_3). Ammonia is lethal but is also soluble. This is convenient for aquatic animals, as most eliminate ammonia by diffusion through the relatively permeable gills and branchial chamber surfaces. Ammonia and other protein waste products are also excreted in low concentrations in the urine.

Salts, including the critically important calcium salts (an integral part of the shell), are absorbed either through the digestive tract from food or by special cells in the gills that absorb them against a concentration gradient. In fresh water, the concentration of dissolved salts is always much lower than it is in the body fluid of crawfish. Thus, the natural tendency is for those small permeable salt ions to constantly diffuse out of the body).

Green Gland Structure and Function. The green glands are the major structures involved in the production of urine. Each green gland is made up of five major parts. This remarkable organ consists of an end sac surrounded by hemolymph and connected to a labyrinth (excretory tube) leading to a bladder. The exit duct of each gland leads to openings (excretory pores) located on the inner side of the basal segments of the antennae. That is why green glands are also referred to as antennal glands. Wastes are removed from the blood by changes in the hydrostatic pressure in the end sac.

There is a natural tendency for fresh water to flow into the body of the crawfish because of the concentration differences. Energy is required to pump water out of the body into and from the green glands. Secretion plays an important role in the production and elimination of hypotonic (dilute) urine. Cross sectional views of the epithelial cells of the green gland labyrinth of one species of crawfish (Astacus astacus, a European species) indicate that small bladders are formed at the edge of the lining while urine is being produced. The small bladders contract and force the fluid (largely water) into the labyrinth. This then flows into the bladder where it collects until it is passed out of the body.

In P. clarkii water has also been shown to be secreted into the excretory tube. The lining of the excretory tube consists of columnar shaped cells that have large cavities called vacuoles extending from them into the lumen (hole in the tube). These function in the same manner as the cells lining the green gland labyrinth.

Molting In Crawfish

If a crawfish is to grow, it must periodically shed its hard, outer shell or exoskeleton by molting, or ecdysis. Molting occurs more frequently in younger animals than in older animals and in warmer water than in colder waters. Under ideal conditions, the molting cycle takes place in as few as five to six days in rapidly growing juveniles.

Molt Cycle. Scientists divide the crawfish molt cycle into five stages, each designated by capital letters. The stages and their common names are A for soft, B for paper shell, C for intermolt, D for premolt, and E for molt. They may be further subdivided by the addition of subscripts A_1, A_2, B_1, B_2, etc.

The intermolt cycle is a period between molts. A series of phases, based on the formation of the new shell and the dissolution of the old shell, have also been established. These overlap the basic stages listed above. To be sure, a number of different physiological processes take place but synthesis of the new and dissolution of old exoskeleton are prominent processes. The intermolt phase (C_4) is that period in which all four layers of the shell have been completed. That is, the epicuticle, exocuticle, endocuticle, and membranous layer are all present. This phase occupies less than 10 percent of the entire intermolt cycle in rapidly growing crawfish.

The premolt phase (D_0, D_1, D_2, D_3, D_4) involves the dissolution of the membranous layer, the endocuticle, and much of the exocuticle. At the same time, the new epicuticle and exocuticle are being synthesized. These exoskeletal layers are soft and pliable; they will undergo tanning, a hardening of proteins in the epicuticle and exocuticle, or calcification of the exocuticle following malt. A detailed description of the events that take place during this phase is as follows. As the premolt phase begins, an actual separation occurs between the old shell and the living epidermal layer beneath it. This substage is called D_0. The crawfish is not, at this time, firmly committed to continuing the molting process and may remain in this state indefinitely. Normally, however, special enzymes begin to destroy the old shell. The process of producing the outer epicuticle and exocuticle of the new shell begins in substage D_2. The epicuticle has one layer, but the exocuticle is multilayered. At that time the old shell has become flexible compared to the intermolt shell. If the old shell is broken, the new, uncalcified shell will be present beneath it. Dissolution of the old shell, then, proceeds at a rapid rate. The crawfish stops feeding and becomes shy and retiring, seeking shelter in roots, crevices, and dense vegetation. By the end of substage D_3 the shell is so brittle that it will readily crack from the slightest pressure. Substage D_4 involves the last few hours before molt. The entire premolt phase occupies about 60 percent of the entire intermolt cycle.

The molt phase (E_1, E_2, E_3, E_4) is the actual period in which the old shell is shed. It is rapid, taking less than an hour. It is first announced by the appearance of a prominent separation on the dorsal surface between the cephalothorax and abdomen (E_1). After this, the carapace itself is thrown forward (E_2); the legs, claws, gills, and other cephalic (head) structures are withdrawn (E_3); and finally the tail is withdrawn (E_4) with the crawfish escaping from the old shell with a quick flip of the tail.

The soft phase (A_1, A_2) is the period in which the new, soft shell is swollen to its new dimensions by the absorption of water. Initial hardening, through tanning of protein in the epicuticle and exocuticle, takes place. Before tanning begins the crawfish is said to be "butter soft." The soft phase is completed in a matter of hours.

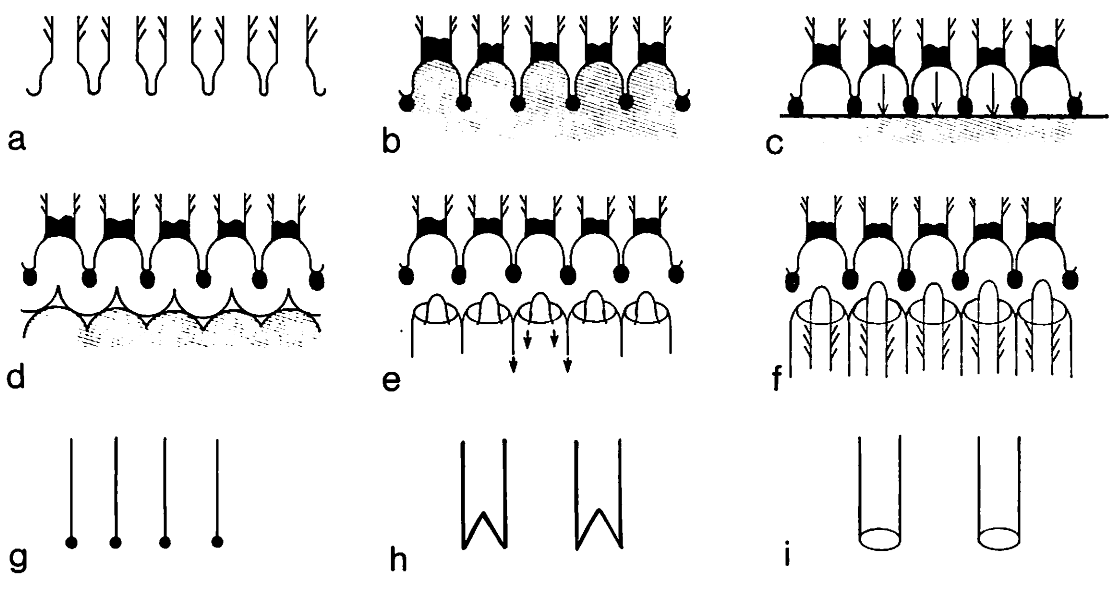
The postmolt phase (B_1, B_2, C_1, C_2, C_3) is the period in which the exocuticle is calcified (B_1, B_2) and the new endocuticle is deposited as layers of protein/chitin matrix. Each layer is calcified as it is synthesized (B_2, C_1, C_2, C_3). This phase occupies about 30 percent of the intermolt cycle.

When the final shell layer, the thin, inner uncalcified membranous layer, is complete, the crawfish is again in the intermolt phase and the intermolt cycle is complete.

Techniques for rapidly identifying molt stages have been developed. The most convenient involve external examination by checking the relative hardness of various parts of the cephalothorax and changes in color. Other methods require microscopic examination of the changes that take place in the setae, or hairs, at the edge of the uropods during the cycle. Table 2 provides information on both subjects. The accompanying figure shows formation of new setae. Fig. 19.

The calcium from the old shell is either excreted into the water or stored in the body. It may be stored in body tissues (primarily in the hepatopancreas), in the hemolymph in association with hemolymph serum proteins, or in the gastroliths, the stomach stones. Enough calcium is stored in the body to permit the crawfish to maintain ionic equilibrium with the influx of water during and after the molt. At that time, the shell hardens to about one-half the intermolt level. The remainder must come from the environment. The chitin in the old shell is chemically broken down into its building blocks, ethyl acetate molecules. Research has shown that the molecules are reused after the molt. If the crawfish has the opportunity, it will always eat the old shell after it has molted, which is an excellent source of calcium and chitin.

Two molting abnormalities in red crawfish frequently observed by hatchery owners are gill damage and tight pants. In gill damage one or more gills protrude from the branchial chamber and eventually disintegrate. In tight pants stage E_4 does not occur; that is, the abdomen does not free itself from the exoskeleton, and the cephalothorax is disproportionately large compared to the abdomen. This problem usually corrects itself at the next molt.



Legend: a. Stages A & B. Bases of setae have hollow appearance; b. Stage C. Inner cones of setae present. No retraction of epidermis not apparent from bases of setae. c. Stage D_0. Epidermis begins to retract from bases of old setae. Line is relatively straight. d. Stage D_1'. Edge of retracted epidermis has definition-columnar shape. Pointed setal organs apparent. e. Stages D_1''. There is evidence of invagination distal to edge of retracted epidermis as new setae form as "tubes within tubes". f. Stages D_1''', D_2, D_3, D_4. New setae form. Distal shafts in center with lateral barbules giving structure a bushy appearance. g. Stage D_1'''. Bases of new setae have no distinct shape. h. Stage D_2. Bases of new setae have V-shaped appearance. i. Stages D_3, D_4.

Fig. 19. Formation of new setae.

Table 2. Description of variation in the appearance of uropod setae§ and of changes in exoskeleton strength during the molt cycle of *Procambarus clarkii*.

Molt Stages	Relative Darkness	
Stages A,B,C*		No retraction of epidermis is apparent at the bases of uropod setae (Figs. 1a,1b).
Stages A&B	Very light	Inner cones just above the bases of the new setae are not developed (Fig. 1a).
Stage A		Fluid may be seen flowing through the shafts of the new setae in live crawfish. The exoskeleton is very soft to slightly rigid (parchment-like).
Stage B		No fluid may be seen flowing through the shafts of the new setae in live crawfish. The exoskeleton becomes progressively more rigid.
Stage C	Light	Inner cones just above the bases of the new setae are well developed (Fig. 1b). The exoskeleton is as rigid as it will become but remains slightly flexible laterally.
Stage D†		Retraction of the epidermis is apparent at the bases of the uropod setae (Figs. 1c,1d,1e,1f).
Substages D_0 and D_1	Dark	The shell remains as rigid as it was during Stage C.
Substage D_0		The edge of the retracted epidermis is smooth without distinct shape. After retraction becomes fully apparent, narrow, pointed setal organs can be seen projecting from this edge. These persist into Substage D_1 when invagination along their edges gives rise to the central, distal shafts of the new setae (Figs. 1c,1d).
Substage D_1'		The edge of the retracted epidermal tissue has distinct definition (columnar shape) but there is no evidence of extensive invagination distal to the edge (Fig. 1d).
Substage D_1''		There is evidence of invagination distal to the edge of the retracted epidermal tissue as new setae form (Fig. 1e).
Substage D_1'''		Invagination is complete and new setae are formed appearing as "tubes within tubes." The bases of the new setae have no distinct end (Fig. 1g). Lateral barbules are seen forming along the distal tip of the central shafts of the new setae.

Table 2. (cont.)

Molt Stages	Relative Darkness	
Substages D_2, D_3, and D_4	Very dark	The old exoskeleton becomes progressively more brittle and the new exoskeleton can be separated from the old one.
Substage D_2		The bases of the new setae have a distinct, inverted V shape (Fig. 1h). Barbule development on the central shafts of the new setae reaches its maximum extent (Fig. 1f).
Substage D_3		The bases of the new setae have a distinct, rounded shape (Fig. 1i).
Substage D_4		A narrow separation appears between the carapace and the abdomen.
Stage E	Very, very dark	The molt itself.
Substage E_1		The thoracic-abdominal membrane is distended and the posterior margin of the carapace is slightly elevated.
Substage E_2		The carapace is thrown forward, and the cephalic structures are withdrawn.
Substage E_3		The abdomen and related components are withdrawn.
Substage E_4		The walking legs are withdrawn and the crawfish flips free of the old exoskeleton.

*Not to be confused with actual colors seen in adult non-molting crawfish. The old exoskeleton is being dissolved and becomes transluscent. One is seeing pigment in the new exoskeleton beneath the old one. Remember crawfish from dark, tannic acid stained waters will be very, very dark at all times.

†The shell of very young crawfish (to about 35 mm in length) is so thin that the gastrolith may be seen directly through the shell just below and to the rear of the eye.

§Uropod setae are examined by holding the animal in one hand, ventral (belly) side down, and placing the tail fan on a slide on the stage of a microscope below the low power (10X) objective. The other hand is used to adjust the microscope. The uropods are manipulated beneath the objective to examine various areas.

DISEASES

Several diseases are a serious hindrance to the survival of European crawfish in natural waters. On the other hand North American species appear to be relatively resistant to most of the disease problems found in European crawfish. These problems have led to considerable study of their causes and possible cures in Europe. Little attention has been devoted to such considerations in North America because no real problem exists at this time.

A number of shellfish diseases that are caused by poor sanitation can adversely affect North American crawfish, especially when they are confined in close quarters. As this rarely occurs in nature and as intensive culture in confined containers is not practiced to a large extent, disease problems in confined containers have not generated much concern. Should intensive culture of North American crawfish become a reality, diseases will undoubtedly receive more attention as their frequency increases.

SPECIFIC DISEASES

Microbial Diseases

Shell Disease. The exoskeleton of all crustaceans is utilized as a source of food by a group of bacteria known as chitinoclastic bacteria. The exoskeleton, consisting of a chitin-protein matrix and calcium salts, is readily broken down by microbes once they get past the protective epicuticle layer. The bacteria produce enzymes that digest the shell. Normally, the bacteria cannot penetrate the thick endocuticle before the crawfish molts. Thus molting temporarily eliminates infection. As the bacteria are always present in the environment, they can reestablish themselves in the new exoskeleton providing there is a scratch or break in the epicuticle layer. If the bacteria penetrate the flesh before a molt, they infect the flesh, destroy body parts, and lead to death.

Filamentous Bacteria. Heavy infestations of filamentous bacteria, which are commonly found on the gills, may clog them and interfere with respiration. Such infestations are normally associated with a buildup of organic wastes in culture systems, which is not to be confused with detrital material needed to supply essential nutrients.

Crawfish Plague. The crawfish plague, caused by the fungal parasite *Aphanomyces astaci*, is apparently native to North America and does not adversely affect North American species. European, Asian, and Australian crawfish are highly susceptible to the plague. In many European areas, native crawfish have become extinct. From the original outbreaks in 1860 in northern Italy, the plague spread through France into Scandinavia, central Europe, and Russia.

A crawfish infected by the crawfish plague becomes sluggish and has yellow or brown stains on the carapace and abdomen. Fungal filaments are found in the joints of appendages and eyestalks. Eventually plague fungus attacks the central nervous system and quickly destroys motor coordination. P. clarkii has been shown to be resistant to the crawfish plague.

Gut Bacteria. Many types of bacteria reside in the gut of aquatic animals. These can produce toxic secretions that are potent neurotoxins if concentrated in confined areas. These can become a problem in poorly kept, crowded tanks and in shallow, drying pools in ponds, swamps, marshes, and ditches. The animals defecate into the hot, stagnant waters rich in organic matter. These conditions are ideal for rapid proliferation of bacteria, which produce toxins that will kill crawfish in 12 to 48 hours. In nature this phenomenal growth represents a clean up mechanism. The environment cannot support the influx of a large number of animals. Death reduces their population to a level that can be sustained by the environment.

Protozoan Diseases

Protozoans are unicellular organisms that are neither animals nor plants but share characteristics of both. Two groups can cause significant health problems in crawfish.

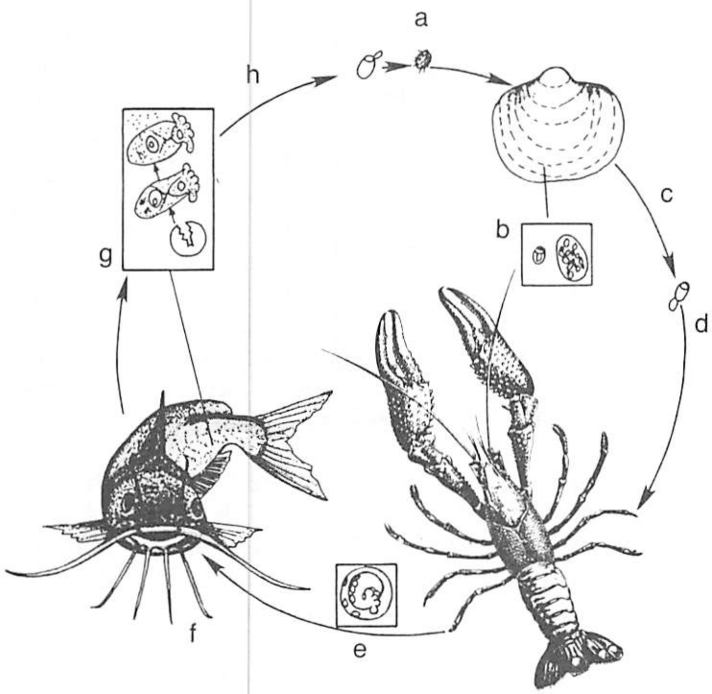
Microsporidians. Microsporidians attack body cells, primarily muscle cells. They multiply by production of large numbers of spores within the infected cells. When they reach very large numbers, the flesh takes on a milky white appearance. When this occurs in shrimp, it is called the cotton shrimp disease. Many scientists refer to the disease as the porcelain disease. The causative agents are microsporidian protozoans normally of the genus Thelohania. These are common in Europe and have been identified in the Cambarid genera, Cambarellus, Cambarus, and Procambarus; however, they have not been specifically isolated from P. clarkii. A number of investigators have sought to isolate these organisms in P. clarkii, but none have been found. This suggests that microsporidians are not a serious problem in the species.

On several occasions, P. clarkii that appear to be heavily infected with microsporidians (flesh turns opaque and white) have been found in southern Louisiana; however repeated examination with the best electron microscopes has failed to show the presence of microsporidians. The condition seems to be some sort of physiological imbalance.

Ectocommensal Protozoa. Ectocommensal protozoa are tiny organisms that live on the exoskeleton surface of crustaceans. Several common ectocommensals found on crawfish are Zoothamnium, Epistylis, and Lagenophrys. These find a convenient haven on body surfaces and in joints. Those ectocommensals that inhabit areas on the gills pose the greatest potential problem. When low oxygen levels prevail, the presence of these protozoans on the gills reduces the level of oxygen flow into the blood. Since the lining of the branchial chambers including the gills is shed at each molt, the ectocommensal protozoa are eliminated frequently in rapidly growing, juvenile crawfish. Unfortunately, molting may slow during periods of harsh environmental conditions and during the reproductive period. At such times, the numbers of ectocommensal protozoa may reach harmful levels. The demise of many adult crawfish obtained for brood stock is attributed to this problem. As reproducing adults are normally in burrows, deaths attributed to protozoa and other problems would not be evident. As with the filamentous bacteria, protozoans thrive in organically rich environments. Sanitary conditions are important if crawfish are closely confined.

Internal Worms

Flukes and Spiny-Headed Worms. Two significant worms that infest crawfish are the flukes (trematodes) and the acanthocephalans (spiny-headed worms). Both of these groups have highly specialized life cycles and all are parasitic. Those worms that parasitize crawfish generally do so during certain immature stages of their life cycle.



Legend: a. egg hatches and miracidum (penetration stage) enters first host, a small clam; b. the redia stage develops within the clam and produces 30-40 new individuals of cercaria stage; c. free swimming cercaria leave clam in search of second host, a crawfish; d. cercaria penetrates crawfish and migrates to area around heart; e. metacercaria, the next stage, develops within a cyst; f. second host is eaten by final host, either a fish or amphibian; g. fluke breaks out of excreted cyst and soon begins to produce eggs; h. when eggs are released and reach a host clam, cycle is complete.

Fig. 20. Fluke life cycle (*Crepidostomum cornutum*).

Immature flukes and spiny-headed worms form small cysts (resting stages) less than four-hundredths of an inch in diameter in various regions of the crawfish body, including the cardiac region, digestive gland, abdominal muscles, gut, and the green glands. One larval spiny-headed worm and eight larval flukes have been recovered from *P. clarkii* in Louisiana. Even though parasitic infestations signify a poor health condition in most animals, most parasites do not kill their host; rather they use it for a part of their life cycle. Crawfish are generally considered to be a secondary host, while fish, egrets, herons, racoons, or other carnivores that eat crawfish are considered to be the final host. The complex life cycle of a parasitic fluke that infects crawfish is shown in the accompanying illustration.

Fluke Life Cycle. Some flukes are known to infect man and other mammals. One group, the Microphallids, infect crawfish-eating mammals. Humans are not considered the normal final host for such flukes, but the lung fluke, *Paragonimus kellicoti*, which is found in Louisiana populations of *P. clarkii*, is known to afflict man. A closely related species, Paragonimus westermani, frequently infects P. clarkii in Japan. Thorough cooking eliminates the problem of human contamination. Fig. 20.

Green Gland Parasite. Most fluke trematode infections of crawfish involve larval flukes with the crawfish as the intermediate host. An exception is the existence of a Dicrocoeliid trematode called Allocorrigia filiformis, which completes its life cycle within the green gland of P. clarkii. In one study, 65 percent of the P. clarkii collected in the southern Louisiana area were infected by these flukes. The significance of their presence remains to be shown.

EXTERNAL INVERTEBRATES

Branchiobdellid Worms

Branchiobdellids are tiny, segmented worms that are related to leeches and earthworms. These small organisms have been described as parasites or commensals. Commensal organisms are those that live in close association with the host but the relationship is not so close that one cannot survive if the other is not present (parasites cannot survive without their hosts). These tiny worms can be seen projecting from body surfaces, especially from beneath the abdomen and around the branchial area, as well as on the carapace itself. Branchiobdellids actually enter and live within the branchial chamber. Cocoon-like eggs are deposited on the underside of the abdomen or rostrum of larger crawfish. It is believed that they are dispersed primarily by bodily contact. Thus, dense populations spread the organism more easily. There is some conjecture as to whether or not branchiobdellids that attach to gills are parasites, as large numbers may physically impair oxygen exchange by blocking gill surfaces.

An interesting relationship has been observed between the red crawfish and mosquitofish (Gambusia affinis) in the laboratory. The mosquitofish will eat any branchiobdellid that is present on an exposed surface. This is reminiscent of the cleaner fish in tropical seas that eat external parasites that infect larger fish. Whether a commensal mosquitofish-crawfish relationship occurs in nature has yet to be determined.

Copepods

These are microcrustaceans (less than 0.5 inch long) that are usually free living. One group, the Entocytherids, are commensal in the gill chambers of crawfishes. Several species, Ankylocythere sinosa, A. copiosa, Entocythere internotalus, E. veddelli, Thermastrocythere riojai, have been reported from the red crawfish.

Nematodes

These round worms are serious parasites of many organisms including man himself. Little is known about nematode infections of crawfish.

CONDITIONS

There are several conditions that are seen in crawfish that may not be parasites or diseases. However, they may adversely affect crawfish just the same.

Water Boatmen Eggs

Water boatmen (family Corixidae) are aquatic hemipteran insects that can fly as adults. They lay their eggs on the shells of crawfish. The carapace of nonmolting adult P. clarkii may be completely covered by such eggs. The eggs do not harm the crawfish; however, extensive concentrations may render a crawfish helpless by interfering with movement of body appendages. This is a rare condition.

Tumors

Tumor-like growths have been observed occasionally on a number of crawfish species including P. clarkii. Almost nothing is known about their origin or significance.

Uropod Swellings

A condition frequently observed in P. clarkii involves the extensive swelling of the tips of the uropods. They become so swollen that they appear ready to burst. Examination of the fluid that can be obtained from such swellings reveals no disease-causing organisms. The condition is common and apparently does not cause any adverse effects on the crawfish.

Gas Bubble Disease

Presumably, gas bubble disease involves the formation of nitrogen gas bubbles in the tissues of aquatic organisms found in waters that are supersaturated with nitrogen gas. Although not a widespread problem, this condition has been observed in specimens of P. clarkii from small ponds and raceways that were being filled with water from deep wells. Crawfish, which cannot normally float, will float to the surface as a result of the bubbles in their flesh. If caught in time this condition is reversible.

Soft Shell Syndrome

When red crawfish are growing rapidly their shells are tender and easily broken and crushed. If too many crawfish are packed in a transfer sack at such times, they will crush each other. Hemolymph and body fluids will accumulate, and the respiratory activities of surviving crawfish will create a bubbling froth on the surface of the sacks. To prevent this problem, crawfish should either be handled with extra care or not harvested until their shells get harder.

Hollow Tail Syndrome

Reproductively spent (senile) adult red crawfish show considerable degeneration of the abdominal muscles. When boiled, the flesh occupies less than one fourth of the space within the area bounded by the abdominal exoskeleton. For this reason, such crawfish are often referred to as hollow tail crawfish by people in south Louisiana. Much has been written about this phenomenon based on observations of red crawfish populations in Kenya. Although considered a mysterious condition by European scientists working with the species there, it is a natural phenomenon, not an unknown disease.

RESISTANCE TO AND CONTROL OF DISEASES

The exoskeleton covering the body provides an effective barrier against most organisms trying to invade crawfish. Parts of the digestive tract, however, are not so protected and can permit invasion. Wounds or superficial scratches may also permit such invasions. Crawfish apparently have components of the hemolymph that inactivate invading bacteria. Amoeboid blood cells are attracted to the bacteria, and they engulf and eliminate them. Large invaders such as fungal filaments (hyphae) and small worms may be encapsulated by blood cells. Formation of the pigment melanin (a black pigment) around invaders also apparently plays a role in the defense of the blood and the exoskeleton against invaders.

External parasites and commensals may be removed from crawfish by the use of solutions of several chemicals commonly used in fish culture. These include table salt (NaCl), formalin (embalming fluid), potassium permanganate ($KMNO_4$), and the green dye, malachite green. The crawfish are dipped into a specific solution for several minutes. The thin bodied parasites and commensals are killed quickly while the crawfish with its resistant exoskeleton is not harmed. Occasional increases in salinity of culture waters to 15 ppt for 10 days are said to help control bacterial problems.

Intensive crawfish culture systems should be kept relatively clean. This means that debris, such as uneaten food and fecal material, should not be allowed to accumulate to levels where anoxic conditions develop within the system. Epiphytic organisms, especially algae, are important but unquantified sources of trace nutrients and are needed to insure healthy growth of confined crawfish. Culturists should keep this fact in mind when setting up and maintaining culture systems.

Strict regulations govern the use of various therapeutic chemicals to control diseases of aquatic organisms. Normally, a concentration of a therapeutic chemical recommended for fish will work with red crawfish. Water quality and temperature affect the response of all aquatic animals to chemicals. A concentration of chemicals that is effective in hard water may prove to be lethal in soft water. Therapeutic chemicals are not now used in pond culture of red crawfish.

TAXONOMY AND ZOOGEOGRAPHY

Taxonomy is the systematic classification of living organisms (according to their natural relationships) into a series of categories, or taxa, each more exclusive than the one before it. The basic taxa include kingdom, phylum, class, order, family, genus, and species. These may be further subdivided by the addition of the prefixes supra- and sub- as well as insertion of categories such as variety, tribe, section, or division.

The basic taxonomic unit is the species. Basically, a species is a group of physically similar organisms that produce fertile offspring. Since it is a living, dynamic unit, each species is constantly changing (see discussion in the Zoogeography section, below).

The foremost North American authority on crawfish taxonomy and zoogeography is Dr. Horton H. Hobbs, Jr., of the Smithsonian Institution in Washington, D.C. The following discussion of the two subjects is taken largely from Dr. Hobbs's publications. See the Bibliography for references to his work.

NOMENCLATURE

Each species is identified by a two-part, descriptive scientific name taken from Latin or Greek, consisting of the genus and the species taxa. This is called the binomial system of nomenclature. This system was formulated by Carolus Linnaeus, the father of modern taxonomy, in the 1700s. When written the genus taxon is capitalized, but the species taxon is not. Both names are either underlined or printed in italics. To be complete, the name of the individual who first identified the species and the date that he or she did so follow the genus and species. An individual's name in parentheses means that the genus was changed subsequent to the original description. For instance, the complete scientific name for the red swamp crawfish is *Procambarus clarkii* (Girard, 1852). That is, a person named Girard (Charles Girard) first described and named the red swamp crawfish in 1852. He named it after John H. Clark, who obtained the first specimen from an area between San Antonio and El Paso del Norte in Texas. Girard's name is in parentheses because he originally placed it into the generic category of *Cambarus*. A convenient shorthand for writing a scientific name is to write it out once and thereafter abbreviate the generic name with its first letter, capitalized, followed by a period. Thus, *Procambarus clarkii* becomes *P. clarkii*.

The purpose of a scientific name is to standardize names among locations and peoples. Some organisms have as many as a hundred common names in several languages, which causes confusion. South Louisiana readers are familiar with a fish that they call a choupique. North Louisiana readers call it a grinnel. Elsewhere in the United States, it is a bowfin, a grindle, or a wolf fish. To all scientists, however, it is *Amia calva*.

CLASSIFICATION OF CRAWFISH

We will now present two classifications for P. clarkii. The first uses the basic taxa mentioned above. The other list is much more complicated and includes many additional taxa. The simplified list should suffice for most people, but the second was developed to insure a more precise classification. All taxonomic schemes can change because scientists continually learn more about the various species. As new information comes to light, concepts of how various taxa are related to one another change. For example, P. clarkii was once Cambarus clarkii, and until recently it belonged to the family Astacidae. Its subfamily, Cambarinae, has been elevated to the family level as the family Cambaridae.

Classification 1

Kingdom	Animalia
Phylum	Arthropoda
Class	Crustacea
Order	Decapoda
Family	Cambaridae
Genus	Procambarus
Species	clarkii

Classification 2

Kingdom	Animalia
Phylum	Arthropoda
Subphylum	Mandibulata
Class	Crustacea
Subclass	Malacostraca
Series	Eumalacostraca
Superorder	Eucarida
Order	Decapoda
Suborder	Astacidea
Section	Macrura
Superfamily	Astacoidea
Family	Cambaridae
Subfamily	Cambarinae
Genus	Procambarus
Subgenus	(Scapulicambarus)*
Species	clarkii

*This is generally placed in parentheses, capitalized, and italicized or underlined.

In North America, crawfish are represented by two families, 10 genera, and 322 recognized species and subspecies. There are several dozen additional species and subspecies yet to be described and named. The smaller family is the Astacidae with one genus, Pacifastacus, and 5 species. The larger family is the Cambaridae, which includes the subfamilies Cambarellinae and Cambarinae. The Cambarellinae are the so-called dwarf crawfish within the genus Cambarellus (13 species). Within the Cambarinae there are 9 genera including Barbicambarus (1 species), Bouchardina (1 species), Cambarus (63 species), Fallicambarus (13 species), Faxonella (4 species), Hobbseus (6 species), Orconectes (74 species), Procambarus (138 species), and Troglocambarus (1 species). Figs. 21, 22.

The standard method for identifying the various North American crawfish is to examine the tips of the first pair of swimmerets (pleopods) of Form I (mature) males. These are called gonopods. Form I males have well-developed hooks at the bases of the walking legs, enlarged claws, and cornified gonopods. The ancestral gonopod was thought to have 4 terminal elements. Subsequent evolution resulted in reduction of the number of elements. For descriptive purposes, the gonopod is considered to hang free from the abdomen. The side toward the head is the cephalic side; that toward the telson is the caudal side; that toward the middle of the body is the mesial side; and that toward the side of the body is the lateral side. Refer to the accompanying figure for examples of gonopods described below. Figs. 14, 23.

The gonopods of the genus Pacifastacus exhibit a far end consisting of a rolled tube. The gonopods the genus Cambarellus have three elements that vary in their relationship to the shaft from straight and parallel to arcing about 90 degrees. The genera Barbicambarus, Cambarus, and Fallicambarus typically bear two elements arced approximately 90 degrees to the shaft. The genera Bouchardina, Faxonella, Hobbseus, and Orconectes also bear two elements, but they are usually relatively straight. Those of Bouchardina are short, broad, and bladelike while those of Hobbseus are short and pointed (they may also be arced 90 degrees to the shaft). In Faxonella and Orconectes, the two elements are relatively long and tapered with those of Orconectes being of more nearly equal length than those of Faxonella, which has one element less than half the length of the other. The genus Procambarus exhibits a great deal of variety in the structures of the gonopods with two to five elements being present although the typical number is three or four. Finally, the gonopods of the genus Troglocambarus have four short, similar elements.

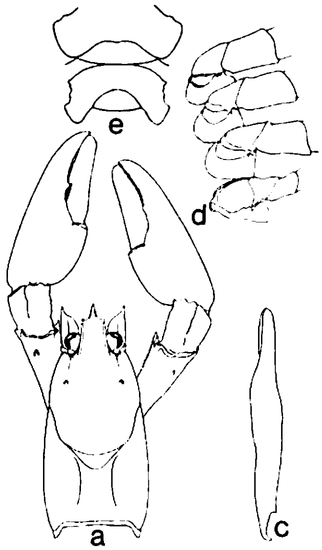
The sperm receptacles of females, also called annuli ventrales are distinctive and may be used to distinguish various species; however, no one has yet been able to develop a biological guide, or key, for systematically distinguishing one species from another. The accompanying figure provides a diagram of the annulus ventralis for a mature female P. clarkii as well as a diagram of the gonopod of a mature male P. clarkii.

As the characteristics of mature males are used for identification, juvenile and female crawfish are frequently identified on the basis of their association with such males. This is not the ideal situation, but any person working with crawfish from a given area will soon recognize juveniles and females.

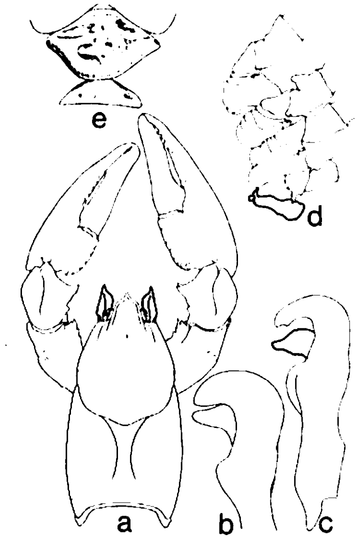
Crawfish taxonomists, of course, use the other physical characteristics of a crawfish species in identifying it as distinct from others. However, gross or general physical appearance can be deceiving, and that is why in many cases the structure of the gonopods is the final means by which differentiation is based. For example, crawfish of different genera will occupy the same general habitats and will have evolved similar physical characteristics in order to live in those habitats. These habitats include permanent water bodies (lakes, streams, rivers, ponds), temporary water bodies (seasonally flooded ditches, sloughs, swamps, and marshes), terrestrial habitats (burrows up to 30 feet deep provide access to ground water), and subterranean habitats (caves). Fig. 24.

Cave crawfish are referred to as troglobites (cave dwellers), while those found at the surface, no matter how briefly, are epigean (surface dwellers). Regardless of genus, troglobitic crawfish are albinistic with very reduced eyes. The eyestalks with their important endocrine organs remain intact.

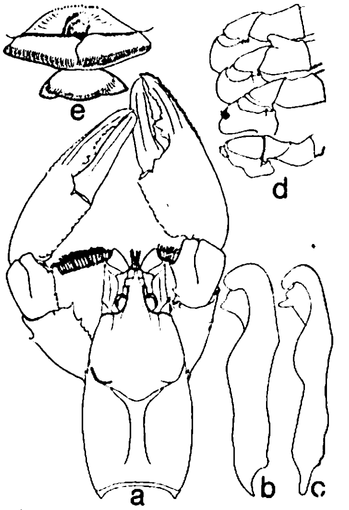
There are three broad categories of epigean crawfish. They are differentiated on the basis of their burrowing habits. Terrestrial crawfish that remain



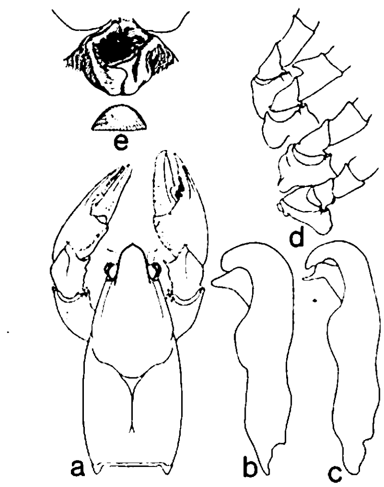
Pacifastacus leniusculus klamathensis
(Stimpson, 1857)



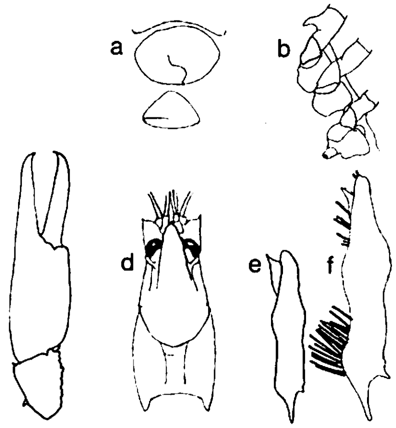
Cambarus bartonii bartonii
(Fabricius, 1798)



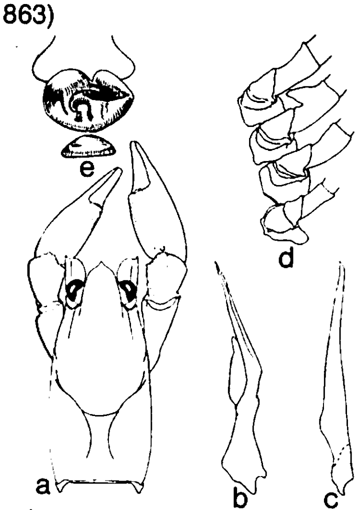
Barbicambarus cornutus
(Faxon, 1884)



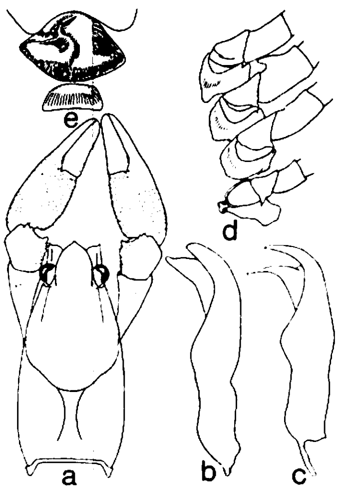
Fallicambarus fodiens
(Cottle, 1863)



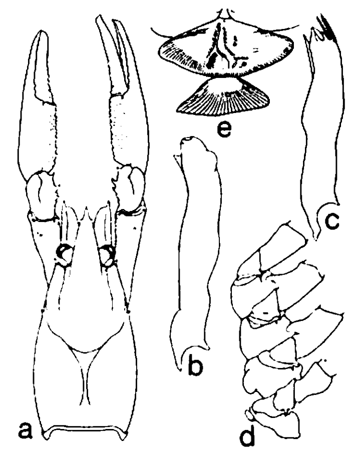
Bouchardina robisoni
Hobbs, 1977



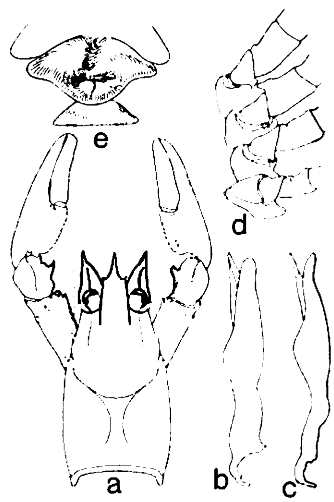
Faxonella clypeata
(Hay, 1899)



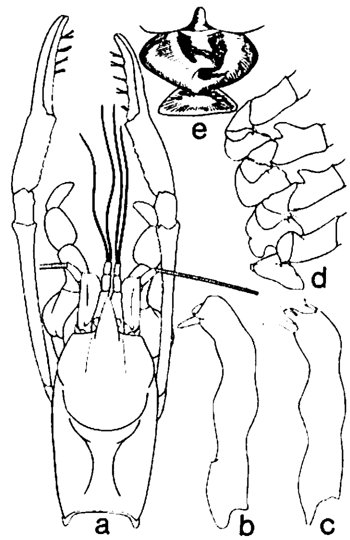
Hobbseus cristatus
(Hobbs, 1955)



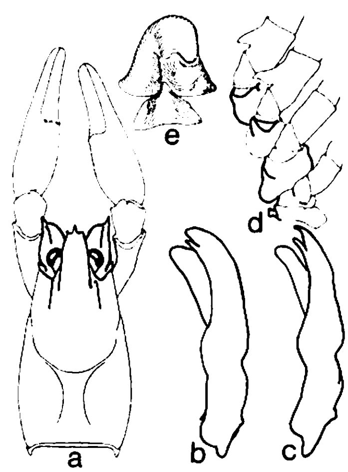
Procambarus blandingii
(Harlan, 1830)



Orconectes limnosus
(Rafinesque, 1817)



Troglocambarus maclanei
Hobbs, 1942



Cambarellus montezumae
(Saussure, 1858)

Legend: a. dorsal view of carapace and chelipeds of mature males, form I (except P. leniusculus)[1]; b. lateral view of first pleopod of sexually inactive male, form II; c. lateral view of first pleopod of male, form I (except P. leniusculus); d. bases of second through fifth walking legs of males, form I (except P. leniusculus); e. annulus ventralis of female.

[1]P. leniusculus does not exhibit the alternative form I-form II body forms seen in North American cambarid crawfishes.

Fig. 21. Key taxonomic features of North American crawfish genera.

in burrows much of the time are called primary burrowers. Those from temporary water bodies that frequently use burrows are called secondary burrowers. The red swamp crawfish falls into this category. Crawfish from permanent water bodies rarely burrow and are classified as tertiary burrowers.

Primary burrowers are specifically modified for life in long, intricate burrows. Claws are typically short and triangular with a broad palm. Such claws are much less cumbersome than the larger, more slender claws with inflated palms found in many of the secondary and tertiary burrowers. They are also very useful in blocking and defending burrows. The abdomen and tail fans of the primary burrowers are also smaller when compared with more surface oriented crawfish. Certainly, a primary burrower is much less likely to have to use its tail for the characteristic backward escape behavior associated with crawfish than would a stream-dwelling crawfish.

There are several adaptations of body form that permit crawfish to live in environments with lowered oxygen concentrations. These include a vaulted carapace and a long, narrow, or obliterated areola that increase the size of the branchial (gill) chambers.

A reduced rostrum is found in both primary burrowers and tertiary burrowers from mountain streams, swift riffles, and gravel beds. Associated with this reduction in the rostrum is a reduction in the size of the eyes and the lengths of the eyestalks. Long eyestalks with large eyes would be subject to much abrasion in a burrow or in the cramped spaces beneath rocks and gravel.

There are, of course, exceptions to these generalities. A good example is the areola of the dwarf crawfish, which are quite broad even though these tiny crawfish are

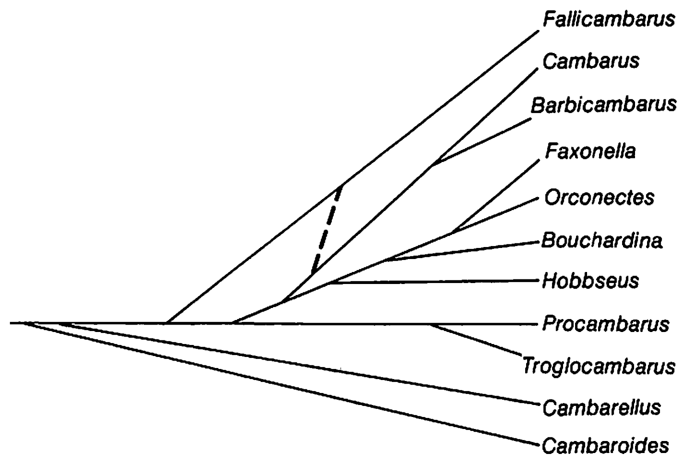
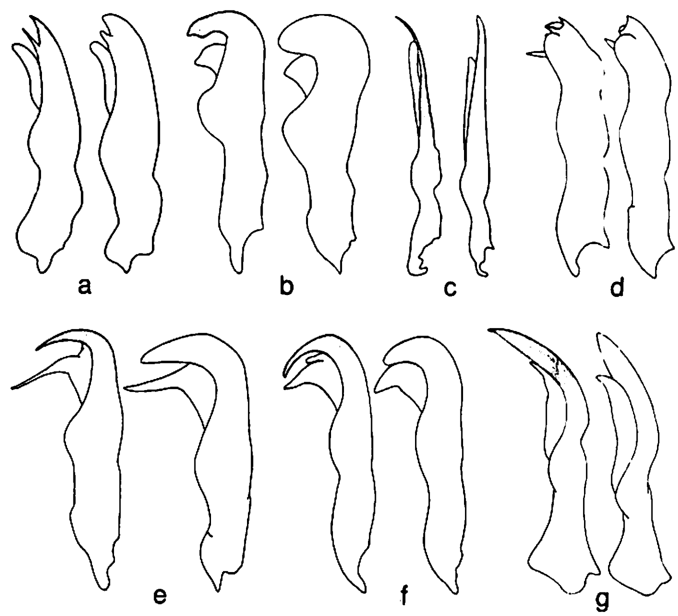


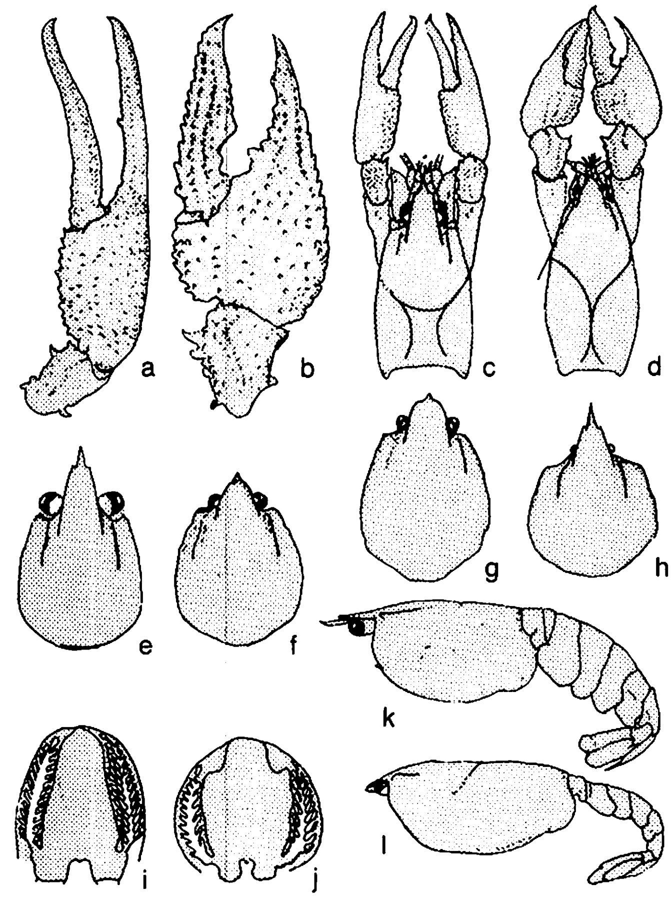
Fig. 22. Affinities of species groups the family Cambaridae.



Legend: a-f. lateral views of left gonopodia of first (form I) and second (form II form males, respectively, with corneous central projection shaded--a. Cambarellus; b. Cambarus; c. Orconectes; d. Procambarus; e. Hobbseus; f. Fallicambarus, g. caudal view of left gonopodium of form I and form II males, respectively, in Faxonella (corneous central projection shaded).

Fig. 23. First gonopodium of representative North American cambarid crawfishes.

normally found in oxygen-poor habitats. A number of secondary and tertiary burrowers have claws that are somewhat triangular in shape. The accompanying figure presents some of the variations in body form discussed above.



Legend: a. chela of Procambarus texanus, a tertiary burrower; b. chela of Fallicambarus jeanae, a primary burrower, c. cephalothorax and chelipeds Procambarus versutus, a tertiary burrower; d. same of Fallicambarus jeanae; e. cephalic region of Cambarus extraneous, a tertiary burrower from rocky streams; g. same of Cambarus carolinus, a tertiary burrower from rocky streams; h. same of Cambarus setosus, a cave dweller; i. cross section of thoracic region of Cambarus diogenes, a primary burrower; j. same of Procambarus versutus; k. lateral view of body of Procambarus versutus; l. same of Fallicambarus jeanae.

Fig. 24. Morphological adaptations of crawfishes to various habitats.

ZOOGEOGRAPHY

Zoogeography is the study of distribution patterns of animals and plants. There are three major groups of freshwater crawfishes: the Astacids and Cambarids in the Northern Hemisphere, and the Parastacids in the Southern Hemisphere.

Briefly, the common ancestor of all three groups was probably marine and has been designated as the Pro-Nephroid ancestor. It gave rise to three groups, the Nephroidean ancestor, the Parastacoidean ancestor (Parastacid crawfishes), and the Astacoidean ancestor (Astacid and Cambarid crawfishes).

The Parastacoidean line evolved separately from the Astacoidean line. There are fourteen genera of Parastacid crawfishes belonging to the family Parastacidae. These include the genera Astacoides, Astacopsis, Cherax, Engaeus, Engaewa, Euastacoides, Euastacus, Geocharax, Gramastacus, Paranephrops, Parastacoides, Parastacus, Samastacus, and Tenuibranchiurus. Most are found in Australia, but two occur in southern South America; one on Madagascar and another in New Zealand.

The Astacoidean line diverged quickly into the Astacids and Cambarids. A key difference between the two was the presence of cyclic dimorphism (alternate body forms--sexually active versus sexually inactive) in mature Cambarids, and its absence in mature Astacids. No further radiation has occurred in the Astacid line. There are three genera (Astacus, Austropotamobius, and Pacifastacus) belonging to the family Astacidae. They are found primarily in Europe and Asia although one genus, Pacifastacus, is native to the West Coast of North America.

The Cambarid line ultimately gave rise to three groups; the Cambaroidines, the Cambarines, and the Cambarellines, all belonging to the family Cambaridae. The Cambaroidines are represented by only one genus, Cambaroides, assigned to the subfamily Cambaroidinae. They are found in eastern Asia, Korea, and Japan. According to Dr. Hobbs, the Cambarines and Cambarellines are much more closely related to each other, having a common, Pro-Cambarine ancestor, than they are to the Cambaroidines. The Cambarines include nine genera (Barbicambarus, Cambarus, Fallicambarus, Faxonella, Bouchardina, Hobbseus, Orconectes, Procambarus, and Troglocambarus) assigned to the subfamily Cambarinae. Prior to introductions by man, they were largely limited to North America east of the Rocky Mountain chain although one species of the genus Orconectes was able to reach the West Coast by natural dispersal routes. The Cambarellines are the dwarf crawfishes (genus Cambarellus) and are assigned to the subfamily Cambarellinae. Their distribution parallels that of the Cambarines.

It should be noted that prior to the introduction of the red crawfish into Uganda in the 1960s there were no freshwater crawfishes native to the continent of Africa.

The relationships between the various freshwater crawfish ancestors will be found in Appendix A. Diagnostic characteristics are given. The relationships between the various genera of the family Cambaridae are shown in the accompanying figure. Further information about the relationships between the various crawfish taxa may be found in references to Dr. Hobbs's work listed in the bibliography. Fig. 22.

DISTRIBUTION OF *P. CLARKII*

P. clarkii occurs naturally from northern Mexico into the southwest through Texas to eastern Florida and northward through the Mississippi River Valley into southern Illinois. This includes the following: in Mexico the states Nuevo Leon, Chihuahua, and Coahuila; in the United States, Texas, Louisiana, Mississippi, Alabama, Florida, Arkansas, Tennessee, Kentucky, Missouri, Illinois, Ohio, New

Mexico, and Oklahoma. It has not been reported in Indiana but is probably there as it occurs in the surrounding states of Illinois, Kentucky, and Ohio. It has been successfully introduced into Sonora (Mexico), Arizona, Nevada, California, Oregon, Maryland, South Carolina, and Virginia. It has been established in Central America (Costa Rica), Europe (Spain), Africa (Kenya and Uganda), and the Pacific (Hawaii and Japan). In the Caribbean area, a small, reproductive population is present on the island of Santo Domingo at a rice experiment station. There are also rumors of other introductions in Europe, Central America, and South America. Figs. 2, 3.

P. clarkii now thrives at altitudes ranging from sea level to 6,000 to 7,000 feet above sea level and from the equator to about 40° north of the equator. Thus, there is probably no reasonably moist area in the populated world where they cannot be established. It is, of course, possible that a native crustacean could prevent it through competition from becoming permanently established in natural waters, but that would not prevent culture. The widespread success of the introductions of P. clarkii outside of its natural range has led to much concern among ecologists, fishermen, and farmers because it has caused considerable changes in native floras and faunas, has created extensive agricultural damage by burrowing in irrigation systems and eating young plants, and has interfered with fishing activities. These subjects are covered further in the section dealing with sociological-cultural aspects of P. clarkii.

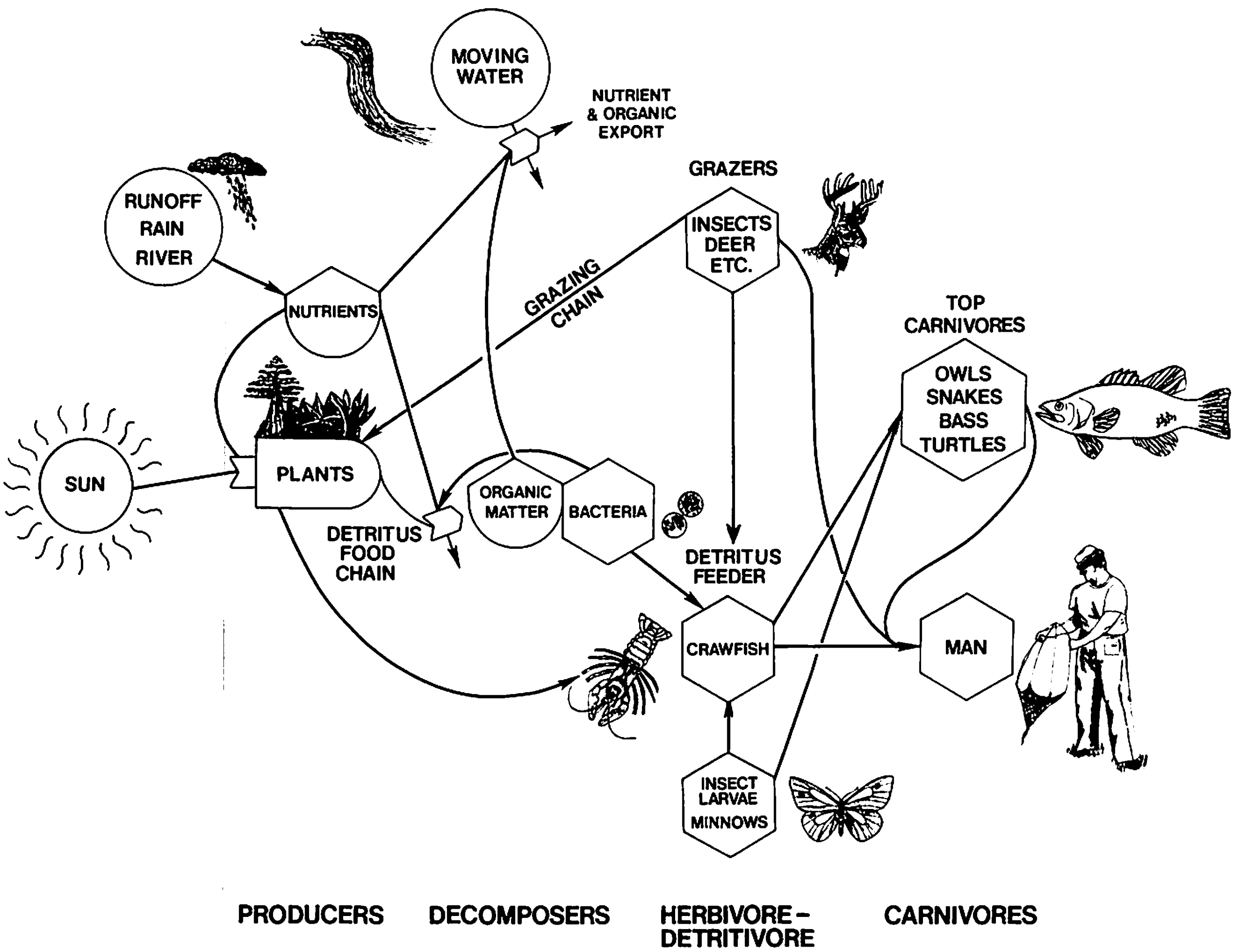
ECOLOGY

An ecosystem is composed of living and nonliving parts. The living part of an ecosystem is made up of the biotic components. The nonliving parts are the abiotic components. This system is driven by the flow of energy through its various living components. The source of all energy is the sun. The sun's energy is trapped in green plants by the process called photosynthesis. Plants use inorganic materials--carbon dioxide, water, and minerals--to produce organic materials and oxygen. The organic materials serve as the food (energy source) for all other organisms. Plants are called producers for this reason. All other organisms consume plants or other organisms and are referred to as consumers. The first level of consumers above plants only eat plants and are called herbivores. Consumers who eat herbivores are called carnivores (meat eaters). In reality, however, most carnivores will also eat plants or plant products and may, more correctly, be called omnivores, but the farther one gets from the herbivore level, the less important vegetation is in its diet. When an organism (plant or animal) dies, decay begins. The decomposing organic matter is called detritus. Unicellular organisms (bacteria, fungi, yeasts) and special representatives of most plant and animal groups use this material as their energy source. In so doing, ultimately they convert it to the basic materials (minerals, carbon dioxide, and water) from which it was originally made by green plants. Organisms that consume detritus are usually called decomposers. Multicellular animals that consume the detritus-decomposer complexes are frequently referred to as detritivores.

Ecosystems are often viewed by ecologists as compartmentalized units made up of groups of organisms, energy sources, nutrients, and physico-chemical parameters. By developing models, ecologists are able to understand the flow of energy through an ecosystem and the role of organisms within that ecosystem. Models of ecosystems may consist of symbols that represent certain organisms, or groups of organisms, nutrients, or some dynamic component. The energy symbols of the well known systems ecologist H. T. Odum are used in Figure 25 to show the dynamics of energy flow through a swamp ecosystem.

ENERGY FLOW

Energy flows through an ecosystem in one direction, as shown on the accompanying illustration. At each step of the way (producer→herbivore→omnivore→carnivore), more energy is lost than is converted into structure. It is lost in the sense that all organisms use food as their energy source. Once energy requirements are satisfied, the excess may be converted into growth or offspring. Only one percent of the sun's energy that strikes the earth is converted into chemical energy in plant matter (biomass). At each successive stage (trophic level) above plants about 90 percent of the energy passed on from the trophic level below it is lost. The remainder (10 percent) become biomass. It is easy to see that it doesn't take too many trophic levels to reduce the amount of energy to a very low level. For example, 100 pounds of wheat is converted into 10 pounds of beef, which can then produce 1 pound of man. That is why a graph relating the amount of biomass or energy in any ecosystem is shaped like a pyramid with plants at the base and carnivores at the top. Carnivores depend very little on plants as a food source. Fig. 25.



Decomposing plant detritus has a living film of microbial (fungi and bacteria) decomposers on its surface. Often these are treated as a unitary detrital-microbial unit. The symbol f or this unit is a combination of the consumer hexagon and the passive storage unit "U" with a hat symbol.

Outside energy and inorganic input into the model system are represented by circles.

Primary producers, such as plants, are represented by a bullet symbol.

The flow of energy is shown by arrows.

Consumers, such as animals or microbes, are represented by hexagons.

Stores of materials such as dead plant matter (plant detritus), seeds, plant nutrients, etc. are shown as passive storage units with the "U" with a hat symbol.

The authors wish to thank Dr. John W. Day, Jr. for his assistance in preparing this figure.

Fig. 25. Energy flow diagram for swamp habitat.

TROPHIC RELATIONSHIPS

Within a trophic pyramid, the basic trophic levels are the producer and consumer levels. With the consumer trophic level there may be several subdivisions. The first level above the producer level is that of primary consumers (herbivores); the second level is that of the secondary consumers (unspecialized omnivores); the third level is that of the tertiary consumers (specialized omnivores, or, perhaps, carnivores); and so forth. Few ecosystems have more than four consumer trophic levels because, as explained above, energy transfers between trophic levels are only about 10 percent efficient.

Crawfish are unique in that they are polytrophic, meaning that they are herbivores, omnivores, and detritivores. They eat plants, animals, and detritus. The bulk of their diet consists of plant detritus. Next in importance are living plant materials. Finally, living animals represent the least important dietary component in volume. Detritus is colonized by unicellular decomposers and epiphytic organisms. The bulk of the nutritional value of the detritus comes from the microbes and epiphytic organisms on the detritus. The crawfish speed up the decomposition process of the detritus by breaking it into smaller pieces, which are more rapidly attacked by microbes. Green aquatic and semi-aquatic plants provide food from their tissue and from the epiphytic organisms that are always present on their submerged stems and leaves. Even though animals represent the smallest contribution to the bulk of a crawfish's diet, they provide essential organic compounds such as cholesterol and proteins (amino acids), that are not specifically produced by green plants. This animal food comes from the benthic, epiphytic, and planktonic communities and consists of nematodes (round worms), oligochaetes (earthworms and their relatives), mollusks (clams and snails), aquatic insects, and various crustaceans (amphipods, copepods, water fleas). Fig. 26.

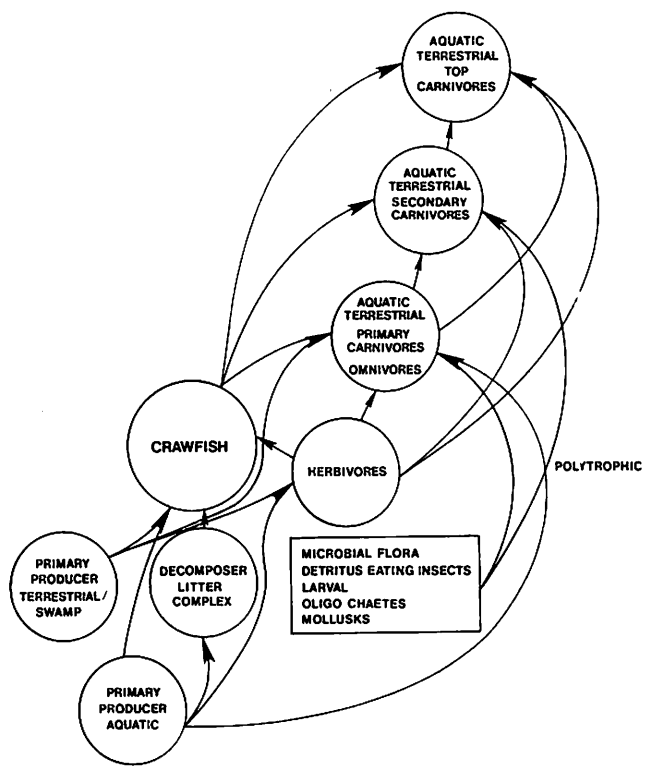


Fig. 26. Crawfish trophic relationships.

Because of their low trophic level, crawfish biomass is high in comparison with other consumers that cannot readily use living or dead vegetation as food. This means that they serve a vital role in the functioning of aquatic ecosystems by making energy from the producer level available to higher trophic levels. In fact, they actually save energy when they convert detritus into living tissue that would otherwise be lost to higher trophic animals. It is not surprising that just about every consumer in the crawfish's habitat eats crawfish at one time or another. Ecologists refer to the feeding associations between organisms in an ecosystem as a food web. The accompanying figure is a schematic diagram of the food web relationships among crawfish and its food and its predators. Fig. 27.

INVERTEBRATE PREDATORS

The most common invertebrate predators of crawfish are aquatic insects, which readily eat the recently hatched crawfish. These include dragonfly nymphs, giant water bugs (adults and nymphs), backswimmers, and giant predacious water beetles (adults and larvae). The large fisher spider will also devour young crawfish. Among the crustaceans, crawfish will eat each other. Blue crabs are also major predators of crawfish. A discussion of the insect and spider predators is found in the Culture section.

VERTEBRATE PREDATORS

Louisiana red crawfish make up an important part of the diets of the sunfishes (family Centrarchidae--largemouth bass, warmouth, green sunfish, bluegill sunfish, and others), the catfishes (family Ictaluridae--bullheads, channel catfish, blue catfish), bowfins (family Amiidae--grindle or choupique), and the gars (family--Lepisosteidae). Amphibians that prey heavily on crawfish include the bullfrog and the congo eel. Some snakes eat crawfish; however, Graham's water snake is one species that specifically feeds on them. Crawfish also play a major role in the diets of the American alligator. Many birds feed on crawfish. Unfortunately, crawfish culturists tend to blame some of their problems on avian predators without just cause. The principal avian predators of crawfish are wading birds such as herons, egrets, and ibises. All will eat crawfish, but some depend more on crawfish as a food source than others. Crawfish make up 90 to 95 percent of the diets of the yellow crowned night heron (gros bec, 'big beak'), 50 to 60 percent of the diets of the white and dark (glossy

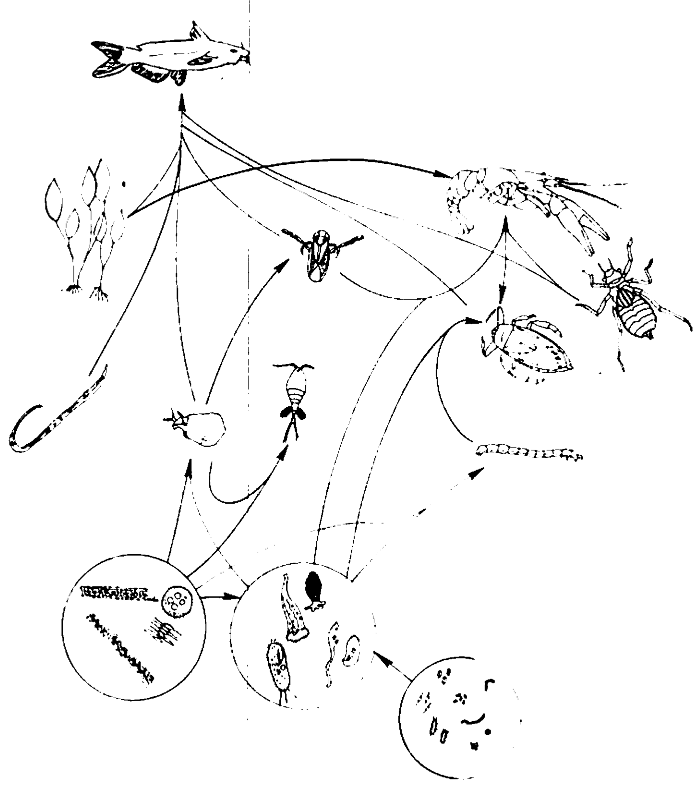


Fig. 27. Food web of crawfish.

and white faced) ibises (bec roche, 'bent beak'), and 45 to 50 percent of the diets of the little blue heron. The great (or common) egret will also consume significant quantities of crawfish, but no quantitative data are available on the subject. Some interesting observations have been made on the feeding patterns of the various birds. All eat small crawfish with little fuss and a quick swallow; however, the larger, adult crawfish are a different matter. The yellow crowned night heron and the common egret will grab a large crawfish sideways and shake the claws off; they then crack the crawfish's shell lengthwise before swallowing it head first. The ibises break the tail from the head and eat the tail whole, shell and all, and remove the viscera from the cephalothorax by probing it with their curved beaks. Little blue herons will either break the crawfish in half, eating the flesh and viscera from the two halves and leaving the shell, or they break the top of the carapace and tail. They then eat the flesh and viscera through the opening and leave an empty shell with a hole in it.

A common name for the little blue heron is levee walker. They received this name for their habit of stalking crawfish on rice field levees. Ibises are said to break open crawfish chimneys and drop bits of broken clay into the opening. When the crawfish comes up to investigate, the ibis uses its curved beak to get it.

The preceding discussion would certainly point to the wading birds as a major problem for crawfish culturists. In reality, it appears that these birds cause minimal damage in well managed ponds. (This subject will be covered more fully in the Culture section).

Other birds that commonly eat crawfish include grackles, starlings, red wing blackbirds, and crows. They attack most often when receding waters expose crawfish in the late spring or early summer. One unusual avian crawfish predator is the barred owl. Hawks have been reported to eat crawfish. Ducks and geese will eat crawfish but only if no other preferred food is available.

Many wetland mammals eat crawfish. These include the raccoon, the opossum, the mink, the otter, the muskrat, and man.

CRAWFISH ASSOCIATES

There are more than 30 species and subspecies of crawfish in Louisiana. Ultimately most find their way into surface waters frequented by P. clarkii, but several appear more commonly than do others.

In ditch type habitats, common crawfish associates of the red crawfish are Procambarus acutus (the white crawfish), Cambarellus puer and Cambarellus shufeldtii (the dwarf crawfish), Faxonella clypeata, and Procambarus hinei. Other species that we have occasionally found in ditches with the red crawfish include Procambarus planirostris; Cambarus diogenes, and Fallicambarus hedgpethi.

Studies in Louisiana's Atchafalaya Basin and the Alligator Bayou swamp near

St. Francisville revealed the presence of P. acutus, Orconectes lancifer, Orconectes palmeri, Cambarus diogenes, Cambarellus puer, and Cambarellus shufeldtii. To date P. acutus, C. puer, C. shufeldtii, P. hinei, O. lancifer, and F. hedgpethi have been found in culture ponds with P. clarkii.

In most Louisiana habitats, P. clarkii constitutes more than 90 percent of the crawfish studied while P. acutus makes up most of the remainder. This domination by P. clarkii with respect to numbers and biomass is an interesting, perplexing phenomenon. With the exception of P. acutus, it is generally at least twice as big as any of the other species. P. acutus does, however, slightly exceed P. clarkii in size. In fact, when similar sized young of the two species are raised together they both have similar growth and survival rates. Possible reasons for the dominance of P. clarkii over P. acutus are that P. clarkii tolerates lower oxygen concentrations than P. acutus; P. clarkii tolerates heat better than P. acutus and perhaps most important, P. clarkii is apparently much more prolific than P. acutus. Stocked together in Louisiana, Arkansas, and Ohio, P. clarkii dominated P. acutus in three years.

BURROWS

Crawfish occupy almost every aquatic habitat from the cold mountain streams of the Appalachians to the dark murky waters of Louisiana's swamps and bayous. All crawfish must live in wet areas, but some can adapt to temporary dry conditions. The red crawfish is primarily adapted to life in habitats that are alternately dry and wet. In the southern reaches of its home range, the lower Mississippi River Valley, the adults burrow in early summer when the high waters from spring rainfall and floods subside. All crawfish--mature and immature--burrow if the habitat dries up regardless of the time of the year. Thus burrows play a vital part in the life cycle of the red crawfish.

The red crawfish constructs several different types of burrow. The simplest burrow is a short, completely submerged structure excavated in the pond or stream bottom. These are rarely more than six inches long and serve as temporary shelters. Fig. 28.

Slightly more complex burrows are built at the water's edge and are common in Louisiana swamps and crawfish ponds. They are frequently associated with some form of cover like a root, piece of debris, mat of vegetation, the overhang of a cut bank, etc. Such burrows are covered by chimneys or mud plugs and are enlarged at the bottom into chambers up to six inches in diameter. The depth of each tunnel is generally determined by the distance from the ground surface to the water table. The total length of burrows normally ranges from 16 to 36 inches. Width and depth are directly proportional to the size of the resident crawfish. The chimneys are built of moist clay lumps about 0.5 inch in diameter. The soft clay cements itself as it dries. These burrows are typically occupied by a pair of adult crawfish with the male normally being closer to the surface.

Complex horizontal burrows have been reported in California and Kenya. These seem to be associated with stable water levels. In California, the Wrights note that the favorite horizontal burrow is constructed in a "U" shape. Both ends of the "U" open 2-3 inches beneath the water surface and are usually 12-20 inches apart. Several short side chambers branch, in the horizontal plane, from the main tube. Crawfish are typically found in these side chambers. At the bottom of the "U," a vertical shaft rises to open air as much as two feet from the water's edge.

In Kenya, I.S.C. Parker found horizontal burrows that extended more than 3 feet from the edge of irrigation ditches. These had many side branches and chambers. These multiple burrows have been called "warrens" by Parker and have entrances both above and below the surface. Up to 53 red crawfish have been removed from a warren.

Numerous interconnected burrows have been observed in California rice fields with severe red crawfish infestations. This resulted in significant damage to weir boxes (undermined) and check levees.

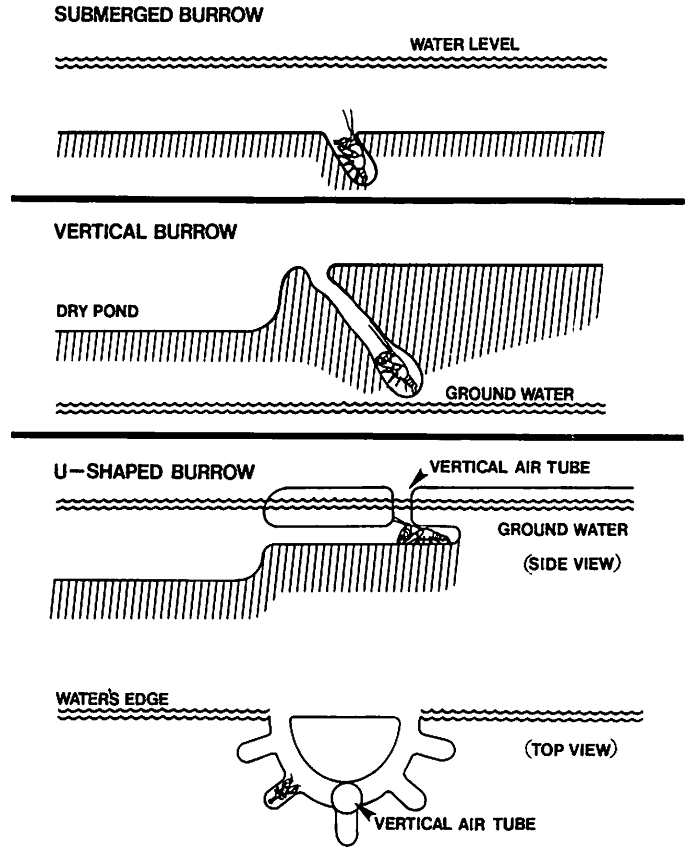


Fig. 28. Representative burrows of the red crawfish.

We have observed extremely complex burrows in association with restricted areas of cover in Louisiana crawfish ponds. For example, the area beneath a board stranded at the water's edge will be literally honey-combed with burrows while adjacent, unprotected areas have none. The sheer numbers of crawfish trying to burrow under the cover insures that there will be numerous interconnections between burrows.

We have observed crawfish as small as 1.25 inches long in burrows. It is questionable, however, whether small crawfish can extend burrows to the water table during prolonged dry periods.

Water that collects in the burrows is slightly acidic. Oxygen levels are low (usually less than 1 part per million compared to surface water oxygen levels of 5 to 10 ppm) while the free carbon dioxide concentrations are high (usually in the 60 to 110 ppm range) when compared to surface waters, which rarely exceed 10 ppm. The water in the burrows is always turbid.

Other animals inhabit the crawfish burrow. Planktonic crustaceans (copepods and water fleas) swim freely in the turbid water. Oligochaetes (earthworms and their close relatives) live in the ooze that surrounds the burrow. Usually no more than two crawfish, a mature male and female, occupy each burrow. However, during winter, four to ten immature crawfish may be found in a burrow.

HABITATS

Ecologists refer to the biological community (assemblage of plants and animals) to which the red crawfish belongs as a benthic community. The benthic community includes those creatures that live in close association with the bottom of any aquatic habitat. Organisms living in the water column, away from the bottom, are divided into the nektonic and planktonic communities. Nektonic organisms are larger creatures such as fish, amphibians, reptiles, and insects that are capable of swimming about freely in the water. Planktonic organisms are minute creatures including fish and insect larvae, which cannot readily control their positions in the water. They are carried by currents. Another aquatic community important to crawfish is the epiphytic community. This community includes those organisms that attach themselves to fixed structures, such as plant stems, logs, and debris. The German word Awfuchs is often used as a synonym of epiphyte.

The red crawfish is adapted to living in areas that are periodically flooded and drained. This alternation permits the growth of vegetation that serves as food when the area is flooded. Often predacious fish are killed before they can spawn and produce young when a pond is drained. When uncontrolled, predatory fish can devour the young crawfish as they leave their mothers. The late Dr. G. H. Penn characterized the habitats in which natural populations of the red crawfish occur in Louisiana. He found the largest concentrations of crawfish in waters that were less than 12 inches deep and exposed to full sunlight. The bottoms of these ideal habitats were usually very turbid and supported a good stand of semiaquatic grasses. They were generally static (lentic) rather than flowing (lotic). The most common plants in the swamp habitats are listed in order of frequency in Tables 3, 4, and 5.

Table 3. Emergent plants found in Louisiana red crawfish swamp habitats (in order of frequency) (after Penn)

Common Name	Scientific Name
Bullrush	*Scirpus* spp.
Cattail	*Typha* spp.
Alligator weed	*Alternanthera philoxerides*
Water primrose	*Ludwigia* spp.
Smartweed	*Polygonum* spp.
Pickerel weed	*Pontederia* spp.
Bull tongue	*Sagittaria* spp.
Spike rush	*Eleocharis* spp.
Rush	*Juncus* spp.
Water hyssop	*Bacopa* sp.
Water pennywort	*Hydrocotyle* spp.

Table 4. Important floating plants in Louisiana red crawfish swamp habitats (in order of frequency) (after Penn).

Common Name	Scientific Name
Water hyacinth	*Eichornia crassipes*
Duck weed	*Lemna* spp.
Water fern	*Azolla caroliniana*

Table 5. Important submerged plants in Louisiana red crawfish swamp habitats (in order of frequency (after Penn).

Common Name	Scientific Name
Water milfoil	*Myriophyllum* spp.
Fanwort	*Cabomba* sp.
Coontail	*Ceratophyllum* sp.
Naiad	*Najas* sp.

Table 6. Grasses and sedges that tolerate periodic flooding, found in Louisiana crawfish ponds.

Common Name	Scientific Name
Millets	*Echinochloa* spp.
Panic grasses	*Panicum* spp.
Paspalum	*Paspalum* spp.
Sedges	*Cyperus* spp.
Beak rushes	*Rhynchospora*
Carex-sedge	*Carex* spp.

Most natural red swamp crawfish habitats are dry during the summer. At that time they are invaded by grasses and sedges. These plants tolerate very wet soils but usually die when flooded for prolonged periods. Although no study has been conducted to quantify the relative numbers of these plants, the most common species are given in Table 5.

Table 7. Characteristic habitats of the red crawfish, *Procambarus clarkii*, in Louisiana (after Penn).

Habitat Type	Percent
Marshes and marsh pools	35
Swamps and swamp forest	30
Ponds and borrow pits	14
Ditches (mostly roadside)	12
Bayous (slow moving streams)	8
Pineland sloughs and springs	1

Culture ponds are not termed natural habitats as they are purposely flooded or drained. They are either planted in grasses such as domestic rice and millet or they are allowed to grow up in plants that invade from the surrounding areas. These plants include those found in natural habitats (Tables 3-6). This is not surprising as crawfish ponds are really just controlled marshes and swamps (Table 7). Outside Louisiana the red crawfish is more likely to be found in permanent, lotic habitats than in lentic ones. This reflects the remarkable adaptability of the species when preferred habitat is not available. Figs. 29, 30, 31, 32.

Fig. 29. Typical ditch-type red crawfish habitat.

Fig. 30. Typical red crawfish habitat in Louisiana's Atchafalaya Basin during the spring flood.

Fig. 31. Open crawfish pond (rice field) in mid-winter.

Fig. 32. Crawfish being harvested in an open crawfish pond.

Introduction of crawfish in Nevada, California, Hawaii, and Japan has been successful in areas with the extensive use of irrigation. This generates the alternating wet/dry cycle necessary for maximum P. clarkii growth. The alternation, of course, reduces fish numbers and permits growth of vegetation.

Large populations of P. clarkii have developed in several lakes in Kenya (Africa). Lake Naivasha is the most extensively studied to date. This permanent lake contains large numbers of American black bass. Crawfish of all kinds are extremely important dietary items to the black bass, yet it seems that there is an abundance of vegetative cover within the lake that affords them enough protection from the fish to thrive and generate in great numbers. In fact, so many young are produced as the result of their ability to produce two to three generations per year that they literally destroy the fish and nets in their search for food. There is apparently some phasing of burrowing and spawning in the region as the result of alternating wet-dry seasons that raise and lower water levels dramatically in the hot African climate.

WATER QUALITY

It would be safe to say that P. clarkii can live just about anywhere as long as winter water temperatures in burrows or habitats do not fall much below 32°F; summer water temperatures do not rise much above 95°F; salinities are less than

12 ppt; and oxygen concentrations consistently exceed 2.5 ppm. Of course certain toxic substances such as heavy metals (lead, mercury, zinc, cadmium, etc.) and pesticides will kill red crawfish. A discussion of toxic materials will be found in the Culture section.

Fig. 33. Red crawfish under oxygen stress obtaining oxygen at the surface.

The preferred temperature range for the red crawfish appears to be around 72°F. They actively feed and molt at temperatures above 55°F but growth seems to be inhibited at temperatures above 90°F. We have encountered red crawfish populations in culture ponds that produce 1,000 lbs/acre/yr where calcium, the material so necessary for shell construction, is virtually absent from the water--in such cases, the crawfish clearly obtain calcium from food and mud. Under normal conditions it is extracted from the water by special tissues in the gills. Thriving populations have been observed in very alkaline waters with a pH of 10 and acid waters with pHs as low as 5.8. They will survive in salinities of 20 ppt for several weeks although they are normally not found in natural waters with salinities much greater than 8 ppt, perhaps because crabs will eat them. The accidental introduction of young blue crabs (Callinectes sapidus) into coastal Louisiana crawfish ponds will lead to drastic reduction in crawfish production.

Oxygen is a limiting feature for all aquatic organisms. That is because there is very little oxygen in the water when compared to air--210,000 ppm oxygen in the air compared to only 4-10 ppm in water. Most of the oxygen in the water comes from the minute planktonic plants in the water, the phytoplankton. These can produce oxygen only in the presence of sunlight because the process of photosynthesis cannot take place in the absence of sunlight. Thus, there is a daily oxygen cycle in each body of water with highs in the late afternoon and lows in the early morning just before dawn. If the oxygen concentration falls below 2 ppm, the crawfish will climb to the surface on trees, bushes, grass, or the bank. There they can obtain atmospheric oxygen. If they cannot reach the surface because they are in traps or they are too far from something to climb to the surface on, they will die within several hours. Fig. 33.

THE FLUSHING ACTION OF FLOODING RIVERS

The Atchafalaya Basin and other large river swamps offer a sharp contrast to the ditches, swamps, and marshes that many crawfish inhabit. The Atchafalaya Basin supplies about 60 percent of the commercial crawfish production in Louisiana and almost 100 percent of the natural production. The Atchafalaya Basin is an 18 x 80 mile wide flood zone that originates in the center of the state where the Red, Atchafalaya, and Mississippi rivers converge. Some 30 percent of the Mississippi River's volume flows from the Mississippi River into the Atchafalaya Basin, which is bounded on the east and west by guide levees running along the south-central region of the state to the Gulf of Mexico. The Atchafalaya River, a major distributary for the Mississippi River, runs down the middle of the basin. The basin serves as a floodway for the overflow water of the Mississippi River. Low areas in the basin are filled in the fall and winter by rainfall. It is at this time the young crawfish enter these areas and begin growth. The habitat available to them is expanded when the spring flood waters flow over the banks of the natural water courses in the basin. Crawfish are found virtually everywhere but are often concentrated in the cypress-tupelo-gum swamps on the east and west sides of the basin. These "hot spots" as they are called by fishermen, are specifically located about 20 miles north of Morgan City in the vicinity of Little Bayou Sorrel and about 30 miles northwest of Morgan City, in the vicinity of Buffalo Cove.

The principal limitation to population expansion appears to be the actual amount of flood water flowing through the area. Prior to any flooding, the massive buildup of rotting vegetation depletes the water of oxygen and colors the water black excess tannic acid. Waters eventually become anoxic, a situation that even the amphibious crawfish cannot tolerate for prolonged periods. The greatest concentrations of crawfish are always found where fronts of turbid oxygenated floodwaters meet with the black anoxic backwaters. Thus the flushing action of the floodwater pushes the existing stagnant water back into the swamp. The greater the amount of floodwaters in any year, the greater the amount of flushing action. The resultant habitat expansion provides increased production.

An ideal hydrological cycle for optimum production of crawfish is as follows. In it a drought of two months in the summer, which reduces the number of predatory fish, is followed by rainfall in the early fall. Flood waters from the Mississippi River would then move into the area at mid-winter to replenish the basin with oxygen and nutrients.

The presence of great rafts of water hyacinths is a mixed blessing in the area. These mats prevent light penetration (necessary for the generation of oxygen by aquatic plants) and reduce the level of oxygen. However, small crawfish abound on the submerged roots and readily eat them. When the mats become stranded in the summer, the adult crawfish burrow beneath them. These areas serve as excellent nurseries in the fall. Often the water hyacinths can become so thick that they can completely stop movement of boats, severely hindering harvesting efforts.

The Atchafalaya Basin is being rapidly filled by silt from the turbid spring flood waters. These waters slow down as they move into the swamp and lose the ability to carry silt, which settles to the bottom. Much of the upper basin no longer floods unless very unusual conditions occur. Those areas no longer produce large crawfish crops. The shallow bays at the mouth of the Atchafalaya Basin are filling in with this same silt. These new swamp and marsh lands will undoubtedly produce crawfish crops in years to come.

One interesting phenomenon that occurs in Louisiana involves the dramatic appearance of huge concentrations of crawfish in the backwater swamps of the Ouachita, Red, and Mississippi rivers every 10 to 20 years. All of the low areas in these swamps support red crawfish populations, but normally they do not receive the annual overbank flooding seen in the Atchafalaya Basin. Thus, they support only small numbers of relatively small crawfish typical of those found in roadside ditches. Yet, when an exceptionally great flood occurs and waters from the Red and Ouachita rivers cannot flow into the Mississippi River, entire swamps are flooded. The expansion of this habitat generates phenomenal growth and survival of crawfish. As a result, crawfish suddenly appear and natives of the area and some biologists think that P. clarkii can survive in burrows for 20 to 30 years.

Many swamps and marshes in south Louisiana not associated with these rivers once produced many crawfish, but much of the ideal habitat has been lost. This loss has been caused by several factors. Many areas have been drained as part of reclamation projects. Roads and building projects have created permanently flooded areas by blocking normal drainage. The formation of these areas rapidly developed predacious fish populations and eliminated the vast majority of the crawfish.

In the Mississippi Valley, the red crawfish are generally adapted to a regimen of spring flooding; however, colder temperatures will limit growth when the waters are high. Falling waters eliminate many of the established habitats as waters warm up. Small numbers of P. clarkii will always be found in ponds, lakes, rivers, and streams throughout its range. Conditions are not favorable enough to produce large populations.

DISPERSAL

Red crawfish are well known for their overland movements in Louisiana. The fall "death" migrations of reproductively spent (senile) males are well reported in the scientific literature. However, adult red crawfish will normally move overland in response to several conditions including heavy rains after dry periods, spring flooding, and low dissolved oxygen in the water. These are poorly directed wanderings and are most conspicuous in the spring when crawfish numbers and sizes are greatest.

One possible explanation for movements when heavy rains follow dry periods is that the cement-hard burrow plugs are softened, making it easier for "trapped" crawfish to "escape." This is an especially conspicuous pattern in the late fall and early winter when rains resume following the typically dry Louisiana fall. Solitary females bearing eggs or young are often found in puddles far from standing waters or wandering aimlessly on dry ground.

When unusually great floods expand prime habitat, crawfish numbers increase dramatically. As waters recede, crawfish move with them and great numbers may be observed crossing roads and fields. They can create traffic hazards both when they are crushed on roads and when people stop to catch them.

Water stagnation is not unusual in Louisiana. The organic content of swamp and marsh soils is very high and microbial decomposition creates a high biological oxygen demand (BOD). Water in such areas must move continuously to compensate for the high BOD. When water flow is restricted, it will stagnate. At such times, crawfish move overland seeking more acceptable living conditions.

All of these movements are important in insuring dispersal of red crawfish throughout their range. Certainly, many die when they fail to reach an acceptable habitat or are killed by predators. However, one average female has the potential for producing 300 offspring, so that a thriving population can easily be reestablished in a suitable habitat.

SOCIAL IMPORTANCE OF CRAWFISH

CULTURAL IMPACT

Crawfish have long been important to European cultures. Northern Europeans relish them for food. Elaborate folk festivals are associated with the annual summer crawfish season. Crawfish have been the subject of various European artists through the ages. Scarcity has driven prices to very high levels (retail prices exceed $1.00 each compared to a maximum of about 5¢-25¢ each in the United States). Prices are so high that few crawfish are peeled for abdominal meat and prepared dishes. Most are boiled in water seasoned with salt and dill. Elaborate ceremonies surround crawfish consumption, and a number of special utensils have been designed to extract even the smallest bits of meat from the most inaccessible places.

Even though specimens are found in Greece and Turkey in substantial numbers, crawfish have never been widely consumed in the eastern Mediterranean region. They are considered to be poisonous and are hung on posts to ward off evil. Many, however, are captured and shipped westward to unsuspecting western Europeans who pay premium prices for them.

Native North American Indians have always exploited crawfish for food wherever they could be accumulated in substantial numbers. One tribe in south Louisiana, the Houma Indians, chose the crawfish as their war totem. A large group of Indians from the Mississippi Valley called themselves the Chakchiuma, which translates as red crawfish. Nordic and Gallic immigrants to the U.S. found the exploited crawfish in substantial quantities in the Great Lakes region, on the West Coast, and, of course, in the swamps and marshes near the mouth of the Mississippi River in Louisiana.

Louisiana accounts for about 98 percent of the known annual crawfish harvest in North America, and that is where they have the greatest socio-cultural impact. In south Louisiana crawfish are an institution, and there it may be truly said that "crawfish is king." Crawfish boils are an important social gathering in the spring when crawfish are most plentiful. These events are comparable in every way to New England clam bakes and southwest barbeques. The crawfish are boiled in salty, well-seasoned water along with potatoes, corn on the cob, sausages, and artichokes. The standard serving is about 5 pounds (100 crawfish) per person--an unheard of quantity in Europe. The crawfish boils are often the culmination of a sports crawfishing outing by a family or a group of families.

Every good restaurant in south Louisiana features crawfish dishes year-round. They serve dishes prepared and frozen during the crawfish season or dishes prepared from frozen abdominal meat. This meat is referred to as tail meat or 'tails,' even though it actually is part of the abdomen. Boiled crawfish are generally available in restaurants from December into the following June. Many recipes have been developed that use the meat, including crawfish pie, crawfish etouffe, crawfish bisque, crawfish stew, crawfish stuffed green peppers, fried crawfish 'tails,' crawfish stuffed egg rolls, and crawfish jambalaya.

Curios featuring crawfish are available throughout the region and come in any number of forms and designs from key chains to lamps. A popular china design features a crawfish on each piece. (Most Louisianians assume that the crawfish on the dishes is the red crawfish, but the china is produced in Germany, and is actually painted with the European crawfish, Astacus astacus.) Comic books and T-shirts now portray the adventures of Crawfish Man, a half-man, half-crawfish superhero, and Clovis and his crawfish friends are the subject of another series.

There are two interesting superstitions about the palatability of red crawfish in south Louisiana. Occasionally, a large snake is unable to find its way out of a submerged crawfish trap. After drowning it may attract many crawfish. Crawfishermen, however, often regard the meat of such crawfish to be poisonous and discard the entire catch unless it is to be sold to persons outside their locality. Infrequently, a crawfisherman will drown in an area where crawfish are being actively harvested. Unless the victim's body is found quickly, many crawfishermen will refuse to eat crawfish caught near the drowning site fearing that the crawfish have been feeding on the body.

The burrowing species, Cambarus diogenes, is called the "devil crawfish" or the "coffin cutter." It is very distinctive with spade-shaped claws and three bright red-orange longitudinal stripes down the back contrasting markedly with the basic olive green or blue background color. Legend had it that C. diogenes will burrow into coffins in order to obtain food. Since this species is found throughout low lying areas of Louisiana, it is certain to be found in poorly drained cemeteries where its ability to burrow 6 feet or more could permit it to reach coffins. However, its reputed preference for cadaverous flesh is hardly established fact.

Fig. 34. Crawfish race.

Several crawfish festivals are held each spring in south Louisiana and east Texas, an area that is a cultural extension of south Louisiana. The most prominent festival is held every two years at Breaux Bridge, Louisiana. Breaux Bridge has, in fact, been declared "La Capitale de Mondiale des Ecrevisses" (the Crawfish Capital of the World). This particular event lasts three to four days. A queen is selected and there is a large parade complete with floats and a ten-foot long papier mâché red crawfish. Other festivities include crawfish races, a contest for the largest crawfish, a crawfish peeling contest, and a crawfish eating contest. Large wagers are said to have been placed on the outcome of some of these contests. Figs. 34, 35.

Fig. 35. Crawfish float at the Breaux Bridge, La., crawfish festival.

Elsewhere in the United States, crawfish races are held at county fairs, but we know of no other extravaganzas to match those found in south Louisiana. For the uninitiated crawfish races are fairly standard. Crawfish are placed in a can without a top or bottom situated in the center of a series of concentric rings. The can is lifted and the first crawfish to reach a specified ring is declared the winner.

ECONOMIC PROBLEMS

Introductions of prolific crawfish such as P. clarkii into areas in which they are not native often have unforeseen consequences. Substantial populations of P. clarkii have resulted from their introduction into California, Hawaii, Japan, Kenya, and Spain. In California, Hawaii, and Japan, their burrowing activity has caused considerable agricultural damage, primarily to irrigation structures such as dams and levees. They are also said to eat the roots and shoots of various crops.

No one is quite sure why P. clarkii was brought to California and Hawaii, but it was introduced in Japan in the early 1900s for food for the imported American bullfrog. P. clarkii is consumed in these areas only by a relatively small number of individuals who have overcome an apparent social aversion and discovered a delightful seafood to add to their diets. In Japan, the red crawfish are avoided partially for health reasons. The Japanese have long eaten their native crawfish, Cambaroides japonicus, raw. Unfortunately, P. clarkii harbors larval stages of the human-lung fluke, Paragonimus westermani. When a crawfish with the larval flukes is eaten raw, the parasite invades the human body tissues with adverse consequences. Of course, thorough cooking, as practiced by Americans and Europeans, easily counters this problem.

Kenyans avoid P. clarkii primarily for the same reason peoples in other countries do--social aversion. The original introductions, around 1970, were thought to be accomplished to control snails that harbor a larval phase of the human-liver fluke. The resultant population explosion of P. clarkii caught everyone by surprise. Huge numbers have become pests by destroying large areas of aquatic vegetation in lakes and by not only eating fish in nets but also destroying the nets in the process.

Very few red crawfish are exported from Kenya. Roughly 11,000 pounds were shipped to France in 1978.

The Spanish introduction is, indeed, a contrast to the dismal record for similar introductions elsewhere. Native European crawfish, including those in Spain, have been almost eliminated in many areas by the crawfish plague (see Diseases section). P. clarkii was introduced in Spain in the early 1970s to replace the virtually extinct native species. The species has not dispersed much beyond the vicinity of Sevilla, the original area of introduction. However, the species is so popular that poachers have transferred them from culture ponds to natural water bodies to insure a steady supply.

According to reliable reports, Spain will produce 350 tons of red crawfish in 1980. There are 380 fishermen currently involved in harvesting them with 600 other persons involved in the business. There are three buying centers near production fields and 17 wholesalers supplying 80-120 retailers in the country. This is especially amazing when one considers that the original introductions of red crawfish were made in 1973-74 and amounted to less than one-half ton of crawfish.

The lesson to be learned by these introductions is that no introduction should be made unless one is prepared to accept the possibility of considerable ecological damage in return for crawfish production. The value of that production is questionable unless one first convinces potential users that the animal is a desirable foodstuff. This is a formidable undertaking in areas except those in which crawfish are well accepted but are no longer abundant. Where introductions have gone amiss, it is incumbent upon resource managers to educate users concerning the value of the crawfish. Intensive harvesting will invariably reduce population levels and resultant damage.

EXPLOITATION

There are excellent technical bulletins available on red crawfish culture and processing. Several recent publications provide additional insight into the exploitation of wild red crawfish stocks. We do not intend to recapitulate those here; rather, we seek to acquaint the reader with the scope of the Louisiana crawfish industry. See references in the Bibliography by Gary, LaCaze, Hill and Cancienne, Huner and Avault, and Viosca for culture; by Carroll and Blades and Hudson and Fontenot for additional information about processing; by Comeaux, Konikoff, and O'Brien about exploitation of wild stocks.

Table 8. Area devoted to crawfish culture in Louisiana over time.

Year	Area (acres)
1949	40
1960	2,000
1966	6,000
1968	10,000
1969	12,000
1970	18,000
1971	24,000
1973	44,000
1976	45,000
1978	48,000
1980	55,000+

Widespread exploitation of the red crawfish is largely limited to Louisiana. In recent years, thirty to sixty million pounds per year have been harvested commercially from natural swamps and marshes, principally the Atchafalaya Basin, and about 50,000 acres of culture ponds (Table 8). The wild harvest normally accounts for 60 percent of the total harvest. Records are not well kept, so all official estimates of catch and its value are low. Pond production is fairly stable, but wild production varies with the amount of sustained spring flooding in the Atchafalaya Basin. In general, the Atchafalaya Basin was 1.3 to 1.8 million pounds for the period of 1971-74. There are no data available on the recreational harvest, which is undoubtedly substantial, from roadside ditches and other swamps and marshes in the state.

Intensive commercial exploitation of the red crawfish in Louisiana is a relatively recent development dating back to the late 1950s and early 1960s. Prior to that time, it was consumed by native Louisianians who caught their own supply for home consumption in nearby ditches, swamps, and marshes. A fisherman might catch more than his immediate family could use and salvage them by hand peeling the meat in a backyard shed. The meat would be frozen and marketed to neighbors or nearby restaurants.

As the population of southern Louisiana grew with the influx of persons drawn by the developing petroleum and petro-chemical industries, the number of people consuming boiled crawfish and crawfish products grew. Frozen crawfish meat permitted restaurants to offer crawfish dishes year round. This led to the establishment of crawfish peeling plants to meet the growing demand for a more stable supply of crawfish meat. Poor wild crops spurred development of crawfish aquaculture to supply peeling plants and the live market.

All crawfish were hand peeled. When crawfish were abundant, processing plants could not handle the glut and prices for live crawfish and crawfish meat fell. As a result, a physical limit was imposed on the total supply of processed, frozen meat in good years. This, then, limited the ability of processors to develop and supply large, potential markets out-of-state (in poor years, no real excess was available to sell out-of-state because of local demand).

At this writing, a mechanical peeling device has been perfected and is in use in one of about 30 Louisiana processing plants. This will undoubtedly revolutionize the crawfish industry and lead to a new era in exploitation. Soon, an adequate supply of crawfish will not be a problem, because the machine can process a vast quantity of crawfish. In addition, several processors are actively developing out-of-state markets, and this could have a stabilizing effect on prices.

Increasing exploitation of P. clarkii is being seen elsewhere. In the U.S., up to 3,000 acres of culture ponds in Texas and 40 acres in South Carolina have been built and put into operation recently. The red crawfish is also harvested for food in certain areas in California where it occurs naturally in irrigation systems. Specific details of that harvest are not available. Recent introductions in southern Spain have led to the appearance of P. clarkii in Spanish markets. The massive numbers of the species in some Kenyan lakes have resulted in an interesting contradiction. That is, the resource is available to the developing nation but the Kenyans are not using it nor are they taking advantage of a potential European market even though shipments have been made successfully to Europe. Very little information is available about the commercial utilization of P. clarkii in Japan, where large, wild populations are said to exist. The Japanese, although known for their tradition of eating seafood and having had the species in their country for 40 years, do not commercially exploit it.

The value of live crawfish to fishermen and farmers has ranged from 25¢ to $1 per pound during the 1970s. Season averages have been in the 40¢ to 50¢ per pound range. It is difficult to estimate the overall value of the catch because as much as one-half of it is never officially reported. However, it clearly has a significant impact on south Louisiana's economy.

Since Louisiana has the largest numbers of red crawfish in the world and is the leading developer of culture methods, we will limit our discussion to the exploitation in Louisiana. First, we will deal with the wild harvest. But since harvesting, distribution, and processing are similar for both wild systems and culture ponds, we will cover the subjects for both fisheries in the following discussion.

PRODUCTION—WILD/DOMESTIC

In the past few years, wild production of crawfish has normally accounted for about 60 percent of the harvest in Louisiana during good years, that is, when the hydrological cycle of the Atchafalaya Basin is ideal. In off years (two out of every five), pond production may account for about 60 percent of the total.

Harvesting

Wild crawfish harvesting begins as soon as sufficient numbers of harvestable crawfish can be obtained. This is dependent on how early rainfall and subsequent flooding from the Mississippi River (into the Atchafalaya Basin) take place in the fall and winter. Abundant rains in the early fall permit holdover adult and juvenile crawfish from the preceding season to leave their burrows and resume growth while temperatures are warm and most conducive to rapid growth. Young-of-the-year crawfish released early in the fall can reach harvestable sizes by late November-early December. Young released later in the fall mature more slowly. Distinct groups of young crawfish are called recruitment waves. In a normal season the first wave of young-of-the-year crawfish begins to reach harvestable size in February.

If enough water is available for crawfishermen to reach the crawfish, some harvesting will begin in December, especially if prices are high. Catches are normally small. Traps average less than 1 pound versus 2 to 4 pounds in the spring. The catch is made up of the holdover adults, juveniles that did not mature in the previous year, and the most rapidly growing young-of-the-year. The crawfish generally become extremely abundant in April and May when most of the young-of-the-year reach harvestable sizes.

Crawfish for food are invariably caught with a device that utilizes bait to attract them. Crawfish for fish bait are normally captured with small mesh dip nets or seines. The simplest technique for capturing crawfish for food is to put a piece of bait on a string. This, in fact, was the technique used by the early Acadian settlers in south Louisiana. When the crawfish begin to eat the bait, the bait and the crawfish are carefully raised to the surface and lifted onto the bank. A dip net may be used for more certain landing. Sportsfishermen tend to favor use of small lift nets that are manufactured primarily in Japan. There are two types of lift nets. The most common type consists of a 17 or 19 inch square piece of 1/2 inch mesh net attached to an A-frame. The frame of the net is made of two V-shaped wires and the frames meet at right angles. Bait is attached to the center of the net and the lift net, which stands about 24 inches high, is placed in water up to 30 inches deep. When depth exceeds height of the net, a bright piece of cloth is normally tied to its apex to aid in recovery of the net. These, then, are lifted every 5 to 15 minutes with a pole. Fig. 36.

The other type of lift net is really nothing more than a crab net with a 1/2 inch mesh net. These are used in deeper waters where the A-frame lift net cannot be employed. The crab-lift net is normally about 18 inches in diameter with 4 inch high sides. The net is attached to two wire rings, one at the top of the net and one at the bottom. A yoke is attached to the top ring so that the net may be recovered after it is set. The 1/2 inch mesh of the two lift nets will retain crawfish as small as 2 1/2 inches. Some sportsfishermen cull them while others eat them.

The standard commercial method for catching crawfish is to use traps made from 3/4 inch hexagonal mesh chicken wire. There are a number of designs but they are all basically cylindrical in shape and 30 to 36 inches long by 18 inches in diameter with one to as many as four funnel shaped entrances located at either or both ends. The entrances have openings that are 1 1/2 to 2 1/2 inches in diameter. The traditional design has one funnel (throat) that is made separately and sewn into the cylinder. A trap with two funnels may be made by closing one end of the trap but leaving 1 1/2 inch openings at either edge and then pushing these corners inward with a soft drink bottle. (The cylinder seam should be centered between the two funnels.) This is the so-called pop bottle trap. There is strong evidence that crawfish can escape more easily from the pop bottle trap than they can from the traditional trap because the funnel is not as deeply recessed; however, the ease of construction of the pop bottle trap has led to its widespread adoption throughout south Louisiana. Figs. 37, 38, 39.

The cylindrical traps are often called pillow traps because they resemble pillows. They can be easily compressed and bailed for transportation. The 3/4 inch mesh will retain a 3 inch crawfish, which is the normally accepted commercial size. If crawfish are small and buyers will accept them, 1/2 inch mesh traps are sometimes used.

The "airliner" is a modified "pop bottle" trap used in some shallow rice field ponds. After two funnels have been made on one end of the trap, the opposite end is closed in a vertical plane. The wire is folded so that that end is triangular in appearance with the seam running from the apex to the center of the base of the triangle. Openings are left at both the center of the base and the apex. The center-base opening is inverted with a bottle to form a third funnel. The apex opening is 6 to 8 inches long and is used to bait and empty traps. It may be crimped or closed with a clothes pin. The apex normally extends above the surface in shallow rice field ponds allowing crawfish to reach the surface.

A modification of the pop bottle trap is a single-throated pillow trap without the separate sewn-in funnel. One opening is left on one corner rather than

Fig. 36. Lift net.

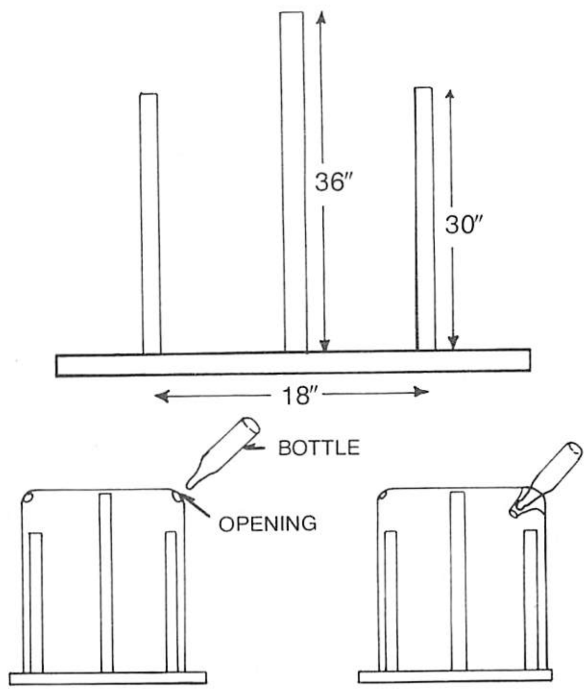


Fig. 37. Construction of a pop bottle trap.

two. The opening is inverted with a pop bottle and forced inward until a deep-throated, cone-shaped entrance is formed. The trap will not be symmetrical unless the free edge is folded inward.

Traps are frequently coated with black net coating material to preserve them by preventing rust. Trap wire is also available pretreated with preservative. One end is normally used for entrances and the other end is used for removing crawfish. The latter end may be folded over on itself or closed with a piece of wire or clothes pins. Traps are made with doors, but these are cumbersome and make rapid running of traps difficult.

Fig. 38. Traditional, single entrance pillow traps.

Waters in the Atchafalaya Basin are generally more than 3 feet deep when crawfish are trapped. Traps must be placed on the bottom. This leads to problems if oxygen depletion occurs. At such times the crawfish in the traps suffocate unless corrective action is taken. If crawfish can reach the surface, they can utilize atmospheric oxygen. In shallow waters (2 1/2 feet or less) traps may be propped against sticks or floats may be attached so that one end reaches the surface. In deep water, crawfishermen may nail traps to tree trunks so that part remains above the surface. When crawfish climb up the tree trunks to obtain atmospheric oxygen, they enter the traps. Alternatively, two or more traps may be connected together. These so-called "extension" traps may be 6 to 8 feet long and extend from the bottom to the water surface. They are propped against tree trunks.

As a major cost in producing crawfish in culture ponds is the labor to run the traps, a special open-ended trap that stands erect in the water has been developed to reduce labor costs. A two man boat crew can fish 300 of these "stand up" traps per hour. The trap is removed from the water, emptied, placed back in the water, and rebaited as the boat continues to move forward to the next trap in a line. Crawfish do not readily escape from such traps by climbing out through the open top as long as the top is above the water line. Stand up traps may be of the pop bottle variety or may have funnels sewn around the base. Reinforcing wire frames are sometimes used to add rigidity to the structure. The stand up trap is generally impractical if the water depth exeeds 30 inches. Fig. 40.

Bait used in the traps is normally some species of rough fish. The gizzard shad, Dorosoma cepedianum, is the bait of choice. Other favored baits include the common carp, Cyprinus carpio, the skip jack herring, Alosa chrysochloris (locally called the slicker), and the buffalofish, Ictiobus spp. In times of bait scarcity, intact marine fishes (or their offal) including the menhaden, Brevoortia spp., and the Atlantic croaker, Micropogon undulatus, and freshwater catfish, Ictalurus spp., will be used. Menhaden are a soft fish and are not particularly favored because crawfish quickly eat all of the bait. Catfish remains have very sharp, serrated spines that can cause nasty cuts and often hang up in the traps. One-sixth to one-quarter of a pound of bait is normally placed in each trap, depending on water temperature (less bait is used in cold water).

Most sportsfishermen seem to prefer to use beef melt (spleen). It is a good bait, but it is generally too expensive for commercial use.

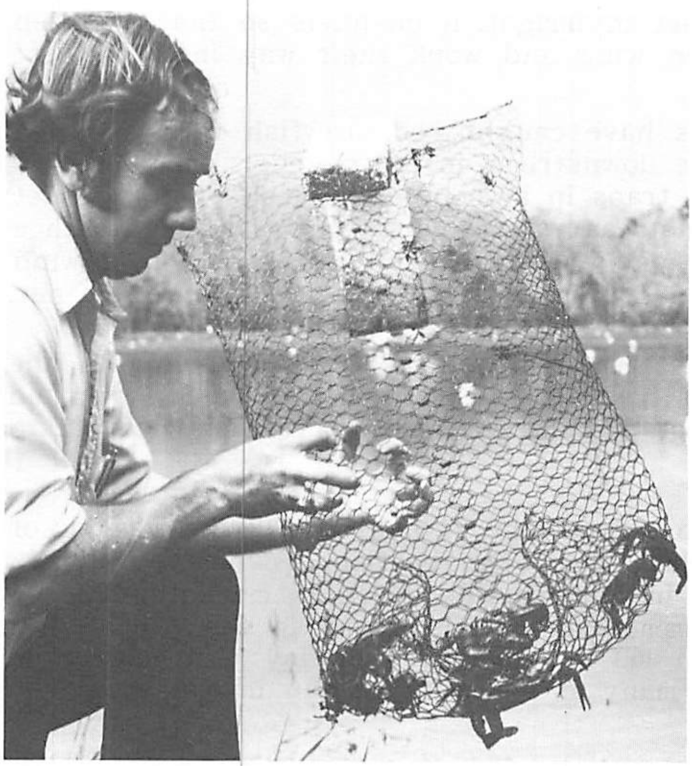


Fig. 39. Double entrance pop bottle pillow trap.

Fig. 40. Standup trap. Note reinforcing wire used to give the trap support.

Attempts have been made to develop artificial baits. Most of these have proven to be poor in comparison to fresh or frozen fish. Some inexpensive canned pet foods have shown promise as baits for red crawfish in Louisiana, Pascifastacus lenisculus in California, and Orconectes spp. in Vermont. They have the obvious advantage of being stored without refrigeration. These are also cleaner to work with than fish. More has to be learned about how to place the soft pet food (a whole can of pet food rather than fish is not cost effective) in traps so that it will attract crawfish over an extended time and about its effectiveness during winter months. A mixture of chicken laying mash and bone/blood meal (20:1) is popular in Australia. It is placed in open-ended mesh-covered tubes; however, it has not been very useful in Louisiana.

Toward the end of the Louisiana crawfish season, fishermen will often add a piece of cottonseed cake (also called oil cake or press cake) to their traps, along with a piece of bait fish. Cottonseed cake is made by squeezing cottonseed meal and hulls through a steam-heated press. The cake is very dense and will withstand considerable chewing by crawfish. It does not seem to be especially attractive to crawfish, being 50 to 80% as effective as fresh or frozen fish when used by itself. However, fishermen feel that it holds crawfish in traps. Corn on the cob is sometimes used for the same reason. Neither cottonseed cake nor corn on the cob is very effective by itself at temperatures below 65 to 70°F.

In Spain, crawfish are caught without bait. Hoop nets originally designed to catch eel are used. These nets are about 5 feet long and 18 inches in diameter. Hoop nets have two inner chambers and a short, 3-foot panel or wing attached to the entrance. Nets are set in irrigation channels so that crawfish moved by water current encounter the wing and work their way into the net.

Several Louisiana crawfish farmers have caught red crawfish with unbaited traps by setting trap entrances to face downstream in pump-generated currents. This follows from the observation that traps in swamps and marshes must be set with at least one entrance facing downstream. In a large crawfish pond with a long fetch, traps should have at least one entrance facing the direction of wind flow. The counter current on the water bottom directs the crawfish into the net.

Crawfish are not now harvested commercially from crawfish ponds in the United States by generating currents. Pond and trap design and associated management practices must be perfected before baitless crawfish harvesting becomes a reality.

Traps are generally baited and checked every 24 hours. During periods of peak crawfish abundance, April and May, traps can be fished every four to six hours. Labor and logistical problems in getting wild catch to market generally limit trapping to a 24-hour cycle. A commercial crawfisherman in the Atchafalaya Basin or other natural waters may run 100 to 200 traps per day. In commercial ponds with 10 to 20 traps per acre, as many as 1000 may be run in a day.

Flooded swamps are not easy places to fish traps. They have dense growths of brush, trees, and floating vegetation. In shallow systems, most trappers walk, dragging a shallow draft boat behind them. In the Atchafalaya Basin, water depth normally permits boat traffic, but dense vegetation necessitates shallow draft, flat bottomed boats (14 to 16 feet long), often with pointed prows. Outboard engines in excess of 50 horsepower are used. Wooden boats were popular for many years, but fishermen are now beginning to switch to custom-made aluminum boats. Fig. 41.

Fig. 41. Typical boat used by crawfishermen in the Atchafalaya Basin, La.

Several systems have been employed to harvest crawfish in culture ponds (Table 9). The simplest system is for a harvester to walk through the pond dragging a boat or tub with bait. Traps are emptied into the boat or tub. The harvester may choose to work from a shallow draft flat-bottomed boat propelled by a push pole. When water is deep enough (at least 12 inches), boats may be propelled by outboard motors or large inboard motors (called mud boats). Fig. 32.

A motor called the "go devil" will propel boats in shallow waters. The go devil consists of a small air-cooled engine with a weedless propeller on a long shaft connected to the drive shaft. The engine is mounted over the boat's transom and steered like an outboard motor. The go devil uses very little fuel compared to outboard motors and boat motors. Thus, it is very popular in south Louisiana crawfish ponds. Fig. 42.

Small, wheeled amphibious vehicles have been used by some farmers to harvest crawfish. However, they are not very popular because of maintenance problems and limited working space.

Some farmers with very small ponds will set traps only along the pond's perimeter. They use a variety of small vehicles (tractors, all-terrain vehicles, etc.), to pull a wagon with bait and containers for crawfish from trap to trap.

Air boats are used to harvest crawfish by some crawfish farmers. The principal advantages of the air boat as a harvesting vehicle are its maneuver-

Table 9. Comparison of various crawfish harvesting systems.

System	Maneuverability	Traps in Straight Line	Crossing Levees (difficulty)	Speed and Number of Traps/hr	Reverse	Handling in Wind	Number of Operators	Depth Limit (12" min.)
Walking	excellent	no	easy	slow/30-50	yes	excellent	1	yes
Boat propelled by push pole	fair	no	difficult	slow/30-50	yes	poor	1	no
Boat propelled by outboard motor	fair	yes	difficult	fast/200+	yes	fair	1-2	yes
Boat propelled by Go Devil motor	fair	yes	difficult	fast/200+	no	fair	2	no
Air boat	excellent	no	easy	fast/200+	yes*	excellent	1-2	no
Mud Bug†	fair	no-preferably	easy	moderate/200+	yes	excellent	1	yes
Cajun Adapter§	excellent	no-preferably	fair	moderate/200+	yes	excellent	1-2	yes

*Air boats do not have a true reverse but can turn in such a short radius that they effectively have a reverse capacity.

†See text for explanation/description. Mud Bug is available from A. A. Roy, Box 220, Mauriceville, TX 77626.

§See text for explanation/description. Cajun Adapter is available from T. D. Habetz, Star Route A, Box 042-A, New Iberia, LA 70560.

ability and speed. An air boat can travel in ponds with a wide variety of depths and can quickly cross most levees. Traps need not be laid out in orderly lines. An air boat can maneuver in very high winds and can turn easily to recover missed traps. Traps may be rapidly moved to different areas in a pond, if need be. Fig. 43.

The Mud Bug is a four-wheeled vehicle developed by A. A. Roy of Mauriceville, Tex., to check crawfish traps. It consists of a raised platform with four 15-inch wide tires powered by a large air-cooled engine. The vehicle has four-wheel drive and full foot pedal control, leaving the hands free to check, empty, and rebait traps as the vehicle passes over them. A major advantage of this harvesting vehicle over other devices is its stability in high winds. It also requires only one operator and readily crosses levees. A potential disadvantage involves the fact that the machine does produce substantial furrows in the pond bottom. This situation can cause problems when a pond is drained. Then, too, if a pond is to be rotated with rice or other crops, two further complications may arise. Extensive field preparation may be required and red rice seeds (a pest species in rice culture) may be raised to the surface, allowing them to germinate.

The Cajun Adapter was developed by T. D. Habetz of New Iberia, La. It is fitted into a flat-bottomed boat. A bow-mounted, notched wheel pulls the boat through the pond. The wheel is rotated by hydraulic pressure. An 8 horsepower air-cooled engine drives a pump that circulates hydraulic fluid to and from the wheel. Hydraulic fluid also drives a piston that is used to turn the drive wheel and steer the boat. A length of hydrostatic chain is dragged behind the boat to serve as a "keel." The drive wheel and keel cut a 6 inch groove in the pond bottom after a few weeks of operation. Eventually, the wheel and keel will naturally follow the groove, reducing the need for constant steering. Like the Mud Bug, the Cajun Adapter has positive control in winds, instant stopping, and a reverse capability. It can also cross low levees but does not do as much damage to the pond bottom.

Fig. 42. Motorized, flat bottom boat used to harvest crawfish in open ponds.

As pointed out, the best crawfishing areas in the Atchafalaya Basin are those in which back swamp waters clash with turbid flood waters. These fronts are dynamic and move throughout the season. Thus, it is not at all unusual for a trapper to move his traps several times during a season. Crawfishermen in other natural areas outside of the Atchafalaya Basin may also move traps in response to localized depletion of harvestable sized crawfish, bad water, and falling/rising water levels. It is important that traps be placed firmly on the bottom with at least one entrance placed downstream if a current is present. In crawfish ponds of more than 20 acres, some traps must be moved periodically or left in place but not fished as certain areas may become totally depleted of harvestable crawfish.

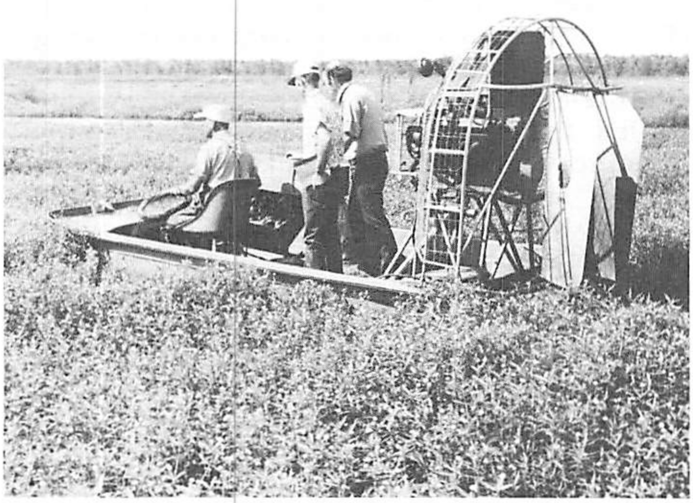


Fig. 43. Air boat being used to harvest crawfish.

Traps are normally emptied onto a sorting table. These tables may be made of wood, iron, or aluminum. They are rectangular with one end slanting to a constricted V where an opening permits the crawfish to fall into an open mesh (1/4 inch) vegetable sack. The sides of the sorting table are 4 to 6 inches high. Debris and bait are removed as the crawfish fall into the sack. They are shipped in these sacks. Until the sacks are refrigerated by the buyer, they should be shaded and periodically rinsed with fresh water to keep gills wet and rinse away excrement. The sacks usually reach the buyer's storage facility in about 6 to 10 hours. Once there, they may be held, or shipped, under refrigeration (39° to 45°F) for up to five days with less than 10 percent mortality. The sacks must be rinsed with fresh water and moved periodically to prevent crushing the crawfish on the bottom. Fig. 44.

Fig. 44. Crawfish are emptied into a sorting table when harvested. Lower level holds bait.

Commercial crawfish are seldom harvested with active capture devices such as seines and trawls. The principal reason is that there is rarely an area where such devices can be used in the dense growths and obstructions in areas where crawfish concentrations are found. In addition, such techniques would not discriminate between those crawfish about to molt or those recently molted. Such crawfish do not feed and will not enter traps. They are sensitive to handling and if they are packed in sacks with intermolt crawfish, they suffer considerable mortality. Some enterprising individuals have used seines and trawls to harvest crawfish in years of abundance, but the practice is very rare. Research is currently underway to determine the feasibility of using electrofishing devices in ponds. To harvest crawfish by seine, "chum" the area 30 minutes or so before seining it. That is, throw chopped fish into the area to attract crawfish from holes and other hideways.

Holding Crawfish

Initial harvests are relatively low on a per trap basis. Farmers, especially those with very small ponds, may not catch enough in a day to warrant trapping. Several days of trapping could yield enough crawfish to market, especially if prices are high. Without a refrigeration system in which to store such crawfish, many farmers hold them in enlarged, sealed traps or in live fish boxes. Since there is more oxygen in cold water and since crawfish are poikilotherms (cold blooded) and less active in cold water, many more crawfish can be held in such containers during the cold months than can be maintained in warmer weather. We have successfully held up to 100 pounds of crawfish for four to five days in a floating cage with a volume of one cubic yard at temperatures below 65°F and up to 50 pounds if temperatures are above 65°F. Detailed experiments will undoubtedly provide more precise information on this subject. One farmer was known to have put crawfish in horse watering troughs and pump water through them, keeping them alive for several days. According to Dr. James Davis, Texas Agricultural Extension Service, Texas crawfish farmers routinely maintain 2,000 pounds of crawfish in 200 cubic-foot holding tanks with one 1/3 hp aerator per 25 cubic feet.

When crawfish are held in troughs or cages for 12 hours, they purge their digestive tracts. This has obvious sanitary value when the crawfish are shipped. Texas crawfish farmers claim that this adds one to two days of "shelf life" to crawfish held in cold storage in vegetable sacks.

Shipping and Storing Live Crawfish

As many as 55 pounds of crawfish may be packed into 1/4 inch mesh vegetable sacks, although 45-50 pounds is the norm. Relatively soft-shelled, rapidly growing crawfish should be packed carefully. Large numbers of these may be crushed if packed more than 35-40 pounds per sack.

Before storing, sacks should be (1) kept out of water in the bottom of the boat as any gas or oil residue would make them inedible, (2) covered to prevent crawfish from drying out, and (3) kept as cool as possible or in shade.

Sacks of crawfish should be turned at least once per day and kept moist. In temperatures between 40-45°F, crawfish can be stored up to 5 days without excessive mortality.

Processing

Louisiana crawfish are sold live or processed. Live crawfish are distributed to fish markets for resale to individuals and restaurants. Individuals usually boil them, while restuarants boil them or clean them for use in entree dishes. Until mid-April prices are usually high, so most crawfish go to the live market. As they become more abundant and the price moderates, crawfish processing plants begin to operate on a large scale, often employing two shifts of workers for a six-day week. Crawfish processing is very primitive. Crawfish meat is hand peeled by workers who either receive an hourly wage or a set amount for each pound of peeled meat. The live crawfish are first rinsed and then boiled in fresh water for 5 to 10 minutes. They are allowed to cool and are transferred to the peeling tables. The peelers, usually women, deftly separate the cephalothoraxes and abdomens. The first two or three segments of the abdominal exoskeleton are removed, and the meat is forced from the rest of the abdomen by pressing it between the thumb and forefinger. This process tends to damage the hands of the peelers, who can produce about four pounds of peeled meat per hour. Various types of gloves and hand coverings have been employed to prevent injury, but torn fingers remain occupational hazards. Several peeling machines have been designed, and one shows good potential; however, it will be at least 2 to 3 years before it is in widespread use. Figs. 45, 46, 47, 48.

The hepatopancreas may or may not be retained. If it is, it may be set aside in separate containers or left on the abdominal meat. This so-called fat is considered to be a necessary ingredient in crawfish dishes by Louisiana chefs; however, it represents an ideal medium for bacterial growth. Although the taste is distinctive, most food service professionals agree that all abdominal meat should be thoroughly washed of hepatopancreas material. Nor do they favor retention of the hepatopancreatic material separately. The abdominal meat with or without the hepatopancreatic material will then be packed and refrigerated. Abdominal meat that is to be frozen is thoroughly washed of hepatopancreatic material. Most processors prefer to include the hepatopancreatic material because many customers insist on it and because its extra weight allows them to use less crawfish meat per pound, providing more profit.

Bacterial contamination of peeled crawfish meat is a serious problem. The best ways to control bacterial levels are (1) to insist on cleanliness in all areas of peeling plant operations including thorough cleanings of all equipment at the end of daily operations; (2) to rinse peeled meat thoroughly to remove hepatopancreatic material; and (3) to keep parboiled crawfish and peeled meat at room temperature for as short a period as possible (meat should never be held at room temperature for as long as one hour). Bacterial genera generally considered to be "rapid spoilers" are Pseudomonas and Achromobacter.

Fig. 45. Crawfish packed in open mesh vegetable sacks.

Yield of abdominal meat may vary from 14 to 25 percent. It is largely dependent upon the maturity status of the crawfish. Young, rapidly growing crawfish have very small claws in relation to the rest of their bodies. Thus, little weight is lost in the claws. Mature crawfish, both male and female, have enlarged claws with those of the male accounting for as much as 40 percent of the total weight of the animal. As only the abdominal meat (and hepatopancreas) is retained, the effect on yield is obvious.

Fig. 46. Crawfish being cleaned prior to parboiling and peeling.

Several approaches have been used in peeling crawfish abdomens mechanically. These all require that the abdomen be separated from the head and that it be parboiled or frozen and thawed. Automatic headers are being developed but are not in use so the task must be performed by hand. Parboiling and freezing loosen the meat from the shell.

Two peeling machines use pressure to force meat from the abdominal shell. One employs compressed air that is forced into the end of the tail through a hollow needle. The other utilizes rollers that squeeze the meat from the shell. The third type of peeling machine has small cutting blades that cut the shell on the top and the bottom. This permits the meat to fall freely from the shell.

Fig. 47. Crawfish being peeled by hand.

The most promising of the three machines is the one that utilizes rollers to squeeze the meat from the abdomen. It is a continuous flow machine and processes a number of abdomens at a time. The other two machines process one abdomen at a time, which is little improvement over hand peelers.

Freezing crawfish to loosen abdominal meat is a very new development. In the past parboiling was the only method used. Boiling is apparently satisfactory if a constant temperature can be maintained; however, this is virtually impossible to achieve in a production facility. Water loses heat when any appreciable number of crawfish is added to it. Those on the outside of the mass are subjected to different temperatures from those on the inside. This is not the case in rapid freezing (5 to 10 minutes) when a brine freezer is used to pretreat the crawfish. If crawfish are to be processed by using this freezing process, they must be frozen rapidly, preferably in less than 15 minutes. If the crawfish are not frozen rapidly, enzymes produced as they chill and die will cause the processed meat to disintegrate after it has been frozen. Brine freezers are ideal for this because several 40 to 50 pound sacks of crawfish may be frozen in less than 5 minutes. Alternatively, sacked crawfish can be cooled rapidly in an ice-brine slurry and frozen in a blast freezer. This will deactivate the enzymes, but it requires double handling.

Flash freezing is opening several new marketing avenues to crawfish processors. Whole, flash frozen crawfish may be held as long as 6 months and boiled. The product cannot be distinguished from crawfish boiled while still alive. Flash frozen crawfish of all sizes may also be stored and shipped in bulk to bait crawfish markets. Peeling plant wastes may be used in enzyme digesters to produce protein rich liquid concentrates when the crawfish were killed by freezing. Parboiling destroys most of the enzymes.

Crawfish meat is a good source of protein (16 to 18%) and is low in calories. It is rich in minerals such as sodium, potassium, calcium, and magnesium. An analysis of crawfish meat is found in Table 10.

Crawfish processing wastes are a major problem for two reasons. First, they represent an expensive commodity--on the average 85% of the purchase price of live crawfish--that brings no return to the processor. Second, the wastes must be disposed of in a sanitary manner. The wastes are excellent lime substitutes and they have been used experimentally as fertilizers with a number of vegetable crops (snap beans, tomatoes, sweet corn, etc.) and agronomic crops (soybeans, sugarcane, etc. More information about the use of wastes as lime substitutes and fertilizers can be obtained from the College of Agriculture, University of Southwestern Louisiana, Lafayette, LA 70504). Wastes can also be processed into high quality meals (discussed below). Finally, a potential market just recently identified involves the use of ground wastes in trout and salmon feeds. Crawfish wastes have high concentrations of red pigments that, when metabolized by trout and salmon, give their flesh a highly desirable pink tint.

Crawfish processing wastes have a fairly high protein content (28-32%) but they also have a very high ash (mineral) content (29-44%). Much of the ash is in the form of calcium (18%). For this reason, only about 10% of an animal feed

Fig. 48. Peeled crawfish meat being packed.

Table 10. A nutritional analysis of crawfish meat.*

Calories (328/lb)†	
Moisture	80.04%
Ash	1.05%
Crude fat	2.83%
Protein	17.13%
Minerals (mg/100 g)	
Sodium (Na)	112.46
Potassium (K)	209.50
Calcium (Ca)	215.80
Magnesium (Mg)	27.35
Zinc (Zn)	2.10
Iron (Fe)	0.95
Copper (Cu)	0.52
Manganese (Mn)	0.19
B-Vitamins (mg/100 g)§	
Thiamin	0.11
Riboflavin	0.04
Niacin	1.94

*Source: James Rutledge, Dept. of Food Science, La. State Univ., Baton Rouge, La. 70803.

†Source: Texas Agri. Ext. Serv., Texas A&M Univ., College Station, TX 77843

§1 ounce = 28 g, 1,000 mg = 1g; carbohydrate levels are negligible.

Table 11. Analyses of dried crawfish peeling wastes before and after processing to remove ash.

	Before Processing (%)*	(%)†	After Processing (%)*
Moisture	5.7	-§	8.2
Protein	28.1	32.2	58.5
Fat	4.4	-§	6.0
Chitin	12.5	14.1	2.1
Ash	44.0	29.0	16.8
Minerals			
Calcium	18.0	18.1	5.7
Phosphorous	1.7	1.2	0.9
Trace minerals (ppm)			
Magnesium	-§	2656.0	-§
Manganese	-§	157.0	-§
Potassium	-§	1400.0	-§
Iodine	-§	1313.0	-§
Iron	-§	8.8	-§

*Source: Meyers, S. P., and J. E. Rutledge. 1971. Economic utilization of crustacean meals. Feedstuffs 43(43):16.

†Source: Lovell, R. T., J. R. Lafleur, and F. H. Hoskins. 1968. Nutritional value of crayfish waste meal. Agri. and Food Chemistry 16:204-207.

§Not determined.

ration should be made up of crawfish wastes. Otherwise the ash content must be reduced in order to convert the wastes into a high quality feed ingredient.

Roughly 79% of the ash in crawfish wastes may be removed by a process where the dried wastes are crushed in a Wiley Mill and screened through a No. 12 mesh sieve. The screened product has about 60% protein but only about 17% ash. Analyses of dried crawfish processing wastes before and after processing is found in Table 11.

Despite all of the potential uses for crawfish wastes, there are no recovery plants available. Failure to process wastes results from several factors including the seasonal nature of the raw material, high energy costs, and the cost of transporting the raw material from a number of widely dispersed peeling plants. Currently, almost all wastes are taken to land fills or spread over pasture lands or fallow agricultural fields.

There is almost no commerce in crawfish for fish bait in Louisiana. There are two reasons for this. First, crawfish can be readily captured with dip nets and seines from roadside ditches by anyone. Second, no out-of-state markets for bait crawfish have been developed.

Marketing

Some interesting information about crawfish processing and marketing comes from a report by Drs. J. C. Carrol and H. C. Blades, Jr., of the University of Southwestern Louisiana. They found that the most important distribution channel for Louisiana crawfish is processor to seafood market to consumer; the second most important channel is processor to restuarant to consumer; and the least important distribution channel is processor to regular food market to consumer. Live crawfish account for 60 to 70 percent of a processor's sales, and many processors use their peeling operations as a salvage activity to avoid losses of unsaleable live crawfish. Approximately three-fourths of the retail crawfish sales in seafood markets is live crawfish. Most restaurant sales (80 percent) consist of peeled abdomens in the form of entree components, although boiled (whole-live) crawfish is the most popular individual restaurant entree. The eight most popular restaurant crawfish entrees in Louisiana were--most to least popular--boiled crawfish, crawfish etouffe, crawfish bisque, fried crawfish 'tails,' crawfish gumbo, crawfish dinner (a combination of entrees), crawfish jambalaya, and crawfish stew.

The best out-of-state markets are for frozen abdominal meat sent to restaurants for preparing entrees. These products are generally more acceptable to people unfamiliar with consumption of whole, boiled crawfish. The strongest out-of-state markets are along the Gulf coast, Texas and Mississippi, where the Louisiana culture has dispersed and mixed with adjacent cultures. It should be noted, however, that processors are reporting increasing interest in their products from larger metropolitan areas throughout the country including Dallas-Fort Worth, Chicago, Atlanta, Washington, and New York. Overseas markets are available, but they have been largely unexploited because of major logistical problems.

The major limiting factor to commercial crawfish exploitation in Louisiana is the lack of widespread out-of-state markets. Virtually all of the state's production is consumed domestically. This deflates prices especially in years when crawfish are in abundant supply. The lack of markets is not unique to Louisiana. California produces about 500,000 lbs of the crawfish Pacifastacus leniusculus annually and could probably produce in excess of 4 to 5 million lbs of that species and the red crawfish annually, but California dealers, too, have a very limited market. Most of their harvest is exported to Europe. They have a poorly defined domestic market.

Legal Considerations

Crawfish trappers generally trap in an area of unposted swamp on a first come first served basis. Markers are rarely used because they attract thieves. Many areas outside the Atchafalaya Basin are posted and one must obtain permission from the owner to harvest crawfish. Much of the Atchafalaya Basin is privately owned; however, traditionally most areas have been open to anyone. If such areas are posted, there is certain to be controversy, as open access has been the practice for so long. Anyone who traps and sells crawfish must obtain a license from the Louisiana Department of Wildlife and Fisheries (LDWF; current cost $5 per year). There are no other regulations governing the harvest of crawfish. Crawfish pond owners are required to purchase a culture permit (current cost $10) from LDWF. Theft of crawfish from a privately owned pond is treated as a felony in Louisiana. Fish markets, crawfish processing plants, and restuarants dealing with crawfish must comply with sanitation codes and obtain permits from the State Board of Health.

In years when the yield from the Atchafalaya Basin is poor, there is considerable discussion about the advisability of fishery regulations to include size limits, seasons, and mesh restrictions on traps. Biologists have successfully argued that such regulations are pointless because annual abundance of crawfish depends almost entirely on climatic conditions with deviations away from the ideal hydrological cycle (see discussion of habitat) resulting in poor yields. In addition, such regulations could not be uniformly applied because of the widespread culture and distribution of the species in natural habitats other than the Atchafalaya Basin.

If permits are required to construct ponds in wetland areas, they may be obtained from the area office of the U.S. Army Corps of Engineers or designated local governmental agencies.

CULTURE

Brief History of Red Crawfish Culture

The origin of crawfish culture can be traced back to the late 1700s when plantation gardeners cultured the tasty animals in small ponds as a special delight for their employers. Later the displaced French Acadian farmers found that crawfish were an excellent lagniappe (a little extra) crop. As rice farmers, the Acadians would flood their fields during the fall and winter months to attract waterfowl for hunting. In doing so, crawfish would move quickly into the predator-free ponds and thrive. Thus, when the ponds were drained in the spring, the farmers actually had a bonus crop or lagniappe.

In the early 1930s, Percy Viosca, a leading Louisiana naturalist, published recommendations for culturing crawfish in ponds. This led to a gradual interest and increase in the culture of crawfish. His interest encouraged others to develop a real industry. The greatest growth in crawfish culture took place after Viosca's death, in the late 1960s. Since then many prominant scientists have developed techniques and performed much of the needed basic research in the area of crawfish culture.

Currently about 50,000 acres are devoted to crawfish culture in Louisiana alone. Growth of the industry is indicated on the accompanying table. As many crawfish are harvested from ditches, bar-pits, and from swamps, accurate records pertaining to the total harvest are nonexistent. However it is estimated that from crawfish ponds in Louisiana about 500 pounds per acre per year are harvested, a total of more than 25,000,000 pounds of crawfish. The expansion of the crawfish industry seems to have leveled off temporarily. But it is believed that the potential of more than 280,000 acres could be developed. This area would probably produce an annual yield of well over 90 million pounds.

Culture of red crawfish is expanding to other regions. Expansion into southern Texas was to be expected in view of the extensive cultivation of rice in the area and extension of the Louisiana Acadian culture westward into that area. About 3,000 acres are now devoted to crawfish culture in Texas. Recently, South Carolina has initiated a vigorous crawfish culture development program with about ten to twelve ponds (about 40 acres) located throughout the state.

Red crawfish have become established in fish culture ponds in Arkansas, California, Hawaii, Missouri, and Ohio. Fallow ponds or ponds used for raising minnows or fingerlings of predacious species produce crawfish crops that justify harvesting. Continued expansion in the United States in areas outside of Louisiana is apparently dependent on the development of markets in those areas.

Louisiana-style crawfish culture has crossed the Atlantic Ocean to southern Spain. Initial work began in 1973 and has shown considerable success. In view of this and the decline of native crawfish stocks, extension of *P. clarkii* culture to other areas of Europe is likely.

LEGAL ASPECTS OF CRAWFISH FARMING

Many prospective crawfish farmers are not aware that there are a number of laws and regulations that apply to crawfish farming. Various subjects that should be considered include (1) definition of fish farming and of a fish farmer; (2) pond construction; (3) permit to begin or continue fish farming; (4) stocking; drainage of ponds; (5) use of chemicals; (6) processing; and (7) theft. Each local (municipal and parish or county) and state governmental unit differs with respect to the nature of its regulation of aquaculture operations. In addition, there are a number of federal laws and regulations that apply to all areas of the country. An excellent guide for researching legal aspects of aquaculture is the Louisiana Agricultural Experiment Station Bulletin No. 689, "Some Legal Aspects of Catfish and Crawfish Farming in Louisiana: A case study," by Elizabeth Williams, Frank S. Craig III, and James W. Avault Jr. These can be obtained from La. Coop. Ext. Serv., Knapp Hall, LSU, Baton Rouge, LA 70803.

Even though this bulletin is written specifically for Louisiana, it should prove useful to others in other states. Extension services can also be helpful in updating interested parties as to the current status of pertinent laws and regulations. It is important to caution readers that many states have laws that require permits to import non-native species for culture purposes and often ban such importation.

CRAWFISH CULTURE

The red crawfish is cultured by establishing sustaining populations within shallow (12 to 30 inch) earthen ponds. The basic pattern, as practiced in Louisiana, involves stocking with adult crawfish in late spring, draining in early summer, reflooding in early fall, and harvesting when numbers justify the effort--as early as November or as late as March. This wet/dry cycle closely simulates the natural hydrological cycle in southern Louisiana.

Holdover adult crawfish and juvenile crawfish (those that had not reached maturity when ponds were drained) comprise the initial harvests. The majority of the young-of-the-year crawfish enter the pond in several groups, or waves, of recruitment from the time that the pond is flooded until mid-winter. Each specific group of crawfish may be referred to as an age class. The young-of-the-year age classes will produce the bulk of the crop. Some red crawfish will spawn in ponds in late spring or mid-summer. (Unless water is present, young crawfish from such hatches remain in burrows.) Numbers are not great, and absolute growth is apparently retarded by warm water temperatures (85-90°F) even though the molting rate is rapid. Growth is also slowed in the winter when temperatures fall below 50-60°F.

In regions like Texas, South Carolina, and southern Spain with climates similar to Louisiana's, P. clarkii has been cultured with great success by following the wet/dry cycle employed in Louisiana. In colder regions such as Arkansas and Missouri, growth is greatly retarded by extended low temperatures during the winter. This prevents harvest until mid to late spring.

We know of one attempt to culture P. clarkii using Louisiana methods in Santo Domingo, a tropical area. Although the program is experimental, it certainly points to the feasibility of culturing them in the tropics.

At the current state-of-the-art, the wet/dry cycle seems essential for several reasons: (1) it serves to prevent the establishment of predacious fish populations; (2) it phases reproductive activity of the crawfish; (3) it permits the growth of vegetation that will serve as food and substrate; and (4) it permits the cultivation of rice as a grain product.

Most aquaculture involves the stocking of known numbers of young fish or shellfish with total harvest after a period of growth. Yields can be easily predicted. In red crawfish culture, there is no simple relationship between adult crawfish stocked and yield. Artificial production of young red crawfish is possible and is practiced by several hatcheries in California. With current economic constraints, yields are adequate for self-sustaining systems. There are many unexplained pond failures. Currently, all that can be done is to advise the owner to restock adults the following spring, assuming that the pond will support crawfish. As profit margins increase, there will be increased emphasis on maximizing production to include stocking of young to supplement the natural reproduction and to add supplemental feeds to augment food that is grown in the pond. Prior to pond construction in agricultural areas, soils should be analyzed for residual pesticide levels. Failure to do so could jeopardize a major investment.

There are five well-written bulletins available on red crawfish culture. Please check the Bibliography for the references by Gary, Hill and Cancienne, Huner and Avault, LaCaze, and Viosca.

ECONOMICS

Can one make money in crawfish farming? Certainly, or there would be far less than 50,000 acres of land devoted to crawfish farming in Louisiana alone. However, precise economic projections depend on each individual situation. For example, is the land owned, is it to be leased, or is it to be bought? Will the ponds be built by the owner using his own equipment and labor, a friend or relative who charges less than a contractor, or by a contractor? To whom will the crawfish be sold? Who will harvest the pond--farm laborers, family, or paid fishermen who are either paid a flat wage or a percentage (usually half) of the harvest. How large a pond will be built? These and a number of other factors must be considered before one enters the business.

Dr. Kenneth Roberts of the Louisiana Cooperative Extension Service and Sea Grant College Program recently compiled an economic servey of Louisiana crawfish farms. Based on the 1978-79 season, net return per acre for a 100 acre crawfish farm with two 50-acre ponds varied from $17 to $210 per acre. Dr. Roberts included a table in his report showing different returns based on a number of management strategies, including market, overhead, stocking, and feeding. He concluded that pond crawfish culture has been financially successful in Louisiana. Key elements of this success were the low cost of pond construction through the use of farm labor and equipment and minimal cost of feed.

Dr. Roberts cautioned that individuals facing the purchase of land and contracting for construction of levees face significantly different costs. He acknowledged that Louisiana's wild crawfish crop was an important factor in determining the price that crawfish farmers could obtain for their crop. He noted that most ponds generate the bulk of their revenue in the late-early spring period before the bulk of the wild crop is harvested.

Fortunately, farmers located 100 miles or more away from the Atchafalaya Basin--the major source of Louisiana's wild crawfish crop, do not suffer greatly from competition. Crawfish farmers in Texas, Mississippi, and South Carolina report prices roughly twice those obtained in Louisiana, as there is virtually no competition from wild crops in those states.

Individuals seriously contemplating crawfish farming as anything but a hobby should obtain the Roberts survey and the LaCaze and Gary bulletins (see Bibliography). Prospective farmers can obtain assistance in making financial decisions through their local county extension service office or the local Small Business Administration office.

SUCCESS IN CRAWFISH CULTURE

The secret to success in crawfish culture is good management. Anyone who has ever raised a garden knows that the individual who takes the best care of the garden will produce the greatest yields. The aquaculturist who visits his crawfish pond on an irregular basis and expects a crop in the spring is generally disappointed. A conscientious pond owner will know when he will have a limited crop before he purchases excessive amounts of bait or traps.

POND TYPES AND CONSTRUCTION

Pond Types

There are two broad categories of crawfish ponds, open and wooded. Most crawfish specialists would then divide these into two subcategories of wooded ponds and four subcategories of open ponds. These depend on the pond soil and the dominant vegetation. These, in turn, influence the general appearance of the water. The accompanying descriptive table is largely derived from a report on pond types written by Donald Gooch, a well-known Louisiana crawfish specialist (Table 12).

No single classification suffices to meet all possible variations. For example, open agricultural ponds take on the characteristics of open highland ponds if crops are not planted each year. Wooded ponds may be partially cleared such that portions are "open." However, the preceding system does provide a convenient, functional means to separate pond types. Certainly, modifications are sure to arise. Open ponds of 10 to 20 acres are the most commonly encountered ponds in south Louisiana. A few wooded ponds may approach 1,000 acres in size. Figs. 31, 32.

Table 12. Subcategories of wooded and open Louisiana crawfish ponds.

	Dominant* Vegetation	Water Color	Observations
Wooded Swampland	Cypress, tupelogum	Usually clear.	Lowland, subject to annual flooding with high organic content in soil. Oxygen problems common.
Highland	Oak, elm, hickory	Usually clear but can become muddy late in season.	Well-drained highlands without high organic content in soil. Oxygen problems common.
Open Agricultural	Normally rice but depends on crop.	Becomes very turbid in spring.	Crops are grown during summer and harvested before pond is flooded in fall.
Marsh	Alligatorweed, smartweed, primrose, sedges, grasses.	Usually clear.	Lowland subject to annual flooding with high organic content in soil. Oxygen problems common.
Highland	Dominated by annual grasses and sedges but alligatorweed, smart-weed, and primrose invade or are transplanted.	Become turbid in spring.	Either cleared highland ponds or agricultural land that is not rotated between crawfish and field crops in same year.
Swampland	Similar to marsh pond.	Tend to be clear but can become turbid in spring.	This is a wooded swampland pond that has been cleared.

*It has become increasingly popular in recent years to sow rice and/or millet in all varieties of crawfish ponds. Coverage is highly variable and the grain is not harvested.

Construction

Crawfish ponds are normally built with a minimum depth of 12 inches and a maximum depth of 30 inches. Deeper ponds are needed in climates with greater temperature variations than the southeastern United States. The levee crown should be at least 12 inches above the full water level. The slope on the inside of the main levee should be 3:1 and on the outside of the levee, 2:1. Levees should be wide enough to permit vehicular traffic. The earth must have enough clay in it to hold water. Sandy soils are to be avoided. It is preferable that the entire pond be drained during the summer. If there are borrow (bar) pits inside the pond, it may be impractical to drain them. Water levels inside the pits should be kept as low as possible.

It is preferable that a pond be cleared of all trees and brush. If this is too costly, as much clearing as is possible should be done. Clearing should be engineered to facilitate water flow from the source to the drain.

Construction is much easier on existing agricultural lands. Rice fields are especially convenient, as established levee systems are generally available. (Note: we refer here to outer ring levees; inner or contour levees are too low to hold water at necessary depths.)

Wooded ponds and open, marsh ponds are notoriously poor producers because of water quality problems. They rarely generate more than 300 pounds per acre, annually. Such areas should be avoided in selecting a pond site. Also, if such areas are designated as "wetlands" by the U.S. Army Corps of Engineers, a permit will be required to construct a pond. Permits are becoming progressively harder to secure.

We do not advocate pond construction in wooded areas or in marshes. Persons considering such areas should be prepared to accept poor yields and constant management problems.

Before actually building a pond one should consult the county extension service and Soil Conservation Service for assistance. In addition, the Soil Conservation Service will survey the site and advise on the feasibility of building a pond. They will also prepare pond construction specifications, including pump requirements and drain sizes, which are then relayed to whoever does the actual construction. The local Agricultural Stabilization and Conservation Service programs may assist with payments to partially defray the cost of pond construction.

WATER MANAGEMENT

Control

A pumping system is needed that can fill the pond in 15 to 25 days. Rainfall will reduce pumping, but one should not depend on it when designing pumping facilities. Drains must be large enough to remove rain waters before they overflow the levees. Filter systems are necessary on both inlets and drains to prevent entry of predacious fish. Baffles will serve to increase oxygen in incoming waters. Figs. 49, 50.

Fig. 49. Water inlet pipe with aeration baffles.

Flooding

If pond flooding begins in early September and ends in early

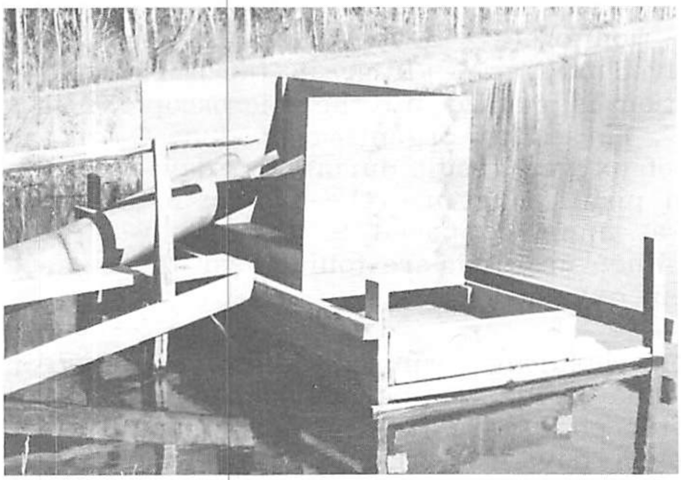


Fig. 50. Water inlet fish screen/aeration baffle.

October, there should be 2 to 3 1/2 months of warm weather for crawfish growth prior to December when water temperatures fall below 50 to 55°F. An objection to flooding earlier is that vegetation will decompose so rapidly that it will create anaerobic, oxygen deficient waters. Filling ponds in September can insure a November/December crop if water quality is carefully controlled and early hatches are successful. Flooding ponds after mid-October invariably reduces the pre-winter growing period and may lead to high mortality of young crawfish in the burrows.

One major advantage to early flooding is that good crawfish yields will begin 6 to 8 weeks before prices are driven down by the harvest of wild crawfish.

Draining

In ponds used only for crawfish culture, draining should begin toward the end of May and be completed by the end of June. Slow draining encourages burrowing and reduces predation.

On ponds used for raising rice and crawfish in the same year, draining should be completed no earlier than the middle of May and preferably by the end of May. Earlier draining reduces harvest of crawfish and appears to reduce the numbers of burrowed broodstock for the next season. Rice production, of course, is reduced because the late planting date subjects the rice to adverse growing conditions; however, a compromise must be reached if crawfish and rice are both harvested successfully. In Texas some farmers are satisfied with results obtained when ponds are drained in April and planted with rice by the first of May.

Water Quality

Crawfish can live in almost any fresh or slightly brackish water (see Ecology section). The primary water quality factor limiting crawfish pond culture is dissolved oxygen. When emergent plants or algae die back in the fall, they rapidly begin to decompose. This occurs again in the spring as water begins to warm. Often the pond water may turn black when much of the available oxygen is used up by the decomposers. There are ways to prevent low oxygen concentrations. Culturists can periodically mow or disk the vegetation during the summer. Leaving it in the field to dry will slow down the decomposition process. Another procedure is to leave rows of standing vegetation in the pond. The rows should be cut to facilitate water flow from inlet to outlet. These serve to provide crawfish with cover and access to the surface if dissolved oxygen is too low. Any sustained periods with oxygen levels below 2 ppm can be fatal. Thus by periodically checking the pond with an oxygen kit or oxygen meter, the level can be monitored. Several factors should be remembered in checking the DO (dissolved oxygen). Early in the morning, the DO level is usually low. This reduction is caused by the microscopic plants (phytoplankton) that live in the water. These tiny organisms produce O_2 in the presence of sunlight; thus high levels of oxygen result during the day when the O_2 is being released. At night, green plants must use the oxygen for metabolism; this reduces the oxygen levels at night compared to the day when the phytoplankton are producing oxygen. When crawfish are found near the surface clinging to vegetation, the pond is low in oxygen.

It is clear that methods for insuring minimal dissolved oxygen concentrations in crawfish ponds will have to be developed. Current recommendations are that two weeks after ponds are full, pumping should begin to insure exchange of water every seven days (30-35 days is preferable--this requires 110 gallons per acre per minute) until temperatures fall below 65°F (the point at which microbial decomposition of vegetation declines markedly). Additional pumping may be needed as water temperatures rise above 65°F in the spring. Water should pass through, preferably fall through, a series of screened baffles so that it will be completely saturated with oxygen. Baffles will also remove many fish from incoming waters if a surface source is used.

There is no doubt that the cost of moving water (and water itself in some areas) is a significant economic factor in crawfish culture. Control of the amounts of vegetation in ponds is critical to insure good water quality and crawfish production. However, management recommendations have not yet been developed. Recent studies suggest that the maximum amount of vegetation, in terms of standing dry weight, that should be present when a pond is flooded is roughly 2 pounds per square yard (8,800 pounds per acre). Higher levels will almost surely lead to oxygen depletion. This amount of biomass has, under carefully managed conditions, generated crops of 800-1,500 pounds of red crawfish per acre when crawfish have successfully reproduced and predacious fishes have been controlled.

Using some semi-aquatic vegetation to provide cover and access to the surface is yet another method. Semi-aquatic plants are excellent since they do not die back if flooded. If alligator weed is used, one must exercise great caution because it is so prolific that it can take over a pond if it is not controlled. A mixture of semi-aquatic and wetland grasses and sedges or rice is preferable to either group alone (see Feeds and Fertilization section).

Artificial areation devices can be used to improve the water quality and should improve production. However the cost/benefit ratio of such processes has not been demonstrated.

Source of Water

The best water source is a well. Such water is normally free of pesticides and fish. It may be high in iron content. Where water enters ponds or irrigation ditches, a reddish-brown scum may develop. This occurs when there is too much iron in the water. In such cases, the water should be allowed to run through a settling pond or across the levee before entering the pond or

Table 13. Relative toxicities of various pesticides to *Procambarus clarkii*.

Pesticides	24 hr LD_{50}	36 hr LD_{50}	48 hr LD_{50}	96 hr LD_{50}
Insecticides				
DDT**	0.6 ppm	ND	0.6 ppm	0.6 ppm
Endrin**	0.4 ppm	ND	0.3 ppm	0.3 ppm
Mirex**	20.0 ppm (NM)	ND	20.0 ppm (NM)	20.0 ppm (NM)
Guthion*	ND	ND	ND	2.23 to 2.52
Azodrin*	ND	1.295†	ND	0.01 to 0.05
Methyl Parathion**	0.05 ppm	0.041†	0.04 ppm	0.04 ppm
Bidrin**	5.5 ppm	ND	4.0 ppm	3.0 ppm
Dibrom**	6.0 ppm	ND	4.0 ppm	4.0 ppm
Phosphamidon**	20.0 ppm	ND	6.0 ppm	5.5 ppm
Malathion**	20.0 ppm (NM)	ND	20.0 ppm (NM)	20.0 ppm (NM)
Dimethioate**	0.1 ppm (NM)	ND	0.1 ppm (NM)	0.1 ppm (NM)
Metalkamate†	ND	ND	ND	0.279 ppm
Carbaryl (Sevin)**	5.0 ppm	0.74 ††	3.0 ppm	2.0 ppm
Matadan (Pounce)¶	ND	ND	ND	0.00039 to 0.00062 ppm
Dieldrin	ND	0.74††	ND	ND
Parathion	ND	0.081††	ND	ND
Fenthion	ND	0.022††	ND	ND
Dursban	ND	0.041††	ND	ND
Agritox	ND	0.814††	ND	ND
Herbicides				
Propanil¶	ND	ND	ND	7.9 ppm
Molinate (Ordram)¶	ND	ND	ND	140.0 ppm
2,4-D¶	ND	ND	ND	1389.0 ppm
Sodium Azide¶	0.6 ppm (NM)	ND	0.4 ppm (NM)	0.4 ppm (NM)
(tech)	1.0 ppm (TM)	ND	0.6 ppm (TM)	0.6 ppm (TM)
Sodium Azide¶	0.8 ppm (NM)	ND	0.8 ppm (NM)	0.8 ppm (NM)
(gran)	1.0 ppm (TM)	ND	1.0 ppm (TM)	1.0 ppm (TM)
Potassium Azide¶	0.5 ppm (NM)	ND	0.5 ppm (NM)	0.25 ppm (NM)
(tech)	1.0 ppm (TM)	ND	1.0 ppm (TM)	0.5 ppm (TM)
Potassium Azide¶	1.0 ppm (NM)	ND	1.0 ppm (NM)	1.0 ppm (NM)
(gran)	2.0 ppm (TM)	ND	2.0 ppm (TM)	2.0 ppm (TM)
Fungicides				
Arasan 70-S Red†	ND	ND	ND	4.3 ppm
Vitavax-R†	ND	ND	ND	217.0 ppm
Benlate 50 WP†	ND	ND	ND	1032.0 ppm
Kocide SD†	ND	ND	ND	2918.0 ppm
Captan 80 WP†	ND	ND	ND	15631.0 ppm

Table 13. (cont.)

LD_{50} = Concentration necessary to kill 50% of the animals in the specified time period.
ND = Not determined
NM = No mortality
TM = Total mortality

Parts per Million	Pounds of Pesticide per Acre
0.01	0.02
0.10	0.20
1.00	2.00
10.00	20.00
100.00	200.00
1000.00	2000.00

References:

* Baker, L. (1975) A toxicity of the organophosphates Guthion® and Azodrin® to molting and nonmolting crawfish Procambarus clarkii (Girard). Papers from the Int. Symp. of Freshwater Crayfish, Vol. 2.

† Cheah, M., J. W. Avault Jr., and J. B. Graves. (1979) Some effects of thirteen rice pesticides on crawfish Procambarus clarkii and P. acutus acutus. Papers from the Int. Symp. on Freshwater Crayfish, Vol. 4 (in press).

§ Hughes, J. S. (1966) Use of the red crawfish, Procambarus clarkii (Girard), for herbicidal assays. Proc. Ann. Meeting SE Assoc. Game Fish. Comm. 20:437-439.

¶ Jolly, A. L. Jr., J. W. Avault Jr., J. B. Graves, and K. L. Koonce. (1977) Effects of Matadan® on newly hatched and juvenile Louisiana red swamp crawfish, Procambarus clarkii (Girard). Papers from Int. Symp. on Freshwater Crayfish, Vol. 3.

** Muncy, R. J., and A. D. Oliver. (1963) Toxicity of ten insecticides to the red crawfish, Procambarus clarkii (Girard). Trans. Amer. Fish Soc. 92:428-431.

†† Chang, V. C. S., and W. H. Lange. (1967) Laboratory and field evaluation of selected pesticides for control of the red crayfish in California rice fields. J. Econ. Entomology 60:473-477.

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aerated in some way. The iron is bad because it uses up free oxygen in the water. The scum can clog crawfish gills as well as be toxic to them. Most well water will be low in oxygen and should be splashed against some sort of flat surface to oxygenate it as it enters the pond. Well water may also be low in dissolved minerals. If alkalinity and/or hardness are low, the pond bottom may have to be limed (see Feeds and Fertilization section). Certainly a complete water analysis should be obtained before well water is used for agriculture.

Surface waters offer all sorts of perils, but they are often the only source of water. Problems that must be addressed and guarded against include the following: (1) predacious fishes can gain access to the pond if proper filtration systems are not employed; (2) ponds are first flooded when surface waters are normally low, and the supply may not be adequate to fill the pond rapidly; (3) surface waters are often low in dissolved oxygen in the fall; and (4) surface waters may be polluted by pesticides from application of such materials on field crops in the area. A crawfish farmer should keep track of what his neighbors are doing and watch the water source for the presence of dead and dying fish.

Pesticides

Chemicals are used to kill a wide variety of organisms. Insecticides kill insects; herbicides kill plants; and fungicides kill fungi. Insecticides are especially toxic to crawfish, as they are intended to kill insects which, like crawfish, are arthropods. Herbicides and fungicides are generally less toxic to crawfish but can also be fatal. Pesticides become problems in regular crawfish ponds if they are pumped into the pond with contaminated surface waters. If pesticides are inadvertantly applied directly to the pond by aerial applications intended for adjacent fields or through aerial drift from adjacent fields, contamination can result. Pesticides are applied directly to rice fields for control of rice pests. A considerable amount of work has been done screening the toxicity of pesticides that might be inadvertently or intentionally applied to crawfish ponds to P. clarkii. Toxicity depends upon many things: the age of crawfish, sex, molt stage, temperature, water volume, dissolved solids in the water. Pesticides tend to be more toxic to younger crawfish than to older ones. Likewise, they tend to be more toxic in warm water than cold water. Pesticides that contain carbon and chlorine (chlorinated hydrocarbons) may accumulate in crawfish tissues and adversely influence reproduction. Finally, pesticide use changes from year to year as a result of changes in government policy. Keeping all of these factors in mind, the accompanying table provides information on the relative toxicities of a number of pesticides to the red crawfish (Table 13). The best source for information concerning the advisability of using various pesticides in or near crawfish ponds is the Louisiana Cooperative Extension Service, Knapp Hall, LSU, Baton Rouge, La. 70803.

Note, as mentioned above, that double-cropping of rice and crawfish requires compromise. One of those compromises is the reduction in use of certain pesticides.

NUISANCE ANIMALS

Semiaquatic mammals such as otters, muskrats, and nutrias can become nuisances in crawfish ponds. Otters flatten baited traps, forcing crawfish tails through the mesh. They will then eat the tails. An effective method to trap them is to bait a submerged hoop net with fresh fish. Leg-hold traps are not always effective, especially when a novice sets them. A rifle is effective but otters are very wary animals and are difficult to approach.

Muskrats and nutrias are vegetarians with a penchant for burrowing in pond levees. Serious levee damage can result. Trapping and shooting (usually at night) can reduce the damage and their numbers. Another control method involves the use of baits made from grain and impregnated with anticoagulant rodent poisons. The mixture is bound with paraffin. But, since the killing of fur-bearing mammals is strictly controlled in all states, local authorities should be consulted first about the proper methods to control nuisance animals.

Both turtles and alligators are reptiles that can prove to be nuisances in crawfish ponds. Turtles will eat crawfish abdomens that protrude through the mesh of traps, especially in the spring when catches are greatest. Alligators can cause problems by burrowing into levees. They can be beneficial, however, by eating larger predacious fishes, turtles, nutrias, and muskrats. State game and fish biologists, Soil Conservation Service biologists, and County Agents can be of great assistance in dealing with alligator and turtle problems.

SUBSTRATE

Substrate is a surface on which an organism grows or is attached. In crawfish ponds substrates are the erect stalks of vegetation. These plants are important for several reasons. First and foremost, they increase the amount of surface area available to each crawfish. Thus the number of crawfish in a given area can be much greater than if no substrate were present. A very good analogy is the building of high-rise buildings to take advantage of limited building space in cities. Substrate, itself, provides both food and a place for epiphyton to grow. The epiphyton is an important food source for crawfish (see Life History section). Substrates provide protective cover from predators. Finally, substrates provide crawfish with an avenue to the surface if oxygen levels fall dangerously low. This is especially important as crawfish cannot swim well and stay at the surface like fish.

If all substrate is restricted to annual vegetation, the combined action of natural decomposition and crawfish grazing will destroy it by early April, concentrating the crawfish on the pond bottom. Semi-aquatic vegetation such as alligator weed does not have this same problem.

Aquaculturists who work with freshwater prawns and marine shrimps are developing artificial substrates for their ponds. This is also being done for crawfish ponds. Inexpensive artificial substrates may someday find their way into crawfish culture ponds.

Smaller crawfish concentrate at the edge of a pond in relatively fine grass such as bermuda grass. Bermuda grass does not die quickly after flooding. Small crawfish avoid areas where thick, heavy stemmed grasses and plants grow because there is little protective cover in such places. Thus, cutting pond edges during the summer dry period is advisable.

FEEDS AND FERTILIZERS

In many aquaculture systems, artificial feeds are used to supplement the natural food supply. Formulated feeds are not used in pond crawfish culture today as they have been in the past. Rather a detritus-based ecosystem is established to provide food for the crawfish. When shallow ponds with emergent vegetation are flooded, the annual plants die back at varying rates. As they die the plant tissue is broken down by microbial action. Initially such decomposed plant material, detritus, has a very high ratio of carbon atoms to nitrogen atoms. This is important to animals that live and feed on the detritus. Plants are mostly made up of tough cellulose molecules whose building blocks are carbon atoms. Plants contain very little protein. Protein is made up of carbon and nitrogen atoms. As the detritus is attacked by unicellular decomposers, the carbon-nitrogen ratio falls from a high of 100:1 to a critical low of 17:1. The decomposers need the carbon for their metabolism. The 17:1 ratio figure represents the point at which detritus will serve as a satisfactory food source for detritivores such as the crawfish.

Natural Feeds

Green plants are essential components in the diets of crawfish if a system is to produce a high quality crawfish. Such a crawfish is described as having a bright yellow hepatopancreas. The color is derived from plant pigments called carotenoids. There has been much discussion concerning the absolute nutritional value of green plants in ponds. Bullrush, cattail, smartweed, alligator weed, bull tongue, primrose, and many other plants do not readily die when flooded. Culturists are often advised to eliminate many of these plants, as they are not eaten by the crawfish and hinder harvesting operations. Green alligator weed, smartweed, and primrose, however, are considered to be an excellent food by some experts. With such an abundance of food, one would expect a dense crawfish population to readily devour many of these emergent plants. However, that is not the case. Ponds with any well established emergent plants can become so densely clogged by the spring growth that water circulation and harvest are hindered.

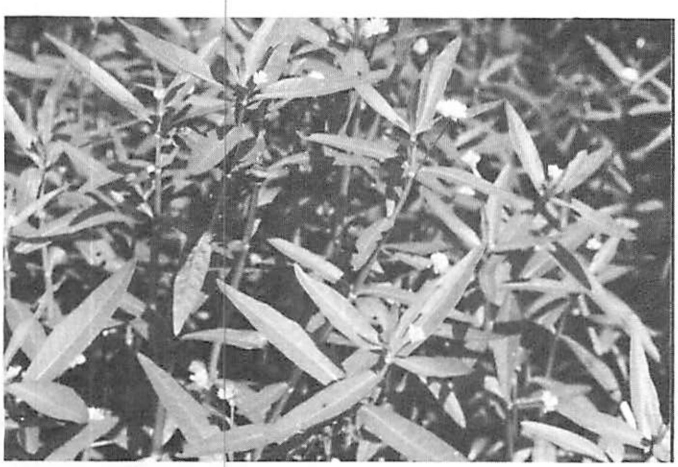


Fig. 51. Alligator weed in bloom.

In autumn there are two sources of detritus, the principal crawfish "food," in open ponds dominated by emergent vegetation. Annual vegetation dies quickly and begins to decompose, and then the lower leaves of the emergent plants die. A second influx of detritus flows into the ponds in the winter. At the first frost, the alligator weeds, smartweeds, and primroses die back to the water line, and this dead plant material above the water accounts for the new detritus. The plants resume growth in the spring. Fig. 51.

Ponds dominated by annual vegetation exhibit a different pattern. The vegetation dies quickly and becomes detritus. Crawfish constantly graze on this material to the extent that such ponds are generally denuded by early spring. At that time, it is not uncommon for crawfish to stunt and develop off-color (gray-brown) hepatopancreas.

Ponds dominated by rice are similar to ponds dominated by alligator weed. The rice stubble begins to decay upon pond flooding, but regrowth occurs at the root level. This regrowth can continue until the first frost. As the cold weather sets in, the entire plant dies and decays. This offers a second load of detritus to the pond ecosystem. Unlike the alligator weed ponds, there is no regrowth of rice during the spring. Stunting problems similar to those in ponds with annual vegetation are often observed.

All of these detritus-rich ponds support a multitude of benthic creatures, which include insects, worms, mollusks, and small planktonic crustaceans. As pointed out earlier, these provide red crawfish, especially young immatures, with essential protein nutrients and other compounds not available from plants and plant detritus.

Plants that decompose rapidly will reach the 17:1 carbon:nitrogen ratio more quickly than other more fiberous plants. If all plants in a pond decayed rapidly, the food source could be depleted too quickly. It is suggested that the ideal situation would involve the use of millets, rice, and alligator weed. The millets would decompose rapidly, providing a basic food supply while the rice would decompose more slowly and provide a second influx of detritus with its regrowth. The alligator weed would also provide detritus at the time of flooding but would insure a spring growth of plants. In addition, the alligator weed would act as a valuable substrate for the benthic community. Naturally, alligator weed would have to be physically separated from other vegetation as cultivation destroys it.

Trees in wooded ponds do not normally drop their leaves until late fall when they are killed by frosts. Thus, the greatest influx of detritus does not normally occur until four to eight weeks after flooding, and dissolved oxygen problems may not be as severe, initially, as they are in open ponds.

Recent research has shown that the addition of hay to experimental ponds in mid-winter will supplement existing food reserves. This will lead to increased crawfish production.

Artificial Feeds

Experiments conducted in large pools have demonstrated that crawfish will readily eat feeds formulated specifically for crustaceans or catfish and will grow rapidly. The cost of such feeds does not justify their use in ponds. Current research is underway to produce a low cost feed for crawfish ponds. The key factor in most feeds is the cost of the protein. Animal protein costs considerably more than plant protein. For other crustaceans such as marine shrimp and freshwater prawns, protein must be supplied by expensive shrimp and fish meals. It appears that the red crawfish does not require as much animal protein in formulated diets as other crustaceans, possibly because they are situated in a lower trophic level.

Feeds developed for use in closed systems must contain all of the nutrients necessary for a crawfish to grow. Most would-be aquaculturists underestimate the essential nutrients supplied by materials available in earthen ponds. The quantity required is often very low but such nutrients are just not available in closed systems unless they are supplied in the feed.

Gross protein requirements for red crawfish cultured in closed systems are in the 20 to 30% range and gross animal protein substrate requirements are in the 15 to 20% range. The range pellets (see below) being used as supplemental feeds on an experimental basis by some crawfish farmers have 9 to 12% gross protein levels. Range pellets are made by compressing grain dust and binding it with bentonite, a type of clay, or molasses; they contain no animal protein.

We have also found that all artificial feeds used to culture red crawfish in closed systems are lacking in carotenoids, natural pigments, necessary to produce crawfish with normal pigmentation. These must be supplied by addition of fresh green plant material such as alligator weed or submerged aquatic plants like elodea to the feeds.

Because ponds supply many essential nutrients, supplemental feeds do not have to be especially nutritious. Farmers have used spoiled hay as an "artificial" feed. Alfalfa, cottonseed meal, cracked corn, and other grain by-products are used by some crawfish producers in Texas, Mississippi, and the Mid-West as supplemental feeds. During the 1979-80 crawfish season, several Louisiana and Texas crawfish farmers supplemented natural feeds in their ponds by adding range pellets (or range cubes) to their ponds. These appear to have improved production but no one has had enough experience with them or any other inexpensive supplemental feeds to make definitive recommendations about their use.

In using materials like range pellets for crawfish feeds, one must be cautious for two reasons. First, the Wrights report that red crawfish do not "like" raw soy meal. This is often included in range pellets, which are nothing more than grain dust cleaned from grain elevators. Second, addition of too much organic matter will deplete oxygen in a pond. Application rates of such feeds should not exceed 30 pounds per acre per day when temperatures are above 65°F with the actual amount dependent upon the number of crawfish present in the pond. At temperatures below 65°F, care must be taken to insure that the material does not accumulate, as it can cause septic conditions when waters warm and microbial activity increases.

When hays and leafy agricultural wastes are used to supplement natural feeds in ponds, they must decompose and form microbially enriched detritus with a C:N ratio of 17:1 or less (see discussion above) before the crawfish will eat them. This differs from true feeding with materials like catfish feed and range pellets because the material is not added daily or on another regular basis. The decomposition process takes about three weeks at temperatures around 70°F, much longer at lower temperatures. Under no circumstances should more than two pounds of dry matter be added per square yard (roughtly 8,800 pounds per acre). As no real experience is available for using such materials in production ponds, farmers would be wise to hold application rates to one pound per square yard or less, until further guidance is available from researchers studying the subject.

The Wrights have made the following observations about the attractiveness of various corn products to red crawfish. In order of preference (most to least), red crawfish eat fresh corn on the cob, fresh corn cut from the cob, frozen whole corn kernels, canned whole corn kernels, dry rolled corn, and cracked corn.

Use of Fertilizers

Crawfish pond production is based on the presence of a luxuriant growth of vegetation. Good management dictates that the pond soil should be fertilized in keeping with recommendations from the local extension service for growing the cover crop being employed in that pond. Naturally, a complete soil analysis should be performed on the soil before a new pond is built, and periodic checks should be made once the pond is in production.

A key element in crawfish culture is calcium, as 25 to 30 percent of crawfish shells are calcium. Sustained harvest of 500-1000 pounds of crawfish per acre per year over several seasons will obviously reduce calcium levels in the pond. A good rule of thumb is that if the soil tests show that calcium in the soil is adequate for growing a crop such as cabbage, which requires calcium-rich soil, the application of calcium (lime) is not needed. If the soil is deficient, lime should be applied as needed.

Application of chemical fertilizers to flooded ponds does not seem to benefit the crawfish production. No recommendations are available on the subject at this time. Organic fertilizers (manures) probably help, as the organic matter is eaten directly by the animals that crawfish eat (and the crawfish, too), increasing their food supply. There are certain to be aesthetic objections to such a practice. However, this is a common aquaculture practice in other countries. This area is one that requires further research that may lead to increased production and thereby benefit farmers.

P. CLARKII VS. *P. ACUTUS ACUTUS*

P. clarkii normally dominates culture systems wherever it is found with *P. a. acutus*. The Ecology section covers reasons for this situation.

POND CRAWFISH POPULATION DYNAMICS

This section will address the following topics: stocking, care and stocking of crawfish, burrowing activity, growth and survival, movements in/around ponds, yield, stunting, and monitoring populations, and predicting yields.

Stocking

Stocking Rates. Current recommendations for crawfish ponds are as follows:

Situation	lbs./acre
Native crawfish in immediate area surrounding pond	20-25
Ponds with good cover, few or no crawfish in immediate area surrounding pond	20-25
Ponds with good cover	40-45
Ponds with sparse cover	45-65
Ponds with little or no cover	60-100

Crawfish yields of 1000 lbs per acre per year are considered outstanding. A little constructive computation reveals that 8 lbs of female crawfish are all that are needed to produce that sort of crop. The average crawfish used for stocking are 3 to 4 inches long. A female of that size can produce about 300 young. About 60 percent of these can be expected to survive to be harvested in a good pond. Considering that 20,000 crawfish at a weight of 20 per lb must be harvested to obtain a yield of 1000 lbs per acre, 144 females are required per acre. At 20 per lb, total weight of required females is slightly more than 7 pounds. As the male-female ratios are normally 1 to 1, stocking 20 lbs per acre should be adequate for any pond. Some crawfish must be left in the pond to produce young for the next year.

In controlled hatchery systems, the Wrights note the following results with various ratios of males to females. When there is a greater number of males to females, females are damaged and female mortality is high. A greater number of females to males results in low egg production. The best ratio is 1:1.

The red crawfish is native to many of the low lying areas of Louisiana and east Texas where crawfish ponds are concentrated. They have absolutely no respect for levees and will enter (or leave) these ponds throughout the year. As a result, "unstocked" ponds have generated substantial yields. However, building a pond without stocking at least a nominal amount of broodstock, regardless of native populations in the area, is foolhardy with one exception. That is, if a pond is built early enough in the year that it is filled with water intentionally or naturally before March, it may develop a surprisingly dense crawfish population from crawfish already present in low lying areas within the pond or from invaders from outside the pond. Thus, a pond should be checked for the presence of crawfish before it is stocked. Catches of one-half pound or more per trap indicate that the pond has been self-stocked and no stocking is necessary. Traps should be used to sample new ponds as it is easy for the layman to confuse small species of crawfish with young red crawfish if a net or seine is used for sampling. Failure to differentiate between species present could result in a poor yielding pond the following year.

The key is survival of the broodstock. With reduced amounts of cover, their chances for survival are reduced drastically. Production less than 1000 lbs per acre per year can be a result of low reproduction in ponds, assuming that harvesting is intensive and poor water quality or fish do not kill young-of-the-year crawfish. As production can approach 2000 lbs per acre per year in extremely well managed ponds, the need for improving survival of broodstock seems to be warranted.

Crawfish take 12 to 48 hours to dig a hole that is deep enough to protect them from predators. Observations of crawfish ponds and natural areas have shown that wherever there is cover (vegetation such as water hyacinth and alligator weed mats, existing holes or depressions, or relatively flat objects such as a board, piece of tin, boat, or log), crawfish will burrow successfully. We believe that farmers could facilitate the burrowing process and thereby improve production by starting holes with a pole around the edge of the pond and placing some form of inexpensive cover such as heavy cardboard or old boards on them. Usefulness of these procedures in established ponds is debatable. If water quality is good and there are no fish problems, they would probably be useful in established ponds where production is not good, especially those with little cover when they are drained. Then, too, crawfish that survived and molted after fall flooding might have a significant impact on early production.

Care and Stocking of Crawfish

Many ponds are stocked with crawfish from the Atchafalaya Basin, as they are relatively inexpensive and readily available in the late spring. Such crawfish have come from moving water systems and will often walk away from a pond. We recommend that pond crawfish should be stocked in preference to Atchafalaya Basin crawfish.

Crawfish that will be stocked in ponds should be stocked within several hours of capture. They should not be refrigerated but they should be kept shaded and moved early in the morning, late in the afternoon, or at night. They should experience as little stress as possible. Cooling to about 50 to 60°F for long distance shipments is advisable, but the crawfish should be warmed slowly before stocking. It is also better to stock crawfish in the center of the pond, to discourage their crawling out of the pond.

Burrowing Activity

An observant pond manager will note some burrowing activity throughout the crawfish season. There are minor peaks of burrowing in October after flooding and again in December. Activity becomes especially apparent during April when many crawfish from that year's crop begin to mature. It becomes even more intense as the time for pond draining approaches. Actual burrowing as ponds are drained does not, however, appear to be especially successful, as most ponds have very little cover in them at that time. Established ponds will have many pre-existing burrows, which will be occupied when the ponds are drained.

There are few observations on crawfish burrowing behavior in pond bottoms away from shore. In areas devoid of any cover, crawfish will tend to dig short, simple burrows to which they retreat when danger threatens. It is not clear whether they return to specific burrows or those that just happen to be conveniently nearby. In areas with abundant cover, it appears that the crawfish secrete themselves beneath the cover rather than excavate burrows; however, more data on this subject are needed before the subject can be fully quantified.

October and December burrowing is done by adult females that had not spawned prior to pond flooding. In addition, some of those burrowing in December also represent fast growing young-of-the-year that have just matured and holdover juveniles from the preceding season that have matured. These females are especially important because they contribute to the second and third waves of recruitment of young-of-the-year crawfish to the pond. Harvesting during November is not advisable if females show considerable egg development and if burrowing activity is noticeable.

Burrowing is most apparent along pond levees. Burrows are least likely to be found in the pond floor proper. Burrows are almost always in association with some cover. Large ponds have much less levee space per unit of pond bottom than do smaller ponds. It may be advisable to engineer large ponds with additional levees--either above the water or low, submerged levees. Those submerged levees will appear quickly when the pond is drained but before the pond bottom is exposed. Crawfish will have additional area to burrow away from the regular pond levee. Such inner levees are generally found in rice field ponds. They are actually contour levees that are used to maintain the 4 to 6 inches of water necessary to cultivate rice. These are submerged when the rice ponds are flooded for crawfish culture.

The construction of extra levees was a recommendation made as early as the 1930s by Percy Viosca, but its value has yet to be proven by research.

Growth and Mortality

Recruitment. The red crawfish can produce up to two generations a year in Louisiana. There are several groups of crawfish in a pond. Each group is referred to as an age class. These age classes include holdover adults from the preceding season, holdover juveniles from the preceding season, and young-of-the-year crawfish. Spawning does not take place at one time so there are several age classes of young-of-the-year crawfish. The appearance of the young-of-the-year crawfish is called recruitment. The various age classes of young-of-the-year appear in sequence so many population biologists refer to them as waves of recruitment. The number of age classes, number in each age class, survival, and food availability will determine overall pond yield.

In producing crawfish ponds there are at least five age classes during the season. The first two are the holdover crawfish referred to above. The remainder are young-of-the-year crawfish. The first age class of young-of-the-year enters the pond when it is flooded in September-October. The others enter the pond in October-November and December-January. Spring recruitment is seen in most ponds in March or April. Some sporadic, low intensity crawfish recruitment will take place in all months.

Early (November-January) harvest is generally low and is usually made up of the holdover crawfish. Early pond flooding combined with warm temperatures can result in rapid growth of the first age class of young-of-the-year crawfish such that they will become harvestable in November or December. In general, however, the various age classes of young-of-the-year crawfish do not add significantly to the harvest until late January or February in warm years and March in cold years. Although catch in traps is low in the fall, prices more than justify the effort necessary to harvest them.

There is invariably a gap between the catch of holdover crawfish and the young-of-the-year age classes. The gap is basically dependent upon temperatures. It is shorter in mild winters than cold ones. The gap is especially pronounced should the age class(es) be eliminated by poor water quality (low dissolved oxygen) or predacious fish.

Harvesting of holdover females in the October-December period that have not spawned can present a serious problem. It can eliminate a theoretical production of 9 lbs of crawfish (300 young per female x 60 percent survival = 180 harvestable young crawfish ÷ 20 per pound = 9 pounds of crawfish) per female. In general, it is now recommended that if more than 10 percent (1 in 10) of the females in the early catch have well developed tan or brown eggs (see Reproduction section), then harvesting should be discontinued.

Survival/Mortality. As crawfish in an age class grow older, some will die. Death can result from natural causes such as predators, diseases, molting stress, low oxygen levels, and climatic conditions or it can result from human activity through fishing. In well-managed crawfish ponds where fish are excluded or controlled and water quality is good, at least 50 to 60 percent of each young-of-the-year age class will survive to reach a harvestable size. Large fish populations or low oxygen levels can destroy almost all crawfish in a pond before they reach a harvestable size.

Experience has shown that well-managed, open crawfish ponds yield harvests of 750 to 1000 pounds per acre of crawfish year after year, regardless of the presence or absence of wading birds, predacious insects, and spiders (see Life History section). They will invariably fail, however, if large numbers of fish such as green sunfish, bullheads (polly-wogs), and bowfin (choupique) are present in the pond. Elimination of predators other than fish might improve yields.

The wading birds are protected by law, and no permits are issued to kill them while they are feeding in crawfish ponds. One can, however, readily keep them away from a pond by frightening them. This is a tedious job and does not appear to be warranted. Certainly, protective cover in burrowing areas is advisable in new ponds or established ponds with little or no cover and a history of poor production.

Fish are usually killed by completely draining ponds or draining them as much as possible and poisoning the remaining water with a fish poison such as antimycin B or rotenone. This normally is done during the summer. A word of caution is in order here. Even if a pond can be completely drained, water will remain in some low areas. These should be poisoned, because green sunfish, bullheads, and bowfin stranded in these pools can survive by finding crawfish holes or root holes and remaining in them until the ponds are reflooded in the fall.

Screen systems should be attached to inlets if surface waters are used, and baffles or screens are needed on the drain to prevent fish from entering ponds.

The principal carnivorous creatures in most aquatic ecosystems are the fishes. These are largely eliminated in crawfish ponds. As a result, the populations of predacious insects explode. Three groups are of concern to crawfish pond managers. These are the hemipterans (true bugs), the coleopterans (beetles), and the odonates (dragonflys). The hemipterans and beetles must breath air while the nymphal stages of dragonflys are truly aquatic and have gills. All hemipterans are very carnivorous but only the water scorpions (Rantra spp.) and the giant predacious water bugs (Belostoma spp. and Lethocerus spp.) are large enough (2-3 in.) to attack most crawfish. The small (0.25-0.50 in) backswimmers such as Notonecta spp. are highly predacious on small aquatic animals. The hemipterans all have a piercing beak that they use to inject proteolytic enzymes (digestive juices) that kill and digest their prey. The fluid is then sucked from their prey through their beaks. Figs. 52, 53, 54.

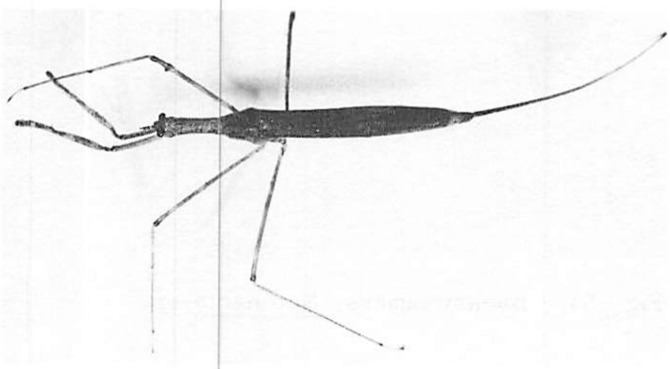


Fig. 52. Water scorpion, Ranatra sp.

Giant predacious water beetles (2-3 in.) of the genus Cybister are dangerous to crawfish as both adults and larvae. The adults have crushing jaws and tear their prey apart. The larvae look like large worms with grotesque fangs. The hollow fangs inject proteolytic enzymes into prey. Figs. 55, 56.

Dragonfly nymphs, especially the large (2-3 in.) Anax spp. nymphs, will readily eat smaller crawfish. Their mouth parts are specially modified to include an extendable, toothed mask. This mask can reach in front of the nymphs about 1/3 of the length of their bodies. Prey are grasped and drawn back to the mouth where mandibles crush and tear them apart. Fig. 57.

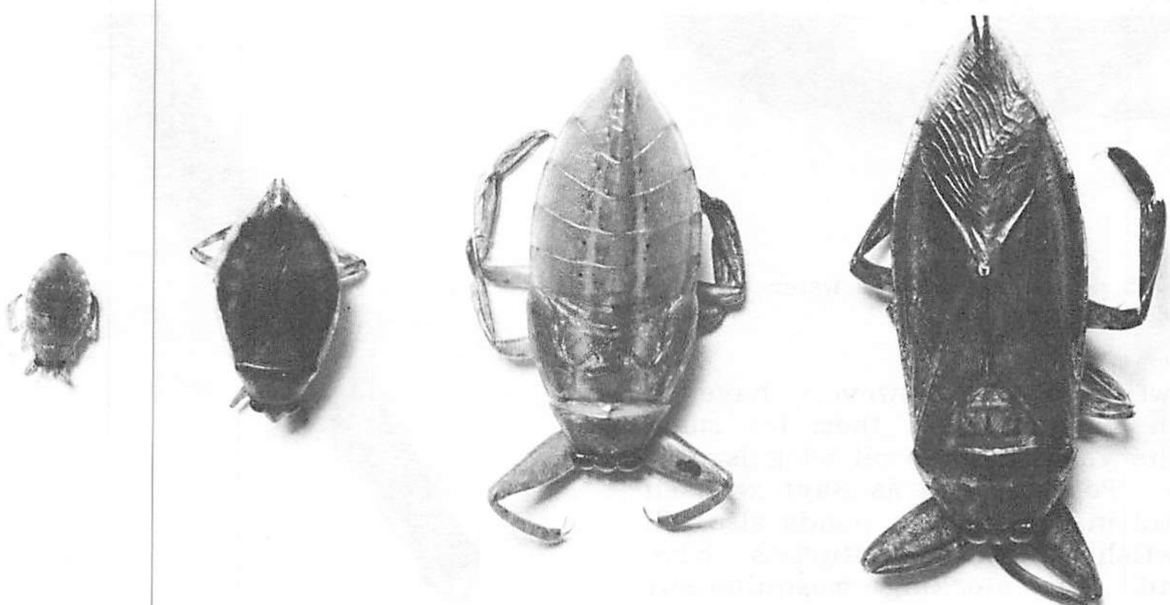


Fig. 53. Giant predacious water bugs, Lethocerus sp. (adult), Lethocerus sp. (juvenile), Belostoma sp. (adult), and Belostoma sp. (juvenile) (left to right).

Besides predacious insects, the large (2 in.) aquatic fisher spiders (Dolomedes spp.) capture and eat crawfish. They too have piercing fangs that inject proteolytic enzymes into their prey. These spiders are at home both above and below the surface of a crawfish pond. Fig. 58.

Most of the mortality of young crawfish in crawfish ponds, other than that caused by bad water, is undoubtedly caused by predacious insects and spiders. Methods for controlling these predators have not yet been developed. Fish culturists use a mixture of old crankcase oil and diesel fuel (50:50) to kill air-breathing arthropod predators. Roughly one gallon per acre suffices to clog air breathing tubes.

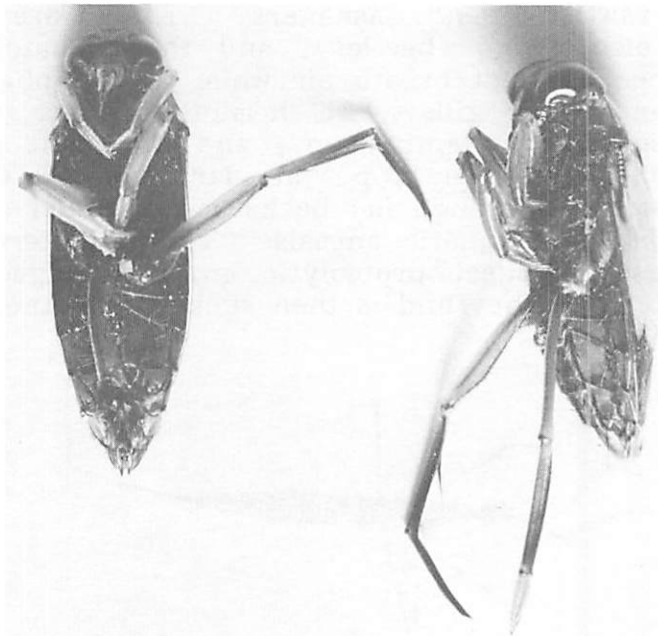


Fig. 54. Backswimmers, Notonecta sp.

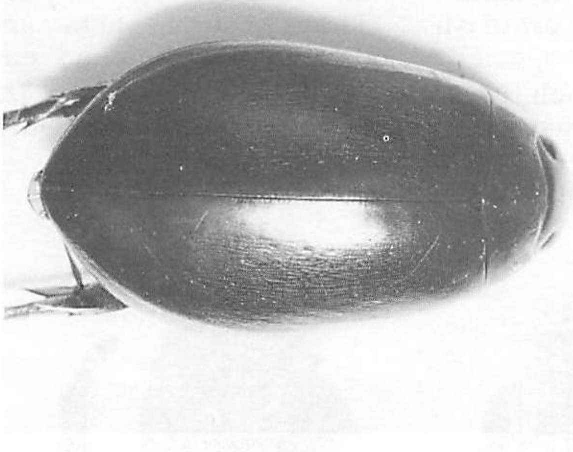


Fig. 55. Giant predacious water beetle, Cybister sp.

Crawfish ponds, however, have so much vegetation in them for much of the year that the oil slick is useless. Poisons such as Baytex® used to kill insects in fish ponds also kill crawfish. Prawn culturists have found that stocking mosquitofish, Gambusia affinis, will help in controlling insect predators in their ponds. This may prove useful in crawfish ponds, but in confined

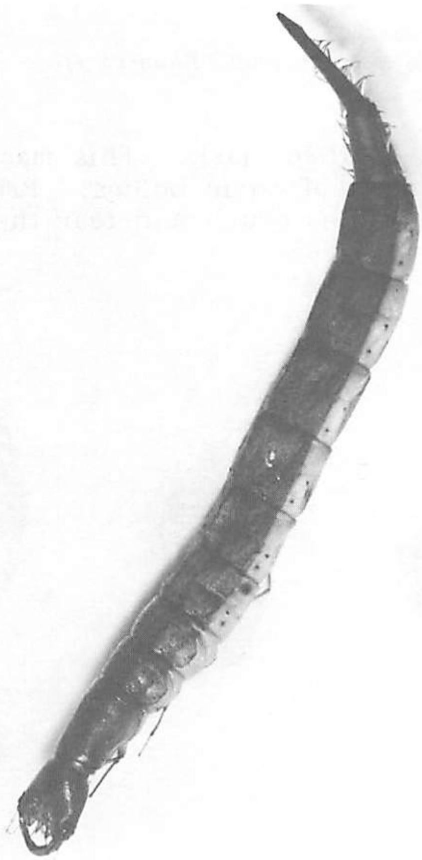


Fig. 56. Giant predacious water beetle larva, Cybister sp.

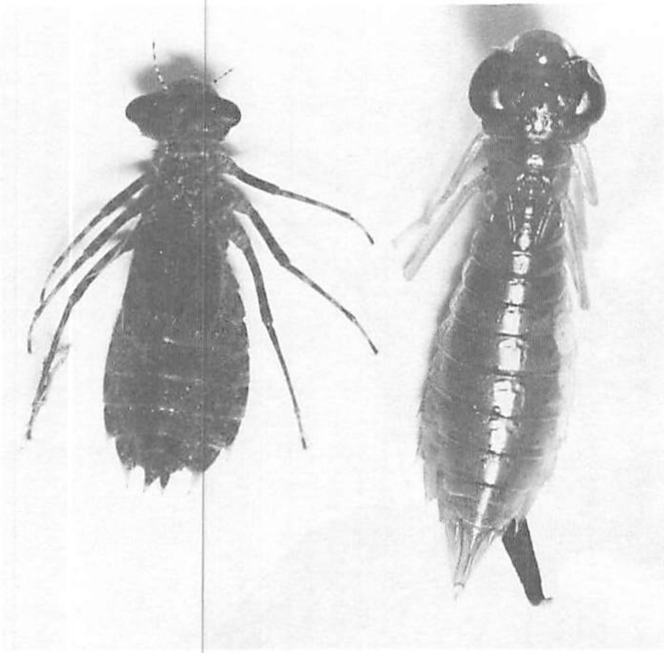


Fig. 57. Dragonfly nymphs, Anax junius (right) and Pachydiplax longipennis (left).

situations mosquitofish will eat third instar crawfish (just released, roughly 0.5 inch long).

The Wrights find that mortality between the third instar stage and the one-inch stage is 90 to 95% in ponds. They culture third instar red crawfish in tanks for roughly 30 days. These are released into ponds at a size of about 1.5 inches. Mortality is less than 10% at that time.

Once trapping begins most mortality of harvestable crawfish is caused by their harvest. Survival of an age class once it becomes large enough to harvest is less than 10 percent in a heavily harvested pond.

As the red crawfish becomes established in new regions, new predators will appear. A recent report from Zambia notes that a local variety of carnivorous iguana (a large lizard) finds young red crawfish very palatable. They are also actively eaten by a carnivorous variety of tilapia fish native to Africa.

Movements In/Around Ponds

Red crawfish are capable of extensive migrations (see Ecology section). This can account for excellent crawfish production in ponds that were never stocked; however, this is normally seen only in ponds in areas with well-established natural crawfish populations.

Movements of crawfish within ponds are not well known. Mark/recapture experiments have involved small ponds less than 5 acres in size and have shown that such areas may be traversed by adult crawfish in less than 12 hours. Most pond populations seem to be very stable with a relatively small percentage leaving the pond in a normal season. Red crawfish are more active when light is subdued. They are most active at night and are more active on cloudy days than clear days. They are much more reclusive in clear water than murky, turbid water.

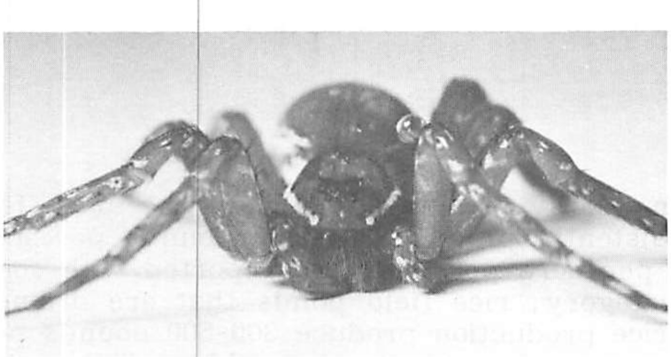


Fig. 58. Fisher spider, Dolomedes sp.

Very little is known about the existence of home ranges in red crawfish. Dr. Alan Covich of the University of Oklahoma, Stillwater,

Fig. 59. Mature, Form I male red crawfish.

has placed radiotransmitters on large adult red crawfish and tracked them in 1/10 acre ponds. He found that they moved mostly at night and that they apparently used several submerged burrows for cover during their nocturnal wanderings. This suggests that these adults had a home range. This seems to be the case with adults in Louisiana ponds in fall and winter. However, it appears that, at least in the spring, when the bulk of the crawfish are maturing, no home ranges exist in Louisiana ponds. This is an important consideration in pond management and specific studies will be needed to determine precisely what is happening.

Yield

Production information has been slowly generated during the past few years. Well-managed open ponds consistently produce 800-1500 pounds per acre per year. Yields up to 2000 pounds per acre per year are reported with some consistency. Within the open pond category, rice field ponds that are drained in April or early May to accommodate rice production produce 300-500 pounds per acre per year. Wooded ponds and open marsh ponds rarely yield more than 300 pounds per acre per year. Even well-managed wooded ponds suffer from major dissolved oxygen deficiencies, have lower temperatures, and probably produce lesser amounts of edible detritus vegetation for the crawfish. Marsh ponds generally have very poor water quality.

Maximum reported production was 4,000 pounds per acre produced in a one-acre pond managed by Archie Warinner. However, he practiced non-traditional management employing an extensive water circulation and aeration system and supplementing natural reproduction in the pond by adding females bearing eggs or recently hatched young.

There is no reason open ponds cannot produce 2,000 to 3,000 pounds per acre with supplemental stocking of young crawfish, supplemental feeding, and circulating/aerating water on a massive scale. These practices, however, are not economical in Louisiana at this time.

Stunting

The red crawfish can reach maturity and stop growing at sizes as small as 2 to 2-3/8 inches. This is below the minimum commercial size of 3 inches and the preferred size of 3-1/2 inches or larger. Stunting will take place in ponds if the crawfish are not heavily harvested. Both social and nutritional factors lead to stunting. The only solution is to harvest the crawfish intensively. Stunting can be detected by checking males for the Form I condition (see Reproductive System section). If most of the males are small and in the Form I condition, stunting is a problem. Fig. 59.

Another sign of impending stunting is the presence of many small 2 to 2-3/4 inch immature male crawfish with extensive growths of algae and assorted plants and animals on their shells. These are not growing rapidly and will probably stunt unless conditions are improved. Research has shown that supplemental feeding will prevent stunting of such crawfish at subcommercial sizes, but the economic feasibility of such feeding has not yet been demonstrated.

Near the end of the crawfish season, stunting may take place in ponds dominated by annual vegetation or rice. This material will have either been decomposed by natural processes or will have been eaten by the crawfish. At such times food becomes a limiting factor; crawfish can no longer get out of each others way by climbing stalks of vegetation; and waters are warming rapidly. The result is that most of the remaining crawfish will mature at small sizes. Again, supplemental feeding may ultimately prove useful in correcting this problem.

Monitoring Ponds and Predicting Yields

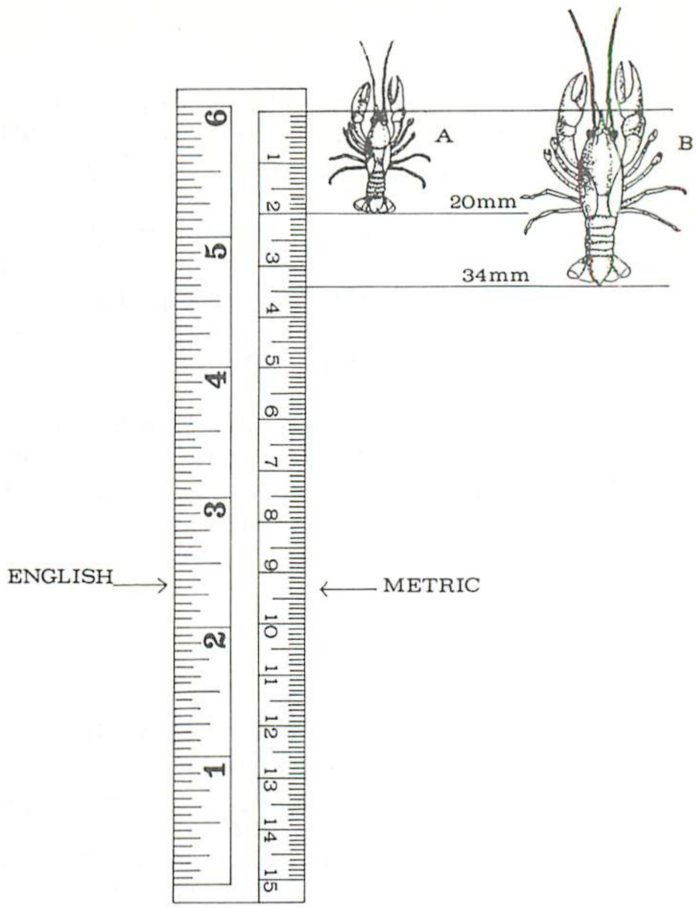
A pond must be monitored to ascertain the status of the crawfish. They cannot be observed like row crops so they must be captured with dip nets or traps and measured. Predicting yield on the basis of information generated from pond monitoring is not an exact science, but monitoring can indicate whether there is a crop and how big it is. The accompanying figure shows how to measure crawfish in millimeters. Fig. 60.

Collection of Crawfish

Nets and Traps. Small crawfish, less than 50 mm (2 inches) long, should be sampled with small mesh--1/8 inch mesh or smaller dip nets. A net with the following dimensions is adequate: handle length, 3.5 feet; net frame, 1.5 feet wide by 1 foot high; net depth 1 foot or more. The net frame should be heavy duty or reinforced at the joint with the handle. As crawfish approach 50 mm (2 inches) in size they become difficult to catch with a dip net. At this time a small mesh trap 1/4 or 1/2 inch mesh is helpful. Half-inch mesh crawfish wire is available commercially. It is much easier to handle than hardware cloth and is adequate for sampling. Fig. 61.

Frequency of Sampling. A pond should be sampled at least once every two weeks beginning shortly after it is almost completely flooded in the fall. Sampling once a week would be preferable, but the effort is probably not justified. A good pond manager should visit his pond daily and occasionally go around the pond at night with a head lamp.

Sampling Effort. One should try to obtain at least 50 crawfish with a dip net (100 would be preferable, but it is not always easy to catch 100 with a dip net) and at least 100 crawfish with small mesh traps.



Legend: The smallest, unnumbered divisions on the metric side of the ruler are MILLIMETERS. The large, numbered divisions are CENTIMETERS. There are 10 MILLIMETERS in 1 CENTIMETER. Thus, you multiply each centimeter division by 10 and add any additional millimeter divisions to get the total number of millimeters.

EXAMPLES:

A. Crawfish A stretches from the 0 mark to the 2 centimeter mark. Therefore, its length in millimeters is 2 centimeters x 10 millimeters per centimeter. This equals 20 millimeters.

B. Crawfish B stretches from the 0 mark to the 4 millimeter mark past the 3 centimeter mark. Therefore, its length in millimeters is 3 centimeters x 10 millimeters per centimeter plus 4 extra millimeters. This equals 34 millimeters.

Fig. 60. Measuring crawfish using the metric system.

Sampling ponds is tedious work. It can also be downright unpleasant if one has to use a machete to get to the water's edge. Problems involved with high grasses around ponds include cuts from briars, wasp stings, and snake bites. In addition, young crawfish prefer recently flooded, fine grasses to gather in. These are shaded out if pond banks are not cut.

When young crawfish are abundant, a hundred or more can be caught in several dips. At other times, no more than 30 crawfish of all sizes can be caught in an hour. Consistency should be observed, that is, with a dip every 30 to 40 paces around the edge of the entire pond. The net should be extended away from the bank and raked quickly back to the bank while the net frame is kept against the bottom. The number of dips made and the number of crawfish caught should be noted. Densities of crawfish can be calculated by dividing number of crawfish caught by the area sampled (area that the net covers times the number of dips made). There is generally no need to keep more than 100 crawfish when monitoring the pond with a dip net. But if and when 100 are caught, that 100 should be kept for measuring later. Other crawfish can be released after they have been counted.

The need to sample the entire pond cannot be overemphasized. We have noted that in some ponds where small crawfish were present in about one half of the pond, there were few present in the remainder of the pond. Production was good, however, because the crawfish dispersed into the rest of the pond as they grew.

Fig. 61. Crawfish ponds monitored with a dip net.

Most small crawfish congregate around the edge of the pond. However, if there is no cover there, they will move off shore until they find it. This fact should be kept in mind when one is monitoring a pond. If it occurs, it will be necessary to dip in such cover away from shore.

Dipping for crawfish can be very difficult in early season if pond banks are heavily grown up. First, it is difficult to get to the water and second, it is hard to drag a dipnet through the heavy vegetation. Then, one may have to dip several times in one area to get a sample. Keeping levees mowed is very helpful.

One should try to maintain one or two small mesh traps per surface acre. More would be preferable, but they are expensive.

<u>Determination of Age Classes</u>. At this time, it is necessary to measure individual crawfish to determine age classes. To facilitate measurement, one can make a simple measuring board by gluing a flat, six-inch (150 mm) plastic ruler on a flat 12 x 4 inch board with a 4 x 4-inch head board butting it. It is easier to measure in millimeters, but millimeters may be converted to inches by dividing by 25.4. Dip net and trap samples should be kept separate from each other. Fig. 62.

The crawfish should be measured from the tip of the head (rostrum) to the tip of the tail by placing it ventral side (belly) down on the measuring board. Each measurement should be recorded and the number indicated in each size class (5-9 mm, 10-14 mm, 15-19 mm, 20-24 mm, 25-29 mm, 30-34 mm, 35-39 mm, 40-44 mm, etc.) on a separate record sheet (see Appendix example problem). When the total number of crawfish measured is obtained, one can determine the percentage of crawfish in each size class by dividing the number in each class by the total number of all crawfish measured, and multiplying by 100. The result is the percentage of all crawfish represented by that particular size class.

When the percentages represented by each size class have been computed, age classes can be identified. There should be at least two or more groups of figures that stand out from those around them. For example, one might have:

5-9 mm	10-14 mm	15-19 mm	20-24 mm	25-29 mm
5%	15%	10%	5%	10%

30-34 mm	35-39 mm	40-44 mm
25%	5%	5%

The numbers 15 percent and 25 percent stand out clearly from those around them. Such numbers are termed modes. Each mode normally represents a specific age class of crawfish. Age class data should be recorded each time the pond is monitored for comparison during the season. Some members of an age class will be larger or smaller than the majority of the members of that age class. Modes may also overlap, especially in the spring when different age classes reach maturity and cease growth at about the same size.

As a monitoring program continues, the location of these modes will shift from the left to the right on the record sheet for that pond as the crawfish grow. Young-of-the-year appear to the left side of the record sheet as new age classes appear. (During very cold weather growth may stop, and modes will stay constant for a time.) Dip net sample modes will normally get smaller as they approach 50-70 mm (2 to 2 3/4 inches). There are two reasons for this: first, crawfish become harder to catch as they grow, and second, a number will die naturally, reducing their total numbers. Such age classes should appear in the small mesh traps.

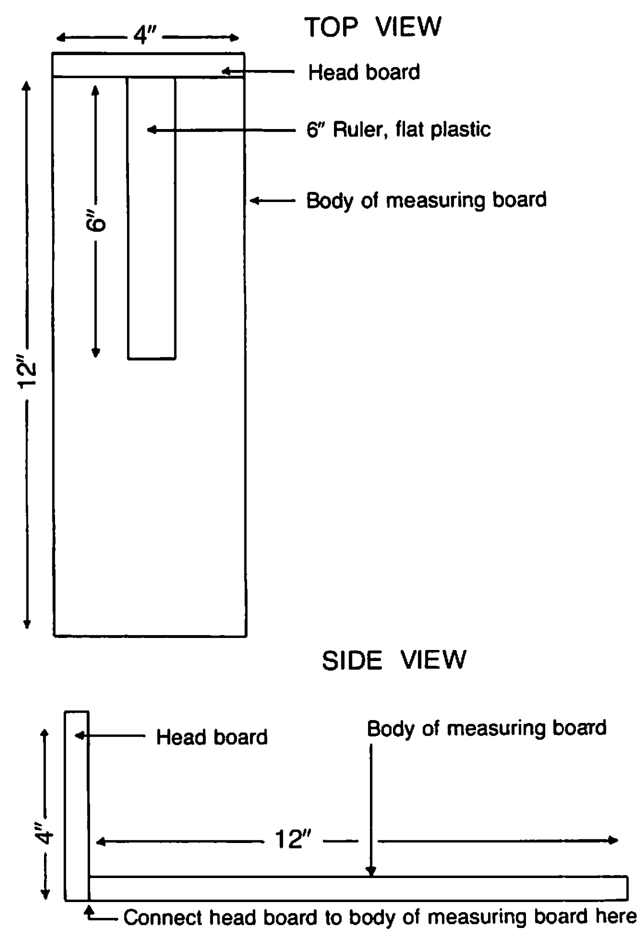


Fig. 62. Measuring board.

The same procedure should be followed with the measurements (data) from the small mesh trap samples. Small mesh traps should be used as soon as the dip net monitoring begins.

Example. See the Appendix example problem for assistance in learning how to determine age classes from field data.

Determination of General Magnitude of Crop (Potential Yield). Table 14 will assist in monitoring a crawfish pond and predicting yield. It is based on work in open ponds (with and without rice) from one-quarter acre to 60 acres in size. If very few crawfish are caught through the fall and into the winter with a dip net (an average of 1 crawfish for every two dips), yield will be poor, probably less than 300 pounds per acre if that much. The presence of three age classes of young-of-the-year crawfish and sustained catch of about 1 small crawfish per dip into and following the colder months (mid-December to mid-February) indicates that yield should exceed 500 pounds per acre. It can approach 1000 pounds per acre if survival is good and average catch per dip is more than 1 crawfish per dip. A good rule of thumb for determining survival is to keep track of the average size of dip net caught crawfish. Average size should increase gradually to about 50 to 65 mm (2 to 2 1/2 inches) by mid-February to early March. This indicates that crawfish are growing well and survival is good. The first age class of young-of-the-year crawfish should be 75-100 mm (3-4 inches) but the addition of younger and smaller age classes reduces the average size. To determine the average size of the crawfish in dip net samples, add all measurements and divide by the total number of measurements. See Appendix example problem.

Table 14. Seasonal monitoring of Louisiana crawfish ponds to predict yield.

- - - - - Seasonal Small Mesh Dip Net Catch - - - - - -			Identifiable Age Classes of Young Crawfish	Production Schedule	Probability of Stunting	Potential Production per Acre
Oct.-Mid. Dec.	Late Dec.-Mid Feb.	Late Feb.-Early April				
High	High to Spotty	High	5-6	Commercial catches (0.5-1 lb/trap) in Dec.; high catches in late March.	High	Greater than 700 lbs*
High	Low	Low	1-3	Commercial catches in November may be high, but low in spring.	High	100-300
Moderate	Spotty	Moderate	3-5	Commercial catches in Jan.; highest catches begin in late March--early April.	Low	700-1000
Moderate	Spotty	Low	2-4	Commercial catches in April.	Low	100-300
Low	Spotty	Moderate to High	1-3	Commercial catches in April.	Moderate	100-300
Low	Low	Low	Cannot be easily determined	Production probably too low to warrant harvesting.	Low	-

*Production may be greatly reduced if intensive harvesting is not practiced. If large crawfish are not removed quickly, smaller ones will stunt.

Notes: Dip net numbers: High = 1.5 or more crawfish per dip; moderate = 0.4 to 1.5 crawfish per dip; low = less than 0.4 crawfish per dip.

Where catches are low, average size will vary greatly without any consistency. Where catches are moderate, they will increase consistently through March to 45-60 mm in length. Where catches are high, average size will still be relatively low (25-45mm) until March when it will begin to rise.

Low numbers of young crawfish can result from reproductive failure of adult crawfish or mortality (usually caused by predacious fishes and/or low dissolved oxygen conditions. Spotty catches are invariably related to very low temperatures (below 45°F) in the winter.

When the number of young crawfish stays 1 or more per dip but average size oscillates and does not approach 50-65 mm (2 to 2 1/2 inches) through the fall and winter, survival is low. Either fish are killing and eating the young crawfish (fish will be caught in small mesh traps) or a problem such as low dissolved oxygen is causing high mortality.

One early sign that stunting may be a problem is the consistent catch of three or more small crawfish per dip during the fall. Average size will increase through the fall, winter, and early spring, but much more gradually than it does in a pond where stunting is not a problem.

One should become especially concerned if young-of-the-year crawfish are not abundant by mid-November, and should keep checking for reproduction, as early recruitment may have died from poor water quality, but make no extensive plans for sales if young-of-the-year are still absent in late December.

It is important to sample the entire pond. Some ponds have few small crawfish present in about one half of the pond but have abundant supplies in the other half. Yield is good because the crawfish dispersed into the rest of the pond as they grew.

Elimination of an age class for any reason will have an adverse influence on yield. If a pond would be expected to yield about 1000 pounds per acre from three young-of-the-year age classes plus holdover crawfish and the first young-of-the-year age class is lost, one might logically assume that yield will be cut by about 300 pounds. But this is not always the case because survival in the other age classes may increase in the absence of the first age class and compensate for the loss. Certainly, however, elimination of the first and second age class will serve to delay the period of onset of sustained catch per unit effort (see below). It is one thing to have a potential yield of 1000 pounds per acre, but it is an entirely different matter when it comes to actually harvesting that yield. A farmer may lose his maximum yield as a result of the inability to harvest the crop. Reasons for this include lack of labor (not available or too costly), lack of bait, and lack of market (a serious problem in April and May if a large wild crop drives the price down). Failure to harvest intensively invariably leads to a stunting problem.

As mentioned above, catch during December, January, and February is generally low--less than one pound per trap per night. Then, the first age class of young-of-the-year crawfish becomes large enough to harvest (sometime between mid-February and late March), and catch exceeds more than one pound per trap per night and total daily harvest from the entire pond reaches a peak and remains relatively stable until the season ends. Since small mesh traps catch crawfish in the 2 to 3 inch size category, use of such traps will permit one to follow growth of crawfish to harvestable size. Modes for each age class will shift to the right side of the record sheet from one sampling period to the next. The amount of shift will give the growth rate for every sampling period. For example, if the first age class of young-of-the-year is about 50 mm (2 inches) long on January 15 and is 62.5 mm (2 1/2 inches) long on January 30, the growth rate is 6.25 mm (1/4 inch) per week. Thus, they would be expected to reach 77.5 mm (3 inches) in size by February 15.

If dipnet catch is consistently very low into the spring, trapping may not be really successful until mid-late April. Trapping then becomes very successful and crawfish are almost always 4 1/4 inches, or larger. Overall yields are normally not over 300 pounds per acre. An explanation for this phenomenon is not readily apparent.

A problem that is encountered with small mesh traps is that small crawfish will often avoid them in mid-spring if they are full of large crawfish. In fact, if regular trapping does not reduce numbers of harvestable crawfish fast enough, younger age classes will grow to harvestable size before they actually enter traps. However, if catch in the regular traps falls off and catch of small crawfish in small mesh traps is poor, one can be relatively sure that further yields will be low. Conversely, if catch in regular traps falls off but many small crawfish are caught in the small mesh traps, yields will be good.

RICE/CRAWFISH CULTURE

Rice farmers in south Louisiana often practice crop rotation involving rice, crawfish, cattle, and soybeans. Two general patterns are followed.

In the first pattern, unplanted rice fields are stocked with crawfish in April. They are slowly drained and are dry by mid to late May. They are then planted with rice. Rice fields are flooded as the rice grows but are drained in mid to late August for rice harvest. Fields are reflooded for crawfish in September. The cycle is repeated each year, but restocking is normally not required. Late planting dates reduce rice yields.

In the second pattern, unplanted rice fields are stocked with crawfish in March. They are drained in April for rice planting. Rice is managed as described above. The following spring, however, crawfish are harvested until late May when ponds are drained. The field may then be planted with soybeans or left fallow for cattle pasture. The cycle is then repeated the next spring with crawfish being stocked in March. An alternative is to flood fields in the fall and harvest crawfish until March when rice is planted. Then restocking of crawfish is normally not necessary.

POLYCULTURE: CRAWFISH/FISH

Normally one should eliminate fish from crawfish ponds since most will eat crawfish; however, one can produce a crawfish crop in some fish ponds. To do this, fish that cannot eat crawfish must be stocked. Such fish are either the small ones of such species as catfish, bass, and sunfish or ones that normally do not eat crawfish--minnows, and some tilapias. Or, crawfish and fish can be separated physically. There are several options for this. Fish can be raised in cages. Crawfish can be raised in sump areas or waste control ponds below, above, or between fish ponds. Finally, if there is a fairly extensive section of shallows in a pond that can be flooded at the appropriate time by water level manipulation, fair crawfish populations will develop as long as there is a good cover crop of grasses and emergent weeds growing in the area while it is dry. The vegetation serves as food and cover for the crawfish.

One polyculture scheme that worked well in Louisiana involved the use of crawfish, buffalofish, paddlefish, and catfish. The ponds were treated as if they were regular crawfish ponds with early fall flooding. Crawfish were harvested during the winter and spring. During the spring, buffalofish and paddlefish, neither of which eats crawfish, were stocked loose in the ponds and channel catfish were stocked in cages. When most of the crawfish had been harvested and those remaining had burrowed in late spring, the catfish were released into the pond. In addition to 1,000 pounds of crawfish per acre, about 3,000 lbs of fish were harvested per acre in the early fall of the next year. Although the ponds were not reflooded until December, there was a fair degree of crawfish recruitment. Growth was poor because there was almost no vegetation in the ponds to serve as food and substrate. Yield of crawfish was less than 225 pounds per acre.

It is clear from the above that second year crawfish yield with such a polyculture scheme is poor unless feed is added to ponds and, if necessary, young crawfish are stocked to supplement natural reproduction. It was suggested that the ponds be allowed to remain fallow but flooded during the second crawfish season and if necessary stocked with adult crawfish in late spring and followed by routine pond draining and pond flooding the following fall. Fish would not be stocked again until the following spring.

ARTIFICIAL SPAWNING OF RED CRAWFISH

At this time, spawning and stocking young crawfish in ponds is not practical because it costs too much to be competitive with natural spawning in ponds. However, production of young crawfish on demand will undoubtedly become important in crawfish culture. Uses for such procedures include (1) supplementing natural recruitment in ponds when it is reduced or lacking. Currently a pond with poor recruitment is lost for the year even if all other factors are optimal; (2) supplying superior, pedigreed crawfish for grow out in ponds; and (3) stocking crawfish in ponds during the summer (in Louisiana) for year-round production.

A method for producing young crawfish during most months of the year has been developed by Dr. Joe Black of Louisiana College. It is relatively simple and could probably be modified to permit large scale production. Dr. Black's method is as follows:

Adult breeding stock specimens are maintained in individual glass 8 x 3 inch bowls (obtainable from almost any biological supply company), which can be stacked on each other safely on any level surface. No aeration is needed if the water is not too deep and is not fouled with overfeeding. A substrate of pea gravel covers the bottom of the bowls and water level is kept at about 1 1/2 inches, or just enough to cover the crawfish. Water is changed every 7 to 10 days. In most cases chlorinated tap water can be used as the water source, but it is best to age it a day or so.

Feeding is simple and cheap. Crawfish, while eating almost anything organic, are basically scavengers and detritus feeders. Green aquatic plants such as alligator weed or elodea, which is preferable, are added to the bowls to provide food and oxygen. Rotted leaves (any type of hardwood leaf; water oak has been used extensively by Dr. Black) from a compost pile are added and seem to provide the greatest bulk of the food consumed. If dry, these should be presoaked. Three times weekly a small portion of high protein, dry cat or dog food (about 1/4 of an average pellet) is added for each crawfish.

The crawfish are kept indoors at an average temperature of 73 to 79°F. No attempt is made to vary the amount of light to which the crawfish are exposed. Thus, they are exposed to about 12 to 14 hours of light per day, but lights are used at night only for emergencies.

A mature, Form I male crawfish (see Reproductive System section) is added to a bowl containing a single, mature female crawfish. Breeding is more likely to be successful under these conditions than if the female is placed in a bowl with the male. After a successful mating, the sperm receptacle (annulus) of the female will contain a clear gelatinous sperm plug. The entire mating process usually lasts about 15 to 25 minutes, after which the male should be removed and returned to his own bowl. Records should be kept as males may be sterile.

Within two months (average time, 4 to 6 weeks) after mating, the female will produce a clutch of 100 to 400 eggs, the number depending to some degree on the size and age of the female. The eggs are dark gray to black, if fertile; orange, if infertile. These are cemented onto the abdominal appendages (swimmerets) of the female, and hatching will occur in two to three weeks. The newly hatched young remain attached to the swimmerets of the mother for another couple of weeks. At this time, when most of the young have released from the mother, she should be transferred to another bowl to prevent cannibalism. The young can be retained in the brood bowls. If this is done, some cannibalism will likely occur with the young crawfish feeding on newly molted ones. This can be held to a minimum by either providing cover for the molting young or by thinning them by moving them to several containers.

The female will usually molt a few days after the young become independent and will start feeding aggressively. During this stage the female is not receptive to the male and cannot be induced to mate; indeed, a smaller male left overnight with the female will often be eaten. After a couple of months, the female will molt again to the breeding form and can be mated once more for a subsequent brood; however, a male should not be placed with a newly molted, soft female. Allow two to three days for hardening of the exoskeleton. Females maintained as described above will regularly produce two and occasionally three clutches of eggs yearly.

Replacements for the older breeding stock are selected from the larger and more aggressive young from each hatching and placed in individual bowls. These are usually ready for breeding within 3 to 4 months. It is especially important to start with young crawfish and grow them in the bowl (or other container) in which they will spend most of their life. The crawfish will grow to 2 1/2 to 3 inches in the bowls described in this brief account. They could grow larger in a larger bowl. Trying to breed and spawn a large, adult crawfish in a small bowl usually fails as crawfish are unaccustomed to such confinement.

MANAGEMENT PROCEDURES IN LA.

Crawfish pond life cycle phenomena and managerial procedures are summarized for Louisiana in the accompanying table (Tables 15, 16). Discussion of various items will be found in the text of the culture section of this bulletin. Most of the information is directly applicable to other relatively warm climatic regions in the continental United States.

PRODUCTION OF CRAWFISH FOR FISHBAIT

Crawfish are so abundant in Louisiana that there are few markets for them in the state as bait, although they can be sold and are sold by some enterprising individuals. There are a number of potential markets out-of-state for both hard and soft shell crawfish. The basic principles of crawfish culture apply if one wishes to raise them for fish bait, but one would expect to encourage overpopulation and stunting to obtain the smaller crawfish (1 1/2 to 2 1/2 inch) desired for fish bait and to use small ponds. Use of several small ponds and sequentially flooding them at 2 to 4 week intervals can sustain production of small crawfish. The "Producing Crawfish for Fishbait" bulletin (see Bibliography) by Huner and Avault should be obtained by anyone desiring further information on bait crawfish (both hard and soft shell) production.

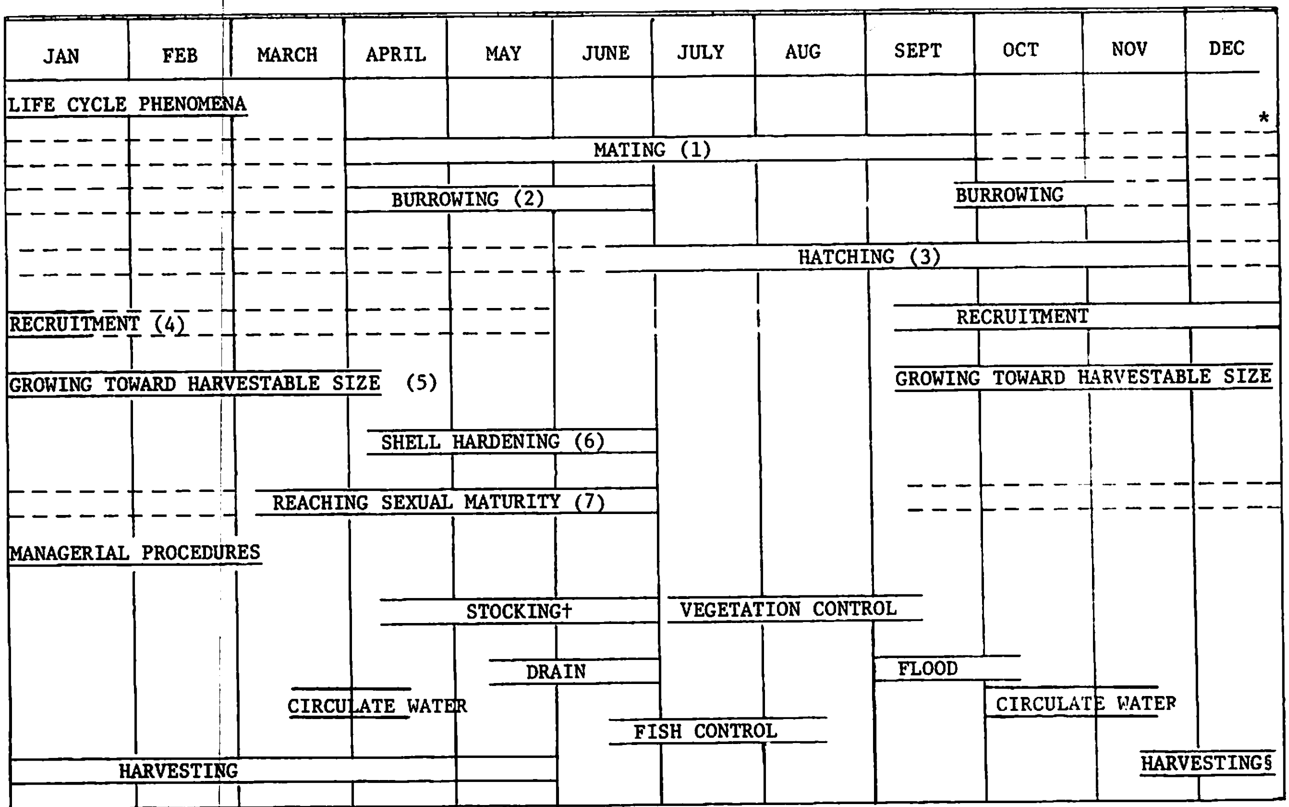
Special effort is needed to produce soft shell crawfish, as they must be handled on an individual basis. One needs to obtain crawfish that are about to shed their shells and hold them until they do. After shedding they should not be fed, and the water in the holding container should be deionized. This eliminates much of the calcium necessary to harden the shell. To prevent cannibalism one must be careful to separate crawfish that will shed in several days from those that will shed in a day or so.

Crawfish will stay in the flexible paper shell stage up to 3 weeks if they are held in deionized water and are separated from one another. Very soft crawfish can be obtained by removing them from water within 3 to 4 hours after shedding. These may be kept alive for 3 to 5 days, under refrigeration (45 to 50°F), packed in loose damp moss or coarse sawdust. One final note: soft shell crawfish are delicious

Table 15. Louisiana crawfish pond management procedures.

Procedure	Approximate Date
Construction and flooding (new pond)	By 15 May
Stocking (new pond)	15 April - 30 May
Draining	Draining may begin as early as 15 May but should be complete by 15 July. Period should be 2-4 weeks and should not begin until at least 2 weeks after stocking in new ponds.
Fish control	15 June - 15 August
Improvement and vegetation control or planting	As soon as possible after bulk of pond is drained.
Flooding	Begin in early September and end by 15 October.
Pumping/circulation	Two weeks after pond is filled, circulate water until water temperature falls below 65°F. Exchange water on a weekly basis (more often, if possible). Circulate again in the spring, if necessary.
Harvest	Old pond 25 November-mid June, continuously during mild winter, intermitently during severe winter. In November, check to make sure that no more than 10% of females have mature eggs.
	New pond 20 December-mid June if hatch successful.

Table 16. Life cycle of a Louisiana crawfish pond.



*Dashed lines indicate that a process is occurring at a reduced rate.
†New ponds.
§Old ponds, 25 Nov. (if less than 10% of females with well-developed eggs); new ponds, 20 Dec.

when they are fried like soft shell crabs. Care must be taken, however, to avoid the stomach stones, or gastroliths, found just behind the eyes of very soft crawfish. A cut just behind the eyes will remove them or one can nibble around them. Although a bit crunchy, crawfish up to 2.5 inches long may be fried whole. The shell is thin enough that the end product has a texture much like paper shell crabs. However, it is not as good as a true soft-shell crawfish.

AUSTRALIAN CRAWFISHES

Australian crawfishes belong to the family Parastacidae and over 100 species have been identified. Sizes range from less than one-half ounce to over 6 pounds. The five largest crawfishes include: Astacopsis gouldi (to 7 1/2 pounds), Cherax teniumanus (to 1/2-3/4 pounds), Cherax destructor (to 1/2 pound), Euastacus armitis (to 5 1/2 pounds), and Euastacus australasiensis (to 1 1/2 pounds). The Australian government has been interested in promoting crawfish culture and has investigated C. teniumanus and C. destructor for culture potential. The other species, although large, have small abdomens compared to the head and none is currently considered suitable for culture. The largest, Astacopsis gouldi, is a cool water, stream dweller and is unsuited for aquaculture in earthen ponds.

C. destructor is very similar to P. clarkii in its habitat requirements and readily adapts to earthen ponds. C. tenuimanus is naturally found in permanent streams but has good promise as a candidate for culture in earthen ponds. One main difference between culture of the Cherax species when compared with P. clarkii is that the Australians will often produce the young crawfish outside the pond and stock known numbers at rates up to 15 per square yard. However, adults may also be stocked to establish sustaining populations. The Australians also "feed" their crawfish with chicken mash, alfalfa pellets, hay, and other agricultural by-products. Rates up to 2 pounds per square yard have generated good results. Production has exceeded 2,000 pounds per acre in one 4-5 month growing season but size is roughly 2-3 ounces--this compares to P. clarkii sizes of 1 ounce.

Many people have inquired about the feasibility of importing various Australian crawfishes to the United States. There are several major reasons why this is not a sound idea. Biologically, we do not know what effect they will have on American ecosystems. They could become as serious a "pest" as P. clarkii has become on the West Coast. Also, all of the Australian crawfishes are highly susceptible to the crawfish plague (see Disease Section), which is known to exist throughout the United States. American crawfishes tolerate the plague but a well-established crawfish farm stocked with Australian crawfish could be ruined in a few days.

There are also legal considerations. For example, the Australian government restricts the export of several species of crawfish. Currently, it is illegal to import non-native species into this country without a permit issued by the Secretary of the Interior. States and local government units may require permits. It is highly unlikely that they would be granted as long as species such as P. clarkii are available for culture.

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This section is not intended to be a comprehensive listing of publications on crawfish in general and the red crawfish in particular. However, we feel that it will provide the inquisitive reader with additional references. We have emphasized the senior author's publications not to slight the work of others but because we felt that they summarized the literature in a number of areas. The bibliography of Sphorer, Williams, and Avault (see General Biology section) lists over 300 references, most dealing with the red crawfish. Copies may be obtained from the Publications Clerk, Fisheries, 249 Ag Center, Louisiana State University, Baton Rouge, Louisiana 70803. A number of references in the following bibliography are to reports from Papers from the International Symposia on Freshwater Crayfish. These are published by the International Association of Astacology. Copies of the various symposia may be obtained from the following sources:

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APPENDIX A

MAJOR CHARACTERISTICS INVOLVED IN THE EVOLUTION OF FRESHWATER CRAWFISHES FROM A PRO-NEPHROPOID ANCESTOR

(To Present Subfamily Cambaroidinae)

CAMBAROIDINE ANCESTOR

First pleopod of male with shallow sperm groove opening distally among terminal elements
Annular plate in female always lacking sinus and fossa
Branchial formula 18 + 3R + EP

(To Present Subfamily Cambarinae)

CAMBARINE ANCESTOR

Male with hooks on ischia of third, fourth, or third and fourth pereiopods
Annulus ventralis fixed, or, if movable, seldom through arc of more than 40 degrees
Branchial formula 17 EP

(To Present Subfamily Cambarellinae)

CAMBARELLINE ANCESTOR

Male with hooks on ischia of second and third pereiopods
Annulus ventralis movable through arc of at least 75 degrees
Branchial formula 16 + EP

PRO-CAMBARINE ANCESTOR

First pleopod of male with deep sperm groove opening distally on central projection
Annular plate in female always with sinus and fossa
Branchial formula 17 + EP, or 16 + EP

(To Present Family Astacidae)

ASTACID ANCESTOR

Cyclic dimorphism absent in male
First pleopod of male subtubular distally and lacking ornamentation other than spoon-like lobes
Ischia of all pereiopods of male lacking hooks
Annular plate in female without sinus or fossa

(To Present Family Cambaridae)

CAMBARID ANCESTOR

Cyclic dimorphism in male
First pleopod of male with shallow or deep sperm groove and with terminal ornamentation
Ischia of one or more pereiopods of male with hooks
Annular plate in female with or without sinus and fossa

ASTACOIDEAN ANCESTOR

First pleopods of male each with sperm conduit
Second pleopod of male with spiral element on endopodite
Podobranchiae with fused branchial and epipoditic portions and with bilobed plaited laminae
Sternum between fifth pereiopods not fused with anterior sternal plate
Eggs hatching as miniatures of adult

NEPHROPOIDEAN ANCESTOR

First pleopods of male serving together to form single sperm conduit
Second pleopod of male without spiral element on endopodite
Podobranchiae with discrete branchial and epipoditic portions
Sternum between fifth pereiopods fused with anterior sternal plate
Eggs hatching as larvae

(To Present Family Parastacidae)

PARASTACOIDEAN ANCESTOR

First pleopods absent in male and female
Second pleopod of male without spiral element on endopodite
Podobranchiae with fused branchial and epipoditic portions but without bilobed plaited laminae
Sternum between fifth pereiopods not fused with anterior sternal plate
Eggs hatching as miniatures of adult

PRO-NEPHROPOID ANCESTOR

*Reference: Hobbs (1974b). Bibliography-Taxonomy/Zoogeography

Appendix B

Sample Problem for Calculating Age Classes and Average Sizes for Crawfish Collected During Pond Population Monitoring with a Dip Net and Small Mesh Traps

1) Prepare a record sheet with the size categories shown on the next page.

2) Measure the crawfish and place a mark in each size category on the record sheet. Keep the dip net sample and the small mesh trap sample separate. The measurements for the example record sheet are as follows:

Dip Net Sample

10	11	11	12	12	12	12	13	13	14	15	15	18	19	17
20	21	20	24	28	30	31	31	32	33	33	30	31	37	42
42	43	45	50	53	53	54	51	51	58	58	61	67	75	78
78	79													

Small Mesh Trap Sample

45	45	49	49	48	50	50	50	51	51	51	51	51	52	53
54	54	52	51	51	53	53	54	54	53	53	54	54	52	51
55	55	55	58	57	58	58	59	59	57	60	61	61	62	63
67	67	70	71	71	73	73	75	75	77	77	78	78	79	78
77	76	76	77	78	78	79	76	75	75	75	76	80	81	81
83	82	81	82	85	86	87	88	85	91	92	93	95	96	97
98	99	98	97	96	95	97	100	101	101					

3) Count the number of marks in each category and write the number down for each sampling technique. The numbers are shown in the sample.

4) Calculate percentages. For the 10-14 mm size category this is 10/50 x 100 = 0.20 x 100 = 20%. The formula for calculating percentages is:

$$\frac{\text{Number in each size class}}{\text{Total caught with that technique}} \times 100 = \text{percentage}$$

(Note that if there are exactly 50 crawfish in a sample, one can multiply the number in each category by 2 to get percentage. If there are exactly 100 crawfish in the sample, the number in each size class will equal its percentage.)

5) The most prominent numbers will represent the Age Classes (modes). These are circled. Note the correspondence between modes for dip net and small mesh trap samples. (In all fairness, the reader should be warned that the modes do not always show up this well. Practice with advice from local county extension agents or state wildlife or fisheries biologists will help a great deal.)

6) Calculation of average size of crawfish from dip net and small trap samples: Average is calculated by adding up all observations and dividing by the total number of observations.

Dip Net Sample

The total of all observations = 1,750
The total number of observations = 50

$$\text{Average} = \frac{1{,}750}{50} = 35.0 \text{ mm (about 1.38 in.)}$$

Small Mesh Trap Sample

The total of all observations = 6,990
The total number of observations = 100

$$\text{Average} = \frac{6{,}990}{100} = 69.9 \text{ mm (about 2.75 in.)}$$

Appendix B
SIZE CLASS IN MILLIMETERS

	5-9	10-14	15-19	20-24	25-29	30-34	35-39	40-44	45-49	50-54	55-59	60-64	65-69	70-74	75-79	80-84	85-89	90-94	95-99	100-104
DIP NET																				
NO./SIZE CLASS	0	10	5	4	3	8	1	3	1	7	2	1	1	0	4	0	0	0	0	0
TOTAL	50																			
PERCENT	0	20	10	8	6	16	2	6	2	14	4	2	2	0	8	0	0	0	0	0
TRAP																				
NO./SIZE CLASS	0	0	0	0	0	0	0	0	5	25	10	5	2	5	20	7	5	3	10	3
TOTAL	100																			
PERCENT	0	0	0	0	0	0	0	0	5	25		5	2	5	20	7	5	3	10	3
		↑ YOUNG-OF-THE-YEAR				↑ YOUNG-OF-THE-YEAR				↑ YOUNG-OF-THE-YEAR					↑ HOLDOVER JUVENILES				↑ HOLDOVER ADULTS	

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