Red Swamp CRAWFISH: Biology and Exploitation

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LOUISIANA SEA GRANT COLLEGE PROGRAM

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FOREWORD

This is the third edition of Red Swamp Crawfish: Biology and Exploitation. Since 1980, when this book was first written, crawfish culture has expanded greatly, and there is now a proliferation of research data where previously only educated guesses were available, especially in regard to exploitation.

The white river crawfish frequently appears with the red swamp crawfish and we have expanded our discussion of this species. It must be noted, however, that the taxonomy of this species has changed. Dr. Horton H. Hobbs, Jr., the nation's foremost crawfish identification specialist (taxonomist) has divided the species formerly called *Procambarus acutus acutus* into three separate species. The one most commonly encountered in the eastern U.S. is *Procambarus acutus acutus*. The common species in Louisiana and Texas crawfish ponds and natural habitats is *Procambarus zonangulus*. The species that occurs throughout the rest of the central U.S. has yet to be named. Unless otherwise noted, any reference to white river crawfish is a reference to *Procambarus zonangulus*, not *Procambarus acutus acutus* or the unnamed species.

The majority of this book is still devoted to the management and culture of the red swamp crawfish, *Procambarus clarkii*, the most cosmopolitan of the crawfish species. The text is not intended to be an all-encompassing technical treatment of crawfish biology and exploitation, but a practical guide for the crawfish culturist. For those interested in further, more technical, information, an excellent scientific text on the subject is *Freshwater Crayfish: Biology, Management, and Exploitation*, edited by D. M. Holdich and R. S. Lowery and published in 1988 by Croom Helm (London and Sydney) and Timber Press (Portland, Oregon).

We hope that this book will provide new and useful information. We welcome comments from readers for future editions.

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INTRODUCTION

Freshwater crawfish 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 a 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.

Crawfish 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. 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 newfound bonanza.

Over the years, food fisheries have developed into a successful business with up to 100,000,000 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 heartland. Such swamps provide virtually unlimited habitats for crawfish. The West Coast catch approaches 1,000,000 lbs per year, but the resource is largely underexploited. Most production is shipped to Europe where native species have been decimated by pollution and disease. Production in the Great Lakes area exceeds 200,000 lbs per year.

In North America, crawfish 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.

Fig. 1. Adult male red crawfish.

Over 100,000,000 pounds of red crawfish are harvested annually in the U.S. from swamps, marshes, and cultivated ponds, with 80-90 percent coming from Louisiana. The red crawfish is native to northern Mexico and the Mississippi Valley as far north as southern Illinois. It has been successfully introduced on both the east and west coasts of the U.S. A hardy, adaptable species, it has also been introduced in the West Indies (Dominican Republic), Central America (Belize and Costa Rica), South America (Brazil, Ecuador, Guyana, and Venezuela), Europe (France, Portugal, Spain, and possibly England, Italy, and Sweden), Africa (Kenya, Uganda, and Zambia), the Middle East (Cyprus) and eastern Asia and the Pacific (Hawaii,

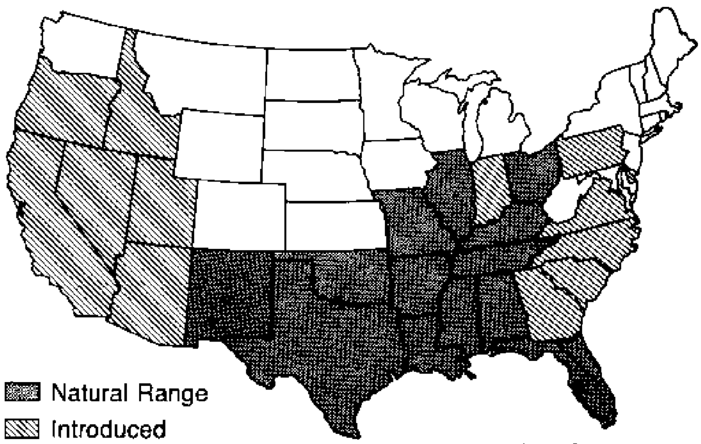


Fig. 2. States where the red crawfish is found in the continental USA. The actual range within the states is not shown.

Hong Kong, Japan, People's Republic of China, and Taiwan). It is, most certainly, present in other countries, having been widely distributed in the "ornamental fish" trade.

The red crawfish is clearly the most cosmopolitan of all crawfish. Commercial harvests are now reported from Spain (5,000 tons), the People's Republic of China (2,000 tons), and Kenya (100 tons). This is small compared with U.S. production, though both the Spanish and Kenyan introductions date from the mid-1970s. Thus, aquaculture of the species has expanded well outside its native habitat.

Crawfish are crustaceans, a class of arthropods that has radiated into more marine and freshwater environments than any of its 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, and 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.

Arthropods are the most successful terrestrial (land-dwelling) invertebrates, and crustaceans are the most successful aquatic arthropods. Insects take a back seat when compared with 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

Some Countries where Red Swamp Crawfish are found.

Fig. 3. Worldwide distribution of the red crawfish.

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, crawfish 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. Entomostracans include the fairy shrimps, water fleas, copepods, and barnacles. Barnacles are common along the shores and beaches of many coastlines. Copepods, water fleas, and fairy shrimps are found in open waters. They are very small and are unable to fight currents. Thus, they are referred to as planktonic creatures. Water fleas and fairy shrimps are typically freshwater creatures, although the brine shrimp is a fairy shrimp that is adapted to life in briny lakes.

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

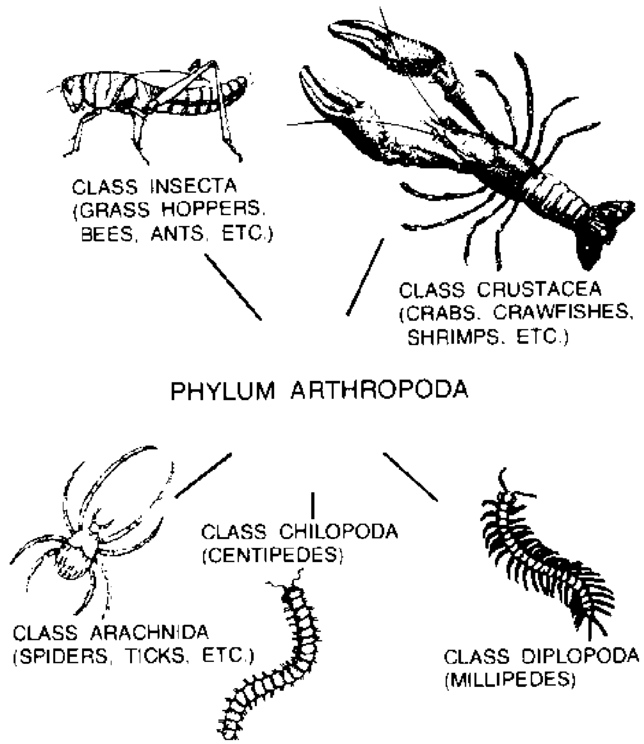


Fig. 4. Phylum Arthropoda—various classes.

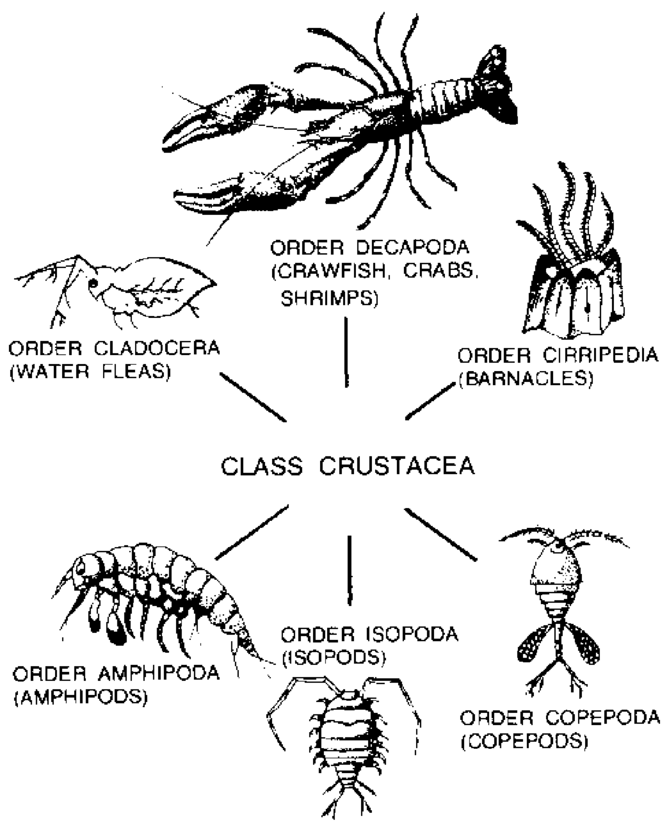


Fig. 5. Class Crustacea.

GENERAL BIOLOGY

EXTERNAL ANATOMY

The characteristic exoskeleton of the crawfish can be divided into 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 (three in the head, ten in the thorax, and six 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).

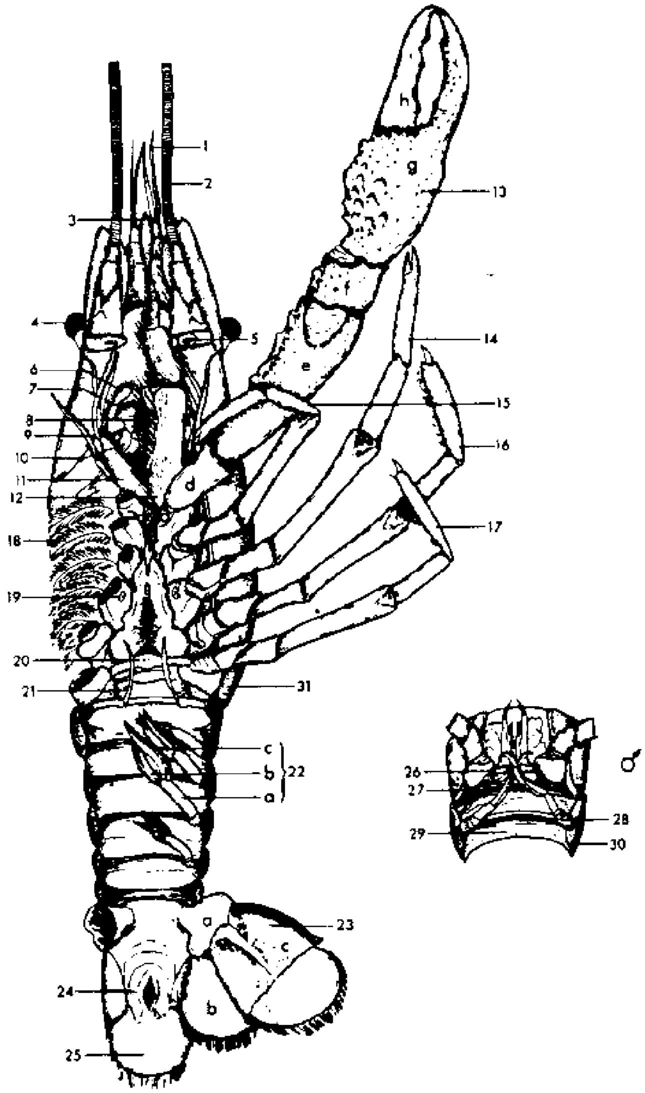
The compound eyes are stalked and movable and are set in front of (anterior to) the carapace. The mouth is on the head, between the *mandibles*. The anus opens ventrally from the large "tail" or *telson* at the end of the abdomen. On each side of the body is a large gill chamber. The anterior end of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



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.

Table 1. Crawfish limbs.

Region	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
	II Antenna	Excretory opening in ventral base/2	Multijointed, long feeler	Thin, pointed blade	Taste & touch
	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
	V Second Maxilla	Bilobed plates/2	Slender exopodite & epipodite form "gillbailer" to move water over gills/1		Filter feeding, food manipulation, touch, & taste
	VI First Maxilliped	Broad medial plate & epipodite/2	Small & narrow/2	Narrow & very small/2	
	VII Second Maxilliped	Short & has gill/2	Short & stout/5	Narrow/2	
	VIII Third Maxilliped	Has gill/2	Longer/5	Narrow/2	
	IX First Walking Leg	Has gill/2	Robust with heavy claw at tip/5	—	Combat & protection
	X Second Walking Leg	Has gill/2	Slender with small claw at tip/5	—	Ambulatory (walking) movements & grasping
	XI Third Walking Leg	Has gill & in female has sex opening/2	Slender with small claw at tip & in mature male P. clarkii has grasping hook on ischipodite/5	—	
	XII Fourth Walking Leg	Has gill/2	Slender & in mature male P. clarkii has grasping hook on ischipodite/5	—	Ambulatory movements; dactylopodites at tips of endopodites juxtaposed on limbs XII & XIII to permit clinging, leaving other 3 legs free
	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
	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 & carrying eggs/young in females
	XVI Third Swimmeret	Short/2	Segmented filament	Filamentous	Water movement in both sexes; carrying eggs/young in females
	XVII Fourth Swimmeret	Short/2	Segmented filament	Filamentous	
	XVIII Fifth Swimmeret	Short/2	Segmented filament	Filamentous	
	XIX Uropod	Short & broad/1	Flat & oval/1	Flat & oval with a hinge/1	Swimming; egg protection in females

NOTE: 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.

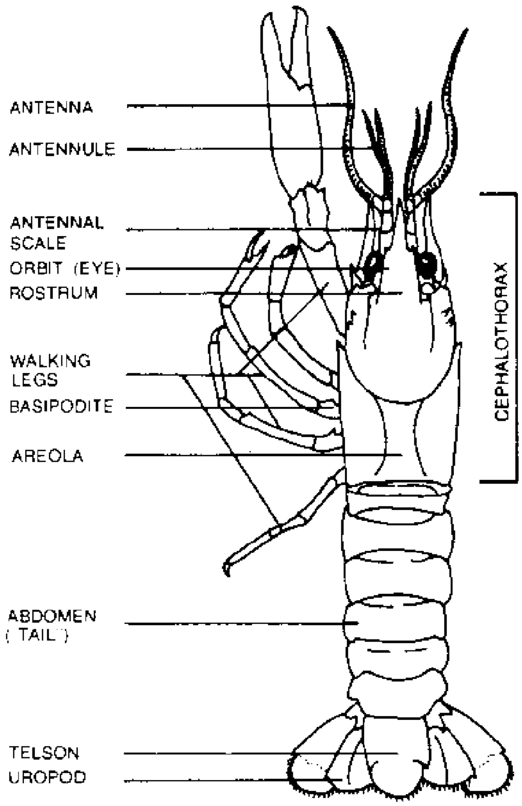
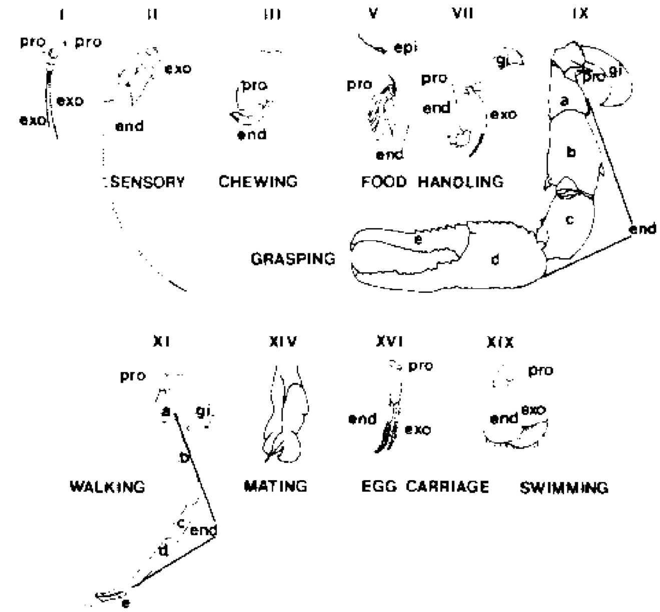


Fig. 7. Dorsal view of generalized crawfish, showing various body parts.

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

appendages, *maxillae* and *maxillipeds*, which handle the food. The large characteristic claw or pincer (chela) is used to grasp the food. An offensive and defensive appendage, the claw is often lost in combat. It is classified as a pereipod, or walking leg. The following four pairs of pereipods are primarily 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, podobranches, attached



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

Fig. 9. Appendages of the red crawfish.

to the protopodites. The pleopods, or swimmerets, are important in supporting and incubating the eggs (developing embryos). Their movement circulates the water in and around the eggs to promote respiration. The first two pairs of pleopods in 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 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 crawfish. Table 1 provides a detailed summary of the parts and functions of the various appendages.

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 continue to be synthesized 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 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 the animals are 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.

Two interesting color variations of red crawfish have recently been identified. One is a pale white chalky color. The eyes are normal so these crawfish are not albinos in the classical sense. In some specimens, a very distinctive yellow pattern is apparent; immature crawfish are greenish-yellow, while mature adults have dark dorsal areas highlighted laterally by golden orange. The extent of the yellow color clearly depends upon the environment in which the crawfish grows; however, fertile eggs are yellow, not dark brown as with all other red crawfish. The genetics of the white and yellow color patterns have yet to be determined.

A most unusual color pattern has been reported twice in 1990, once in Louisiana and once in Florida, by reliable crawfish farmers. The crawfish were reddish orange on one side and bluish on the other. This phenomenon has been reported in

American lobsters, *Homarus americanus*. Its genetical base can be explained only after specimens are bred in captivity.

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 in the outer part. The eyes have been variously described as yellow, white, silver, and platinum. 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 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. The palm of the claw of mature males is elongated when compared with that of mature females.

INTERNAL ANATOMY AND PHYSIOLOGY

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.

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 betwen 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 upward 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 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 absorb 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 at 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 the uropods are the true tail of the crawfish. It should be called, more correctly, abdominal meat.

Respiratory System

Crawfish obtain oxygen and eliminate carbon dioxide through gills. The gills contain blood sinuses and are located on both sides of the thorax in gill or branchial chambers. The branchial chamber is formed by the lateral sections of the carapace, and external to (outside) 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 pereipods and from the rear of the chamber passing forward to the upper portion of the chamber and exiting below the mouth (Fig. 11).

In crawfish there are two types of gills—the podobranches and the arthrobranches. In the red crawfish the podobranches arise from the protopodites of the second and third maxillipeds

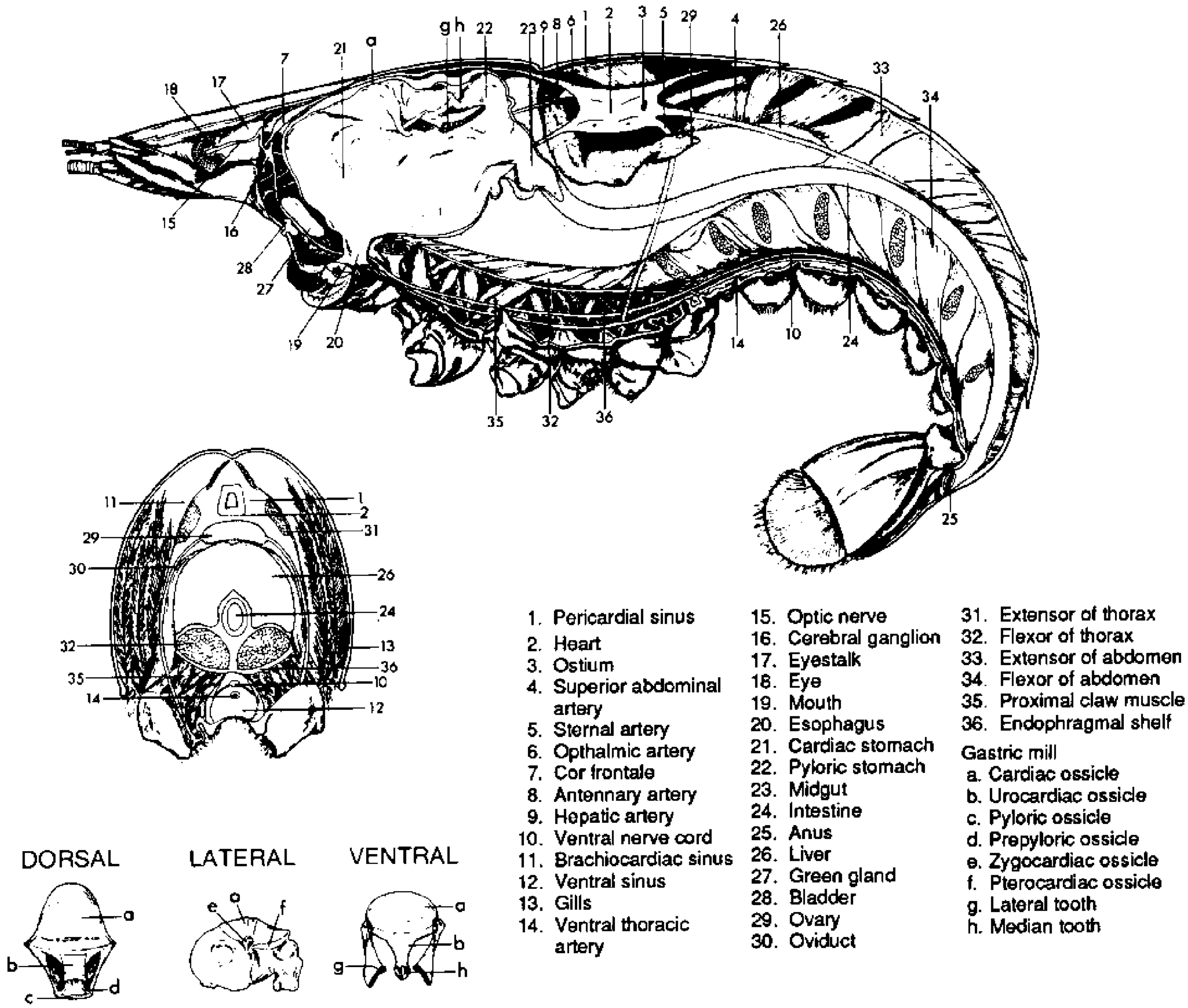


Fig. 11. Crawfish internal anatomy.

and the first four pairs of pereiopods (one per appendage). The paired arthrobranches arise from the body wall adjacent to the second (one pair only) and third maxillipeds and the first four pairs of pereiopods. 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 the damp, humid parts of burrows rather than in the water below which is often very low in dissolved oxygen. This ability permits them to live in surface waters when oxygen depletion takes place because of 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.

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 cephalo-thoracic 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 green glands, digestive gland (hepatopancreas), 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 and 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" cells called hemocytes. There are three types of hemocytes: the hyaline cells, the semigranular cells, and the granular cells. The hyaline cells are small, usually spherical, and contain only a small number of tiny cellular bodies. The granular cells are much larger and are filled with numerous large, highly visible cellular bodies. The semigranular cells are intermediate between the other two although they are similar in size to the granular cells. They do not have as many cellular bodies as the granular cells and can be spindle-shaped and have distinct nuclei. The granular and semigranular cells are very important in attacking pathogens such as bacteria and fungi and function more like white blood cells in vertebrates. They do not carry oxygen as red blood cells do in vertebrates. Some release substances that act to clot the hemolymph.

Oxygen diffuses into the hemolymph largely through the gills. Cells do not carry the oxygen. Rather, it is carried within the hemolymph, normally combined with hemocyanin. Hemocyanin (similar to hemoglobin in vertebrate animals) contains a copper porphyrin molecule that responds to oxygen as does the iron in hemoglobin 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.)

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 system 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. Fused *segmental* ganglia in each segment are found in pairs along the ventral nerve cord; these 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 so 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 from tactile receptors, which detect vibrations and water movements.

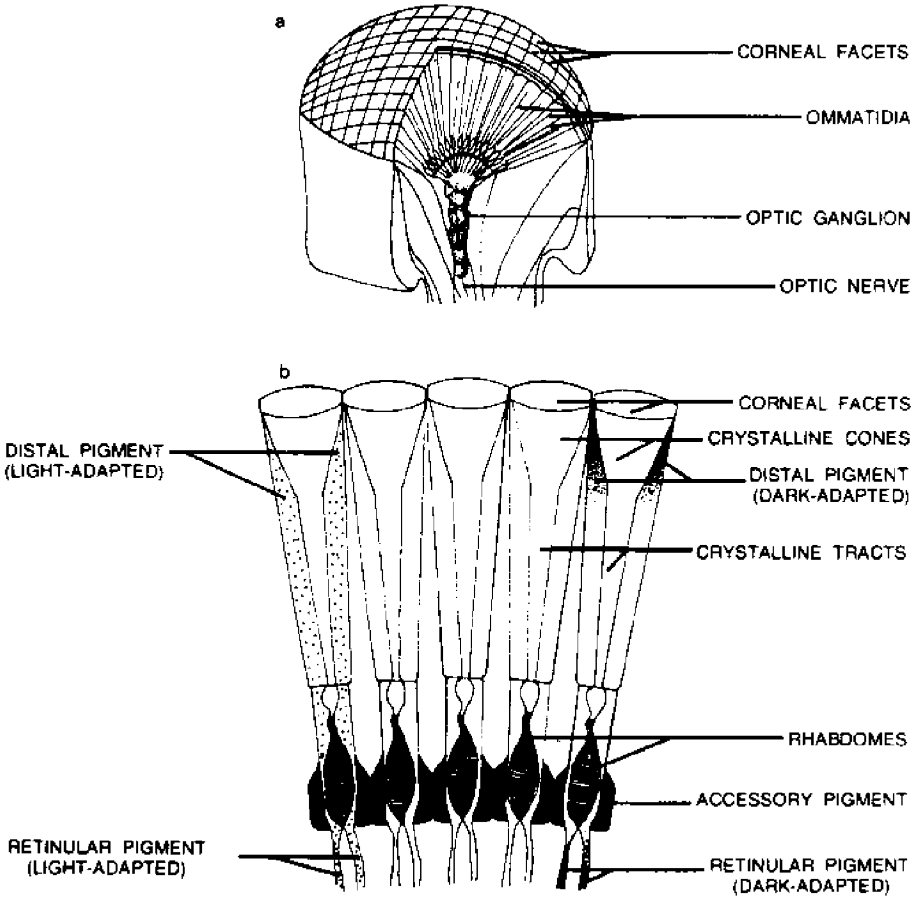
The compound eyes of crawfish are similar to those found in insects. They are covered by a transparent membrane called the *cornea*. The compound eye is composed of many smaller units or facets called *ommatidia*; as many as 2,500 ommatidia make up one eye. Each ommatidium is composed of several different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

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 rhabdome* 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 rhabdome 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 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.



Legend: (a) eye cut to reveal structure; (b) ommatidia 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.

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 pattern 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

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, the 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 (accelerates heart beat), antidiuretic hormones (regulate body water levels), metabolic hormones, and ovary-inhibiting hormones. Related neurohormones are produced by the supra-, circum-, and subesophageal 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 crustecydsone, 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. At one time, it was thought that MIH inhibited molting by acting directly on the gland(s) producing MSH. Now it appears that MIH modifies the response of tissues to circulating ecdysteroids, rather than by preventing their synthesis or speeding up their inactivation. 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 have 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.

Molting. As previously stated, molting in crawfish is hormonally controlled. Current evidence suggests that ecdysone (alpha ecdysone) is secreted by a molt gland (or glands), which causes separation of the epidermis from the overlying shell and gastrolith formation. It also activates an enzyme system that transforms ecdysone to ecdysterone (beta ecdysone). The subsequent rapid rise in ecdysterone levels is responsible for the formation of a new exoskeleton beneath the old one and other internal premolt activities. High levels of ecdysterone turn off the enzyme system that converts ecdysone to ecdysterone at the appropriate time in the cycle. Crawfish also have a system that can inactivate ecdysteroid hormones if necessary. They can be rapidly excreted; however, there is a point during the premolt process after which nothing can prevent the molt from taking place, apparently after phase D_1 has been initiated.

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 connections 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 steroid 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 section on reproduction system).

Insects are known to secrete *juvenile hormone*, the amount gradually declining during their development. At very low hormone levels, the insects molt into adult body forms. Juvenile hormone has been recently isolated in crustaceans, including red crawfish. The specific compound is methyl farnesoate and it is produced by paired endocrine glands called *mandibular glands*, located close to the paired mandibles just below the eyestalks.

Some juvenile hormone compounds are now in use as "third generation" insecticides. They are thought to be safer than chlorinated hydrocarbon and organophosphate insecticides because they are not persistent in the environment. But no one yet 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 with their mother maintains her brooding behavior. A mother will normally not undergo the post reproductive period molt until the young leave.

There is currently some controversy as to whether adult crawfish, 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. They could detect (smell) each other at distances of 10 inches, but could not distinguish sex. Further studies will be needed to clarify this matter.

Behavior

Behavior is a complex series of responses that an organism may perform in its environment. Behavior patterns that are programmed genetically are called innate behavior. Behavior patterns that develop as a result of past experiences are called learned behavior. Most of the behavior of the 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 retreat 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.

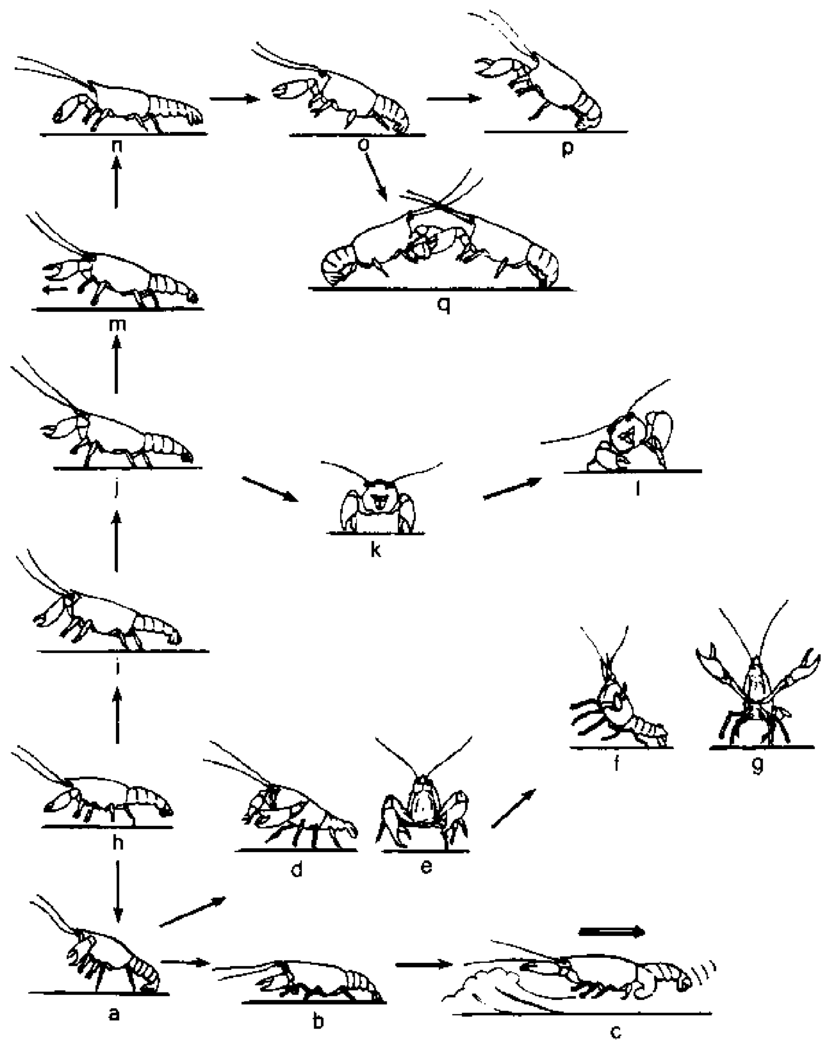
One unique reflex is autotomy. Autotomy in crustaceans is the casting off of a limb at the level of a joint between the protopodite and ischiopodite when strong stimulation occurs. Muscles contracting in the joint are capable of forcing the joint apart. This reflex is characteristic of a similar defense 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, Oklahoma, 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 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 the chelae of captured specimens. Wild fights are fairly uncommon. Most combat ends in the retreat of one opponent after battles without severe injury.

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 the 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 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.

As do other animals, red swamp crawfish form distinct dominance orders, much like the "pecking order" of chickens. Basically, one crawfish is the dominant crawfish and all others stay away from it to avoid conflict. A second crawfish dominates the others, but not the first one. The same holds for the other crawfish, depending on their order in the dominance hierarchy.

Courtship and Mating Behavior. Crawfish exhibit distinct courtship behavior, which has been described in red crawfish by Dr. Ameyaw-Akumfi while he studied crawfish biology at the University of Michigan. A description of the components of courtship and mating behavior follows:

"At first encounter, male and female make chelae (claws) contacts, with either sex being the initiator. A short fight can ensue but rarely lasts over a minute, ending when the male drops his chelae in a "refusal" to fight. If a female continues to attack, the male will fight until she moves away in an apparent defeated state.

"Such fighting lasts one to five minutes. The male then assumes a nonaggressive stance whenever he meets the female, with chelae down, closed pincers, and curled tail fan. The female generally assumes the same posture.

"Once aggression ends, a sexually mature male initiates courtship behavior. The male approaches the female with his pincers closed. As he approaches, he rhythmically moves the first two pairs of walking legs toward and away from his belly while moving his mouth parts. These movements are normally associated with feeding. He may also move the other body limbs associated with grooming. The moving appendages eventually make contact with the female when the male comes close to her. His tail fan is curled, a submissive posture. A sexually active female assumes a resting posture with chelae down and tail fan curled.

"After antennae and chelae contact, the male often moves close enough to make antennule-to-antennule contact with his prospective mate. The mouth parts of both partners sometimes come in contact. Next, the male may turn sideways to face the submissive female's side. He may then do a complete 180° turn so that the telson faces the female. If the female remains passive, the male then moves to her rear or side and begins to mount her.

"While mounting, the male constantly grooms the female's side and back with his walking legs and mouth parts. Meanwhile he grasps the female's chelae by the merus or carpus of the respective side, as well as several of the female's first sets of walking legs. The male holds the female's antennae and antennules with his other chela. He then turns her over, grooms her belly, and positions himself. The male crosses one of the last walking legs under his body so that they keep the gonopods erect and in contact with the female's annulus ventralis (seminal receptacle). The pair then falls over on either side with abdomens fully outstretched and copulation proceeds."

Copulation can take a very long period, over an hour and a half. Such lengthy periods are widely reported in crawfish, but no one has ventured an explanation. However, the late E. A. Andrews noted that the male would thoroughly clean the seminal receptacle before depositing sperm. So, perhaps the length of the copulation period depends, at least in part, on the cleanliness of the seminal receptacle.

Dr. Ameyaw-Akumfi found that the chelae were not essential for successful mating. When one or both chelae were removed, a male could mate with a female of the same size. When both chelae were removed, the male used the small chelae of the first pair of walking legs as if they were the regular chelae. Males could mate with females up to an inch longer than themselves. This demonstrates the obvious advantages associated with the inflated chelae of mature males. *P. clarkii* mate readily, even in crowded, light-filled conditions. After mating occurs, sperm remain viable in the seminal receptacle for more than eight months.

Multiple matings among crawfish are common phenomena. However, the presence of a sperm plug that seals the seminal receptacle in the female suggests that no further sperm may be added to the seminal receptacle in subsequent matings. The only way to prove this hypothesis is through the study of matings between animals with known genetic "markers" such as yellow eye color or blue body color. Dr. Joe Black of Louisiana College in Pineville, La., mated individual females to successive males with different genetic markers. He found that the resulting young exhibited traits that could be explained only by the mixing of genes from both males. Thus, multiple matings result in multiple paternity. This probably insures genetic diversity in natural crawfish populations and should reduce the problems associated with inbreeding in crawfish ponds. However, this is hardly desirable if one is attempting to breed a "pure" strain of crawfish, as the absolute isolation of males and females is essential.

Fig. 14. Mating red swamp crawfish. Photo, J. Huner.

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 perpendicularly to the object. The crawfish then uses the walking legs to climb upward. *Swimming*: A crawfish swims backward 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. *Burying*: 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 crawfish notices the scent, 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 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 then 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 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 easily. Heavy-shelled snails like the ramshorn cannot be easily crushed. The crawfish gradually chews 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 backward in an arc toward the surface by vigorously flipping its tail. When it reaches the surface, it will grab floating feed with its claws and then settle 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.

The oral appendages (mouth parts) of crawfishes are covered with fine hairs, or setae. These are used to sieve fine food particles including small living organisms like algae, diatoms, copepods, and water fleas from the water so that they can be eaten. Every crawfish regardless of age and size has and uses this filter-feeding apparatus, but smaller crawfish seem to be more efficient at it.

Egg-Laying Behavior. In the early 1900s E. A. Andrews took great pains to describe egg laying in *Orconectes limosus*, a northern crawfish. His description is generally applicable to *P. clarkii* and other cambarid crawfish.

Preparation for Laying. Several days before laying eggs, the female cleans the underside of her abdomen until it becomes very white. To do this, she raises her body from its normal crouching position and stands like a tripod, supported on the two outstretched claws in front and the oddly bent-down abdomen behind. The other walking legs have little to do with support and are primarily concerned with cleaning. The fourth pair of walking legs and at times the first and second pairs thrust back under the abdomen and gradually remove all the dirt from the undersurface, including the pleopods.

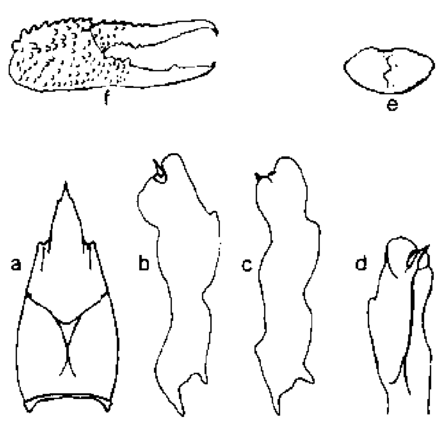
The tips of the fourth walking legs are plied with great vigor against abdominal structures, but cleaning takes considerable time. The terminal segments of these legs are like strong combs, each with a series of sharp, regularly spaced setae along one free edge. Tufts of serrated setae of varying length also serve to remove debris from body surfaces. The tips of the last leg segment and the second to last segment are tipped with sharp picks. Thus, as Andrews notes, the female crawfish has "a double pick to loosen dirt, a stiff comb, and a brush with sawtooth hairs" for cleaning.

The third pair of walking legs has structures similar to those of the fourth pair. The first and second pairs bear small, well developed claws and "pluck" encrusted material from the exoskeleton. These claws are also equipped with a long row of opposing, flat, serrated plates that assist in cleaning.

Laying the Eggs. Just before the eggs are laid, the female produces copious quantities of a glue-like substance called "glair." This is secreted by the cement glands, located at the bases of the abdominal limbs and on the belly from just in front of the annulus ventralis back to the abdomen.

Once the swimmerets are thoroughly covered with glair, the female turns over on her back with legs stiffly spread and abdomen curled. A faint film of glair extends from the widely expanded tail fan to the first pair of walking legs and adjacent areas. The female moves very little, but eggs are extruded from the opening of the oviducts at the bases of the third pair of walking legs. The process takes several hours.

Once the eggs are laid, the female turns over with the glair apron raised and intact. She then proceeds to spend several hours turning from side to side, spending several minutes on one side, turning to an upright position for several minutes, and then lying on the other side. This behavior insures that the zygotes (fertilized eggs) are firmly fastened to fine setae on the swimmerets. (Fertilization takes place sometime between egg laying and attachment.) Complete hardening of the membranes attaching the eggs (zygotes) to the swimmerets takes about 12 hours. Excessive activity during this period results in a loss of zygotes. It was once thought that the glair formed the membranes that attach the eggs to the swimmerets; however, it is now apparent that the membranes are derived from the surface of the eggs themselves. The glair's purpose is to provide a safe place for fertilization and attachment.



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. 15. Key taxonomic features of the red crawfish.

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 pahlic papillae (one on each side) at the bases of the fifth pair of walking legs. (According to a recent study by Dr. James F. Payne of Memphis State University in Memphis, Tennessee, one of the two vas deferens of male cambarid crawfishes is nonfunctional. The significance of this finding is not yet apparent.) 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, 15).

The sexually mature crawfish, male or female, assumes distinctive secondary sexual characteristics. 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 serve to transfer sperm to the female. The large claws and hooks 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 annulus ventralis also cornifies and a very distinct groove forms when the female molts to the sexually active phase. 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, 15).

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.

The Form II condition arises after a male or female has reached sexual maturity (Form I) and molted to the sexually inactive state. Thus, any male that has not matured is properly described as a juvenile. Distinction between juvenile and Form II males is not easy. Initially, there is a distinct gap between the bases of the first pair of swimmerets, or gonopodia, of juvenile males; but this gap narrows as the male goes through successive molts, to the

Fig. 16. Juvenile red crawfish.

point that just before the Form I molt, the gap is very narrow. As a result, a narrow gap between the swimmerets is indicative of either a juvenile male about to molt to the Form I state or a true Form II male.

Development and Growth

Egg Laying. Courtship and mating behavior have been fully described in the preceding section. Burrowing generally begins after mating; 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 usually contain both a male and female crawfish, the female often drives the male out of the burrow at the time of egg laying. Typically, the male is found near the entrance of the burrow and the female is behind the male near the bottom of the burrow.

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.

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 female two and one third inches long 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. A detailed account of egg-laying behavior is found in the preceding section.

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. Fertile eggs are 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.

The normal chromosome number (the 2N condition) for the red crawfish was reported to be 192 (96 pairs). This is similar to the numbers for other cambarid crawfish, including 200 (100 pairs) for *Orconectes virilis*, native to the north-central USA and southern Canada, and 196 (98 pairs) for *Cambaroides japonicus*, native to Japan. For comparison purposes, man has 46 chromosomes (23 pairs).

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 nuclei. At this point the nuclei migrate to the surface and superficial cleavages occur, producing the blastula stage. Once the blastula forms, a new process called gastrulation begins. Gastrulation occurs when some of the cells on the surface (blastula) begin to invaginate or fold inward forming a pouch. This infolding 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 many appendages of the crustacean (Fig. 17).

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. The newly hatched crawfish is basically equipped with all the parts necessary for survival, but it must remain with its mother and undergo two molts before it can fend for itself. 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 were able to adapt and invade freshwater habitats from their ancestral homes in the sea.

Embryonic development is temperature-dependent. According to Professor Tetsuya Suko of Saitama University in Japan, the temperature-dependent periods for embryo growth are: 48°F, 150 days; 59°F, 46 days; and 72°F, 19 days. Professor Suko found that the "critical" temperature below which embryonic development would not proceed was approximately 42°F. Most egg laying took place at 68-70°F. The lowest temperature at which he observed egg laying was 59°F and the highest temperature at which he observed it was 82°F.

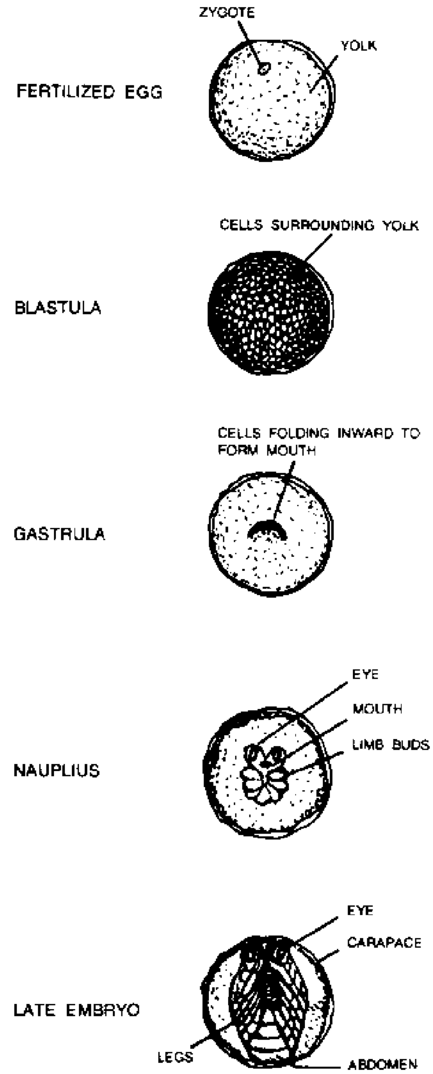


Fig. 17. Crawfish embryonic development.

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, so long as the eggs are wet, oxygen can diffuse from the atmosphere into them and waste products can diffuse out of them. The female fans her swimmerets, constantly exposing the eggs to the humid burrow atmosphere.

Growth. E. A. Andrews has described the early life stages of *P. clarkii* in considerable detail.

Shortly before the young crawfish hatch, they can be seen clearly through the egg shell. Each is covered with a loosely fitting cast-off exoskeleton. Their eyes are immobile. Yolk is present as a large

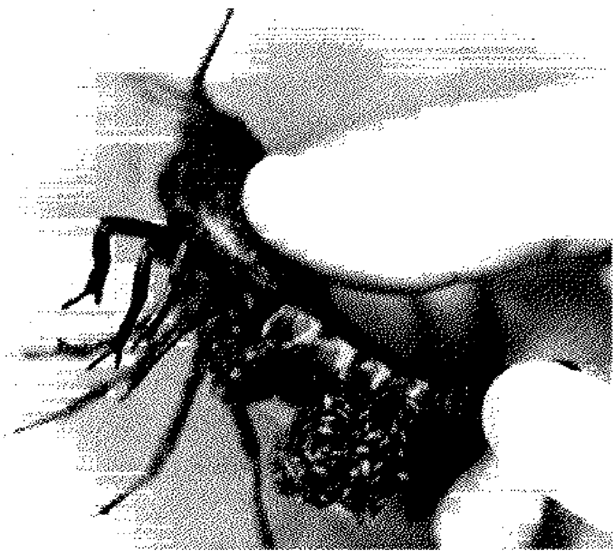


Fig. 18. Female red crawfish with newly hatched young attached to swimmerets.

dark mass with a saddle shape in the visceral region. Their bodies are covered with crimson shells. The telson is simple, flat, and rounded, and a row of simple spines is along the back edge. "Threads" pass through these spines to the loose larval exoskeleton.

When the young crawfish hatch, they free themselves both from the egg shell and the old exoskeleton, which turns inside out. They are attached, however, to the old exoskeleton by the telson spines. The old exoskeleton remains attached to the inside of the egg case. This is important, because the entire structure (called the telson thread) insures the attachment of the weak young crawfish to its mother's pleopods until it can grasp

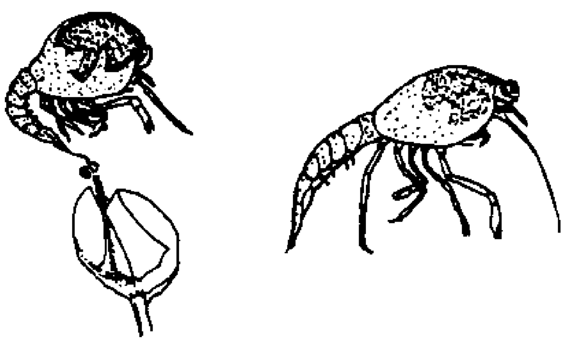


Fig. 19. Left: Newly hatched larva still connected to the egg case by the telson thread (first instar). Right: Right side of living larva in second stage (second instar).

the pleopods with its claws. Certain death awaits a young crawfish that becomes detached from the mother, as it is unable to take care of itself. In its early period of growth—called the first instar—the crawfish goes through several stages. At first it has a huge swelling of the cephalothorax from stored yolk; poor development of all appendages; poorly developed, sessile eyes; a transparent body; and rapidly beating scaphognathites (gill bailers) and a heart. The rostrum is bent down between the eyes, and the tail is conspicuous by the absence of uropods. Total body length is about 0.18 inch.

First instar crawfish molt to the second stage (instar) several days later. They are about 0.21-inch long and look more like a true crawfish. Limbs are better developed and the cephalothorax, though retaining yolk, is much less swollen. The rostrum is still bent between the eyes but is completely visible between the distinctly stalked eyes. The uropods protrude, making the telson distinctly trilobed. The mandibles show distinct "teeth," presumably meaning that the crawfish are capable of feeding. When separated from the mother, these second-stage crawfish can stand up and walk feebly and can manage some swimming (backwards) by flapping their abdomens.

Third-stage (instar) crawfish are about 0.30-inch long. They are, for all practical purposes, miniature adults and are fully capable of living apart from the mother. They do remain fairly close for up to several weeks, attracted by a maternal brooding pheromone. This attraction probably is useful in dispersal, as the mother moves about after leaving the burrow.

Not all crawfish hatch at the same time, so young crawfish in all stages may be present at any one time. Thus, it is inadvisable for hatchery owners to remove all young when the third-stage young are first observed. Those that fall away from the mother when she is handled are probably ready to leave her and fend for themselves.

At this point, it should be noted that astacid crawfish, such as *Pacifastacus leniusculus*, have larger eggs than cambarid crawfish and their larvae are more developed when hatched than those of cambarid. Astacid crawfish can leave the mother at the second stage rather than the third, as is the case with the cambarids.

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 greal 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.

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, California, 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 is 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.

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 and color. The backs of males and females turn black and their sides turn red; the darker the water, the more vivid these colors will be.

We have noted that egg production can take as few as six weeks; that incubation and maternal attachment take 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°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 the 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	$\text{Log } W = -4.885 + 3.2186 \text{ Log } L$
Form II immature males	$\text{Log } W = -4.8537 + 3.1552 \text{ Log } L$
Females	$\text{Log } W = -4.9659 + 3.2196 \text{ Log } L$

(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.)

Length/weight equations for *P. zonangulus*, the other important Louisiana commercial crawfish, are as follows:

Form I males	$\text{Log } W = -4.9015 + 3.2465 \text{ Log } L$
Form II immature males	$\text{Log } W = -5.0034 + 3.2586 \text{ Log } L$
Females	$\text{Log } W = -4.9702 + 3.2420 \text{ Log } L$

As with *P. clarkii*, the carapace length of *P. zonangulus* is roughly one-half its body length. The mathematical relation- ships between carapace length and total length for this species are:

$TL = 4.4095 + 1.8306\ CL$
$CL = -2.4089 + -0.5436\ TL$

The largest mature male red crawfish recorded to date was 6.3 inches long. It came from Lake Naivasha in Kenya. The smallest mature male red crawfish was 1.6 inches long. It had been reared in a glass finger bowl, four inches in diameter.

White crawfish over seven inches long, total length, have been observed by scientists but there are no formal records in the scientific literature of this fact. Clearly, however, white crawfish do get larger than red crawfish. In addition, at any given length, white crawfish are heavier than red crawfish. (See the discussion on processing yields for more information.)

Aging in Crawfish. How long does a red swamp crawfish live? In nature, it is doubtful that many live more than one and one-half years, with two to two and one-half years representing exceptional cases. In the laboratory, Dr. Joe Black has maintained them for up to three and one-half years. John and Katherine Wright maintain that hatchery-reared animals can live up to four years. The senior author of this publication maintained a female red crawfish for five years.

Excretory System

Water and Salt Balance. Crawfish such as *P. clarkii* have water constantly flowing into their bodies because the concentration of dissolved substances, organic molecules, and inorganic minerals (salts), is much higher in body fluids than in the water surrounding them. This movement of water is a special kind of diffusion called osmosis because the water is diffusing through semipermeable body membranes. The flow of water increases the osmotic pressure inside the body. Most of the crawfish's body is covered with impermeable, heavily calcified shell, and this adaptation reduces the amount of osmosis; however, the branchial chamber, including the gills, is semipermeable and permits osmosis to occur.

Excess water is eliminated largely 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 solids. One investigator found that the adult *P. clarkii* normally produces a volume of urine equal to about 4.5 percent of its 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, if any, water; therefore, very little urine is produced. This conserves water within the body.

Crawfish are considered to be euryhaline because they can live in waters with quite varied salinities, from fresh water (salinity less than 0.5 parts per thousand—P) to brackish water (salinity up to 20 P). The preferred salinities in which reproduction will occur range from 0.0 P to 4-5 P. Growth will continue at salinities up to 12 P.

Salts, including the critically important calcium salts (integral parts 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 so much lower than that in the hemolymph that the natural tendency is for those permeable salt ions to constantly diffuse out of the body.

In *P. clarkii*, the levels of salts and water in the hemolymph and body tissues are controlled by hormones produced by neurosecretory centers in the "brain" and eyestalks. Eyestalk hormones are stored and released by the sinus glands.

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.

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 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 the molt proper. They may be further subdivided by the addition of subscripts A_1, A_2, B_1, B_2, etc.

Fig. 20. Newly molted crawfish. Note cast-off exoskeleton nearby. Photo, J. Huner.

The intermolt cycle is a period between molts. A series of phases, based on the formulation 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 the old exoskeleton are prominent processes. The *intermolt phase* (C_4) is that period in which all four layers of

Table 2. Variations in the appearance of uropod setae§ and 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.
Stages A & B	Very light	Inner cones just above the bases of the new setae are not developed.
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. 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.
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.
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.
Substage D_1''		There is evidence of invagination distal to the edge of the retracted epidermal tissue as new setae form.
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. Lateral barbules are seen forming along the distal tip of the central shafts of the new setae.
Substage D_2, D_3, 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. Barbule development on the central shafts of the new setae reaches its maximum extent.
Substage D_3		The bases of the new setae have a distinct, rounded shape.
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 nonmolting crawfish. The old exoskeleton is being dissolved and becomes translucent. One can see 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.

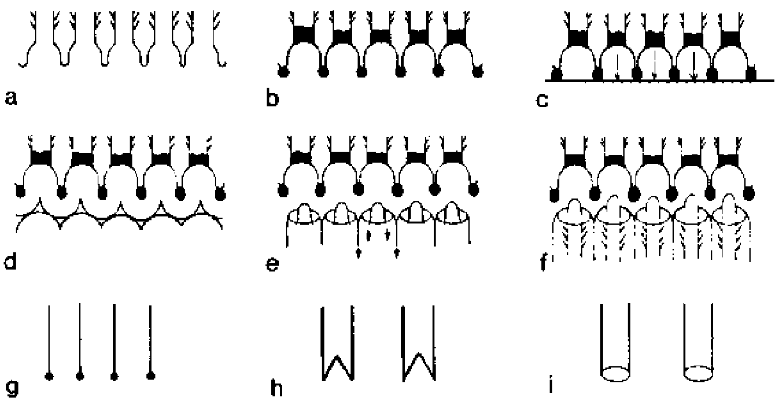
§Uropod setae are examined by holding the animal in one hand, ventral (belly) side down, and placing the tail fan on a slide on the stage of a microscope below the low power (10X) objective. The other hand is used to adjust the microscope. The uropods are manipulated beneath the objective to examine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

the shell have been completed. That is, the *epicuticle*, *exocuticle*, *endocuticle*, and *membranous* layers 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 molt. 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. 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 with 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, 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 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) and the crawfish escapes 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.



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. 21. Formation of new setae.

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 the formation of new setae (Fig. 21).

Chitin is an organic molecule called a polymer. That is, it is composed of a number of identical, small molecules, acetylglucosamine to be specific. Chitin can be recycled. During the premolt period, the old exoskeleton is digested, releasing inorganic calcium carbonate and acetylglucosamine. While some calcium carbonate is retained in blood, hepatopancreas, and gastroliths, most of the acetylglucosamine becomes available for synthesizing new chitin. This is especially important during the late premolt period when the crawfish ceases to feed and the basic unit of glucosamine, the simple sugar glucose, is no longer available. After molting, the crawfish resumes eating and can use both glucose and acetylglucosamine to synthesize new chitin. If the crawfish has the opportunity, it will always eat the old shell after it has molted. The old shell 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, gills protrude from the branchial chamber and eventually disintegrate. In tight pants, stage E 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.

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. Until recently, this has not been a problem but vibriosis (see below) has become at least a minor problem in some crawfish ponds and in soft-shelled crawfish production systems. However, no one has yet been able to demonstrate that any crawfish disease is a major factor with which to contend in crawfish aquaculture.

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. More recently it has decimated native astacid crawfishes in the British Isles, Turkey, and Spain.

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. Potentially dangerous bacteria include *Flavobacterium sp.*, *Pseudomonas sp.*, *Citrobacter freudii*, and *Aeromonas sp.* These can produce toxic secretions that are potent neurotoxins if concentrated in confined areas—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 the 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.

Vibriosis. Vibriosis is an internal disease of many aquatic organisms by bacteria of the genus *Vibrio*. Both *Vibrio cholerae* and *Vibrio mimicus* have been associated with significant mortalities in crawfish ponds and soft-shelled crawfish shedding systems. The malady seems to occur primarily when water temperatures exceed 81°F. It does not seem to be a major problem, but it may be responsible for poor over-summer survival of brood crawfish in burrows.

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*, including *P. clarkii*. Microsporidians do not appear to be a serious problem in *P. clarkii*.

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.

Psorospermium. Researchers have only recently identified the microscopic "parasite" *Psorospermium haeckeli* in the body tissues of several North American crawfishes, including the red crawfish and the white river crawfish. This organism can become abundant in the cells of its hosts but whether it has any adverse impact, as with *Thelohania*, is simply not clear. *P. haeckeli* does not discolor infected tissues and may have escaped detection for that reason. Researchers will certainly have to study this phenomenon more closely to ascertain if it represents a real problem to crawfish culturists. At this point they are not even sure if the organism is an animal (microsporidian) or a fungus.

Ectocommensal Protozoa. Ectocom-mensal protozoa are tiny organisms that live on the exoskeleton surface of crustaceans. Several common ectocommensals found on the 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 and immature crawfish in soft-shelled crawfish systems 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. If molt is unduly delayed in soft-shelled crawfish systems, the protozoa can accumulate so much that the crawfish take on a "fuzzy" appearance.

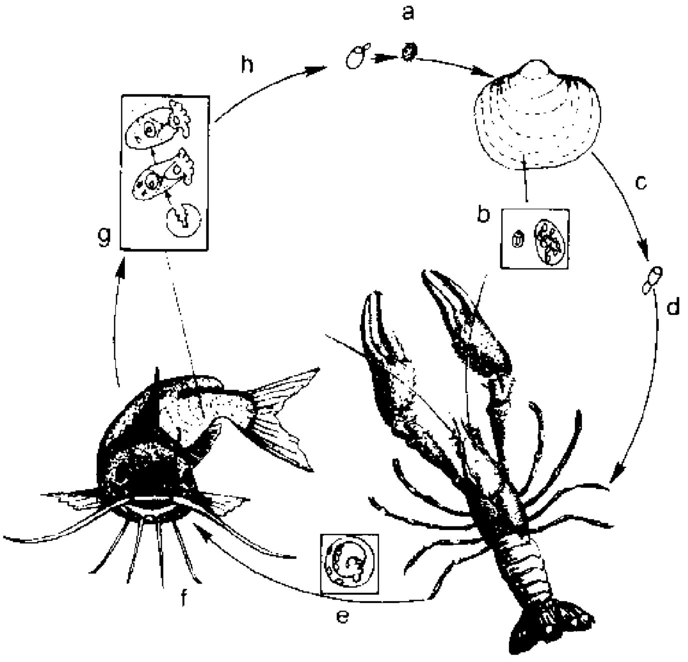
Internal Worms

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.

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, raccoons, and other carnivores that eat crawfish are considered to be final hosts. 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. 22).

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



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. 22. Fluke life cycle (*Crepidostomum cornutum*).

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.

Microcrustaceans

Copepods are commonly found in association with crawfishes. These and other microcrustaceans are usually less than 0.1 inch long and free living. One group of copepods, the Entocytherids, is commensal in the gill chambers of crawfishes. Several species, *Ankylocythere sinosa*, *A. copiosa*, *Entocythere internotalus*, *E. veddelli*, and *Thermastrocythere riojai*, have been found in the red crawfish.

Amphipods are another type of microcrustacean. A common name is "scuds". They are shaped somewhat like a half circle and so laterally compressed that they lie on their sides out of water. It is not unusual to find amphipods clinging to red crawfish, especially in heavily vegetated areas in late spring. They apparently do no harm and are readily eaten by crawfish, although it is not clear if the crawfish eat the ones clinging to them.

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 not parasites or diseases, but may adversely affect crawfish just the same.

Water Boatman 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 have 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, from 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 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 at which 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. Before treating crawfish, always try the chemical on a few animals to see if it is safe. Never use insecticides to treat crawfish as they are formulated to kill arthropods such as crustaceans and insects.

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.

It is not legal to use any therapeutic agent to control diseases and parasites of any crawfish unless the compound is approved for use with crawfish. Your local Cooperative Extension Service can assist you with locating approved therapeutic compounds.

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).

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' publications. See the bibliography for references to his work.

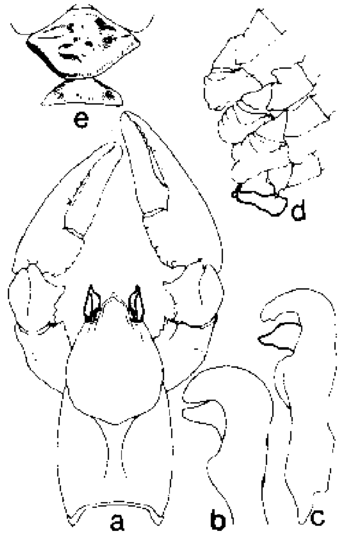
NOMENCLATURE

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 and 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 and thereafter abbreviate the generic name with its first letter, capitalized, followed by a period. Thus, *Procambarus clarkii* becomes *P. clarkii*.

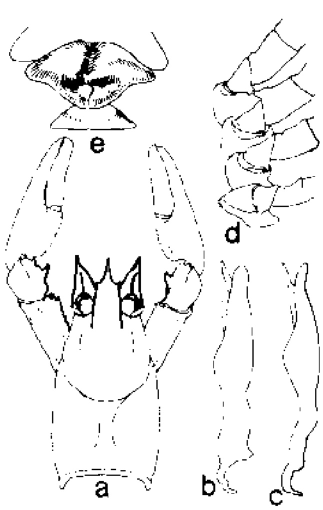
The purpose of a scientific name is to standardize names among locations and peoples. Some organisms have as many as a hundred common names in several languages, which causes confusion. South Louisiana readers are familiar with a fish that they call a "choupique." North Louisiana readers call it a "grinnel." 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

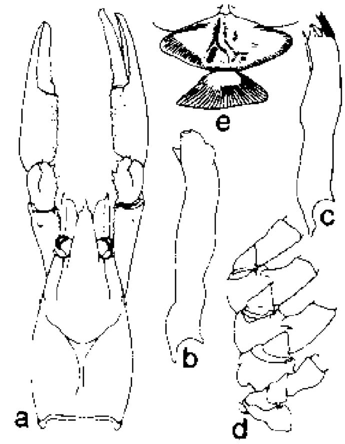
We will now present two classifications for *P. clarkii*. The first uses the basic taxa mentioned above. The other list is much more complicated and includes many additional taxa. The simplified list should suffice for most people, but the second was developed to insure a more precise classification. 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



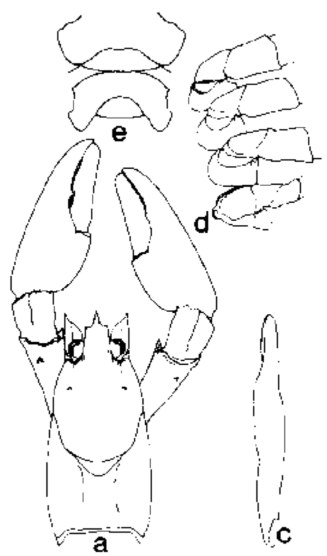
Cambarus bartonii bartonii
(Fabricus, 1798)



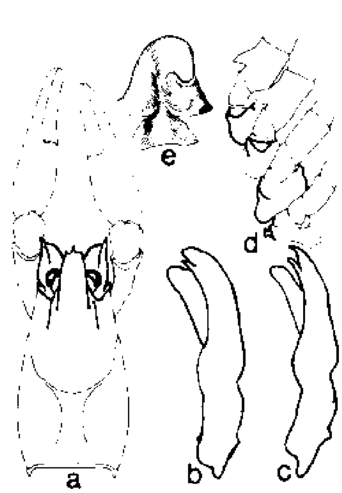
Orconectes limosus
(Rafinesque, 1817)



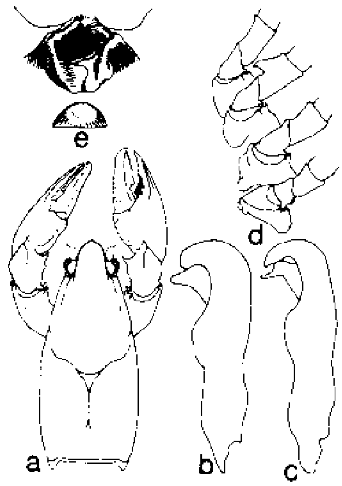
Procambarus blandingii
(Harlan, 1830)



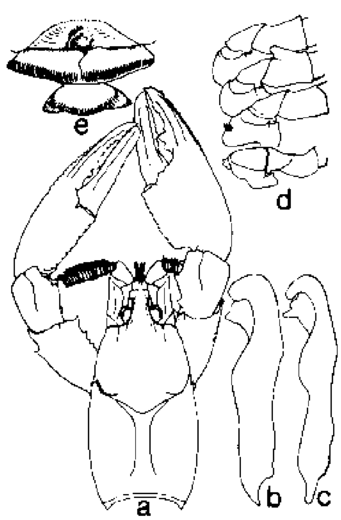
Pacifastacus leniusculus klamathensis
(Stimpson, 1857)



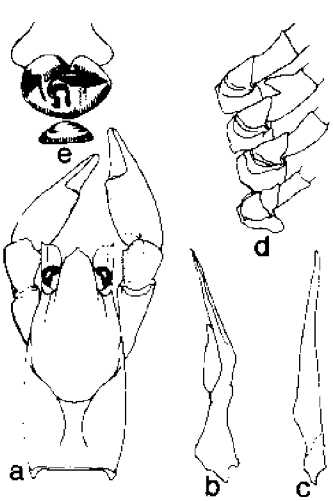
Cambarellus montezumae
(Saussure, 1858)



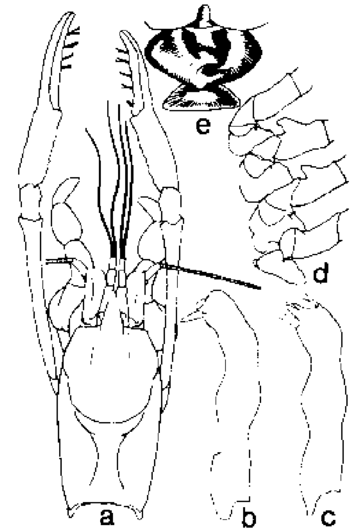
Fallicambarus fodiens
(Cottle, 1863)



Barbicambarus cornutus
(Faxon, 1884)



Faxonella clypeata
(Hay, 1899)



Troglocambarus maclanei
(Hobbs, 1942)

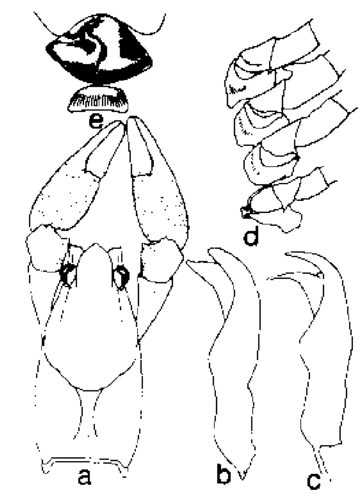
Classification 1

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

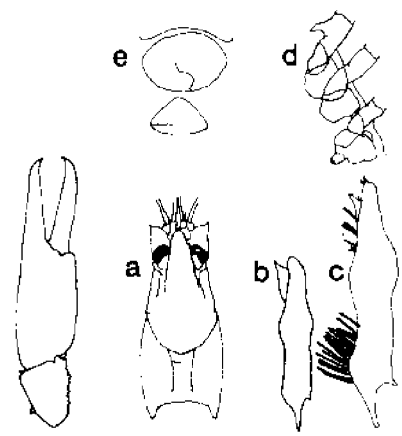
Classification 2

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.



Hobbseus cristatus
(Hobbs, 1955)



Bouchardina robisoni
(Hobbs, 1977)

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. 23. Key taxonomic features of North American crawfish genera.

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.

In North America, crawfish are represented by two families, 12 genera, and over 362 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 five species. The larger family is the Cambaridae, which includes the subfamilies Cambarellinae and Cambarinae. The Cambarellinae are the so-called dwarf crawfishes (size is one to two inches) within the genus *Cambarellus* (17 species). Within the Cambarinae there are ten genera, including *Barbicambarus* (one species), *Bouchardina* (one species), *Cambarus* (80 species), *Distocambarus* (two species), *Fallicambarus* (13 species), *Faxonella* (four species), *Hobbseus* (six species), *Orconectes* (77 species), *Procambarus* (143 species), and *Troglocambarus* (one species) (Figs. 23 and 24).

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 four 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

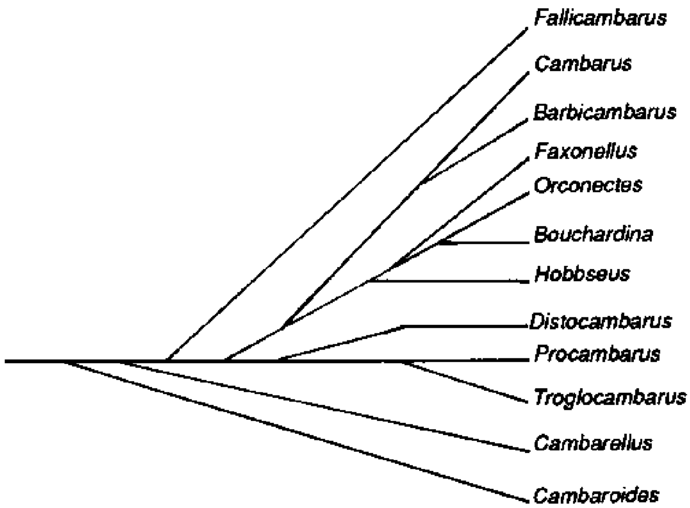
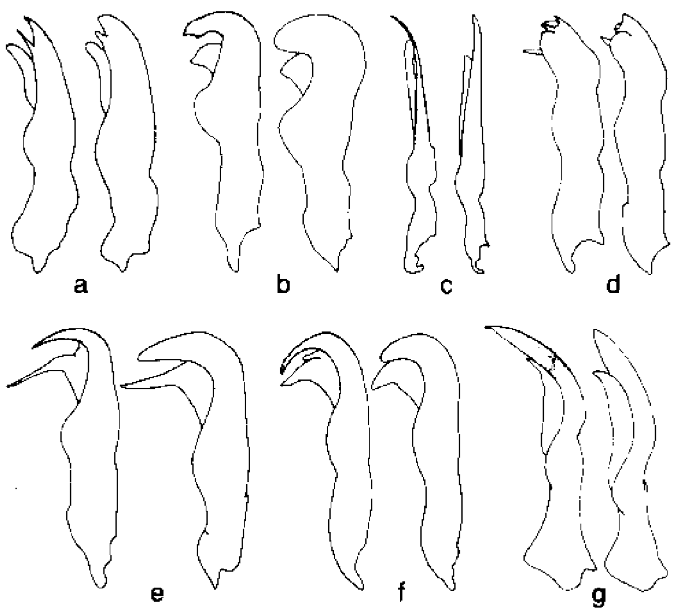


Fig. 24. Affinities of species groups, the family Cambaridae.

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. 15, 25).

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. *Distocambarus* is similar to *Procambarus* and was recently elevated to generic status from that genus. The gonopodia appear to have only two blade-like elements but a third, high reduced, may be present. Finally, the gonopods of the genus *Troglocambarus* have four short, similar elements.



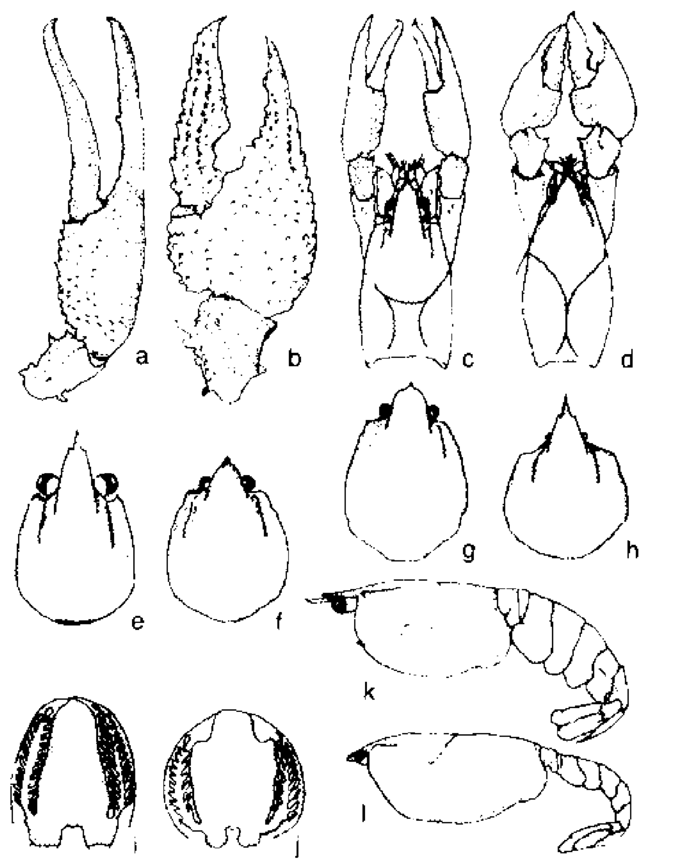
Legend: (a-f) lateral views of left gonopodia of first (form I) and second (form II form males, respectively, with corneous central projection shaded—(a) *Cambarellus*; (b) *Cambarus*; (c) *Orconectes*; (d) *Procambarus*; (e) *Hobbseus*; (f) *Fallicambarus*, (g) caudal view of left gonopodium of form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

Fig. 25. First gonopodium of representative North American cambarid crawfishes.

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



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 tocky streams; (f)

(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. 26. Morphological adaptations of crawfish to various habitats.

marshes), terrestrial habitats (burrows up to 30 feet deep provide access to ground water), and subterranean habitats (caves) (Fig. 26).

Cave crawfish are referred to as troglodytes (cave dwellers), while those found at the surface, no matter how briefly, are epigean (surface dwellers). Regardless of genus, troglodytic 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 in burrows much of the time are called primary burrowers. Those from temporary water bodies that frequently use burrows are called secondary burrowers. Crawfish from permanent water bodies rarely burrow and are classified as tertiary burrowers. There are no sharp distinctions among these categories and the red swamp crawfish falls between the secondary and tertiary categories.

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 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 length 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. For example, the areola of the dwarf crawfish are quite broad, even though these tiny crawfish are 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.

ZOOGEOGRAPHY

Zoogeography is the study of distribution patterns of animals and plants. There are three major groups of freshwater crawfish: 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

Paratacoidean ancestor (Parastacid crawfish), and the Astacoidean ancestor (Astacid and Cambarid crawfish). The Parastacoidean line evolved separately from the Astacoidean line. There are 14 genera of Parastacid crawfish 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 in Madagascar, and another in New Zealand.

Crawfishes of the genus *Cherax* have been widely promoted for aquaculture outside their native Australia. As a result, culturists have transplanted them to all continents except Antarctica. There are no known wild populations of any *Cherax* species outside Australia, but one can expect eventual establishment somewhere. None of the Parastacidae is known to be resistant to the deadly crawfish fungus plague (see section on diseases), so their establishment in Europe and North America where the disease is present may be severely constrained.

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. H. H. 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, Distocambarus, Fallicambarus, Faxonella, Bouchardina, Hobbseus, Orconectes, Procambarus,* and *Troglocambarus*) assigned to the subfamily Cambarinae. Prior to introduction 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 crawfish (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 crawfish native to the continent of Africa.

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

DISTRIBUTION OF *P. CLARKII*

P. clarkii occurs naturally from northern Mexico through Oklahoma, to eastern Florida, and northward through the Mississippi River Valley into southern Illinois. In Mexico, *P. clarkii* occurs in the states of Nuevo Leon, Tamulipas, Chihuahua, and Coahuila; and in the United States, they are found in the states of Texas, Louisiana, Mississippi, Alabama, Florida, Arkansas, Tennessee, Kentucky, Missouri, Illinois, New Mexico, and Oklahoma. The species has been successfully introduced in the Mexican states of Sonora and Baja California, as well as in Arizona, Nevada, California, Oregon, Idaho, Utah, Delaware, Maryland, South Carolina, North Carolina, Georgia, Indiana, and Ohio. It is probably present in Pennsylvania, and the scientific literature reports transplantations to Virginia and New York.

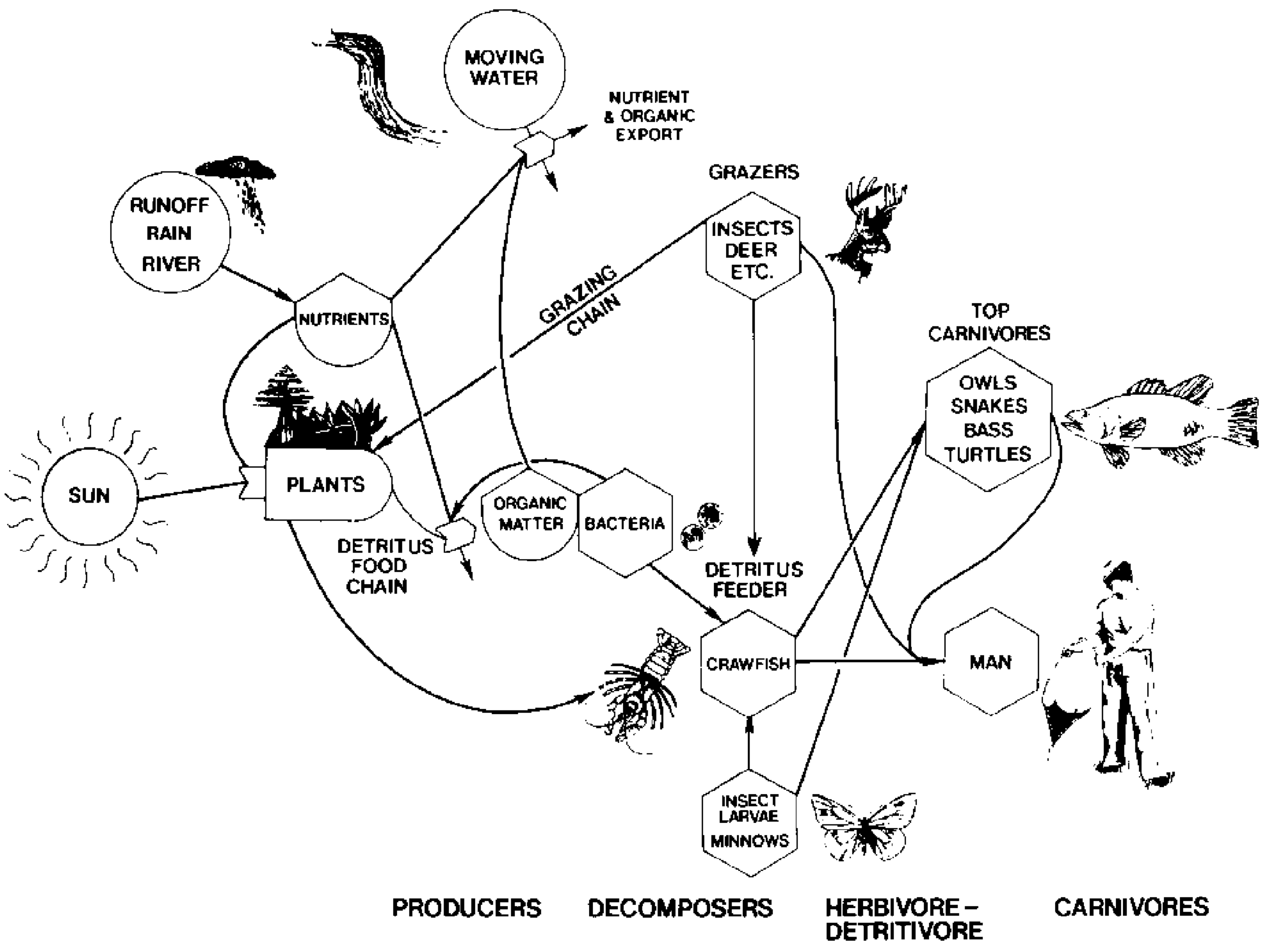
Outside North America, *P. clarkii* has been successfully introduced into the Caribbean (Dominican Republic), Central America (Belize and Costa Rica), South America (Brazil, Ecuador, Guyana, and Venezuela), Europe (France, Portugal, Spain, and possibly England, Italy, the Netherlands, and Sweden), Middle East (Cyprus), Africa (Kenya, Uganda, Zambia, and Zimbabwe), and Pacific Asia (Hawaii, Hong Kong, Japan, People's Republic of China, and Taiwan) (Figs. 2 and 3). It is, no doubt, present in other countries although formal reports of its presence are not yet available.

P. clarkii now thrives at altitudes ranging from sea level 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 through competition a native crustacean could prevent it 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 the animal 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, and 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



- 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 for 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. 27. Energy flow diagram for swamp habitat.

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*. Consumers at the first level above plants eat only plants and are called *herbivores*. Consumers that eat herbivores are called *carnivores* (meat eaters). In reality, however, most carnivores 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 the 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 physicochemical 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 Fig. 27 to show the dynamics of energy flow through a swamp ecosystem.

ENERGY FLOW

Energy flows through an ecosystem in one directon, 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) becomes 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 ten pounds of beef, which can then produce one pound of man. That is why a graph relating the amount of biomass of 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 direct food source (Fig. 27).

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 unusual in that they are polytrophic, meaning that they are 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 semiaquatic 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),

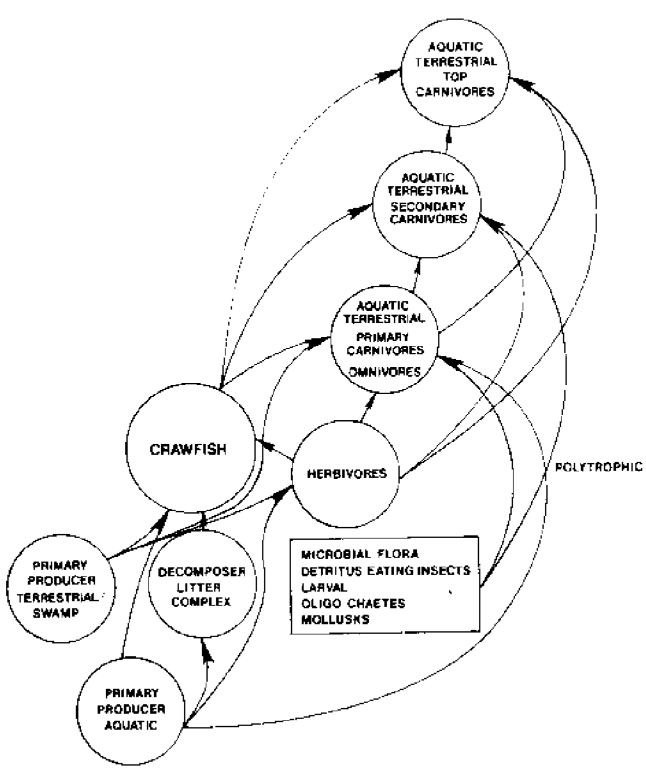


Fig. 28. Crawfish trophic relationships.

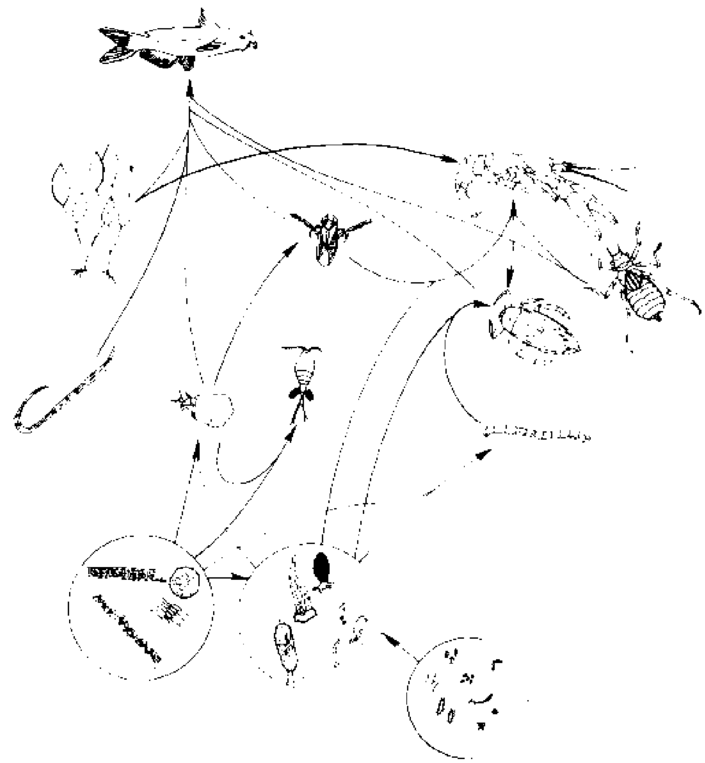


Fig. 29. Food web of crawfish.

mollusks (clams and snails), aquatic insects, and various crustaceans (amphipods, copepods, water fleas). (See Fig. 28.)

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 the crawfish, its food, and its predators (Fig. 29).

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 (adult and nymphs), backswimmers, and giant predaceous water beetles (adults and larvae). The large fisher spider also devours young crawfish. Among the crustaceans, crawfish eat each other, and blue crabs are major predators. A discussion of the insect and spider predators is found in the section on culture.

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 (*Amphiuma*). 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 diet of the American alligator, especially young alligators, which prey heavily on them. Many birds feed on crawfish. Unfortunately, crawfish culturists 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 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 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 also consumes 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 either break the crawfish in half, eating the flesh and viscera from the two halves and leaving the shell, or 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 spring sight in areas where crawfish are abundant is a compact ball, the size of a small child's fist, made almost entirely of ground crawfish shells. This is a "bolus," regurgitated by a heron or egret that has been eating crawfish. It is formed in the bird's gizzard. These can be very numerous on crawfish pond levees.

The little blue heron is often called *levee walker* for its 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 catch 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 is covered more fully in the section on culture.)

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 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 zonangulus* (the white crawfish), *Cambarellus puer* and *Cambarellus shufeldtii* (the dwarf crawfishes), *Faxonella clypeata*, and *Procambarus hinei*. Other species that have occasionally been found in ditches with red crawfish include *Procambarus planirostris*, *Cambarus diogenes*, and *Fallicambarus foidens*.

Studies in Louisiana's Atchafalaya basin and the Alligator Bayou swamp near St. Francisville revealed the presence of *P. zonangulus*, *Orconectes lancifer*, *Orconectes palmeri*, *Cambarus diogenes*, Cambarellus puer, and Cambarellus shufeldtii. To date *P. zonangulus*, *C. puer*, *C. shufeldtii*, *P. hinei*, *O. lancifer*, *C. diogenes*, and *F. foidens* have been found in culture ponds with *P. clarkii.*

Red Swamp and White River Crawfish[1]

Red swamp and white river crawfish frequently live together. It is not unusual to find a new pond stocked with red crawfish in the spring to be full of white crawfish the following spring; but over the course of the next several seasons, the number of white crawfish either stabilizes at a level less than 50 percent or the animal disappears altogether. This pattern has been seen throughout Texas, Louisiana, Mississippi, and Arkansas. It has even occurred in ponds in western Ohio.

The two species are similar in growth rates, appearance, and ecological niche, but it is unclear exactly which factors favor one over the other. There are several possibilities.

White crawfish are usually found in permanent waters and seem to prefer flowing waters where, presumably, oxygen levels are higher. They do, theoretically, have less gill area because of the presence of a distinct aerola; however, short-term

[1]The white river crawfish in southern Louisiana and Texas was called *Procambarus acutus acutus*. It is now called *Procambarus zonangulus*. At one time *P. a. acutus* was considered to be native to the eastern half of the U.S. Now, however, *P. zonangulus* is identified from southern Louisiana and Texas. Northward into the Mississippi River Valley, a differing form of *P. a. acutus* exists but the name will be changed. *P. a. acutus*, then, is native to the Atlantic coastal region of the U.S.

oxygen tolerance studies show no differences between white and red crawfish in their tolerances to lethal oxygen levels. Both species die at concentrations of about 0.4 ppm.

The white crawfish appears more abundant in colder periods of the year. This might lead to the conclusion that white crawfish do not tolerate high temperatures as well as do red crawfish. While this may be true, short-term exposure to lethal temperatures of 93-97°F showed no differences in the reactions of the two species. This does not mean that white crawfish cannot function better at lower temperatures than red crawfish. They may even have a distinct advantage over red crawfish at low temperatures. Growth studies suggest that white crawfish grow faster than red crawfish of equivalent age and size during colder months in Louisiana.

It seems that differences in fecundity and the timing of reproduction are the most important influences in the relationship between red and white crawfishes. In Louisiana, Texas, and Mississippi, red crawfish spawn year-round, although spawning is most common in late summer and fall. White crawfish seem to spawn later than red crawfish do and only once a year, generally in mid to late fall. Furthermore, red crawfish produce significantly more eggs than do white crawfish, although they are considerably smaller. As a result, in a well-managed pond, there are often several age classes of red crawfish present before the young, smaller white crawfish emerge with their mothers from burrows. It is a well-known fact that larger crawfish dominate smaller ones, so it is not surprising that red crawfish should dominate. If, however, the pond is poorly managed and oxygen levels become lethally low in the early fall, red crawfish die in large numbers and cannot dominate the white crawfish that emerge later when oxygen levels are higher. Likewise, if habitats are not flooded until after the weather cools, white crawfish could have an advantage over red crawfish.

In first-year ponds, any number of things can cause reproductive failure in red crawfish, including the death of brood stock at stocking and poor water quality in the early fall. Thus, if the pond is built in an area with native white crawfish populations, they could be expected to thrive, even though red crawfish were stocked. Ultimately, red crawfish would dominate as a result of superiority in reproductive potential.

Virtually no white crawfish have been found in swamp and marsh ponds. Both pond types are noted for highly organic sediments and poor water quality. It is not known why white crawfish are not found in such ponds, but they may be responding to one or more factors involving lower pH, lower oxygen levels, and high tannic acid levels.

Distinguishing Red Swamp and White River Crawfish. Differences between the two species are shown in the accompanying diagram (Fig. 30). The color of young red swamp crawfish is light olive-green (sometimes shading into brown) with two dark, narrow stripes on either side of the tail and a broad lighter brown "stripe" between them. Mature adults have dark red sides and a reddish-black upper surface. The change from olive-green to red-black is gradual and takes place over a period of six to eight weeks after the crawfish mature.

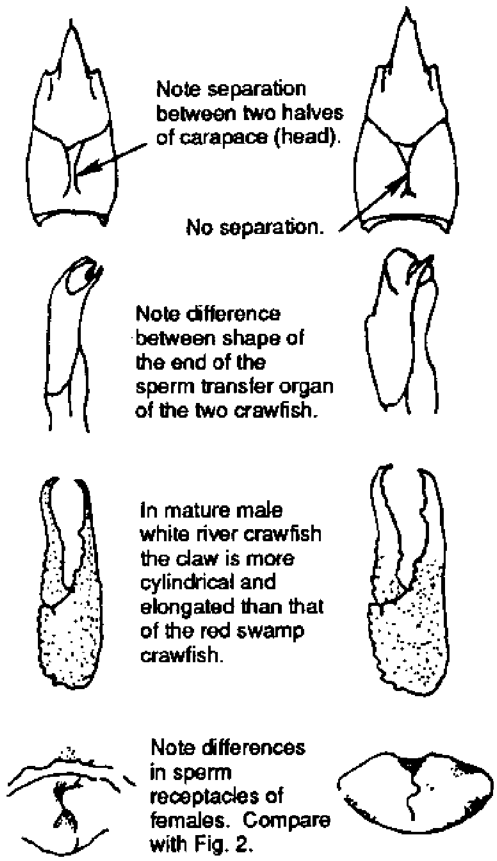


Fig. 30. Basic differences between red swamp crawfish and white river crawfish.

Young white river crawfish are light sandy white with numerous black spots over the upper surface, head, and tail. Adults are light brown with a wide black-brown stripe down the upper surface of the tail. Adults that have not molted for several months assume a deep purple color, but the dark stripe remains. In general, both species of crawfish are very "dark" if they come from clear, dark waters, or very "light" if they come from muddy water.

The diagram is useful for distinguishing adult red and white crawfish from each other. The same characteristics are useful in distinguishing young crawfish, with the two best being the general shape of the claw (longer and narrower in white crawfish) and the separation between the two halves of the shell (distinct in white crawfish). Some insist that red and white crawfish can be differentiated from each other by the presence of a blue blood vessel, or "vein," on the underside of the abdomen ("tail") of the red crawfish. This may be valid, as such a vessel has not been observed in the white crawfish.

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.

Perhaps the most impressive characteristics of crawfish are their burrowing behavior and the earth "castles" that rise above each burrow's entrance. Dr. Horton H. Hobbs, Jr., has provided an excellent description of the burrowing process and the categories of burrows built by various types of crawfish.

A burrowing crawfish loosens the soil with its walking legs. As earth accumulates, the third maxillipeds are thrust below the loosened material. When they are loaded, the chelipeds are pressed over the load and the crawfish moves headfirst through its burrow to the surface, where the compressed load, actually a pellet, is deposited and tapped into place with the claws. The crawfish then descends, tail first, to repeat the process. Most digging takes place at night.

Crawfish "chimneys" can be quite impressive and Dr. Hobbs has suggested a unique function for these turret-like structures: it is possible that they function as ventilation systems for the burrow and associated tunnel systems (if present). Ventilation, except in times of drought, would make burrows more livable, as oxygen concentration in the water is normally very low.

Most astacologists assign crawfish to one of three categories with respect to burrowing behavior: primary, secondary, and tertiary. Burrowing behavior is not restricted by genus, as representative species of several genera may share the same category. Descriptions of burrows follow.

Primary Burrowers. Primary burrowers spend almost their entire lives below the surface of the ground; occasionally they move about at the surface, presumably searching for mates, food, or new territories. Their burrow systems are normally quite complex and rarely communicate with open water (Fig. 31). The only consistent general feature of these burrows is the presence of at least one spiraling-to-subvertical tunnel that extends downward below the water table and a series of near horizontal ones that radiate from the former. One or several of the radial galleries may be as long as 10 feet, may dip below the water table, and may open to the surface. Most of the openings are marked by chimneys that may exhibit a distinctive design. In wooded areas, tunnels wind among roots that sometimes serve as walls.

The complexity of a primary burrower's burrow may be influenced by the depth of the water table. That is, the deeper the water table, the simpler the burrow. Also, the systems of galleries occupied by females are more complex than those of males and have more chimneys marking current and abandoned openings to the surface.

Red and white crawfishes are not especially accomplished burrowers but some species can literally honeycomb subsurface areas in poorly drained soils. One species, *Fallicambarus destructor*, was collected in southern Texas and named "destructor" by Dr. Horton H. Hobbs, Jr., because population densities were so high in some low areas that the ground collapsed under the weight of farm machinery!

Secondary Burrowers. Secondary burrowers spend much of their lives in burrows but frequently move into open water during rainy seasons. Their homes (Fig. 31) are fairly simple, usually consisting of a single subvertical passageway that may slope gently or descend in an irregular spiral. Seldom are there more than two openings to the surface, and there is rarely a second passageway toward the water table.

The chimneys of secondary burrowers do not differ greatly from those of primary burrowers. Some may be symmetrical while others are irregular. The burrows of secondary burrowers may not extend to the water table. In such cases, the crawfish seem to enter a state of torpor, becoming

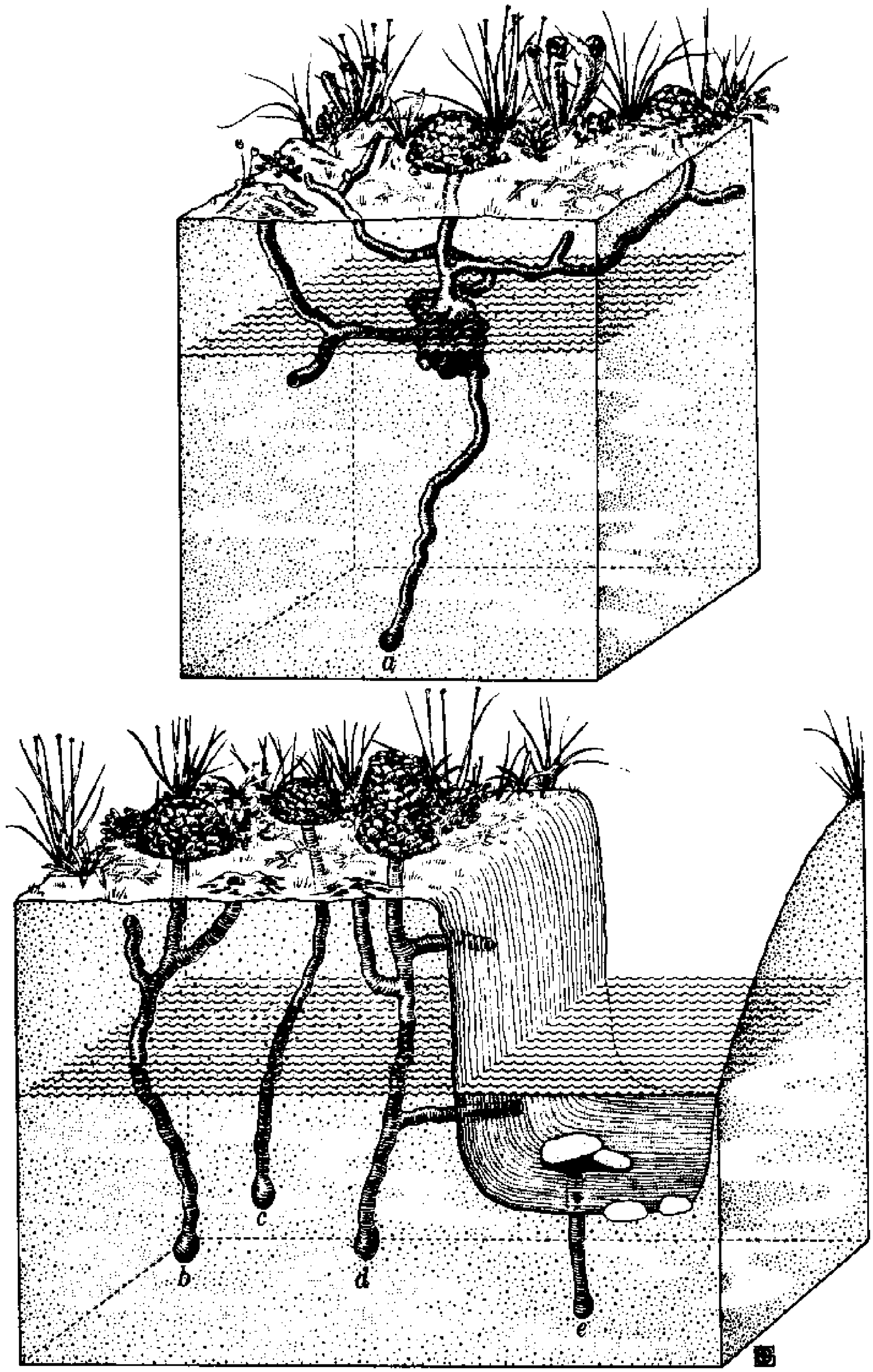


Fig. 31. Crawfish burrows: *a*, *d*, those of primary burrowers; *b*, that of secondary burrower; *c*, *e*, those of tertiary burrowers. (From *The Crayfishes of Georgia*, Horton H. Hobbs, Jr., Smithsonian Contributions to Zoology, #318, 1981.)

active only after rains raise water tables into burrows. The soil moisture is, however, adequate to maintain the humidity in burrows at or near saturation.

Tertiary Burrowers. These are crawfish that live in open water and retreat to burrows in the winter, moving below the frost line. As the time of egg-laying approaches, females remain in the burrows to lay and brood eggs. Tertiary burrowers vary in degree of burrowing intensity. Those associated with permanent water bodies dig simple subvertical passages in stream or lake bottoms. Some stream-dwellers construct highly elaborate burrows, apparently digging below mean water level and, once in the bank, extending galleries in all directions. Tertiary burrowers that frequent temporary habitats construct simple, subvertical burrows (Fig. 31).

The red swamp and white river crawfish are normally considered to be tertiary burrowers; however, it is often difficult to distinguish them from secondary burrowers. Their burrows can be more elaborate than simple subvertical tunnels, especially in regions having prolonged droughts.

Red Swamp Crawfish Burrows. 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. 32).

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, and the overhang of a cut bank (Fig. 32). 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 a burrow normally ranges from 16 to 36 inches. Width and depth 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 two to three 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 three feet from the edges of irrigation ditches. These had many side

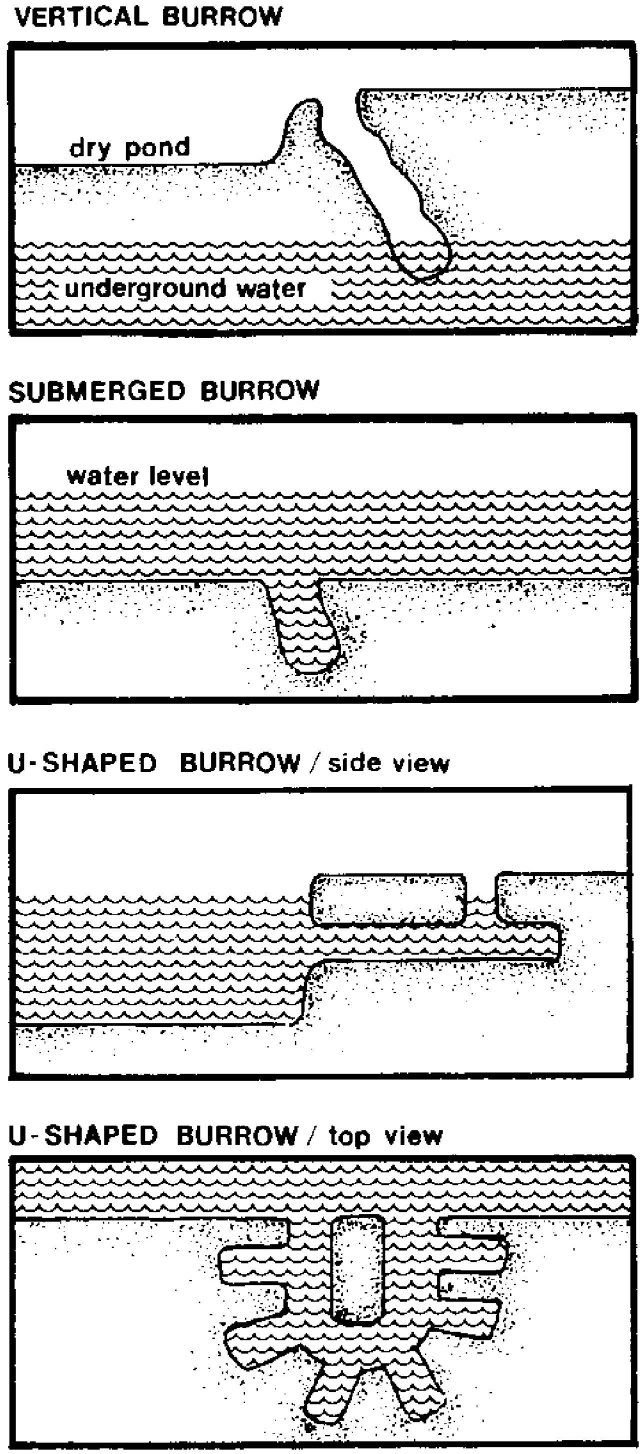


Fig. 32. Representative burrows of the red swamp crawfish.

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. 33. Entrances to crawfish burrows, protected by debris.

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 honey-combed with burrows while adjacent, unprotected areas have none. The large number of crawfish trying to burrow under the cover insures that there will be numerous interconnections between burrows.

We have observed crawfish as small as 0.75-inch 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 one part per million compared with 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 with 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.

Adult red and white river crawfishes can survive for long periods, up to one year under simulated burrow conditions, without any food so long as there is some free water present in the container. They may survive up to four months in sealed containers with no free water but 100 percent humidity. Small, immature crawfishes rarely survive more than a month under such conditions although some have survived up to four months when water was present. There seems to be no difference between species. Tests were conducted at about 70°F as temperatures in burrows rarely rise above that level; however, because temperatures are much lower than that during the cold months, it is conceivable that crawfish in burrows could survive longer because of the reduction in their metabolisms.

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 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, predaceous 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.

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 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*

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 8). 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. 34, 35, 36, 37).

Dr. Penn found that white crawfish were often associated with vegetation similar to that where he found red crawfish. He noted differences in habitat preference, in that white crawfish were more often found in permanent habitats. This is shown in Table 5.

Introductions of crawfish in California, Hawaii, Nevada, Japan, the People's Republic of China, and Spain have been successful in areas with extensive 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.

Table 5. Characteristic habitats of white crawfish in Louisiana (after Penn).

Habitat Type	Percent
Ditches (mostly roadside)	26.2
Pineland sloughs	9.4
Burrows	3.7
On land (migrating?)	0.6
Creeks and rivers	25.0
Ponds and borrow pits	26.3
Swamps and swamp pools	8.8

Table 6. Grasses and sedges that tolerat periodic flooding and are 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* spp.
Carex-sedge	*Carex* spp.

Table 7. 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 8. 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

Fig. 34. Typical ditch-type red crawfish habitat.

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.

Fig. 35. Typical crawfish habitat in Louisiana's Atchafalaya basin during the spring flood.

Fig. 36. Open crawfish pond (rice field) in mid-winter.

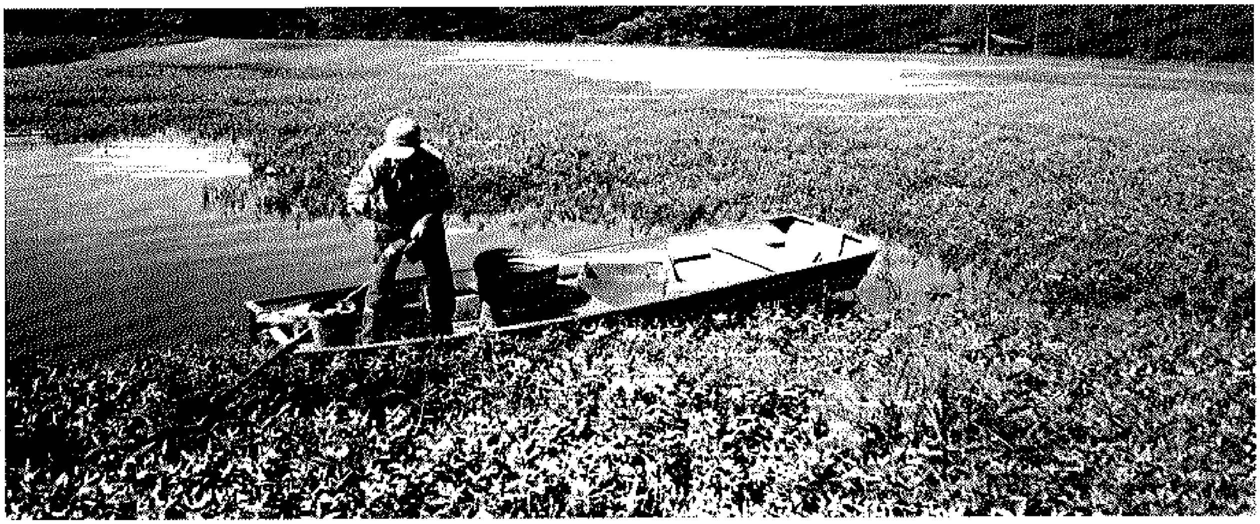


Fig. 37. Crawfish being harvested in an open pond.,

WATER QUALITY

It would be safe to say that *P. clarkii* and *P. zonangulus* can live just about anywhere so long as the water in their burrows does not freeze; summer water temperatures do not rise much above 95°F; salinities are less than 12 ppt (2-3 ppt for reproduction); and oxygen concentrations are consistently above 3 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.

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 with air—210,000 ppm oxygen in the air compared with 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. 38).

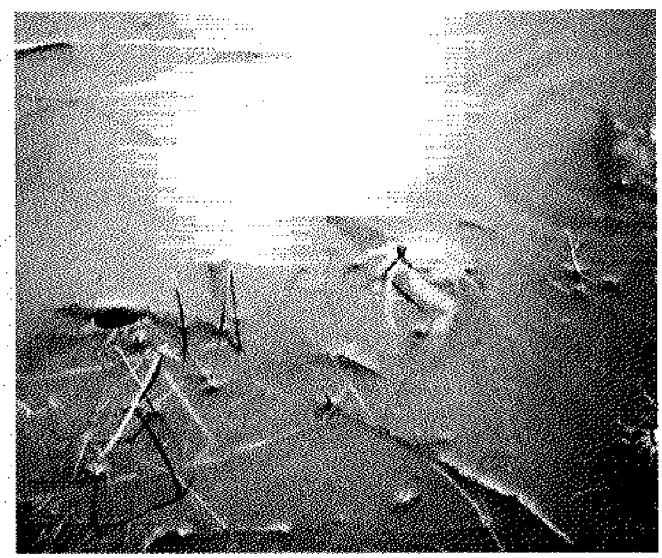


Fig. 38. Red crawfish under oxygen stress obtaining oxygen at the surface.

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 40 to 60 percent of the commercial crawfish production in Louisiana and almost 100 percent of the natural production. The Atchafalaya basin is a flood zone 18 miles wide by 80 miles long 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 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 with 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 midwinter 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 predaceous 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 large 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 a favorite subject for various European artists through the ages.

Scarcity has driven prices to very high levels (retail prices exceed $1.00 each, while there is a maximum of about 5-25 cents 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. Many Moslems will not eat them because of dietary taboos based on their Koran. In some areas they are considered to be poisonous and are hung on posts to ward off evil. Many, however, are captured and shipped westward to western Europeans who pay premium prices for them.

With its history of crawfish exploitation, Europe has been the source of numerous crawfish tales. One involves the magical powers of crawfish stomach stones, or gastroliths. Powdered, they are reputed to be a powerful aphrodisiac, though chemical analysis suggests that they would have no more effect than ground chalk. They serve as the symbol for cancer in the European zodiac.

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 its 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 90 percent of the known annual crawfish harvest in North America, and that is where they have the greatest sociocultural impact. In south Louisiana crawfish are an institution, and there it may be truly said that "crawfish is king." Crawfish boils are important social gatherings 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 three pounds (60 crawfish) per person—an unheard of quantity in Europe. The crawfish boils are often the culmination of a sport-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 Crawfish and his swamp friends are the subject of another series. The blending of cultures in Louisiana has generated a unique object called the Cajun Shamroque, a blend of the cajun crawfish and Irish shamrock.

Several crawfish festivals are held each spring in south Louisiana, east Texas, southern Arkansas, and eastern South Carolina. The most prominent festival is held 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 mache 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. 39, 40).

Elsewhere in the United States, crawfish races are held at country 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, the People's Republic of China, and Spain. In California, Hawaii, Spain, 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

Fig. 39. Crawfish race.

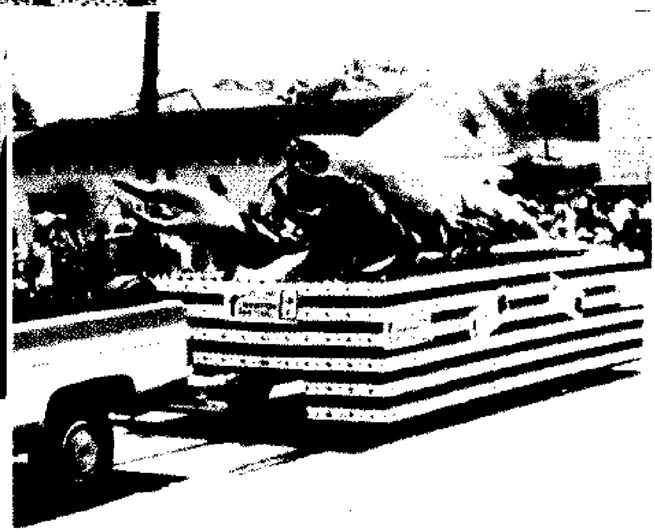


Fig. 40. Crawfish float at the Breaux Bridge Crawfish Festival.

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 people 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.

As many as 500 tons of red crawfish have been exported from Kenya in recent years to Europe. Production is very sensitive to changes in rainfall and is very poor in drought years.

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 section on diseases). *P. clarkii* was introduced in Spain in the early 1970s to replace the virtually extinct native species. The species has been dispersed widely in the vicinity of Sevilla, the original area of introduction. It is not cultured. Rather, it thrives in ricefields and associated marshes.

Though Spain produced only 350 tons of red crawfish in 1980, its output rose to 2,000 tons in 1982. By 1988, annual harvest exceeded 5,000 tons worth over $13 million U.S. to the fishermen. In 1980, there were 380 fishermen involved in harvesting crawfish; 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 and 1974 and amounted to less than one-half ton of crawfish.

Though Spanish fishermen have welcomed the advent of the crawfish, rice farmers view them with far less enthusiasm. Environmentalists are very concerned with changes to faunas and floras where the red crawfish is now abundant. Farmers must tolerate the damage done by crawfish to levees and water control structures but, by Spanish law, cannot harvest and sell the animals. Only fishermen can do that. Thus, crawfish are a most obvious financial benefit to southern Spain's economy, but they still create problems.

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

Widespread exploitation of the red crawfish is largely limited to Louisiana. In recent years, 60 to 100 million pounds per year have been harvested commercially from natural swamps and marshes, principally the Atchafalaya basin, and from thousands of acres of culture ponds (Table 9). The wild harvest accounts for 40 to 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, recreational harvest from the Atchafalaya basin was 1.3 to 1.8 million pounds for the period 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.

Table 9. 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
1982	100,000
1984	103,600
1986	118,500
1988	140,000
1990	125,000

Low prices in the 1987-88 and 1988-89 seasons led to a decline in pond acreage in the 1989-90 season (Table 9). This has been the first decline in the state's history. A more drastic reduction, in percentage, was noted in Texas, from 18,000 to 6,000 acres in the same period. Ironically, prices have been higher in Texas and have attracted many Louisiana crawfish producers. Potential for expansion is great in both states when financial considerations improve.

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 petrochemical 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).

A mechanical peeling machine developed in the early 1980s showed much promise but is no longer in use at this writing. The need for a mechanical peeling machine is even more pressing today as labor costs escalate. The modification of shrimp peeling machines is underway and shows promise, but it is still uncertain if and when machines will be used to process much of the Louisiana crop of crawfish.

Increasing exploitation of *P. clarkii* is being seen elsewhere. In the U.S., there are about 6,000 acres of crawfish ponds in Texas, 2,000 acres in Florida, 1,500 acres in South Carolina, and 50-1,000 acres in Arkansas, Mississippi, Georgia, North Carolina, and Maryland. 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. Although they are known for their tradition of eating seafood and have had the species in their country for 40 years, the Japanese do not commercially exploit it. In contrast, about 15,000 tons are harvested and consumed annually in the People's Republic of China.

The value of live crawfish to fishermen and farmers has ranged from $.25 to $1 per pound during the 1980s. 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 one pound, versus two to four 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. Sport fishermen tend to favor the use of small lift nets that are manufactured primarily in the Orient.

There are two types of lift nets. The most common consists of a 17- or 19-inch-square piece of 1/2-inch mesh net attached to an A-frame. The frame is made of two v-shaped wires meeting 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 the depth exceeds the height of the net, a bright piece of cloth is normally tied to the net's apex to aid in recovering it. These are lifted every 5 to 15 minutes with a pole (Fig. 41).

Fig. 41. Lift net.

A second 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 sport fishermen cull them while others eat them.

Europeans often use traps shaped like round "bee hives" with flat bottoms and sides and an entrance on the top, all supported by a collapsible metal frame. This prevents crawfish from escaping when traps are lifted from depths as low as 15 feet. The dimensions are roughly: diameter—14 inches; height—6 inches; and entrance diameter—6 inches. A crawfish net with a similar design has been available in Louisiana in recent years but is not widely used. It has a rectangular rather than round base and, with sides only 2 to 4 inches high, is designed for use in shallow water.

Trap Designs

Much of the research on the effectiveness of traps and the factors affecting crawfish catchability has been done by Dr. Robert P. Romaire of Louisiana State University and his students. The following commentary relies heavily on his work.

Many types of crawfish traps are used to harvest crawfish. They differ in design and configuration; physical dimensions; construction materials and mesh sizes; number of entrance funnels (flues); and the presence or absence of support rods, retainer bands or collars, and bait wells. Traps are constructed of 3/4-inch hexagonal mesh wire (19- or 20-gauge PVC-coated wire is the most common) or plastic netting. The mesh size is selective for crawfish over 3 inches in length. Traps with smaller mesh are not legal for use in natural waters in Louisiana but may be used in private ponds.

Crawfish traps are generally categorized as being either "stand-up" (upright position in the water with the top of the trap extending above the water surface) or "pillow" type (lies horizontally on the pond bottom and is completely submerged). Stand-up traps are made in several designs and are the most common traps used in ponds (Fig. 42). Pillow traps (so named because of their pillow-like shape) are generally reserved for fishing in waters too deep for conventional stand-up traps, as in the Atchafalaya basin. A pillow trap that is propped up is called a stand-up pillow trap.

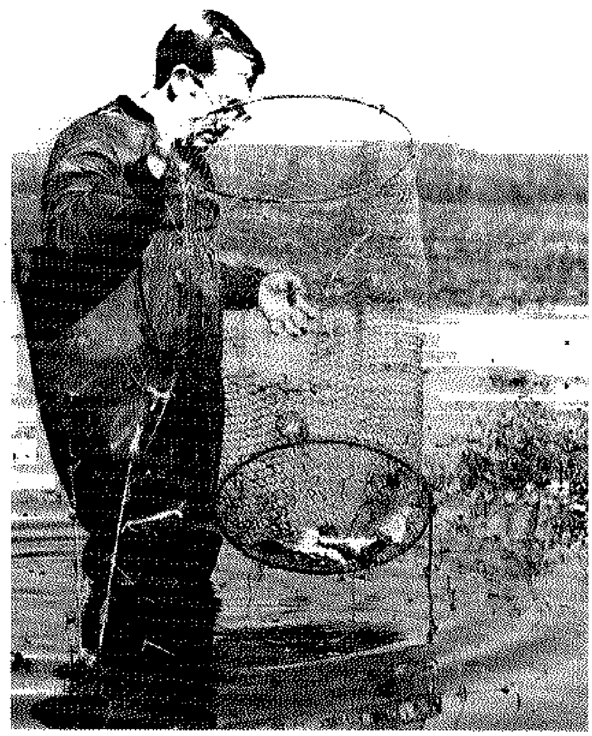


Fig. 42. Standup trap. Note reinforcing wire used to give the trap support.

Traps may be made by either inverting an opening at a corner of a closed cylinder with a bottle ("pop bottle" trap, Fig. 43) or by inserting a separate funnel (flue) into an opening near the base of the cylinder. The original traps developed for fishing in natural waters had one large cone-shaped funnel sewn into one end of the cylinder with the opposite end closed, Fig. 44).

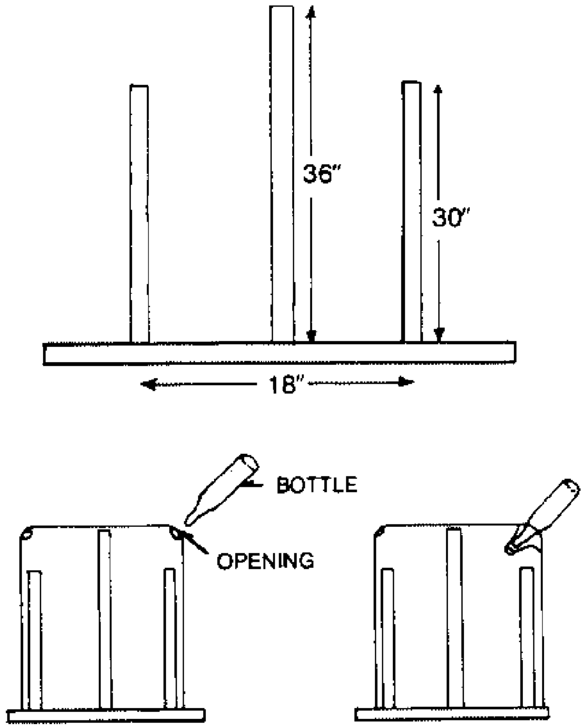


Fig. 43. Construction of a pop bottle trap.

Fig. 44. Double-entrance pop bottle pillow trap.

Four basic trap designs are used by crawfish farmers: stand-up pillow, pyramid, rooster tail, and barrel (Figs. 45, 46, and 47). The stand-up pillow is the most common, followed by pyramid, barrel, and rooster-tail traps. The pyramid trap is the newest design. Stand-up pillow traps are oval in shape, pyramids are triangular, and barrel traps are cylindrical. The rooster-tail trap is a "hybrid" of the stand-up and pyramid designs.

Several design factors enhance the effectiveness of a trap. Traps made from PVC-coated wire or plastic catch 15 to 25 percent more crawfish than traps made from galvanized wire. A trap's life is also increased by using coated wire or plastic. Two-funnel (stand-up pillow or barrel designs) and three-funnel traps catch equally on 24-hour sets. Retainer bands (3-inch-wide strips of thin aluminum on the inside circumference at the top of the open area of the trap) or collars (6-inch-diameter PVC pipe at the top of the trap) increase crawfish catch 15 to 20 percent over traps without retainers on 24-hour trap sets. However, the crawfish catch for 12-hour trap sets is not enhanced with the use of retainer rings. The retainers prevent crawfish from climbing out of the open trap. Retainer rings add rigidity to the traps. About 15 to 20 percent of the crawfish that enter traps are able to escape within 24 hours through the entrance funnel (40 percent escape after 48 hours). Traps with bait protected in bait wells catch 40 percent fewer crawfish than traps with exposed bait.

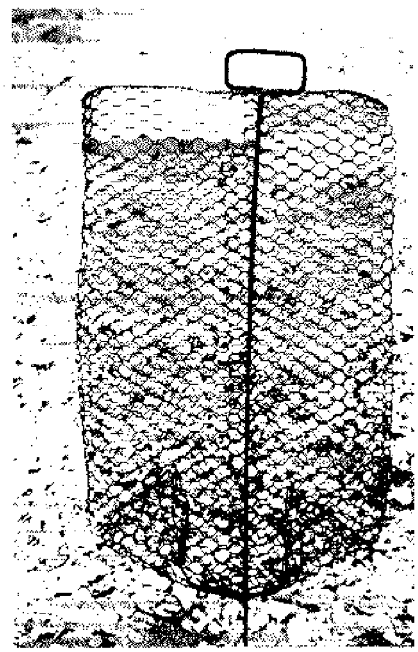


Fig. 45. Pillow trap with vertical support and retainer ring at top.

Trap dimensions are varied by using wire of different heights (24 to 42 inches wide) and lengths or "cuts" (36 to 54 inches long). Larger traps (30 inches x 46 inches) catch more crawfish in ponds

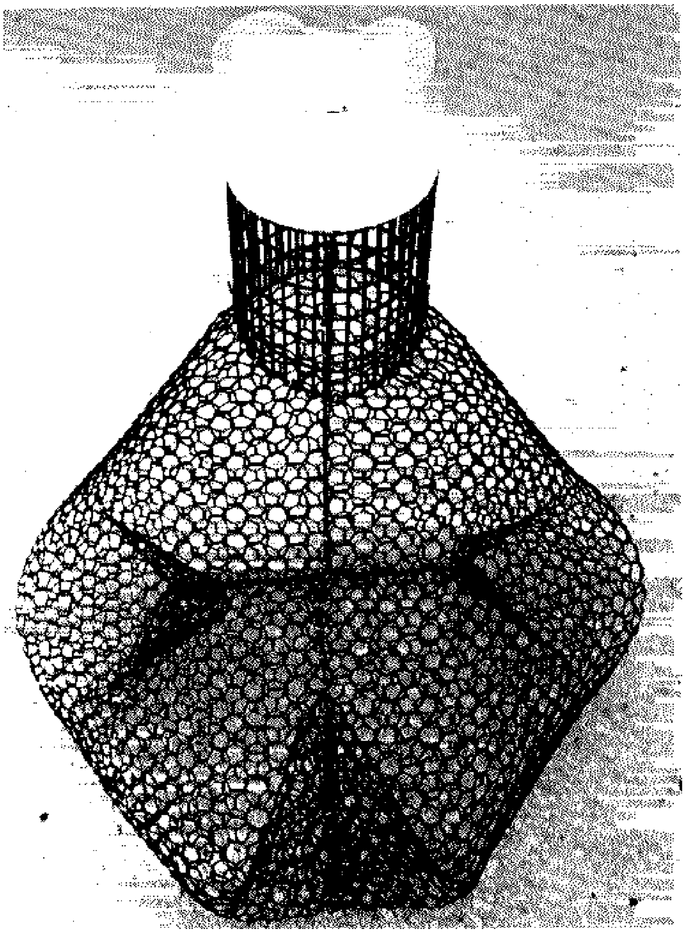


Fig. 46. The pyramid crawfish trap is the most effective trap yet developed for crawfish ponds. Photo, J. Huner.

with large harvestable crawfish populations than smaller traps (30 inches x 36 inches) because smaller traps fill up with crawfish quickly. Metal rods (0.375-inch in diameter) with handles are used to hold stand-up pillow and barrel traps upright. Pyramid traps may have rods to increase stability.

Stand-up pillow and submerged pillow traps catch equally but stand-up traps (stand-up pillow, pyramid, and barrel) can be more efficiently lifted, emptied, and rebaited than pillow traps. Pyramid traps are clearly more efficient than other trap types and are recommended for pond use. It takes a fisherman 1.5 times longer to run a line of closed and/or submerged pillow traps than stand-up traps. The contents of an open-top stand-up trap can be emptied directly onto a sorting and sacking table, but a submerged pillow trap must be lifted to the surface with an attached line, opened, emptied, rebaited, and closed before it can be returned to the water. Submerged pillow traps also prevent the crawfish inside from reaching the water's surface during oxygen depletion and many of them die (Figs. 48 and 49).

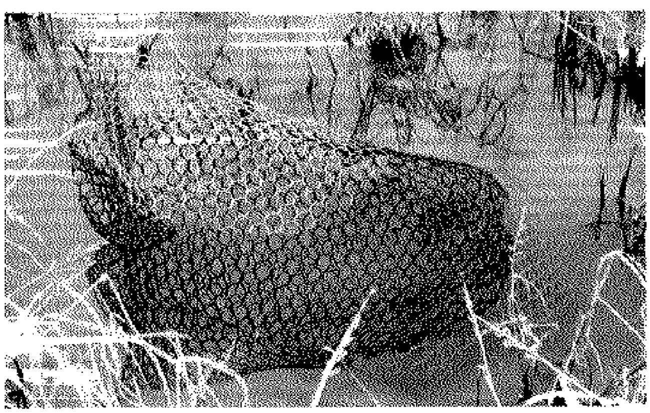


Fig. 47. The airliner, or rooster tail, trap is used in areas of shallow water like rice-field ponds.

Wind, birds, raccoons, and rodents (nutria and muskrats) often knock traps over if support rods are not used. As a result, most fishermen attach floats to their traps. Birds and rodents may also enter traps and eat the bait. Fishermen often damage or destroy wire traps by the careless operation of harvesting boats but damage to plastic traps is minimal.

Trap Density

A density of 20 to 30 traps per acre was recommended for well-managed crawfish ponds. With increased emphasis on production of larger crawfish the current recommendation is 15 traps per acre. However, inadequate harvesting from too few traps (10 traps per acre) may lead to overpopulation, forage depletion, and crawfish stunting. In smaller ponds (fewer than 20 acres), 40 traps per acre can be used if the catch justifies the effort. Traps are placed in rows to facilitate harvesting; spacing depends on the number of traps. A space of 40 to 60 feet between individual traps and trap rows is common. The most efficient crawfish harvesting method uses a system in which the fisherman begins with a baited trap, setting it in front of the next trap to be lifted. The lifted trap is then emptied and rebaited while the boat moves to the next trap in the row.

Traps set for 12 hours usually catch as many or more crawfish as those set for 24 hours, particularly if water temperatures exceed 70°F, crawfish are abundant, and manufactured baits are used. Traps are usually emptied once per day (every 24 hours) in cool water (November through mid-March), but they can be emptied two to three times per day (in 6- to 12-hour sets) from March through May if the catch and crawfish price justify the additional effort. After several days of intense trapping, a decrease in crawfish size can be expected as the density of larger crawfish is temporarily reduced.

It is not possible to "overfish" a healthy crawfish population with the harvesting technology now used, but it is common for ponds to be underfished. Insufficient harvesting can cause overpopulation and crawfish stunting. Recent advances in pond design (baffle levee systems) and water management techniques will increase the survival of young crawfish and may require the practice of intensive crawfish harvesting.

Fig. 48. Traditional, single-entrance pillow traps.

Trapping in Natural Waters

Fishermen harvesting crawfish in natural waters such as the Atchafalaya basin face problems different from those encountered by crawfish farmers. Waters are usually more than three feet deep and usually in constant flow. Because traps are being placed in a flooded forest (that is, swamp), they cannot be laid out in simple lines. Traps are normally set on the bottom with the funnels facing downstream, as the crawfish approach the traps by moving into the current. The funnels, at least, must be on the bottom. Poles with terminal hooks are used to ensure that the traps are properly set and not resting on brush above the bottom. Oxygen depletion becomes a real problem in backwater areas, especially when the water is over three feet deep. Where it is shallower, the traps may be propped above the surface against a bush or tree trunk. Where it is deeper, fishermen may nail their 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. These so-called "extension" traps may be six to eight feet long and extend from the bottom to the water's surface. They are propped against tree trunks.

Labor and logistical problems in getting a wild catch to market generally limit trapping to a 24-hour cycle. A commercial crawfisherman in the Atchafalaya basin or other natural waters may empty 100 to 200 traps per day, although some very energetic individuals may empty two to three times as many.

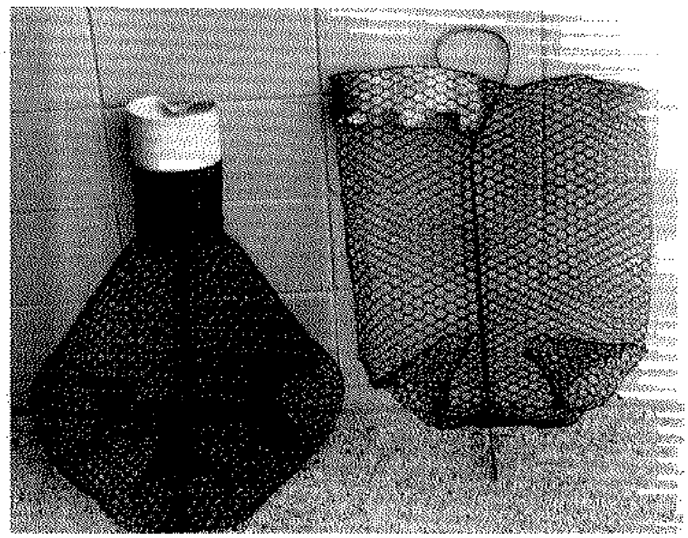


Fig. 49. Standup pop-bottle trap (right) and pyramid trap (left). Photo, J. Huner.

Bait

Bait is the single most important expense in harvesting crawfish. Bait generally costs from 12 to 25 cents per pound, or $200 to $500 per acre, depending on the bait type, quantity used per trap,

trap density, and frequency of trap runs (days per season and trap sets per day). Bait is normally replaced after each trap set, although one manufactured bait may be reused for several days in a row because it is firm enough to resist crawfish feeding activity under most conditions. Between 15,000 and 30,000 tons of bait are used annually in the Louisiana crawfish industry (both wild fishery and aquaculture). About 50 percent is natural bait and the remainder is manufactured (often called "artificial").

Because of the economic impact of bait on the profitability of any crawfish harvesting operation, much research has been done in this area. Drs. James W. Avault and Robert P. Romaire of Louisiana State University and their students, as well as the senior author of this text, have conducted extensive research in this area, and much of the following commentary is based on their work.

Bait used in the traps is normally some species of rough fish. The gizzard shad, *Dorosoma cepedianum*, is a popular bait, as are the common carp, *Cyprinus carpio*, the skip jack herring, *Alosa chrosochloris* (locally called the "slicker"), the marine "herring," menhaden, *Brevoortia* spp., and the buffalofish, *Ictiobus* spp.. Menhaden has become very popular during cold months. Gizzard shad has been a traditional bait used in the wild fishery during the spring. When these baits are scarce, substitutes include marine fishes (or their offal) such as the Atlantic croaker, *Micropogon undulatus*, or freshwater catfish, *Ictalurus* spp. One quarter to one half a pound of bait is placed in each trap, depending on water temperature and crawfish density. Less bait is used in cool water or when the number of harvestable crawfish is low.

Most sport fishermen seem to prefer to use beef melt (spleen) for bait. It is a good bait but generally too expensive for commercial use. Contrary to popular opinion, chicken necks, bacon, and salt pork are not especially good crawfish baits.

Manufactured crawfish baits are made from fish meal, fish solubles, cereal grains and byproducts, attractants, and binders. Manufactured baits are cylindrical pellets, 1 to 3 inches in diameter and 3 to 4 inches long, that weigh 0.15 to 0.25 pounds each. They generally have a formula similar to that of a poor-grade sinking fish feed, with protein levels in the 15-20 percent range.

Natural baits have several disadvantages. Supply and price vary seasonally, freezers are required for storage, and labor is required to cut and handle the bait. In addition, fish generally has an unpleasant odor and is unsanitary to handle. The primary advantage of natural baits, particularly shad, menhaden, and carp, is that they attract more crawfish in cold water (less than 65°F) than do current manufactured baits. Conversely, manufactured baits are cost-competitive with fish (frequently cheaper) and are easier to store and handle. The most attractive manufactured baits are stable in water, lasting 12 to 18 hours, and a crude protein content of 17 to 20 percent. Many manufactured crawfish baits are at least as effective as fish in water warmer than 65°F (mid-March through May). The manufactured baits compare favorably with each other when water temperatures are greater than 80°F and the ponds have a large number of harvestable crawfish and little forage. The pond type (open, rice, or swamp/wooded) appears to have no major influence on the relative attractability of one type of bait over another. If a bait performs well or poorly in one type of pond, it will generally perform the same way in another type of pond.

A combination of manufactured and natural bait generally catches 15 to 30 percent more crawfish than either one used alone. Traps should be baited with 0.25 to 0.33 pounds. Greater quantities do not result in increased catches. Crawfishermen and farmers traditionally baited their traps when they checked them in the morning, usually 24 hours after the last inspection. They have found that catches increased significantly when they returned later and rebaited in late afternoon.

Other baits used in Louisiana and elsewhere include punctured cans of inexpensive cat and dog food and cottonseed press cake. All are also more effective in warm water. In addition, pelleted fish feed and crawfish feed may be used as baits in two forms, loose or contained within some form of mesh bait bag. If the pelleted material is used loose, it is effective only in broad-based barrel or pyramid traps. These baits *disintegrate* (not dissolve) quickly and the particles fall through the bottom of the trap. They remain "in" the trap in broad-based traps but fall outside in narrow-bottomed pillow traps.

Baitless Traps

In Spain, crawfish are caught without bait in hoop nets originally designed to catch eels. These nets are about 5 feet long and 18 inches in diameter. Hoop nets have two inner chambers and a 3-foot panel or wing attached to the entrance. Nets are set in irrigation channels so that crawfish that normally move against the current encounter the wing and move into the net.

Several Louisiana crawfish farmers have caught red and white 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 trap.

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.

Factors Affecting Crawfish Catch

Water temperature and crawfish population density are primary factors affecting daily crawfish catch. Crawfish are poikilothermic ("cold-blooded") animals that are relatively inactive below 50°F, so crawfish catch declines substantially in January and February when water temperatures are lowest. Crawfish catch is greatest at temperatures of 75°F to 85°F (November and early December and March through May) and lowest in late May and June when the water temperature exceeds 85°F, dissolved oxygen levels fall below 1.5 ppm, and the animals mature and burrow.

Young-of-the-year and holdover crawfish are recruited into the harvestable population when they are at least 3 inches long. This occurs continuously throughout the October-May production season, but peaks normally occur at flooding in October (holdovers), November (holdovers), and December (holdovers and young-of-the-year), and in the period from mid-March through April (young-of-the-year). If the recruited crawfish have not attained harvestable size, the catch will be reduced even though water temperature and other environmental parameters are ideal for maximum catch. Crawfish molting patterns, the continual recruitment of young crawfish to harvestable size, and depletion through harvest account for much of the cyclic variation in daily crawfish catch, even when all other factors are optimum. Crawfish cease to feed during the molting cycle and do not enter traps then. After the crawfish harden, they begin to forage and the catch increases, provided other conditions are favorable.

Crawfish catch is also affected by changes in water quality, weather, and lunar phase. The catch is reduced when the animals are continually exposed to dissolved oxygen concentrations less than 1.5 ppm. Low oxygen distresses crawfish and reduces feeding, growth, and activity so that they are less inclined to enter traps. Rain showers enhance the catch because they increase water circulation and, thus, the rate of dispersion of bait attractants. Crawfish catch declines with the approach of the full moon and with the passage of cold fronts. Cloudy weather associated with short cold fronts (one to three days) reduces water temperature and crawfish activity, resulting in a temporary catch decline. The relationship between crawfish catch and changes in environmental conditions is complex and at present no single environmental factor can accurately predict daily changes in crawfish catch.

Harvesting Methods in Natural Waters

Flooded swamps are not easy places to set and check traps, as such areas 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) with pointed prows. Outboard engines of over 50 horsepower are used. Wooden boats were popular for many years, but fishermen have switched almost exclusively to custom-made aluminum boats (Fig. 50).

The best crawfishing areas in the Atchafalaya basin are those in which back swamp water clashes with turbid flood water, creating a dynamic front. Thus, it is not at all unusual for a trapper to move his traps several times during a season. Crawfishermen in other natural areas out-side the Atchafalaya basin may also move traps in response to local depletion of harvestable crawfish, bad water, and falling or rising water levels.

Harvesting Methods in Ponds

Crawfish were traditionally harvested in ponds by walking fishermen who pulled a small boat into which they placed the harvested crawfish. Some farmers still use this method. Walking requires little investment, but it is laborious and inefficient in large ponds, as a walker can normally empty only about 400 traps per day. In deeper ponds a fisherman may use a push pole to propel a small boat. This method is no more efficient than walking while pulling a boat. Boats with outboard motors are also used in deep ponds to increase harvesting efficiency. Significant improvements in harvesting boats and machinery have occurred since 1980.

A more efficient harvesting system employs large, flat-bottomed boats, 14 to 16 feet long, 48 to 60 inches wide, and 18 to 24 inches high. They are made of welded aluminum and propelled with air-cooled outboard engines (8 to 12 horsepower) with a long shaft and weedless propellor adapted for operation in water from 12 to 30 inches deep. The engines are commonly called "Go-Devils." A gear box and cleated wheel to replace the propellor is added to such motors in some cases. The wheel cuts into the pond bottom and pushes the boat forward. The boats generally require two persons to operate, one to empty and rebait the traps and another to steer the boat. Two people using this system can empty 200 to 300 traps per hour. The boat and motor cost $3,000 to $4,000 (1990 prices). Although this type of boat and outboard motor is efficient for use in harvesting crawfish, it is difficult to operate in windy conditions and must sometimes be fitted with a heavy chain on the bow to provide added stability. A one man, foot pedal control, go-devil has recently been made available to the industry (Fig. 51).

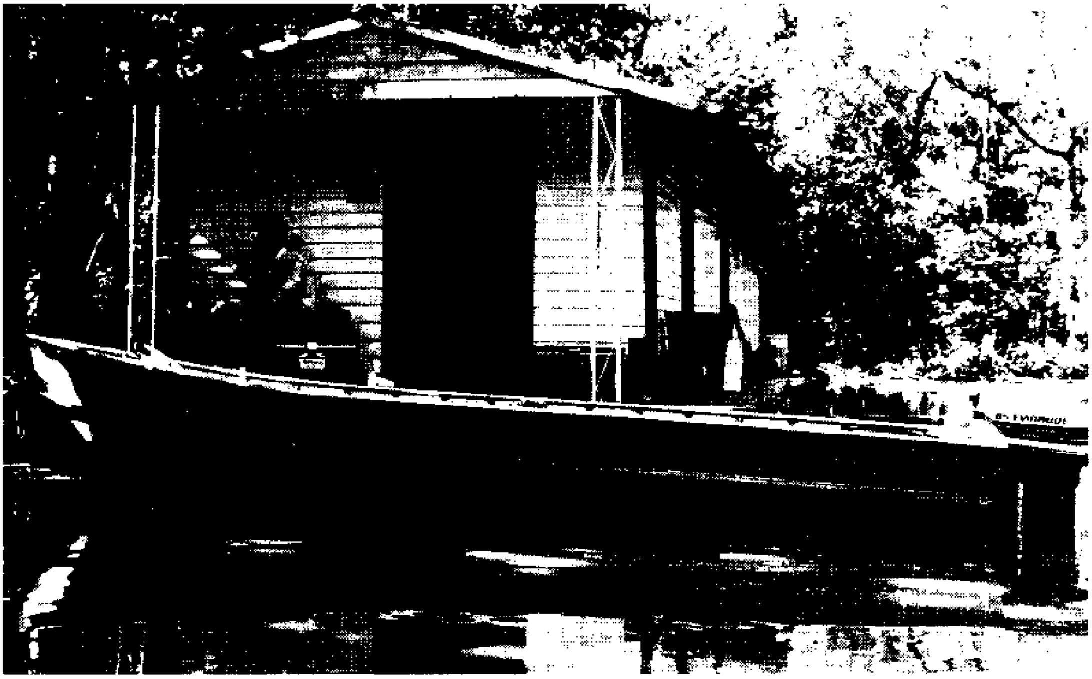


Fig. 50. Typical boat used by crawfishermen in the Atchafalaya basin, Louisiana.

Commercial crawfish farmers most commonly use a "crawfish combine." The combine is a large flat-bottomed boat (similar in dimensions to a Go-Devil boat) to which is attached cleated metal wheels, each about 30 inches in diameter. The wheels, powered with hydraulic motors, can be mounted to the front, rear, or sides of the boat. A cultivator blade is attached to the side of the boat or pulled behind to prevent the boat from drifting in the wind. The hydraulic pumps and motors are powered with an air-cooled engine, 8 to 12 horsepower, mounted inside the boat. The hydraulic oil reservoir is mounted either inside or outside the boat. The boat can be steered by a single person with hand valves or foot pedals. Foot pedals allow the driver's hands to be free to empty and rebait traps. A single operator can empty about 150 to 200 traps per hour and two operators, up to 250 traps per hour. Crawfish combines (boat, motor, and wheels) cost about $4,500 to $6,500 (1990 prices). The crawfish combine can cross small ricefield levees but must be pulled across larger perimeter levees (Fig. 52).

Fig. 51. Motorized, flat-bottomed boat used to harvest crawfish in open ponds.

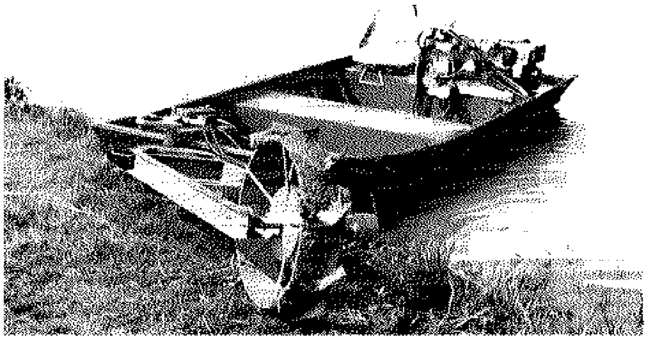


Fig. 52. Cajun Combine.

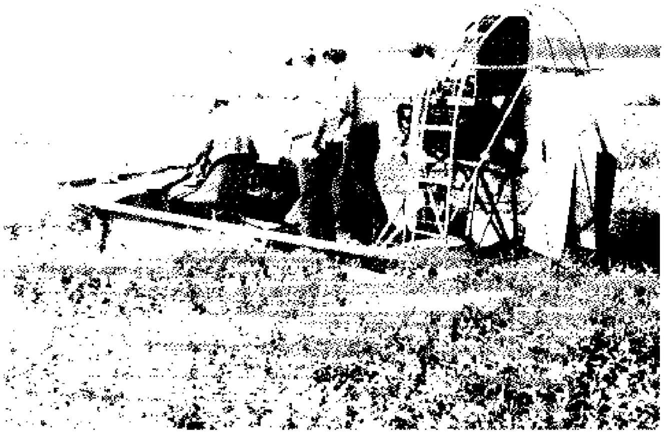


Fig. 53. Air boat being used to harvest crawfish.

The crawfish "mud buggy" has been used by several crawfish farmers in Louisiana and Texas. The buggy is a four-wheel-drive modified ricefield levee sprayer powered by a 16-horsepower air-cooled engine. The single operator who sits on an elevated platform lifts and empties traps as they pass between the wheels of the vehicle. A person using the crawfish mud buggy can empty about 200 to 250 traps per hour and the vehicle can easily cross large perimeter levees. The mud buggy, which costs about $7,000 (1988), has several disadvantages: it makes deep ruts, gets stuck easily, and requires frequent maintenance.

Two somewhat exotic methods used to harvest crawfish include air-boats and small, amphibious, all-terrain vehicles originally designed for recreation. The all-terrain vehicles do not stand up well to daily use. Air boats are fast and easy to maneuver. They 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 or move them to different areas in a pond if necessary (Fig. 53).

Table 10 compares various crawfish harvesting methods.

Table 10. 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 Combine[¶]	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 Combine is available from T.D. Habetz, Star Route A, Box 042-A, New Iberia, LA 70560.

Trap Mechanization

The mechanization of crawfish trapping systems has not been especially successful. Some groups have used cables and pulleys to move traps in a pond and return them to a fixed point, but this system has not proved to be practical. Another group used a modified linear irrigation system to move traps slowly across a pond.

The moving superstructure stopped at intervals, emptied its open-topped traps into a collection conduit, and moved forward to the next trapping station. When it reached the far end of the pond, it reversed. While the system worked well in Agricultural Experiment Station tests, it was very expensive and required the extensive refinement of levee systems to support its wheels. It has never left the prototype stage.

At least two new systems have been patented which use irrigation pipe to move crawfish to a central collection area. In one, traps are attached to the pipe with one funnel opening into the pipe. Crawfish enter the traps and then move into the pipe where they are swept along by moving water. In the other, there are no traps. The crawfish enter holes in the side of the pipe and are moved to the collection area by cylinders pulled through the pipe on a continuously moving cable.

Seine and Trawl Systems for Harvesting Crawfish

Commercial crawfish are seldom harvested with active devices such as seines and trawls. The principal reason is that such devices cannot be easily used in the natural areas where large concentrations of crawfish are found because of dense vegetation and other kinds of obstructions. In addition, seines and trawls do not discriminate between intermolt (hard-shelled) crawfish and those that are entering the molting cycle or have recently molted. These crawfish are very sensitive to handling, and if packed in sacks with intermolt crawfish, they suffer considerable mortality. Some enterprising individuals use seines and trawls to harvest crawfish in years of abundance when large numbers are concentrated in flooded agricultural fields and pastures, but the practice is relatively rare. Where seines can be used, fishermen often "chum" the harvesting area with bait about 30 minutes before actually pulling the seine through the area.

Several mechanized push trawl systems have been tested in Louisiana over the past several years. Some depend on a scoop-like metal trawl, usually made of aluminum tubing, or a similar device to catch the crawfish. Others utilize modified shrimp trawls supported by a frame. These devices are mounted on the bows of flat-bottomed boats or the fronts of small wheeled vehicles. Some are powerful enough to push them through the dense vegetation normally present in the crawfish pond. Others are effective only in devegetated ponds in late season. The most effective unit uses pulsed high-voltage, low-amperage direct electric current to shock crawfish off the bottom and into the water column, where the "trawl" catches them.

Much interest has been directed to soft-shelled crawfish because of their value, often 8 to 12 times greater than the value of hard-shelled crawfish. These active harvesting systems can produce large numbers of soft-shelled crawfish, or those about to molt, which can be placed in standard shedding systems (see below). Much research must be conducted before such push trawl systems are in widespread use; however, it should not be too many years before at least one such unit is a common sight in Louisiana crawfish ponds.

Handling Crawfish

Traps are normally emptied onto a rectangular sorting table, which may be made of wood, iron, or aluminum. One end slants into the point of a 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, in which they are shipped.

Until the sacks are refrigerated by the buyer, they should be shaded, protected from wind, and periodically rinsed with fresh water to keep crawfish gills wet and rinse away excrement. The sacks usually reach the buyer's storage facility in 6 to 10 hours. Once there, they can be held or shipped under refrigeration (39°F to 45°F) for up to five days with less than 10 percent mortality.

Holding Crawfish

Crawfish are maintained alive in holding systems for two reasons. First, markets may not be available for the catch every day, especially if the catch rate is low. Second, crawfish in a holding system evacuate their guts and the abrasive action of their shells as they rub against each other cleans away fouling materials. Thus, a much cleaner product, said to be "purged," is available for market. Holding crawfish does, however, exact a cost, because the crawfish lose weight and some die.

Fig. 54. Mr. and Mrs. Doyle Schaer are crawfish farmers near El Campo, Texas. They hold their live crawfish in large cages instead of onion sacks in coolers, as is the traditional method in Louisiana. Crawfish held in cages purge themselves and are much cleaner than those sacked in coolers. Photo, J. Huner.

Thus, before setting up a holding system, crawfish producers must thoroughly evaluate the costs versus the benefits.

For purging, crawfish should be held for 24-48 hours. The length of time depends on temperature; at lower temperatures, the animals should be held longer.

Three purging systems have been evaluated—the batch, the flow-through, and the spray. In the batch system, crawfish are held in baskets or boxes suspended in tanks. The water is periodically drained and replaced with fresh water. In the flow-through system, the crawfish are held in baskets or boxes and placed into tanks of flowing water. In the spray system, crawfish are placed in tanks or boxes and a fine spray or mist of water is directed over them. Aeration and considerable volumes of water for flushing are required for the batch and flow-through systems. In contrast, no aeration is needed in the spray system because the crawfish use atmospheric oxygen, and shallower containers and much less water are required than with the other two systems.

Using a 40-hour purge period, the recommended loading density and water exchange rate for the flow-through system are 5 pounds per square foot and 1.5 gallons per minute per square foot. In contrast, the recommended values for the spray system are 5 pounds per square foot and 0.09 gallons per minute per square foot. Mortality should be less than 10 percent if crawfish of good quality are stocked in these systems at water temperatures in the 72-79°F range. More crawfish can be purged at lower temperatures, but purging time increases considerably.

Shipping and Storing Live Crawfish

As many as 55 pounds of crawfish may be packed into a plastic vegetable sack with 1/4-inch mesh, often called an onion sack, but mortality may be great when such a large volume of crawfish is packed in one sack. As a result, the industry has generally adopted smaller sacks that hold approximately 35 pounds of crawfish each.

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

Sacks of crawfish should be turned at least once per day and kept moist. They should never be stacked more than three high for prolonged periods to prevent the crawfish in the bottom layer from being crushed. The temperature should be kept at 40-45°F. Healthy crawfish can be stored for up to five days without excessive mortality.

Sacked crawfish can be easily damaged. Some producers have found that the use of reusable plastic or heavy cardboard boxes to hold crawfish reduces mortality, as the boxes prevent damage.

Fig. 55. Crawfish are emptied into a sorting table when harvested. Lower level holds bait.

They are not now widely used in the industry because sacks are cheaper and disposable. It is likely that boxes will become more popular for transporting crawfish in the future.

Current techniques for shipping crawfish could be improved upon. For example, crawfish ship and store much better if they are graded according to size and allowed to purge (clear their guts) for 24 hours. Whether this is done is a matter of economics, as additional labor and time are required to grade and purge crawfish for shipment. One must weigh the potential returns against expected losses, and there are no data readily available on the matter. Thus, each shipper must collect his own information. However, transoceanic shipments should always involve grading and purging if one expects to guarantee "healthy" viable crawfish upon arrival in the receiving country, barring unforeseen delays and exposure to unexpected temperatures.

The Wrights have several suggestions about the long-distance shipment of crawfish that should interest potential shippers. These include five distinct steps or operations.

"Crayfish must be graded not only for size and lack of blemishes, but also for health and vigor. Late premoults must not be shipped, nor should soft or 'paper-shell' animals (except in bait situations). The animals who are to travel should eagerly raise their chelae at least 45 degrees above the horizontal—no droopy claws! If held by the forward part of the carapace, they should flap their tails vigorously.... Ungraded animals tend to damage each other, and, on long trips, the corpses contribute greatly to toxic and stressful conditions. If you want to, or must, ship several sizes of animals, use separate containers for each size group.

"The second step is the purge. Adults should not be fed the day before shipment or the day of arrival.... Purging should be done in constantly changing super-clean water, and extra oxygenation seems to help in the overall picture. Depuration should last about twenty-four hours.

"The third step is to decide the amount of water to use in shipment. Every ounce is paid for at the same rate as the animals, so you must decide whether the extra cost is justified. *No* moisture is actually *needed*. Free-standing moisture is positively lethal. Total immersion is their natural habitat, and is the *only* medium in which they can be transported without trauma and consequent complications. Thus the end use of the shipment, time considerations, and the value of the animals all enter the equation.

"The fourth point is *oxygen*, and this seems to be the least understood. The normal environment of crayfish contains 5 ppm of free oxygen. Air contains 200,000 ppm!!! Thus ventilation is nowhere near as important as one instinctively feels. When we ship by Express Mail to people who expect plenty of moisture, we protect ourselves from trouble with the Postal Authorities by providing a totally air- and water-tight enclosure of plastic film between the actual container and the outer wrapping of brown paper. Such shipments arrive in perfect condition. The silly little holes that people customarily drill in shipping containers are totally ineffective. They may possibly serve to impress a tender-hearted transportation worker to stack the boxes in the shade, or otherwise be good to the animals, but otherwise they are a waste of effort. If you really are a ventilation nut, use a wicker basket for shiping, or an onion sack. Both work better than a box with holes. The safest way to ship and provide oxygen is to fill the shipping box one-third to one-half full of animals, and add enough light packing to keep the animals from rattling around.

"The last general point is temperature. Lowered temperature during shipment lowers metabolism, activity, self pollution, and bacterial proliferation. Ice, however, should be used with great caution, as melted ice is a great killer, and most transportation companies balk at self-draining containers. We use 'Blue Ice' exclusively. When using 'Blue Ice' buy the kind that freezes at high temperatures, and be sure that it cannot come in direct contact with the animals. Mark the boxes 'keep out of the sun, and away from hot pipes,' but few such markings are obeyed by transportation workers. Better, if you can afford it, line your shipping boxes with styrafoam, or use an inner box like a picnic cooler.

"Countless tons of crayfish are shipped in Europe by the following method, which is good for about four days in transit, and results in less than 5% mortality. Animals are depurated, graded, and dried until they no longer leave tracks on sanded wooden floors—that is, totally dry. They are then packed in wicker baskets with excelsior or shavings, both bone dry, separated from the basket and the ones above and below by a layer of packing. No refrigeration is used. In this method the crayfish represent over 80% of the total shipping weight of basket, packing, and animals. (The catch is, that although the animals may be carefully bubbled and reintroduced into water at the end of the trip, *none* of them will live over six months. Their gills have suffered irreparable and irreversible danger.)"

Grading

Grading has become a very important part of the crawfish industry. Grades are based primarily on size. No formal standards have been mandated but common convention generally delineates three grades: export, 10-15 per pound; restaurant, 16-24 per pound; and peeler, 24-35 per pound.

Small grading units are appearing on boats. All processors have some form of grader. Graders include two diverging rollers that gradually separate, grids of shaking plastic pipes, and round, long drums of diverging plastic pipes with gradually increasing spacings. Other graders used in egg and vegetable industries are being tested for use in grading crawfish.

Fig. 56. Crawfish packed in open-mesh vegetable sacks.

Crawfish Products

Basic crawfish food products include live crawfish; whole boiled crawfish; peeled crawfish abdominal muscle (tail meat), with or without the hepatopancreas; and whole soft-shelled crawfish. Other commercially important products include smaller crawfish sold for fish bait (most commonly in northern states) and those sold as biological specimens for testing or classroom dissection.

Frozen crawfish, either boiled or uncooked, is a relatively new product in the industry, but freezing permits considerable flexibility to the processor, who may prepare the products when crawfish are abundant and hold them for later sale over an extended period. If sold uncooked, however, the crawfish must be frozen while still alive, as they spoil rapidly after death. Both products must be properly "glazed" with a light coating of ice to prevent dehydration ("freezer burn") during storage. Crawfish legs and claws are very brittle when frozen with minimal amounts of fluid in the container.

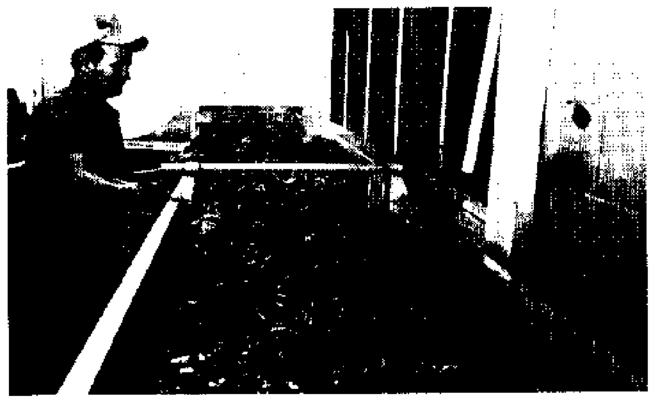


Fig. 57. Crawfish being cleaned prior to parboiling and peeling.

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 restaurants boil them or clean them for use in entree dishes. 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 ten 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.

The hepatopancreas may or may not be retained. If it is, it may be set aside in a separate container 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, many food service professionals feel 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*.

Yield of abdominal meat may vary from 10 to 25 percent (See Appendix D for a comparison of meat yields for red swamp and white river crawfishes). 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.

Although there are several patented crawfish peeling machines, none has yet been adopted by the industry. Such machines should automatically remove the cephalothorax and generate a relatively high meat yield. Roller systems such as those used in the shrimp processing industry appear to be the most promising method for peeling crawfish meat economically. These squeeze the meat out of the tail after the crawfish has been deheaded. A major problem for those developing crawfish peeling machines has been devising methods to prepare the crawfish for peeling. Roller systems are not especially effective for use with boiled and steamed crawfish, as the meat tends to stick to the shell so that yield is reduced.

A unique peeling system uses compressed air to force crawfish meat out of the deheaded body. The air is injected with a needle inserted into the anal end of the abdomen.

Several years ago, one firm found that tail meat slipped readily out of the shell if the whole crawfish was first quick-frozen and then thawed before processing. Recently, another inventor developed a system in which the crawfish were steamed under pressure, then quickly released from pressure, a process that reportedly caused the shell to separate from the underlying flesh. Presumably, the meat could then be easily forced out of the shell by a roller system.

A major consideration for processors is whether to sell cooked or fresh tail meat. The market is accustomed to buying a cooked product and has little experience with an uncooked product such as that generated when the crawfish are pretreated by freezing. The cooked product is basically white with various amounts of red pigmentation on the surface. The uncooked product is whitish-amber in

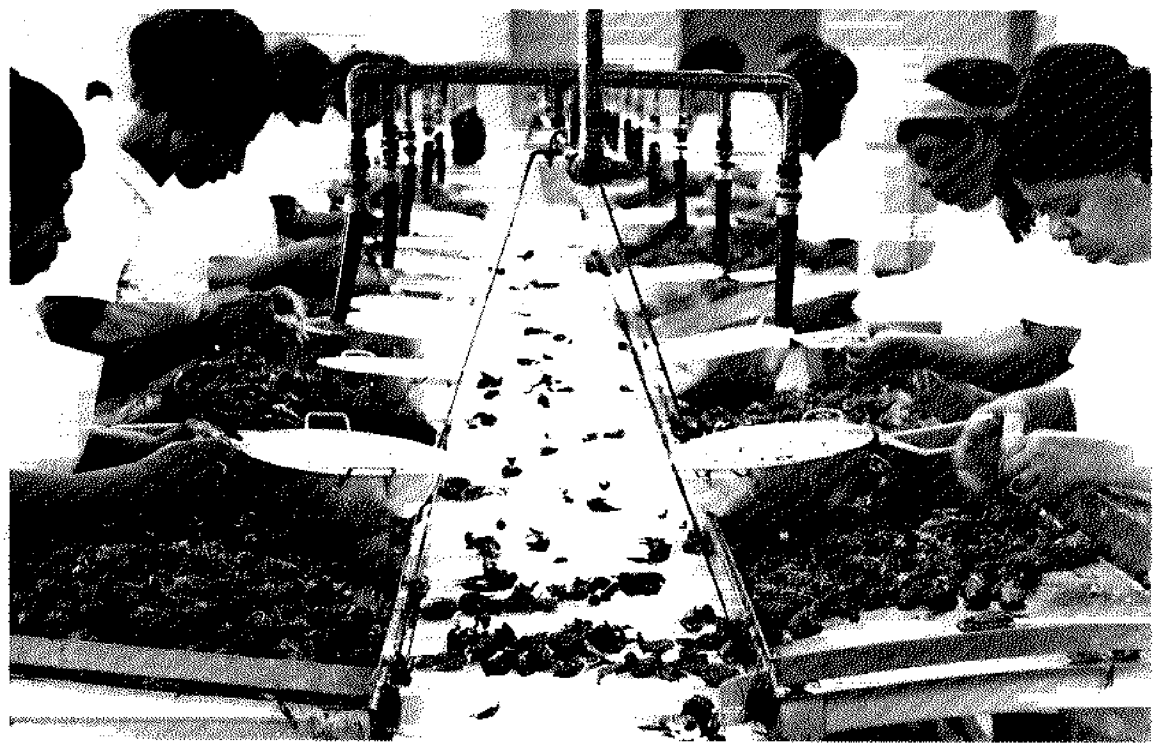


Fig. 58. Crawfish being peeled by hand.

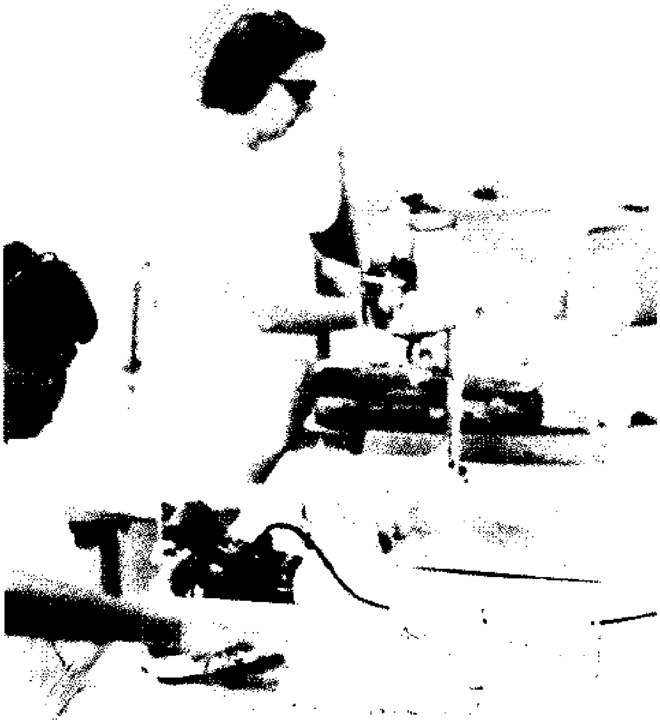


Fig. 59. Peeled crawfish meat being packed.

color, with a bluish surface. In addition, freezing does not neutralize proteolytic enzymes that make crawfish meat disintegrate, and it is usually necessary to heat uncooked meat to provide the product expected by the consumer.

When this text was revised in 1984, it appeared that a crawfish peeling machine would be widely and rapidly adopted by the industry. This was not the case, though at this writing several firms are developing new peeling machines. If one or more is cost effective, the influence on the industry will be dramatic, as an efficient machine could reduce the cost of peeling crawfish meat by as much as 80 percent.

Crawfish meat is a good source of protein (16 to 18 percent) 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 11.

Cholesterol is a major concern of diet-conscious persons. Both crawfish meat and crawfish fat (hepatopancreas) contain cholesterol. Dr. Nellie Derise and R. Druilhet of the University of Southwestern Louisiana have found that the cholesterol content of crawfish meat is 80-90 milligrams per 100 grams. Crawfish fat has 240 to 261 milligrams per 100 grams.

Crawfish processing wastes are a major problem for two reasons. First, they represent an expensive commodity—on the average, 85 percent 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) and agronomic crops (soybeans, sugarcane). 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). 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 percent) but they also have a very high ash (mineral) content (29-44 percent). Much of the ash is in the form of calcium (18 percent). For this reason, only about 10 percent of an animal feed ration should be made up of crawfish wastes. Otherwise the ash content must be

Table 11. A nutritional analysis of crawfishmeat.[¶]

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, Tex. 77843.

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

reduced in order to convert the wastes into a feed ingredient of high quality.

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

Table 12. 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
Phosphorus	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.

An important feature of crustacean meals, including crawfish meal, is the concentration of carotenoid pigments. These are valuable natural food additives for animal feeds in which product and color is important—salmon and trout flesh, aquarium fish, and egg yolks in domestic fowl are a few products whose color is enhanced by these pigments. Dry crawfish waste contains 153 migrograms per gram of the pigment astaxanthin. Extraction of oil containing astaxanthin from freshly ground crawfish waste has resulted in a significant concentration of the valuable pigment. Levels of at least 60 milligrams per 100 grams of oil are commercially significant in terms of the economics of recovery and ultimate use in animal diets.

Reclamation of valuable products from crawfish wastes is becoming a reality. This by-product industry has been suffering growing pains but significant progress is being made.

Marketing

The development of crawfish markets in other states is becoming important to the Louisiana industry, though Louisiana remains the major market for most crawfish products. Most of the live crawfish, as well as the fresh and frozen meat produced in Louisiana, is consumed in the state, although more and more crawfish products are being exported. For example, in-state consumption declined from about 80 percent in the early 1980s to 70 percent in the late 1980s.

The south-central states immediately around Louisiana represent the major "export" market for Louisiana crawfish, followed by the southeast and mid-Atlantic regions. Considerable emphasis has been given recently to exporting whole, cooked, and frozen crawfish to Europe, primarily Scandanavia. While the export volume is small relative to overall production, producers now have much opportunity for market expansion both within the U.S. and abroad.

Dr. Lynn Dellenbarger of the Louisiana State University Agricultural Economics Department conducted a nationwide mail survey in 1985 to obtain information about crawfish markets outside Louisiana. The survey showed that the major problems in securing such markets were the lack of consumer awareness about the product and the lack of reliable product sources.

Earlier marketing studies were conducted 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 restaurant-to consumer; and the least important distribution channel is processor-to grocery store-to consumer. Live crawfish accounted for a large part of all processor sales. Though meat processing (peeling) was often a salvage operation when Carrol and Blades examined the industry, more and more processors are now producing crawfish tail meat as a primary endeavor.

A large part of seafood market crawfish sales is live crawfish. Important crawfish entrees in restaurants include boiled crawfish, crawfish etouffee, crawfish bisque, fried crawfish tails, crawfish gumbo, crawfish dinners (combination of various entrees), crawfish jambalaya, and crawfish stew.

Legal Considerations

In Louisiana, crawfish trappers generally catch crawfish in open, unposted swamps on a first-come, first-served basis. Markers are frequently not used because they attract thieves. Many areas outside the Atchafalaya basin are posted and one must obtain permission from the owner to harvest crawfish there. Though much of the Atchafalaya basin is privately owned, traditionally most areas have been open to everyone. This situation may not persist indefinitely and confrontations may result.

Catching Crawfish for Fun

Catching crawfish in roadside ditches is a springtime ritual in Louisiana that can be just as fun as boiling and eating them. In locating crawfish waters, watch for areas where others are catching crawfish, either for food with small "set" nets or for fish bait with dip nets. Normally, successful roadside crawfishing can take place in February and March in south Louisiana, and as late as May in north Louisiana. As productive crawfish ditches are filled with rainwater, there is little activity in the summer and early fall because there is less rain then.

Look for areas that hold water for six to eight weeks at a time, with depths of 6 to 30 inches. Areas that hold water for four to five months are best, but if water stands longer than that, fish populations become established. Since fish eat young crawfish, few can be caught.

Look for semi-aquatic vegetation, like alligator weed, smartweed, and water primrose. This indicates a high water table, which is necessary to insure the survival of crawfish in burrows. This vegetation supplies protective cover for crawfish and food for them when water is in the ditch. Crawfish eat succulent leaves, algae, and small animals (snails, insect larvae, worms) that attach to these plants.

Look for larger ditches and sloughs, as they will have a greater volume of water and more space in which crawfish can grow. However, do not ignore small ditches. Sometimes those that are only wide enough to accommodate a 17-inch-square set net can provide a few pounds of crawfish.

When ditches or sloughs are dry, look for crawfish burrows and dried crawfish shells. When ditches are filled with water, look for murky, turbid water, a sure sign of crawfish activity, and use a dip net to see if small crawfish are present.

Ditches and sloughs associated with swamps and marshes adjacent to highways are invariably the best places for finding edible crawfish, especially when swamps and marshes start to dry in the spring. Then the crawfish move out of the swamps and marshes and concentrate in the remaining water in the ditches.

A few more hints may help you to catch more crawfish. You can usually catch edible ones within six weeks after a productive ditch is flooded in fall or winter. Few can be caught in the summer, no matter how much water is present, because crawfish do not leave their burrows, at least in the lower South. But sometimes bait crawfish are locally abundant then. Success is more probable at night, as crawfish, especially the large ones, are nocturnal, and rainy days and nights are always better than clear ones.

Do not expect to catch a sack of crawfish (30-40 pounds) in one place many times. You will invariably have to move several times to catch enough crawfish to boil, unless the season has been very rainy, with high water. At such times, swamps and marshes all over south Louisiana can produce large numbers of crawfish.

Red crawfish have adapted well to irrigation systems in the western USA. When these systems are periodically drained for maintenance, red crawfish often concentrate in great numbers in the remaining water. This has been reported in both Nevada (near Las Vegas) and California (Sacramento delta rice fields). People living in such areas can reap quite a bonanza.

FISHERIES MANAGEMENT

Management of the red crawfish and its frequent companion, the white crawfish, has not been extensively pursued by government. Though state and federal agencies routinely monitor important commercial species such as shrimp, oysters, spotted weakfish, and largemouth bass, there are no sampling programs for crawfish. Catch statistics underestimate the crawfish harvest so greatly that their value as a fisheries management tool is questionable.

The commercial importance of red crawfish in southern Louisiana is so great that one would expect state fisheries management personnel to take stock assessments and monitor the crop's condition. Though this is not the case, commercial fishermen are quite successful without governmental assistance.

The crawfish is a fast-growing, prolific animal and its growth and abundance are determined by the annual hydrological cycle. When flood waters fill the Atchafalaya basin for sustained periods in fall, winter, and spring, there is a bountiful crop. If not, the crop is poor, but the red crawfish cannot be destroyed by overfishing. It is so prolific that fishing effort will stop, for economic reasons, before any possible irreparable harm can be done to local crawfish populations.

In most fisheries, state and federal biologists monitor crops and advise users about abundance and locations. Red crawfish populations are monitored by the fishermen and hunters who traverse the swamps during the fall and winter of the year. Their keen sense of observation is as valuable as any government monitoring program could be.

Government plays its major role in water-control programs. If water entering the Atchafalaya basin is not controlled properly, crawfish crops can be very poor. The problem, of course, is that the Atchafalaya basin is a flood control "structure" designed to protect property, not to produce crawfish. In the past, government hydrologists gave little consideration to the effects of flood control activities on biota, but they are now attempting to incorporate a multipurpose management plan for the area; that is, whenever possible, water levels are manipulated to insure maximum benefit to all users.

Atchafalaya Basin Studies

Studies of crawfish in the Atchafalaya basin have been very limited, though researchers have generally tried to identify suitable microhabitats and to monitor crawfish growth and relative abundance. In the Atchafalaya basin, red crawfish are more abundant in cypress-tupelo gum swamps and sluggish flowing bayous than they are in permanent lakes, lake shores, willow swamps, canals, and riverine habitats; however, they can become concentrated in any habitat during the dewatering period in the late spring-early summer. White crawfish tend to be abundant in riverine areas and on main levees on either side of the basin.

Growth and catch are strongly correlated with temperatures and are greatest in the spring. Flood waters in the basin are cold because they come from the northern Mississippi River Valley; thus, the maturation of basin crawfish is four to six weeks behind that of pond crawfish just over the levees. Growth rates of two inches per month have been observed in the April-May period. Peak catches are usually reported in May.

Estimating crawfish production per unit area in natural areas including the Atchafalaya basin is very difficult to do. Preferred microhabitats, such as cypress-tupelo gum swamps with generous water flows, can probably produce over 2,000 pounds per acre. This estimate can be made on the basis of optimum production from ponds, limited population estimate studies, and estimations of quantities removed from given areas by observed fishing pressure. However, it is well known that crawfish move in response to shifting water fronts and crawfish from various areas probably do concentrate in one place. As a result, extensive areas can appear highly productive when they are not.

Studies in natural habitats elsewhere in Louisiana found that harvestable quantities of crawfish did not exceed 20 pounds per acre per year. This hardly justifies trapping unless falling waters concentrate the crawfish. A further complication is found when one realizes that the area of optimal habitat varies according to the vagaries of nature, so that actual production projections cannot be made with great accuracy for more than a month in advance.

Population Estimation

Estimating crawfish numbers, whether it be in pond, marsh, or swamp, is an important aspect of fisheries management. Techniques for estimating numbers of crawfish present are very time-consuming and are subject to much error. But data generated by research studies in semicontrolled conditions have revealed methods of monitoring populations to provide information for management decisions. Monitoring programs for crawfish ponds are discussed in the section on culture. Wild populations are usually monitored in a similar way.

Population estimation usually re-quires marking and recapturing crawfish. The total number marked is multiplied by the ratio of the number caught in subsequent samples and the number of recaptured (marked) crawfish in the subsequent samples. There are many variations of this basic formula that are designed to eliminate many sources of bias.

Crawfish are difficult to mark. Tags are lost or they damage the crawfish when the animals molt. Brands or cuttings are obscured by regeneration processes. Only the largest adults can be fitted with radio transmitters. Various insoluble, nontoxic inks have been injected beneath the translucent shell on the underside of the abdomen, but each crawfish must be turned over to check for marks. One researcher even inserted bits of radioactive material in place of ink and followed marked crawfish with a Geiger counter. Others have sprayed crawfish with fluorescent paint, specks of which glow under special lights, or have used paints, such as fingernail polish and typing correction fluid, to mark them. Such methods last no more than one molt.

The most commonly used marking techniques for crawfish are the branding of the carapace with a small soldering iron and the clipping of the uropods to make notches. Neither lasts more than four molts and complicates long-term marking studies.

Another method of population estimation involves the removal of large numbers of animals from an area in a short period of time, usually two to three days. The daily catch is plotted against the cumulative catch. Extension of the graph indicates the estimated total number of animals in the area. This can then be projected to a larger area but requires a great deal of effort. It is somewhat futile if animals are moving rapidly back and forth into and out of an area. Animals do not have to be marked in the second method, but some statisticians have blended the two methods together to eliminate some of the biases found in both.

Any time that animals, crawfish or others, are marked, it is important to remember that the creatures are being put under stress. Accurate predictions about numbers, growth rates, and survival can be obtained only if the marked animals survive in large numbers. It is not uncommon for animals to go into shock when roughly handled or to suffer delayed mortality, dying as much as a week later. Thus, it is wise to investigate a marking method ahead of time or to keep reference animals for a time to estimate such delayed mortality.

A good text on animal population ecology will describe population estimation procedures fully. Further information about population estimation techniques is presented in Appendix C.

Population Condition

It is very easy to determine when male cambarid crawfish have reached maturity and have stopped growing. Indications include inflated claws, cornified gonopodia, and ischial hooks on the walking legs, which are all diagnostic of the mature, Form I condition. The average size of Form I male red and white crawfish is generally indicative of the nature of a habitat. Red crawfish may be very abundant in harsh and/or restricted habitats but their size will invariably be small, less than 2 3/4 inches in total length. Any improvement in habitat permits additional growth. In general, when population levels and yields are low, size is greatest. In ponds with high densities of crawfish, the size of Form I males is greatest in late winter-early spring, with a progressive decrease in size throughout the spring. Absolute size is a function of water quality, harvesting intensity, and food resources. Table 13 provides representative average sizes of Form I male red crawfish, along with comments about the habitats.

Table 13. Average sizes of Form I mature male red crawfish from different Louisiana habitats.

Habitat	Average Total Length (inches)	Comments
Roadside Ditch	2.55 (n = 98)	Shallow ditch, less than 12 inches deep. Rarely full more than 3 months at a time. Located at LSU Aquaculture Center, Baton Rouge, La.
Culture Ponds		
Ben Hur Rice Ponds	3.36 (n = 533)	0.1-acre research pond at LSU Aquaculture Center, Baton Rouge, La. Planted in rice. Yield about 800 pounds per acre; under-harvested with stunting.
Boyce Pond		
1975-76	3.48 (n = 262)	1.0-acre pond located near Sorrento, La. Planted in rice both years. 1975-76 yield about 3000 lbs; not harvested in 1977-78.
1977-78	4.15 (n = 209)	Extensively harvested in 1976-76 with aeration and heavy vegetation; not harvested in 1977-78 because fish reduced population to unharvestable levels and levels and survivors grew well.
McCahill Pond		
1975-76	3.66 (n = 189)	5.0-acre pond located near Springfield, La. Planted in alligator weed. Yield about 1000 lbs per acre in both yrs.
1977-78	3.58 (n = 85)	Well managed but with minimal water circulation; heavily harvested.
Atchafalaya Basin		
Buffalo Cove	3.68 (n = 167)	May 1978 sample taken from commercial catch. Cypress-Tupelo gum swamp about 30 miles northwest of Morgan City, La. Noted "hot spot" for crawfish; heavily fished with good water flow.
Grand Lake	4.05 (n = 115)	May 1978 sample taken from commercial catch. Lake edge-willow swamp about 6 miles northwest of Morgan City, La. Excellent water flow. Very limited area well known for large crawfish. Fishing pressure intense but total harvest low.

Source: Huner, J.V. and R.P. Romaire. 1979. Size at maturity as a means of comparing populations of *Procambarus clarkii* (Girard) (Crustacea, Decapoda) from different habitats. Papers from the International Symposium on Freshwater Crayfish 5: 63-64.

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 (bonus) crop. As rice farmers, the Acadians would flood their fields during the fall and winter months to attract waterfowl for hunting and to level the bottoms. Crawfish would then 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 prominent scientists have developed techniques and performed much of the needed basic research in the area of crawfish culture.

Currently about 125,000 (1990) 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 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 62,500,000 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 140 million pounds without improvement of current cultural practices.

The culture of red crawfish is expanding to other areas. Expansion into southern Texas was to be expected in view of the extensive culture of rice there and the presence there of the Louisiana Acadian culture. About 6,000 acres are now devoted to crawfish culture in Texas. Elsewhere, Florida has about 2,000 acres and South Carolina has about 1,200 acres. The states of Arkansas, Mississippi, Georgia, North Carolina, and Maryland have identifiable crawfish culture ponds with acreage in the 100-500 range.

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; (5) draining ponds; (6) use of chemicals; (7) processing; and (8) 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 Louisiana Cooperative Extension Service, Knapp Hall, LSU, Baton Rouge, La. 70803.

Though this bulletin is somewhat dated now, it is still a good guide for those contemplating crawfish culture. Your local Cooperative Extension Service office can assist you in obtaining the most recent legal information available on farming crawfish.

Extension services can also be helpful in informing interested persons of the current status of pertinent laws and regulations. It is important to caution readers that many states have laws that require permits to import nonnative 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) compose 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 midwinter. 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 and South Carolina, 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 middle to late spring.

We know of successful attempts to cultivate *P. clarkii* using Louisiana methods in Santo Domingo and at higher elevations in Zambia. Thus, these crawfish can be grown in tropical regions.

At present, 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. The 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.

ECONOMICS

Can one make money in crawfish farming? Certainly, or there would be far fewer than 125,000 acres of land devoted to crawfish farming in Louisiana alone. However, precise economic projections depend on each situation. For example, is the land already owned by the farmer, 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, by 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 fishermen who are paid either a flat wage or a percentage (usually half) of the harvest? How large a pond will be built? These and a number of other questions must be considered before one enters the business.

The most complete economic guide to crawfish farming currently available was written by Dr. Lynn E. Dellenbarger, entitled *Estimated Investment Requirements, Production Costs, and Breakeven Prices for Crawfish in Louisiana, 1987* (see References for complete citation).

Economies of scale are very clear. That is, costs per acre are significantly reduced as the size of an operation increases. Costs are also lower when crawfish and rice are double-cropped in the same year. Dellenbarger and his coworkers compared the costs of producing crawfish as one crop with the costs of production as a double crop in two areas of Louisiana. Table 14a shows investment costs per acre for crawfish production, as well as annual operating costs for ponds with crawfish alone or in combination with rice. Tables 14b and c show breakeven prices for these two situations at different production levels. Notice that the costs of production are clearly lower when crawfish and rice are grown in the same pond(s).

Prices paid for crawfish have varied dramatically in the past several years. The main problem is competition within the state from wild basin crawfish. When these are abundant, prices often fail to or near the breakeven level. Basin crawfish become abundant in mid-spring, and prices reach their lowest levels then. They are at their maximum in early season. In past years, most ponds

Table 14a. Investment Costs and Annual Operating Costs for Crawfish Production in Southwestern Louisiana, 1987.

Pond Size	Investment Cost/Acre*	Annual Operating Costs Crawfish	Crawfish & Rice
10 acres	$5124	$1102	$1047
20 acres	2775	762	669
40 acres	1639	604	533
2 x 40 acres	1068	523	438

*Land ownership is assumed.

Table 14b. Breakeven Costs for Crawfish Monoculture in Southwestern Louisiana, 1987.

Pond Size	Production Level Lbs/Acre				
	700	900	1100	1300	1500
10 acres	$1.90	$1.48	$1.21	$1.02	$0.89
20 acres	1.25	0.97	0.79	0.68	0.59
40 acres	0.94	0.73	0.60	0.51	0.44
2 x 40 acres	0.79	0.61	0.50	0.43	0.37

Table 14c. Breakeven Costs for Crawfish Double-Cropped with Rice in Southwestern Louisiana, 1987.

Pond Size	Production Level Lbs/Acre				
	700	900	1100	1300	1500
10 acres	$1.79	$1.39	$1.14	$0.96	$0.83
20 acres	1.12	0.87	0.71	0.60	0.52
40 acres	0.83	0.65	0.53	0.45	0.39
2 x 40 acres	0.68	0.53	0.43	0.36	0.32

generated the bulk of their revenue over the winter into early spring when prices held at higher levels. However, as the industry entered the 1990s, prices have tended to fall to a season long level. To be sure, larger crawfish have commanded good prices but smaller, peeler crawfish, the bulk of the crop, have not. As a result, average prices have been so low that few farmers, according to the tables presented above, have operated profitable farms.

Farmers located 100 miles or more away from the Atchafalaya basin do not suffer as greatly from competition. Crawfish farmers in Texas, Mississippi, and South Carolina report prices roughly twice those obtained in Louisiana, as there is lit-tle competition from native crawfishes in those states.

The crawfish farming sector of Louisiana's economy currently awaits marketing and production improvement to promote significant expansion (1990). A major target for improvement is the cost of harvesting. Over 60 percent of all operating costs are associated with harvesting, so significant gains in harvest efficiency are essential to the long-term profitability of the industry. Like farmers, processors and marketers face high operating costs, with 40 percent claimed by piece-rate labor. Means must eventually be developed that will bring this cost down to the competitive levels set by other seafood products. Clearly, then, it is an oversimplification to attribute industry problems to either producers or processors.

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 highest yields. Aquaculturists who visit their ponds irregularly but expect a crop in the spring are generally disappointed. Conscientious pond owners will know when they will have limited crops before they purchase bait and traps.

A checklist is included in Appendix E. This will be a helpful guide for prospective crawfish culturists.

PONDS

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 15).

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, so 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.

It is common to find reference made to wooded, open, and rice field ponds. This is not a very precise system, which is why we prefer to use the classifications presented in Table 15.

Table 15. 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, smartweed and primrose invaded or are transplanted.	Becomes turbid in spring.	Either cleared highland ponds or agricultural land that is not rotated between crawfish and crops in same year.
Swampland	Similar to marsh pond.	Tends to be clear but can become turbid in spring.	This is 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.

Site Selection

Advisory agencies advocate paid construction in areas with heavy clay or silty clay soils—that is, areas that will hold water. Areas suitable for rice production should also be suitable for crawfish if there is no residual pesticide contamination. However, success is generally assured if the area already has a resident population of red swamp crawfish and/or white river crawfish. Checking drainage ditches and canals for crawfish and looking for burrows is advisable in selecting a site for a pond.

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 in 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.

Ponds are now built with inner baffle levees to insure thorough mixing and flushing of water. These are located 150-200 feet apart and are open at opposite ends (Fig. 60).

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.

Major levees must be well built if problems from crawfish and rodent burrows are to be avoided. It is not unusual to see ponds with narrow, inexpensive levees that fail because the owner cannot keep water in them.

Fig. 60. Baffle levee in crawfish pond. Photo, J. Huner.

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. 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.

One often overlooked factor in pond siting is soil fertility. There appears to be a direct relationship between pond fertility and production. When fertile topsoil is removed for levee construction, the less fertile subsurface soils are left for the growth of pond cover-forage crops. Thus, where feasible, ponds should be sited in rich soils, and topsoil should be set aside and returned to the pond bottom. If this is not possible, a fertilization-liming program is advisable (see section on feeds and fertilizers).

Before actually building a pond one should consult the county extension service and U.S. Soil Conservation Service for assistance. In addition, the U.S. Soil Conservation Service will survey the site and advise on the feasibility of building a pond. They also prepare pond construction specifications, including pump requirements and drain sizes, which are then relayed to the builder.

WATER MANAGEMENT

Control

A pumping system is needed that can fill and/or flush the pond in four 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 predaceous fish. Baffles will serve to increase oxygen in incoming waters (Fig. 61).

Flooding

If pond flooding begins in early September and ends in early October, there should be 2 to 3 1/2

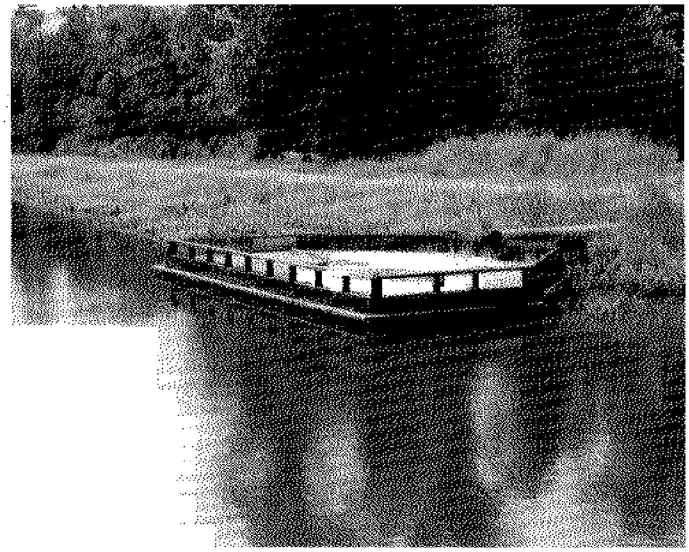


Fig. 61. Water inlet with fish screen and aeration baffle. Such systems are not as efficient as aeration towers. Photo, J. Huner.

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.

The Louisiana Cooperative Extension Service generally recommends that ponds not be filled until daytime temperatures are in the low to mid eighties (°F) and nighttime temperatures are in the low to mid seventies (°F). This usually occurs from early to mid October.

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

Don Gooch has long been an advocate of digging burrows to check for the presence of young crawfish before flooding a pond. There is obvious merit to this undertaking, as it is senseless to flood ponds before large numbers of young are ready to enter open water. However, the dates given above generally seem to coincide with this period. Checking burrows represents a commitment to good management and is encouraged if the time is available.

Some people have successfully used a hose to suck water containing small crawfish from burrows. This technique almost completely eliminates the need for burrow excavation but does require some skill.

There is no real information about pond flooding dates other than the ones presented above. In northern climates, it is probably best to keep water in a pond during the winter, especially if the frost line extends deep enough to freeze burrows and kill resident crawfish. Even in Louisiana, fish ponds that have been dry through the winter produced fair crops of crawfish in July after being filled in May, but they contained well-established crawfish populations.

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 by birds and mammals.

In 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 the 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.

No research has been conducted to determine the best time to drain ponds. It is very clear, however, that they must be drained to kill predators and permit growth of vegetation. Whether this draining has to correspond to the summer months is not well established. It is obviously not possible in northern states where summer is the growing season.

Water Quality

Crawfish can live in almost any fresh or slightly brackish water (see section on ecology). The primary water quality factor limiting crawfish pond culture is dissolved oxygen. When emergent plants and forage plants like rice and sorghums 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 slows down the decomposition process. However, standing vegetation is necessary for maximum crawfish growth, so enough time must be left before flooding for the vegetation to grow at least to a level above the initial flood. Otherwise, it is likely to die when covered with water.

A more effective way of improving water quality is to add inner, low levees to force fresh water to all parts of the pond. This can be done in addition to cutting vegetation periodically.

Most farmers cut or disk lanes through vegetation before flooding ponds. These facilitate harvesting and can also be effective in circulating water. Because water follows the path of least resistance, continuous lanes take oxygenated, fresh water away from vegetated areas that need it most. Therefore, lanes should be arranged so that they are discontinuous and force the water into the standing vegetation as it moves through the pond.

Ponds are now constructed with recirculation systems. Deoxygenated water leaves the pond and returns to the pump via a ring canal or ditch. It is reoxygenated as it passes into the pond through an aerator baffle that consists of several screens of successively smaller mesh from 1 inch to 1/4 inch. Once-through systems are most effective, as recirculated water loses oxygen more quickly to dissolved, decomposing organic matter, but they are more expensive.

Oxygen levels below 2 ppm can be fatal, and ponds should be monitored with oxygen kits or oxygen meters. 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 oxygen in the presence of sunlight; thus, high levels of oxygen result during the day when the oxygen is being released. At night, green plants must use the oxygen for metabolism; therefore, oxygen levels are lower at night than during the day when phytoplankton produce oxygen. When crawfish are found near the surface clinging to vegetation, the pond is low in oxygen.

To insure minimal dissolved oxygen concentrations, one should begin to flush a pond two weeks after it is flooded. This requires a pumping rate of about 100 gallons per minute per acre for an 18-inch water depth. This should continue 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.

Fig. 62. Crawfish pond aeration tower in action. Note cascading water and, behind th tower, the circulation and harvesting lanes. Photo, J. Huner.

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. 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 two pounds per square yard (8,800 pounds per acre). Higher levels will almost surely lead to oxygen depletion without high pumping rates. 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.

Fig. 63. Water aerator, which also screens out larger fish.

Methods to reduce pumping costs have been developed. If ponds are filled to depths of 6-10 inches rather than 18 inches, pumping rates of 50-60 gallons per minute are adequate to flush ponds in four days. Water levels are then raised after the weather cools. Furthermore, planting forage crops of rice or hybrid sorghum-sudangrass will insure that vegetation will remain green when the ponds are flooded and that decomposition rates will be greatly reduced.

Use of some semi-aquatic vegetation to provide cover and access to the surface is yet another method to reduce oxygen needs. Semi-aquatic plants like rice and alligator weed are excellent for this because they do not die back after they are flooded. Alligator weed must be carefully controlled because it is so prolific that it can take over a pond. A mixture of semi-aquatic vegetation and annual grasses and sedges is preferable to either group alone (see feeds and fertilization section).

Research has shown that the paddlewheel aerators used in catfish ponds can be effective in aerating and circulating/recirculating water in crawfish ponds. Ponds must be properly engineered with baffle levees and bottom grades.

Turbid Water

There is no doubt that turbid water reduces problems associated with filamentous algae and may reduce drastic daily oxygen changes in ponds. However, turbid water is usually associated with little or no emergent vegetation or is obtained by cutting the vegetation before pond flooding. The value of that vegetation is too great to dismiss lightly although it has yet to be fully assessed. It has been our experience that ponds with abundant crawfish eventually become turbid, and ponds without them are not helped by activities designed to increase their turbidity. Turbidity, especially in early fall, is an indication of "overpopulation" and eventual stunting problems. Further studies on the subject of pond turbidity and its value are clearly needed.

Sources of Water

The best water source is a well. Such water is normally free of pesticides and fish, and 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 should be 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 or hardness is 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 guarded against include the following: (1) predaceous 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

Herman H. Jarboe of the Louisiana State University Agricultural Center has conducted much research into the toxicity of various pesticides to the red swamp crawfish. This section depends heavily on Mr. Jarboe's work.

Crawfish and insects are both arthropods and share very similar physiology and appearance. Thus, it is not surprising to discover that crawfish are generally more susceptible to insecticides than any other pesticides. Crawfish appear to be most sensitive to the synthetic pyrethroid insecticides and those with chlorinated hydrocarbons. The trade names for several synthetic pyrethroid insecticides are Ambush (Permethrin) and Scourge II (Resmethrin + Piperny] Butoxide). Some common chlorinated hydrocarbon pesticides include Aldrin, Anofex (DDT), Dieldrix (Dieldrin), and Endrin. Chlorinated hydrocarbon insecticides are not commonly used in the U.S. because of major environmental problems. Organophosphate pesticides appear to rank second in terms of their toxicity to crawfish. Trade names for some common organophosphorous insecticides include Guthion (Azinophos Ethyl), Baytex (Fenthion), Niran M-4 (Methyl parathion), and N E-4 (Parathion). An oddity among the organophosphorous insecticides is Cythion (Malathion). It is a very effective, broad-spectrum insecticide, but its toxicity to crawfish is very low.

In general, herbicides are much less toxic to crawfish than insecticides. The exception to this generalization is Gramoxone (Paraquat) which is moderately toxic to crawfish. The application of herbicides for weed control is usually done when there is no water in the pond, thus limiting the potential for crawfish to come in contact with these chemicals. Farmers should be aware that effective herbicides are generally persistent, with residues remaining in the soil for a long time after application. Unfortunately, there are few data regarding herbicide residues in crawfish pond mud.

Fungicides are generally the least toxic of the pesticides to which crawfish may be exposed. Fungicides are often applied directly to seeds, so unless seeds are planted in water or eaten by the crawfish, exposure to herbicides is minimal. Araxon (Araxon 70S Red) is the most lethal of the fungicides tested on crawfish to date.

It should be noted that studies of residual toxicants (pesticides and heavy metals) in wild and cultivated crawfish have shown no levels that would be dangerous to humans. Crawfish are too short-lived, apparently, to accumulate such compounds.

Various factors affect the toxicity of pesticides to crawfish, including crawfish size, water temperature, suspended matter, and pH. Smaller crawfish are generally more susceptible to pesticides. Research to date suggests that the exposure of female crawfish broodstock to pesticides has a negative impact on reproduction. Pesticide toxicity is invariably increased as temperature increases. Suspended materials, both inorganic and organic, in the water decrease the impact of pesticide toxicity by binding the pesticides and preventing them from reaching the crawfish. Pesticide toxicity is radically changed by the influence of pH. Most pesticides exist as two or more chemical substances, or isomers, with unique toxicological properties. The isomers are altered by pH, thus altering the toxicity of the pesticide in question. Several compounds, nontoxic when alone, can have significant negative impacts on crawfish populations when mixed.

Table 16 lists the relative toxicities of a number of commonly used pesticides.

Crawfish Control Toxicants

Crawfish are welcome visitors throughout Mississippi, Louisiana, and Texas, but are considered pests in many areas. Any of the toxic insecticides listed in Table 15 can be used to kill crawfish in open water. Another compound, Baytex, is an organo phosphate pesticide. It is commonly used to kill crawfish in finfish spawning and fingerling ponds. Good control is achieved at 0.25 ppm. However, the use of this material and the insecticides listed in Table 16 is not approved by the Food and Drug Administration for most fish ponds (and presumably for crawfish ponds). Thus, prospective users of compounds that kill crawfish should check with their county agents before purchasing poisons.

Complete eradication of crawfish is never achieved, as residual brooders escape by burrowing during pesticide application periods. They may also migrate into the ponds from nearby wet areas.

NUISANCE ANIMALS

Semi-aquatic mammals such as otters, muskrats, and nutrias can become nuisances in crawfish ponds. Otters flatten baited traps, forcing crawfish tails through the mesh, and 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 wary animals and difficult to approach.

Ponds built in marshes and swamps or adjacent to them are havens for wildlife. Nuisance animals are especially bothersome in such ponds.

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 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 predaceous 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.

The use of conventional crab traps and monofilament gill nets to control turtles has shown promise. So long as crab traps extend one to three inches above the surface, turtles readily enter them and find it almost impossible to exit; they do not enter submerged crab traps. The monofilament gill nets entangle turtles as they forage about in a pond.

Recent studies have indicated that there is less turtle damage during warm weather (water over 70°F) if traps are baited with grain-based baits or cottonseed cake. The turtles are invariably attracted in greater numbers to traps baited with meat or fish.

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. Semiaquatic vegetation such as alligator weed or late-planted rice does not have this same problem.

Aquaculturists who work with freshwater prawns and marine shrimps are developing artificial

Table 16. Concentrations of pesticides (pounds active ingredient/acre foot) which will kill 50 percent of test crawfish at various time intervals. Pesticides are listed using trade names. The common name is listed in parentheses underneath the trade name.

Pesticide	LC50 (lbs. A.I./acre ft. Time Interval (hrs.)					
	24	36	48	72	96	120
INSECTICIDE						
Agritox (Trichloronat)		2.2				
Aldrin (Aldrin)						0.001
Altosid (Methoprene)						120.4
Ambush (Permethrin)						0.001
Anofex (DDT)	1.6		1.6	1.6	1.6	
Arosurf (Isostearyl Alcohol)				>27194.9		
Azodrin (Monocrotophos)		3.5				
BSP-1 (Bacillus sphaericus Neide)					215.4	
Bactimos (Bacillus thuringiensis var. isrealensis)					280.8	
Baygon (Propoxur)					3.9	
Baytex (Fenthion)		0.060				
Bidrin (Dicrotophos)	15.1		10.9	8.2		
Bux (Metalkamate)					0.761	
Cythion (Malathion)					133.7	
Dibrom (Naled)	16.3		10.9	10.9		
Dieldrix (Dieldrin)		2.0				
Dimecron (Phosphamidon)	54.4		16.3	15.0		
Dursban (Chlorpyrifos)		0.111				
Dylox (Trichlorfon)					0.136	
Endrin (Endrin)	1.1		0.816	0.816		
Ficam (Bendiocarb)					15.1	
Guthion (Azinophosethyl)					0.272	
Niran E-4 (Parathion)		0.220				
Niran M-4 (Methyl Parathion)	0.156		0.109	0.109		
Scourge II (Resmethrin+ Pipernyl Butoxide 1:3)					0.002	
Sevin (Carbaryl)	13.6		8.2	5.4		
HERBICIDE						
2,4,D (2,4,D)					3777.3	
Basagran (Bentazon)					190.7	
Bolero (Thiobencarb)					25.1	
Gramoxone (Paraquat)			14.1	6.5		
Krenite (Fosamine Ammonium)	5719.1		4579.6	4201.6	4003.1	
Modown (Bifenox)					3638.7	
Ordram (Molinate)					38.1	
Oust (Methyl-Sulfometuron)	>27194.9		>27194.9	>27194.9	>13597.4	
Roundup (Glyphosate)					112.3	
Stam (Propanil)					21.5	
Treflan (Trifluralin)	35.3				32.6	
FUNGICIDE						
Arason (Arason 70 S Red)					11.7	
Benlate (Benomyl)					2806.5	
Kocide (Kocide SD)					7935.5	
Orthocide (Captan)					42508.3	
Vitavax (Vitavax)					42508.3	

To convert these values to mg/l divide the number in the table by 2.7195.

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 will encourage growth of grasses like bermuda grass that is preferred by the small crawfish.

FEEDS AND FERTILIZERS

In many aquaculture systems, artificial feeds are used to supplement the natural food supply. Formulated feeds are not used routinely in pond crawfish culture. Instead, 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 (fungi, bacteria, yeasts, etc.), the carbon-nitrogen ratio falls from a high of 100:1 to a desirable low of 17:1. The decomposers need the carbon for their metabolism. The 17:1 ratio figure represents the point at which detritus will become an especially good food source for most detritivores such as the crawfish. Note: The crawfish eat the microbially enriched detritus but digest only the living layer of microbes on the surface. Remember, as the detritus is broken up, more microbes grow on it. Furthermore, surface area to volume ratio increases.

If one examines plants in ponds closely, a film of living organisms can be seen below the water line. This animal and plant assemblage dominated by plant-algae is called *epiphyton* or *awfuchs* and, along with microbially enriched plant detritus, is an important source of basic sustenance for crawfish. Crawfish keep this material closely grazed. Epiphyton may, in fact, be the major food source in newly filled ponds where the plant base—rice, alligator weed—is still living and no detritus has begun to form.

Green plants (including the algae in epiphyton) are essential components in the diets of healthy crawfish, which have a bright yellow hepatopancreas and well-pigmented shell. The color is derived from plant pigments called carotenoids. There has been much discussion concerning the absolute nutritional value of green plants in ponds; however, it is clear that if crawfish do not have access to such plants, they will not be healthy. This is certainly one value of alligator weed, which is common in ponds dominated by natural vegetation.

All crawfish ponds support a multitude of benthic and clinging creatures, which include insects and their larvae, worms, and mollusks (mostly snails), as well as planktonic creatures like water fleas, copepods, and ostracods. These provide essential animal nutrients not otherwise available in plant foods—especially important for immature crawfish.

Natural Feeds and Crop Rotation

Three basic feed "delivery" methods have been developed in the Louisiana crawfish industry. Dr. Martin Brunson has been a leader in crawfish forage research and much of the following commentary is based on his work in this important facet of crawfish farming. He categorizes these delivery systems as follows: (1) use of volunteer natural vegetation, (2) use of agricultural wastes and supplemental feeds, and (3) use of planted and cultivated forage crops.

Natural Vegetation

The oldest, simplest, and least expensive feed delivery method is the use of volunteer natural vegetation. Native plants are allowed to grow unchecked in the pond during the summer and then flooded in the autumn. Many plant species, both aquatic and upland, have been used in this manner, but aquatic plants are typically better suited to crawfish production. Native terrestrial or "dry land" plants are much less desirable and generally decompose so rapidly after autumn flooding that they affect production negatively: oxygen is depleted and forage does not last through the season.

Aquatic and semiaquatic plants thrive in crawfish ponds and persist longer under winter flooded conditions than do upland plants. Among the most commonly used native plants are alligator weed (*Alternanthera philoxeroides*), water primroses (*Ludviqia* spp.), and smartweeds (*Polygonum* spp.). Others, such as delta duckpotato (*Sagittaria* *platyphylla*) and wild rice (*Zizania aquatica*), have also been used. Various grasses and sedges, especially semiaquatic species, are found throughout such ponds. Generally, crawfish production from ponds with native vegetation is lower than that achieved when a cultivated forage crop is used, but it is not necessarily because of inferior forage. In many instances, the intensity of management in such ponds is lower than that in planted ponds.

The detritus base in wooded ponds includes soft-stemmed vegetation as well as leaves, the amount depending on how open the pond is. Leaves with low levels of tannins and lignins, like maple, are preferred as food by crawfish and other detritivores. Oak leaves take much longer to decompose although they seem to provide a good surface on which epiphyton can grow.

In the typical situation, one or more of these native plants is allowed to grow voluntarily in the pond during the summer and fall. In some cases, limited cultivation or fertilization is used to stimulate growth. At the autumn flooding, the farmer has a readily available forage base for crawfish production, and because many of these plants are aquatic or semiaquatic, they continue to thrive until freezing temperatures arrive.

Using native aquatic vegetation has several major disadvantages. First, since these are volunteer plants, it is not certain that an adequate stand and suitable biomass for crawfish forage will be obtained. Cultural practices for these plants are not well developed, thus contributing to greater uncertainty in stand establishment. Secondly, many native plants are considered to be weed species and, as such, are undesirable in agricultural fields where other crops, especially rice, will be grown in later years. Finally, unless a pond has a large crawfish population, alligator weed can grow so quickly in the spring that it can stop water flow and sometimes interfere with harvesting.

Agricultural Wastes

Many by-products and waste products from agricultural activity have been evaluated as crawfish feed. Among the materials tested were sugarcane (*Saccharum officinarum*), sugarcane bagasse, sugarcane filter cake, chicken manure, sweet potato (*Ipomea batatas*) trimmings and vines, rye hay (*Secale cerale*), soybean stubble and hay (*Glycine max*), rice hay (*Oryza sativa*), and bahiagrass hay (*Paspalum notatum*). Although several of these supported crawfish growth, only the hays were found to have practical potential for large-scale commercial crawfish ponds. Hays such as rice and bahiagrass can be used to supplement food supplies in ponds late in the crawfish season (spring) when the primary vegetation in the pond becomes limited or depleted. The addition of 300-500 pounds per acre of hay provides vegetative matter that enters the detrital food chain, thus providing suitable crawfish food. This practice is common, and although its efficiency is not thoroughly documented, positive results have often been reported.

Planted Forage Crops

The most efficient and dependable method of providing crawfish forage is through the use of a cultivated crop. Using a crop species has several advantages. The crawfish farmer controls the type of forage that will be available, instead of relying upon volunteer vegetation. An adequate stand of vegetation is assured, and concern about subsequent problems from unchecked weed growth is eliminated. In many cases, the farmer can realize a cash crop from the forage plants while supplying fodder for crawfish.

Several commercial plants have been evaluated as crawfish forage, including rice, Japanese millet (*Echinochloa frumentacea*), sugarcane, and soybeans. The most promising is rice. Crawfish have been incidentally harvested from rice fields for decades, and rice has proven superior, both to other planted forages and to natural vegetation, for crawfish production. With 300,000 to 600,000 acres of rice in Louisiana, the potential for integrating rice and crawfish is great. Cultivation timing for rice fits nicely into the crawfish production cycle. Additionally, because rice is a semiaquatic plant, it persists longer during the autumn and winter months than would other species that are less well adapted to wet conditions.

Recent studies indicate that certain varieties of rice are better suited than others for crawfish forage. Most of the rice-crawfish studies before 1984 used the rice varieties "Labelle" and "Saturn," which have been popular in Louisiana. With such forage parameters under winter flood, and nutritional quality, other varieties appear superior to these for crawfish systems.

There are a number of varieties that not only provide adequate crawfish forage during the autumn and winter, but persist through the winter, thus providing crawfish with fodder at a time when other forage crops have been depleted. Recommended long-grain varieties include Labelle and Lemont for use in double-cropping and Starbonnet, Newbonnet, or Bellevue for crawfish monoculture.

An excellent medium grain for both double-cropping and monoculture is Mars, and Nortai is a good short grain for both types of culture.

There are basically two approaches to rice-crawfish culture. In the first, both rice and crawfish are raised as cash crops. Rice is planted in early spring and harvested for grain in late summer. The rice stubble is left standing and ratoon growth (green regrowth) is encouraged. The field is reflooded in early autumn and crawfish subsist on the decaying rice stubble and green regrowth. In the second approach, rice is planted solely for crawfish culture, with no concern for grain production. In this strategy, rice is planted in mid to late summer and the grain, if produced, is not cut. The entire rice plant then remains to provide crawfish forage. This method is most often used by landowners participating in governmental "set-aside" programs that mandate later planting dates, or by farmers who extend their crawfish harvest seasons into early summer, thereby necessitating the late planting of rice.

Although crawfish have been harvested from rice fields for many years, intensive commercial rice-field crawfish culture has only recently been established. Thus, production techniques are not highly refined and many questions are as yet unanswered. For example, some of the pesticides used on rice are highly toxic to crawfish. Consequently, the double-crop farmer assumes that he must choose whether to emphasize rice or crawfish. To maximize crawfish production, the use of rice chemicals is limited, and many times grain production ultimately suffers. Cultural and management practices for rice and crawfish must be developed to aid the full production of both crops.

Rice is currently the most frequently recommended forage, but it is not the ideal choice used alone. In many respects, the ideal forage may be a combination of rice and natural vegetation such as alligator weed.

Other agronomic crops may have potential as crawfish forage and for double-cropping with crawfish. One group of plants recently identified is the sorghums (*Sorghum* spp.). Grain sorghum, or milo (*Sorghum bicolor*), acreage in Louisiana has increased more than twenty-fold since 1979, and preliminary studies reveal that it might be a viable and desirable alternative to rice for double cropping with crawfish. Another sorghum that appears to have great potential is a sorghum-sudangrass hybrid. Most commonly used as silage or hay, this plant exhibits prolific growth and regrowth, producing during the summer several tons of dry biomass, which may later be used as crawfish forage.

Both sorghums are drought-resistant and might provide the farmer with the necessary "dry land" crop in his normal cropping system rotation. In rice producing areas, farmers typically rotate their rice fields into another crop (traditionally soybeans) every second or third year. Soybeans have little potential as crawfish forage, but the substitution of a sorghum provides the opportunity for production of a crawfish crop during the "off year." A field used for crop-crawfish rotation is typically drained in late May or early June and planted with soybeans after the crawfish crop is har-vested. However, it is not reflooded in the autumn after the soybean crop is harvested as it would be otherwise had rice been grown over the preceding summer. This is because there is normally not enough vegetation remaining in the field to sustain a good crawfish crop.

In the rice-crawfish-soybean rotation, it is possible to produce three cash crops in two calendar years, an idea that gave rise to the "3 in 2" multicropping concept. However, with the substitution of sorghum for soybean the potential exists for a "4 in 2" system, in which multicropping is fully developed and maximum productivity of soil, water, and energy resources can be realized.

Management practices for various crawfish-vegetation plans follow:

Rice-Crawfish-Rice-Rotation

March/April	Prepare ground and plant rice.
June	At permanent flood (rice 8-10 inches high), stock 50-60 pounds of adult crawfish per acre.
August	Drain pond over one week and harvest rice.
October	Reflood field.
November to March/April	Harvest crawfish.
March/April	Replant rice.

NOTE: This rotation has been done for years but consideration must be given to the pesticides used in rice culture and pond circulation patterns through rice fields. Dates in north Louisiana will be one month later for planting rice.

Rice-Crawfish-Soybeans Rotation

March/April	Prepare ground and plant rice.
June	At permanent flood (rice 8-10 inches high) stock 50-60 pounds of adult crawfish per acre.
August	Drain pond over one week and harvest rice.
October	Reflood field.
November to May	Harvest crawfish.
Late May/ June	Plant soybeans.
March/April	Repeat with rice.

NOTE: This rotation has worked well in areas where land is switched to another crop every other year. It allows three full seasons for three crops and does not cut short the crawfish season. Use of pesticides is an important consideration in this rotation. *If a sorghum is substituted for soybeans, then the field is reflooded in October and there will be no need to restock the pond with crawfish unless there has been a loss of stock over the previous summer.*

Rice—Set-Aside

April/May	Flood field and stock 50-60 pounds of adult crawfish per acre.
May/June	Slowly drain pond over three weeks.
August 1	Plant rice and lightly flood or flush rice. Check ASCS (Agricultural Stabilization and Conservation Service) office for first planting date.
October	Reflood pond.
January to May	Harvest crawfish.
May	Slowly drain pond. Stocking not normally necessary, as surviving crawfish are usually adequate to produce young for next season.

NOTE: This rotation is for farmers in the extant set-aside program, which allows them to use idle land for crawfish. Regulations are subject to change, so farmers must check with their local ASCS offices to assure that they are in compliance with current regulations.

Permanent Crawfish Ponds

April/May	Stock 50-60 pounds of adult crawfish per acre.
May/June	Slowly drain pond over three to four weeks.
June/August	Plant rice at 60-70 pounds per acre. Mars is the variety recommended for Louisiana.
October	Reflood pond.
November to May	Harvest crawfish.
May	Slowly drain pond. Stocking not normally necessary, as surviving crawfish are usually adequate to produce young for next season.

NOTE: Most farmers prefer this rotation because they can set up the pond properly once, keep traps and pumps in one location, and need not restock the pond. *Sorghums are being substituted for rice as a forage. Check with your local Extension Service office for current recommendations on forage crops for your area.*

Artificial Feeds

Laboratory and pool studies have demonstrated that crawfish readily consume fish and crustacean feeds. The cost of artificial feeds is such that those designed specifically for crawfish have only recently been developed. They are so new, in fact, that precise recommendations and economics for pond use have not been refined. The basic problem is simple. There is, as yet, no way to predict the actual numbers of crawfish present in a pond because known numbers are not stocked as is the case in most forms of aquaculture. Crawfish ponds are "self stocking" and "stock" themselves over a period of several months. Furthermore, it is almost impossible to observe feeding activity, as is the case with fish systems, in which floating feeds are used. Even when crawfish densities can be predicted, feeding has not led to significant gains in the weight of individual crawfish in very dense populations where density-dependent factors interfere with growth.

Protein is the most expensive part of an artificial animal feed. It appears that in tanks and pools red and white crawfishes require 25-30 percent protein in artificial feeds, of which 15-20 percent must be of animal origin. In one laboratory study, the fastest growth and protein deposition in red crawfish were observed when they were given a protein:energy ratio of 120 milligrams of protein per kilocalorie, in a diet containing 30 percent crude protein and 2.5 kilocalories per gram of dietary energy. Both red and white crawfishes are very efficient at utilizing plant proteins and carbohydrates in feeds. Lipids (fats) should probably not exceed about 6 percent of any artificial feed. In confined systems, crawfish on artificial feeds become very pale after several molts. If they are to retain normal pigmentation, their diets must be supplemented with a source of carotenoid pigment such as fresh, succulent plant material (elodea, alligator weed). In general, feeding rates of about 3 percent of estimated body weight per day when water temperatures exced 68-70°F produce good growth in tanks and pools.

Supplemental feeds in crawfish ponds may be effective with protein levels of 15-20 percent. This is because there is much natural food in ponds. However, there is not enough experience with supplemental feeds in ponds to make any recommendations.

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.

POND CRAWFISH POPULATION DYNAMICS

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

A general statement about crawfish ponds as they are now managed is needed here. Ponds are managed by establishing sustaining populations. In areas with no resident red swamp or white river crawfishes, it may take several years before good populations are established. In such areas, first year production is usually several hundred pounds per acre of very large crawfish. Production can reach 1000 pounds or more per acre of smaller but very nice crawfish in the second or third year. In areas with resident crawfish populations, production is usually high in the first year but size is moderate.

Farmers report more frequently now poor production after a year of producing 1000-2000 pounds per acre. This seems to be associated with many small crawfish. That is, reproductive success of surviving brood stock was so great that high densities inhibit growth. Density should be reduced to enhance growth rates but prices for the small crawfish are so low that the farmers do not harvest then, compounding the problem. We do not stock known numbers of crawfish in our ponds the way catfish and trout farmers do. Until we can control numbers and match them to pond conditions and production goals, crawfish management will be an art, not a science. Planning economics on yields over 600 pounds per acre is not advisable.

The development of a computer simulation model of crawfish pond population dynamics by Dr. Robert P. Romaire of Louisiana State University is a major first step in effective crawfish pond management. It is particularly ironic that the model depends heavily on basic red swamp crawfish biology data reported in the 1950s and 1960s by Professor Tetsuya Suko of Saitamu University in Japan, a land that considers the red swamp crawfish to be a pest!

Stocking

Species to Stock. We recommend stocking only red crawfish because we do not have enough data about white crawfish to make recommendations. In addition, the red swamp crawfish is the preferred food species in Louisiana.

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 to 1500 pounds per acre per year are considered to be attain-able in well-managed ponds. A little constructive computation reveals that 8 pounds of female crawfish are all that are needed to produce that sort of crop. The average crawfish used for stocking is 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 pound must be harvested to obtain a yield of 1000 pounds per acre, 144 females are required per acre. At 20 per pound, the total weight of required females is slightly more than 7 pounds. As the male-female ratios are normally 1 to 1, stocking 20 pounds per acre should be adequate for any pond. Some crawfish must be left in the pond to pro-duce young for the next year.

Average production in Louisiana is 500-600 pounds per acre. Mortality rates of both brood crawfish and young crawfish are, obviously, quite high.

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 enter (or leave) these ponds throughout the year. As a result, "unstocked" ponds have generated substan-tial 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. If a pond is built early enough in the year so 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 poorly yielding pond the following year.

The white river crawfishes occupy most of the same range as *P. clarkii*. It is not surprising, then, to find them in ponds stocked almost entirely with red crawfish. New ponds where red crawfish introductions were not very successful in the initial year are often "saved" by strong production from white river crawfish that inhabited the area prior to pond construction. Subsequently an equilibrium is reached between the two species, with red crawfish almost always dominating the system, as previously discussed in the ecology section.

The key is survival of the broodstock. With reduced amounts of cover, their chances for survival are reduced drastically. Production less than 1000 pounds 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 pounds per acre per year in extremely well-managed ponds, the need for improving the survival of broodstock seems to be warranted.

Another reason for poor production is **too many** crawfish. That is, growth is density dependent, and when there are too many young, none grow very well. So, how many are too many? This depends on the amount of forage, vertical substrate in the pond, water quality, and harvesting activity. Unfortunately, scientists have not yet worked out the relationships between densities and these factors. Production has reached 4000 pounds per acre. At 20 crawfish per pound, density would be around 80,000 per acre. However, this is probably the upper limit with lower densities needed to insure production of 20 per pound for larger crawfish. The use of baffle levees in crawfish ponds may lead to overpopulation because of increased burrowing sites.

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. The 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.

Care of Brood 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 often walk away from a pond. We recommend that pond crawfish be stocked in preference to Atchafalaya basin crawfish. There is no justification to the belief that they will improve the genetics of existing pond 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.

If crawfish have been out of the water for a long time, their gill chambers may be full of air. They will float when put into deep water and may be unable to reestablish water flow over the gills. If this is the case, they must be allowed to walk into the pond so that they can refill their gill chambers.

When crawfish are moved, their gill chambers must remain moist. Crawfish can have moist air in the chambers, but if the gills dry, the crawfish will dehydrate. Moist packing material, like newspaper, sponge rubber, and shavings, and/or periodic showers of water must be employed.

There is much doubt about the effects of shipping on brood crawfish. As the Wrights point out elsewhere, the natural environment of crawfish is water, and they are under stress when out of it, especially when jammed into an onion sack. The Wrights recommend that brood crawfish be shipped in water, either in plastic bags filled with oxygen or in regular fish-hauling tanks. Otherwise, females under stress often reabsorb their developing eggs. Without conclusive research, one can only speculate on the proper shipping rates. However, those figures used for catfish, which have a similar physiology, are probably appropriate.

Purged catfish are shipped in 65-70°F water at rates of about 1-2 pounds per gallon of water in tank trucks with agitation aeration systems or compressed oxygen systems over 24 hours. Small catfish are shipped in plastic, oxygen-filled bags at rates of 3-4 pounds of fish and 16 pounds of water (about 2 gallons) for 24 hours. It is best to use two bags, 6 mil thick, one inside the other.

No person should, however, contemplate substantial shipments of crawfish anywhere without making experimental "dry runs" first. Crawfish physiology changes according to the time of year, and a shipping method that works in December may be fatal in May.

The system for shipping stocking crawfish described initially is probably effective in most production areas simply because distances and times are short. Yet we really do not know how effective they are because native crawfish often invade new ponds from surrounding areas. Our experience in restocking crawfish caught the same day suggests mortality rates of about 50 percent even where every effort was made to insure their survival. Further research is certainly needed to establish the most effective and least expensive methods of shipping brood crawfish.

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 have many existing burrows, which are 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 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 happen to be convenient. In areas with abundant cover, it appears that the crawfish secrete themselves beneath the cover rather than excavate burrows; however, more data are needed before the subject can be fully understood.

It is rare to find many burrowers on pond bottoms proper. The crawfish prefer to burrow in levees. When ponds are drained, the bottoms are slurries of anoxic potentially toxic muck. It is basically too soft to make anything but a shallow hole, and the crawfish must constantly rise to the surface to obtain atmospheric oxygen. Thus, the crawfish is constantly exposed to predators until water tables fall well below the surface, a period of 10-15 days. Often, the combined stresses of anoxic water and high temperatures kill the crawfish that escape predators.

For the red swamp crawfish, burrowing is critical not only to the survival of natural populations but also to successful culture in earthen ponds. Few published reports discuss this critical phase of this species' biology in cultural situations; however, Billy Craft (state biologist, Soil Conservation Service, Alexandria, La.) has conducted several unpublished studies of the burrowing behavior of this species in crawfish ponds. A summary of his findings follows.

Craft studied two ponds during a dry summer when the water table had declined to nine feet below the surface by the time the ponds were reflooded in late September. Thirty-three burrows were excavated, but only one crawfish was found to continue burrowing to follow the declining water table. Except for that one, none of the other crawfish were found below a depth of five feet. Eighty percent were found at a depth of about three feet.

Craft's study was done to determine whether crawfish need free water to survive the summer. He found free water in only one burrow when the burrows were excavated in late September, though all had 100 percent humidity from the soil moisture. While the crawfish fared well in their burrows, none bore eggs, so the water requirement for egg laying and egg development is still an unknown factor. Then, too, the ability of juvenile crawfish to burrow deeply enough to reach saturated soil is still not known.

It is the general consensus that ponds with clay soils do not need supplemental wetting during dry summers; however, silty clay soils should be soaked if normal rains do not fall. Caution must be taken to insure that any water, whether from rainfall or irrigation, soak in quickly. If it is allowed to stand, the crawfish will be forced from their burrows into shallow waters that are hot enough during the summer to be lethal.

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 maturing holdover juveniles. These 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 four to six 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. Note: It is still not clear as to how many levees are too many. That is, if there are too many burrows, density of young crawfish may be so high that the crawfish stunt.

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 productive 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.

New ponds should lack holdover juveniles unless native crawfish, red or white, were already present in the pond area when it was built. Reproductive failure, coupled with absence of native crawfish, usually means very poor crawfish production in the first year. It is probably wise to restock such a pond lightly if substantial numbers of crawfish do not appear and crowd the pond at the end of the season.

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 predaceous fish.

In the October-December period, the harvesting of holdover females that have not spawned can present a serious problem. It can eliminate a theoretical production of 9 pounds 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 that reaches 1 inch in length will survive to reach a harvestable size. Survival to 1 inch can be highly variable and may be as low as 5 percent. 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 1,000 to 1,500 pounds per acre of crawfish year after year, regardless of the presence or absence of wading birds, predaceous insects, and spiders (see life history section). They will invariably fail, however, if large numbers of fish such as green sunfish, bullheads (polliwogs), 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.

What does one do if excessive numbers of predaceous fish are present in a pond in the fall? Regrettably, one can only speculate about the effectiveness of various options. These can include complete draining and reflooding, partial draining and poisoning of the fish, and marginal poisoning with fish toxicants to kill the fish along the shore where they usually concentrate. Cost-benefit ratio is just not known. It is easy enough to calculate the costs of toxicants, labor, water, and pumping, but the increase in yield is impossible to predict. For example, if the fish are small enough, generous crawfish crops can still be harvested because the fish are too small to harm the majority of the young-of-the-year crawfish; however, if the fish are bigger and the initial yields of young crawfish die for various reasons, a pond may not even produce a harvestable crop. The close monitoring of the crawfish pond is necessary to provide appropriate management information as quickly as possible.

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 predaceous 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 (*Ranatra* spp.) and the giant predaceous 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 predaceous 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. 64, 65, 66).

Giant predaceous water beetles (2-3 inches) 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. 67, 68).

Dragonfly nymphs, especially the large (2-3 inches) *Anax* spp. nymphs, 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 one-third of the length of their bodies. Prey is grasped and drawn back to the mouth where mandibles crush and tear it apart (Fig. 69).

Fig. 64. Water scorpion, *Ranatra* sp.

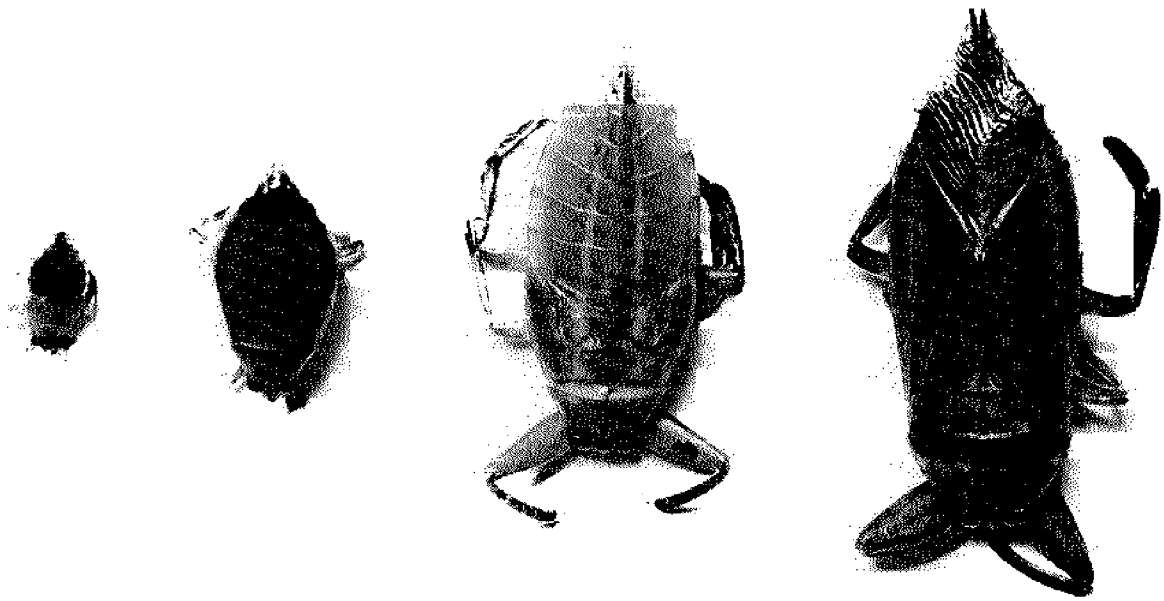


Fig. 65. Giant predaceous water bugs, *Lethocerus* sp. (adult), *Lethocerus* sp. (juvenile).

Fig. 66. Backswimmers, *Notonecta* sp.

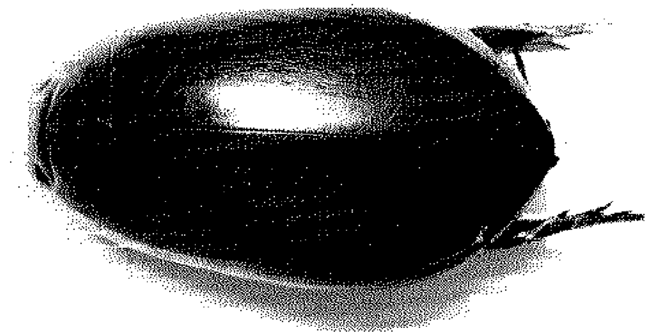


Fig. 68. Giant predaceous water beetle larva, *Cybister* sp.

Fig. 67. Giant predaceous water beetle, *Cybister* sp.

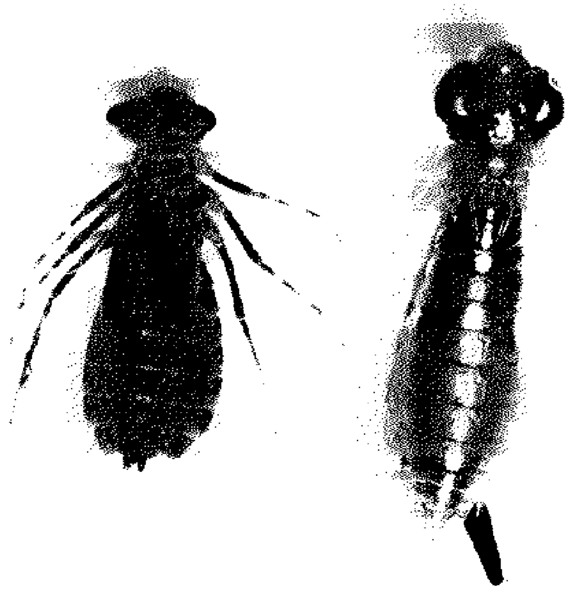


Fig. 69. Dragonfly nymphs, *Anax junius* (right) and *Pachydiplax longipennis* (left).

Fig. 70. Fisher spider, *Dolomedes* sp.

Besides predaceous insects, the large (2 inches) 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. 70).

Most of the mortality of young crawfish in crawfish ponds, other than that caused by bad water, is undoubtedly caused by predaceous 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. 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 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 percent 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 percent 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. Otters, *Lutra* spp., relish crawfish and have been reported a problem in such diverse places as Louisiana, Spain, and Zambia.

Movements In and 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 five 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.

Very little is known about the existence of home ranges in red crawfish. Dr. Alan Covich of the University of Oklahoma, Stillwater, has placed radiotransmitters on large adult red crawfish and tracked them in 1/10-acre ponds. He found that they moved 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. The Louisiana state average has consistently been 500-600 pounds per acre. 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 March to accommodate rice production produce 300-500 pounds per acre per year. Those kept flooded into late April or early May can be as productive as open ponds. 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 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. Mr. Warinner practiced nontraditional 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. However, yields up to 3,500 pounds per acre have been generated in uncirculated, traditional ponds, suggesting that there is much to learn, yet, about pond management.

There is no reason open ponds cannot produce 4,000 or more pounds per acre with supplemental stocking of young crawfish, supplemental feeding, and circulating/aerating water on a massive scale. These practices, however, are not yet 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 the section on the reproductive system). If most of the males are small and in the Form I condition, stunting is a problem (Fig. 71).

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.

One theoretical approach to stunting problems is to kill as many of the crawfish as possible in late April or May by applying a toxicant or by draining the pond very rapidly. This practice is thought to reduce the number of crawfish in the pond so that those remaining will grow larger in the next season and fewer young will be produced, also reducing competition. We must emphasize that though this appears to have been effective in some ponds with chronic stunting problems, replicated studies have not yet been conducted to verify the applicability of this practice. A strong argument against this is that prices have been highest in the fall and winter regardless of crawfish size. Because

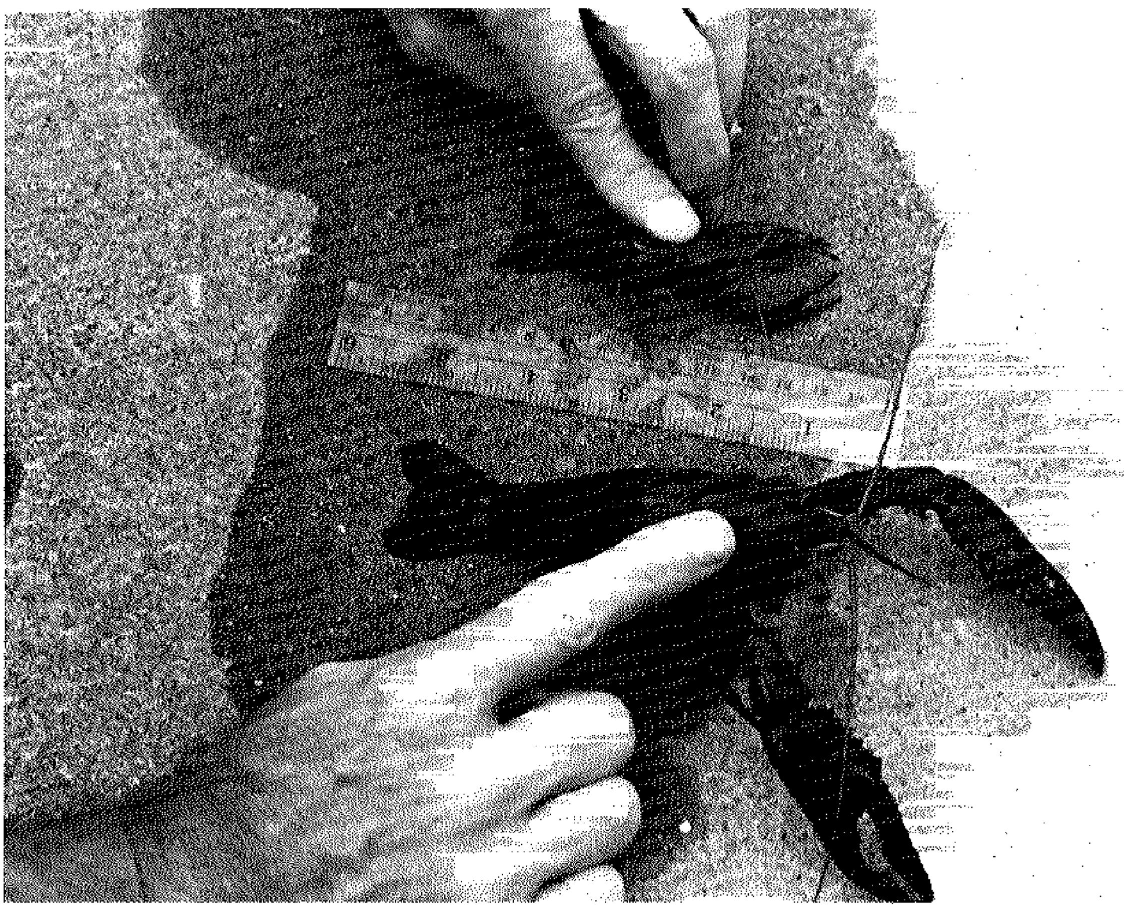


Fig. 71. Mature, Form I male red crawfish.

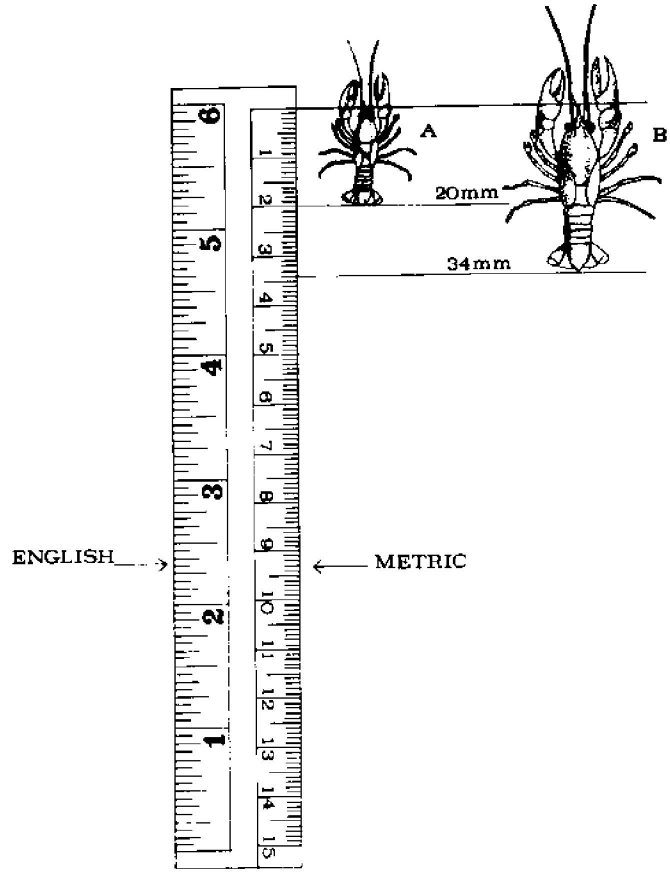
the greatest income is generally earned during this period, the reduction in numbers of holdover crawfish could seriously reduce profits.

An alternative approach to killing stunted crawfish is to move them into an unstocked pond before they mature and stop growing. This has proved to be an economically viable activity when premium prices are paid for large crawfish. Stocking rates of 400 to 500 pounds per acre in April or May have realized yields of 1200 to 1300 pounds per acre in 6-12 weeks.

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 other's 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. 72).



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. 72. Measuring crawfish using the metric system.

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. Plastic-coated five-eighths-mesh crawfish wire is available commercially. It is much easier to handle than hardware cloth and is adequate for sampling (Fig. 73).

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.

Sampling ponds is tedious work. It can also be 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

Fig. 73. Crawfish ponds monitored with a dip net.

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, they 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 high, however, because the crawfish dispersed into the rest of the pond as they grew.

Most small crawfish congregate around the edge of the pond. However, if there is no cover there, they move offshore 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 cover away from the shore.

Dipping for crawfish can be very difficult in early season if pond banks are grown up. First, it is difficult to get to the water, and second, it is hard to drag a dip net through the heavy vegetation. 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.

Determination of Age Classes. 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, 6-inch (150 mm) plastic ruler on a flat 12 x 4-inch 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. 74).

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 (Fig. 75).

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
5%	15%	10%
20-24 mm	25-29 mm	30-34 mm
5%	10%	25%
35-39 mm	40-44 mm	
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.

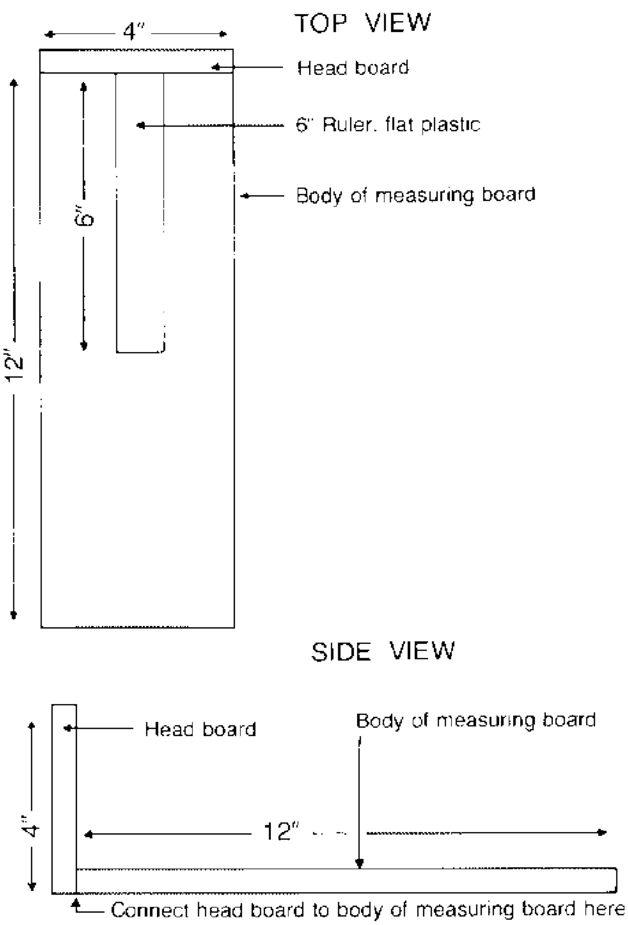


Fig. 74. Measuring board.

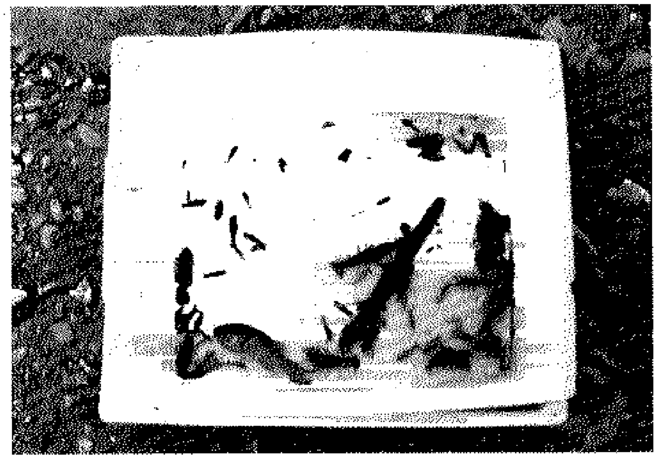


Fig. 75. Different size classes should be present in ponds if production is to be abundant.

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. See Appendix B for assistance in learning how to determine age classes from field data.

Determination of General Magnitude of Crop (Potential Yield). Table 17 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 one 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 one 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 one crawfish per dip. A good rule of thumb for determining survival is to keep track of the average size of crawfish caught by dip net. 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 classes of young-of-the-year crawfish should be

Table 17. Seasonal monitoring of Louisiana crawfish ponds to predict yield.

Seasonal Small Mesh Dip Net Catch Oct./ Mid Dec.	Late Dec./ Mid Feb.	Late Feb./ Early April	Identifiable Age Classes of Young Crawfish	Production Schedule	Probability of Stunting	Potential Production Per Acre
High	High to Spotty	High	5-6	Commercial catches (0.5-1 lb/trap) in Dec.; high catches in late March.	High	>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	

NOTE: Dip netcatch—high, over five per dip; medium, one to five per dip; and low, less than one per dip. Catch per dip is very subjective. In areas with heavy cover, several dips must be made to catch crawfish, though one dip would be sufficient in areas with short-soft-stemmed grasses on a gentle slope.

*Pond good candidate for supplemental stocking of small crawfish (40-70 per pound) if economics are favorable.

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 B).

When the number of young crawfish stays one or more per dip, but average size varies 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 high 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. 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 size 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 dip net catch is consistently very low into the spring, trapping may not be really successful until middle or 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.

Other Pond Monitoring Methods. Dip net samples do not adequately sample crawfish over 2 inches in length. Conventional seining is effective in open water, but emergent vegetation makes this difficult in most ponds. One way to solve this problem is to add a heavy chain to a seine's lead line. This will knock down soft-stemmed vegetation and provide a more representative sample of the pond's crawfish population. It is also an effective way of obtaining modest numbers of soft-shelled and premolt crawfish. Seines are useless in ponds with thick-stemmed vegetation and extensive algae mats. In addition, seines require two operators.

Some specialists report success in sampling ponds by dragging a small-mesh dip net through the pond from a harvesting boat. Such a net should have a heavy-duty handle and frame, and great care should be exercised to avoid stumps and other fixed objects, lest the operator be thrown from the boat.

It is possible to make a sorting table from different meshes of hardware cloth at different levels. The crawfish are dumped on the upper, coarsest mesh. They subsequently sort themselves, with the smaller ones falling downward, until a lower mesh retains them. There is some disagreement about the number of meshes needed to separate the crawfish into legitimate age classes, but this is definitely a labor-saving technique.

Crawfish and Waterfowl Management

The vegetation grown in crawfish ponds produces seeds, corms, and tubers that are relished by waterfowl. Ponds in which rice was intentionally cultivated for harvest or crawfish fodder are especially attractive to waterfowl. Shallow water and the proximity of natural feeding and resting areas add to the lure of crawfish ponds. Thus, one can expect crawfish ponds to generate waterfowl hunting and they do, providing owners with recreation and additional income from those willing to lease hunting rights.

There are some problems with crawfish-waterfowl management. Waterfowl are generally most abundant in ponds after sunset and before dawn, feeding and roosting in the ponds during the night, before and after legal shooting hours. The least disturbance tends to drive them from the crawfish ponds during the day. Thus, extensive crawfish harvesting substantially curtails waterfowl hunting in crawfish ponds. The most successful waterfowl hunting invariably occurs during cold, stormy weather and anyone hunting at a pond should be flexible enough to take advantage of weather changes. Also, most waterfowl prefer to land in open areas, and these should be available. Finally, shallow water levels, about 12 inches, are required for the more sought-after puddle ducks like mallard, pintail, teal, and widgeon. If there is much slope in a pond, substantial areas may have little or no water over them during the late fall-early winter waterfowl season.

Marsh-type impoundments managed strictly for waterfowl can produce crawfish crops. These systems are drained in the summer to permit the growth of various waterfowl feeds and filled during the fall, winter, and spring. Generally, crawfish production has been low, 100 to 300 pounds per acre. The major problem has been one of water quality. Waterfowl impoundments are usually so large that pumps are ineffective in circulating water to improve water quality. Also, vegetation biomass is generally great and this complicates oxygen problems, especially if ponds are filled before the weather cools in the fall. There is no doubt that ducks, especially diving ducks, and coots eat crawfish. There is probably little real damage as compared with that caused by low oxygen levels; however, definitive research is necessary to assess the severity of this potential problem.

Green tree reservoirs are swamp areas that are drained in the spring and filled during the waterfowl season. Trees like water oaks produce mast (acorns), which is actively sought by puddle ducks. Theoretically, there is no apparent difference between green tree reservoirs and wooded, swamp-type crawfish ponds. However, green tree reservoirs are usually drained in March, two to three months before swamp crawfish ponds are drained. This is done to prevent stress and damage to the desirable mast-producing trees in the reservoirs but is contrary to good crawfish pond management. Research needs to be conducted on the effects of extended flooding on mast-producing trees in green tree reservoirs before crawfish cultivation can be advocated in them.

POLYCULTURE: CRAWFISH AND 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 1000 pounds of crawfish per acre, about 3000 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.

In one study, 5- to 7-inch fingerling channel catfish were stocked directly into small experimental crawfish ponds in late September at rates up to 5000 per acre. Crawfish production was as high as 1000 pounds per acre and was adversely affected only in ponds that were contaminated with green sunfish. Catfish growth was poor; the production was around 500 pounds per acre, but this was attributed to poor water quality and low winter growing temperatures. The catfish were only one year old when harvested in late May and had reached the so-called stocker size suitable for growth to one pound in four to eight weeks.

Crawfish production up to 800 pounds per acre has been generated during the summer in small ponds stocked with freshwater prawns, *Macrobrachium rosenbergii*. These ponds had well-established crawfish populations but were fallow and dry for most of the winter and spring. They were drained completely, refilled, and stocked with post larval prawns (1/2-inch) in May. Most of the crawfish were harvested from mid-June to mid-July. The crawfish generally disappeared when, in early August, the prawns reached a size large enough to kill them. Similar predatory relationships, in which large prawns eliminated crawfish, have also been observed in tropical Hawaii.

Tilapias (*Sarotherodon* spp.) grow well in shallow ponds such as those used to cultivate crawfish. This is a possible summer crop in areas of the United States where these exotic fishes may be cultivated, though no tilapia is legal in Louisiana. One report from Zambia suggests that crawfish may, in fact, interfere with tilapia spawning by disrupting activities in nests. If this is true, crawfish should be most useful in controlling the overpopulation of tilapia and the resultant stunting, the most common management problem in tilapia culture. Tilapias do not normally prey on crawfish.

ARTIFICIAL SPAWNING OF RED CRAWFISH

At this time, setting up hatcheries and stocking small red swamp crawfish in ponds is not practical because it costs too much to be competitive with natural reproduction in crawfish ponds. However, the production of young crawfish on demand will undoubtedly become important in crawfish farming in future years, especially as high-value products like soft-shelled crawfish make it feasible to manage ponds intensively.

A method for producing young red swamp crawfish for laboratory use during most months of the year has been developed by Dr. Joe B. Black of Louisiana College in Pineville. It is relatively simple. Mr. and Mrs. John Wright of the Newberry Crayfish Hatchery in Santa Barbara, California, developed a somewhat similar but large-scale method to produce small crawfish. Mr. Donald Gooch modified Dr. Black's method while he was director of the Crawfish Center at the University of Southwestern Louisiana to permit more cost-effective production of small crawfish for early autumn. These methods are discussed as follows.

Black Method

Adult breeding specimens are maintained in individual glass stacking bowls, 8 x 3 inches (obtainable from almost any biological supply company). No aeration is needed if the water is not too deep and is not fouled by overfeeding. A substrate of pea gravel covers the bottoms of the bowls and water levels are kept at about 1 1/2 inches, or just enough to cover the crawfish. Water is changed every seven to ten days. In most cases, chlorinated tap water can be used, but it is best to age it a day or so.

Feeding is simple and cheap. Though they eat almost anything organic, crawfish 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 from a compost pile are added and seem to provide the greatest bulk of the food consumed. Though maple is a good choice, any type of hardwood leaf can be used. Dr. Black uses water oak extensively. If dry, the leaves should be soaked first. Three times weekly a small portion of high protein feed such as the new crawfish feeds or dry cat or dog food is added for each crawfish. *Do not feed them more pellets than they will eat in 15-30 minutes.*

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, about 12 to 14 hours of light per day, but lights are used at night only for emergencies.

A mature, Form I male crawfish (enlarged claws and hooks on the bases of the walking legs) is added to a bowl containing a single, mature female crawfish (claws somewhat enlarged and distinct groove in the sperm receptacle). Breeding is more likely to be successful under these conditions than if the female is placed into a bowl with a male. After successful mating, the sperm receptacle of the female contains 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 or the same female may be bred to several different males if paternity is not a concern.

It is possible to obtain an estimate of the time that eggs will be laid by observing the female's glair glands. These are structures on the bottom of the tail fan and around the bases of the abdominal appendages (swimmerets). They are not normally distinct but as the time for egg laying approaches, the glair glands enlarge and become white patches. These are especially apparent on the tail fan. The glair glands produce a mucus-like material that protects the eggs as they are laid. One can also look directly at the eggs by raising the top of the carapace carefully while depressing the abdomen. A strong beam of light is very useful for this purpose.

Dark brown eggs filling the body cavity, along with enlarged, white glair glands indicate that egg laying is about to take place.

Two months after mating (average time, four to six weeks), 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 mother for another couple of weeks. When most of the young have been released from the mother, she should be transferred to another bowl to prevent cannibalism. The young can be retained in the brood bowls. Some cannibalism will occur, with young feeding on newly molted brothers and sisters, but this can be held to a minimum either by providing cover for the molting young or by distributing them among several containers.

The female usually molts a few days after the young become independent and starts 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 and can be mated once more for a subsequent brood; however, a male should not be placed with a newly molted, soft-shelled female. Allow two to three days for the exoskeleton to harden. Females maintained as just described 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 in each hatching and placed in individual bowls. These are usually ready for breeding within three to four months. It is especially important to start with young crawfish and raise them in the bowls (or other containers) in which they will spend most of their lives. The crawfish grow up to three inches in the small bowls used by Dr. Black, though they could grow larger in a larger bowl. Trying to confine, grow, breed, and spawn larger crawfish in these bowls is usually not successful because the animals are not accustomed to such confinement.

Wright Method

Adult breeders are held in shallow troughs five inches deep at densities of one to two per square foot and a sex ratio of one male to one female. They are not grown in the tanks but are fed. After females lay eggs, they are removed from the breeding tank for "incubation" in nursery containers. This should not be done until the eggs have firmly set on the female's swimmerets, about 72 hours.

The nursery containers used by the Wrights are gallon-sized plastic bottles such as those used for bleach. A round hole is cut in the top for access and the females are deposited there in about two inches of water. Incubation takes two to three weeks at 72°F. The crawfish are normally not fed, and water is changed every three to four days. The young crawfish are removed when they can swim freely and are placed in shallow (six inches deep) troughs for about 30 days until they reach an inch in length. Stocking densities are about 20-30 per square foot. Water is slowly trickled into the containers to replace evaporation losses and the young are fed cut fish, cracked corn, baby food, and vegetables. Survival is 80-90 percent, well above the estimated 10-20 percent in ponds.

Gooch Method

Adult females are collected from ponds in mid to late spring, having already been bred. They are placed individually into six-inch lengths of PVC pipe, four inches in diameter, which are arranged vertically in a shallow trough containing one to two inches of water. The tops must be covered. Trough size should be such that the pipes fit tightly and will not move readily. There will be some mortality over the first two to three weeks of confinement. Dead females need to be removed and replaced. Water should be changed if it fouls, but there should be no feeding and aeration is not required. Of course, water level must be held at the one- to two-inch level. These troughs are kept in a cool (70-72°F), relatively dark place. The majority of the females will lay their eggs during the period from mid-September through mid-November, with most laying during October. See Fig. 76 for a modification

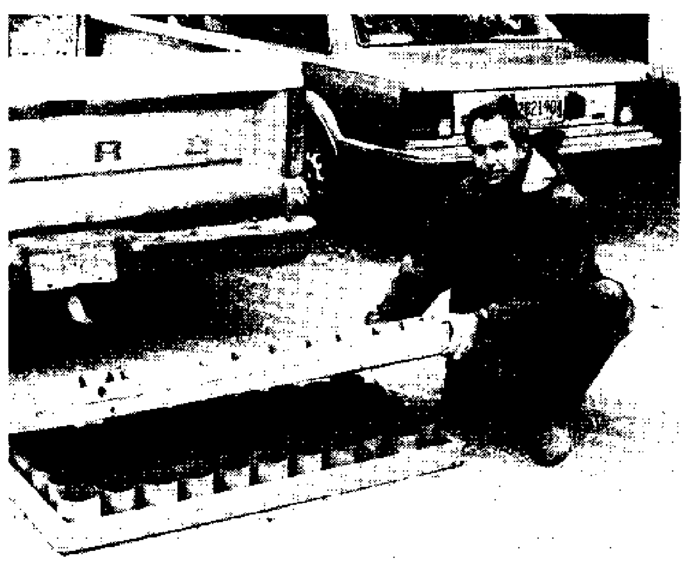


Fig. 76. Albert Gaude demonstrates modifications of the Gooch red swamp crawfish hatchery system. Photo, J. Huner.

of this method. [Note: Pipe sections may also be placed in cafeteria trays and stacked several high.]

Off-Season Production and Other Species

To produce young red swamp crawfish in large numbers at some time other than mid-autumn, one would have either to raise his own broodstock out of synchrony with the normal pond hatch or obtain adult crawfish from ponds. Young-of-the-year crawfish generally do not mature until the March-April period because colder winter temperatures slow growth. In contrast, they can mature in about two months in a warm hatchery so long as they have adequate growing space and food. Adult crawfish can sometimes be obtained in the December-January period from ponds; however, we must emphasize that no one has, to our knowledge, actually produced young by stocking such crawfish in a Gooch system. Theoretically, it should work, but we must await proof before we can advocate that approach.

The reproductive activities of many crawfish species are affected by temperatures and photoperiods. It is not clear yet how the manipulation of these factors affects red swamp crawfish, so it is not possible at present to make recommendations about off-season production of young.

The methods described above were developed using the red swamp crawfish and are effective with this species. Results with the white river crawfish (*Procambarus zonangulus*) have not been as consistent, so we cannot make any recommendations for producing young of this species.

GENETICS

Studies of crawfish genetics have generally been neglected by the scientific community, though limited information is available about karyology, the number and morphology of chromosomes. The number of chromosomes in the red crawfish is approximately 188, compared with 46 for humans.

Inheritance of simple color patterns has been discussed in the biology section. *Heterozygosity*, the amount of genetic variation, has generally been reported to be low in crawfishes. Heterozygosity is important to selective breeding programs because it is easier to breed organisms selectively if heterozygosity is great. In one study comparing heterozygosity in red crawfish, Dr. Craig Busack found that there was little heterozygosity in red crawfish populations around the U.S. Dr. Busack also studied white crawfish populations from around the U.S. when all were considered to be *P. a. acutus*. He found considerable heterozygosity, by crawfish standards. This helped to justify the separation of this "species" into three species by Dr. Hobbs.

Dr. William Wolters of LSU and his students Mr. Joe Craig and Dr. Gregg Lutz have studied selective breeding in red crawfish, examining for growth, body size, and processing traits. They concluded that it should be possible to genetically improve growth and dressout percentage. Drs. Wolters and Lutz also addressed the topic of negative selection as a consequence of current pond management practices. That is, the selective trapping of the largest, fastest growing crawfish could lead to negative selection for growth. However, they concluded that current harvesting practices in commercial ponds pose little threat of negative selection on harvested ponds.

MANAGEMENT PROCEDURES IN LOUISIANA AND ELSEWHERE

Basic management procedures in Louisiana are summarized in the sections on natural feeds and crop rotation and Tables 18 and 19. Elsewhere, winter crawfish growth is so slowed in middle south latitudes (Arkansas through central California) that low latitude (southern Louisiana and southeastern Texas) management schemes specifying rice in the warm months and crawfish in the cool months are not feasible. When pesticide use is minimal in middle latitude rice fields, significant quantities of crawfish accumulate in drainage canals when waters are drained before rice harvest in the late summer. These crawfish have only recently been exploited commercially but on a very limited scale. This is essentially the same way that red crawfish are "managed" in Spain.

OFF-SEASON CRAWFISH PRODUCTION IN THE SOUTH

Until recently, there was no real reason to produce crawfish during the warm summer months when ponds are normally dry in the south. Now, premium prices are paid for crawfish during the summer months in some areas, and there are markets for bait-sized crawfish grown in the summer. Finally, producers of soft-shelled crawfish are interested in obtaining hard-shelled crawfish during the summer to permit year-round production of soft-shelled crawfish. Crawfish, primarily red

Table 18. 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 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.
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, intermittently 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.

crawfish, are numerous in fry and fingerling ponds in many areas of the south from June through August but most producers tried to eliminate them with toxicants, because they caused management problems in the fish ponds. Now, however, such nuisance crawfish can be a valuable crop.

Some red crawfish hatch in the spring and are responsible for the crawfish produced in fish ponds during the summer. However, it is not possible to predict just how many small crawfish will be produced. An alternative that appears workable is to stock "summer" ponds with stunted but still immature crawfish in mid-spring and grow them into the summer. Regardless of the source of stock, producers are faced with very high water temperatures in typical crawfish culture ponds. This can be countered either with a canopy of green rice plants or by deepening the pond. Some management plans used in the U.S. are presented below.

Louisiana Off-Season Crawfish Production Cycle

November-December	Stock brook crawfish, drain pond, plant forage (wheat/rye grass)
December-April	Grow forage.
April-May	Fill ponds with water 24 to 36 inches. Natural recruitment of young crawfish.
June-October	Harvest crawfish.

*Average yield in one test was 860 pounds per acre with the range being 360 to 1,200 pounds of crawfish per acre.

South Carolina Off-Season Crawfish Production Cycle

February	Fill pond with water to a depth of 36 inches. Natural crawfish recruitment (no supplemental stocking).
February-September	Feed crawfish supplemental hay and alligator weed.
June-September	Harvest crawfish.
October-November	Drain pond and repeat cycle.

*Average yield in one study was 1,000 pounds per acre.

Texas Off-Season Crawfish Production Cycle

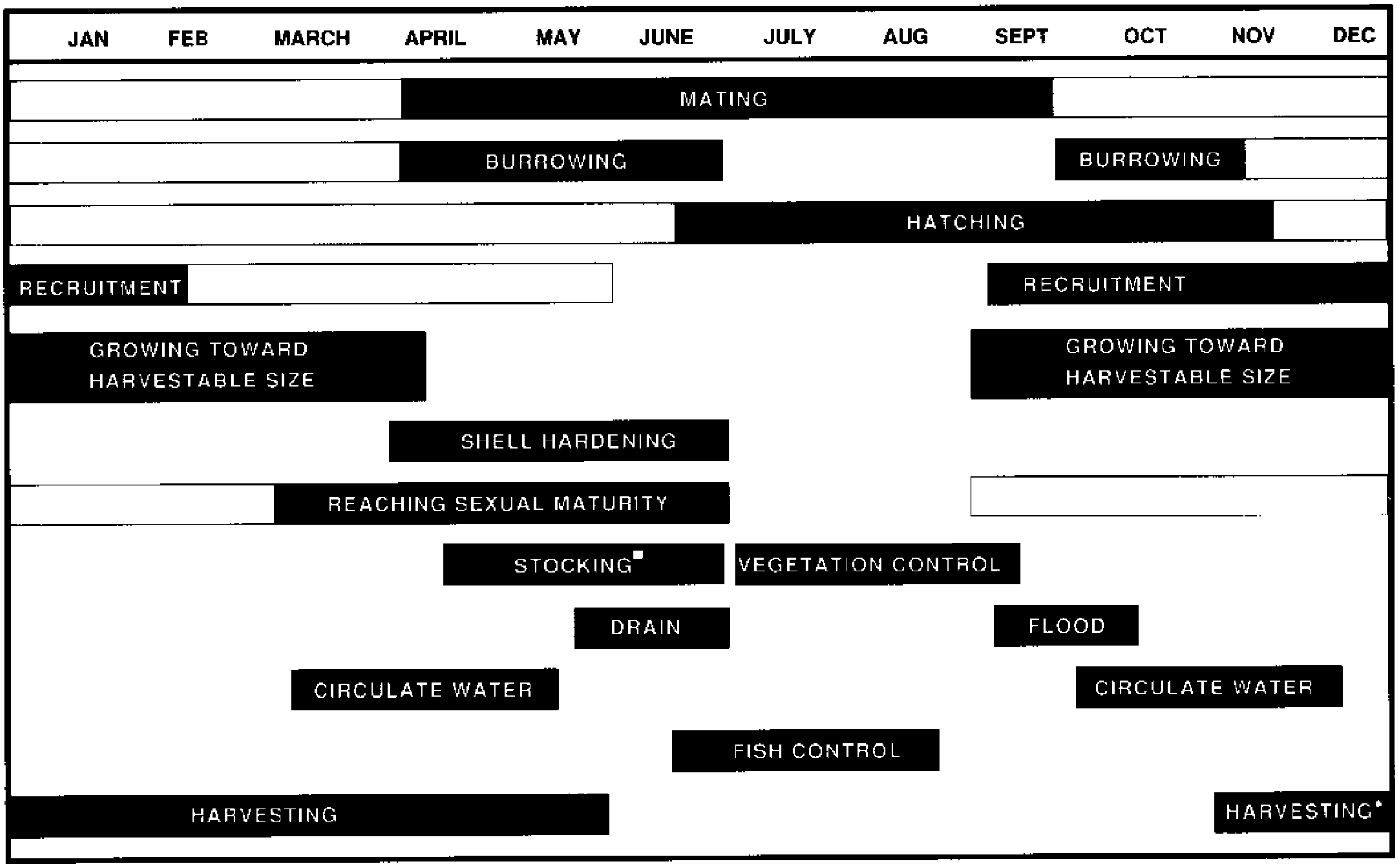
March	Plant rice as crawfish forage.
March-May	Raise water levels as rice grows. Stock 100-300 pounds of crawfish per acre.
July-September	Harvest crawfish.
October-March	Drain pond or keep pond filled for autumn, winter, and spring production.

*Ponds have been stocked with very small crawfish at sizes above 50 per pound. Production can reach 1,500 pounds per acre.

PRODUCTION OF CRAWFISH FOR FISH BAIT

Crawfish are important foods for many species of sport fishes, and thus are very popular fish baits. Manufacturers of fishing lures have produced

Table 19. Life cycle of a Louisiana crawfish pond.



☐ Indicates 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.

numerous lures that mimic live crawfish to capitalize on this biological phenomenon. Both hard and soft-shelled crawfish may be used, although soft-shelled crawfish are superior baits and command much higher prices. Unpeeled tails make excellent baits for larger fishes like catfish and freshwater and saltwater drums. Peeled tails are equally attractive to sunfish, perch, and carp.

Over 100,000,000 pounds of crawfish are harvested annually in the United States and the red swamp crawfish accounts for at least 80 percent of this total. Therefore, by sheer volume, it has the potential for overwhelming bait markets. Most of this total is grown in ponds or harvested from natural waters in Louisiana during the November-May period. Markets for bait crawfish in the heavily populated midwest and northeast have been restricted to summer months when local crawfishes are abundant. So far, no distribution systems have been developed for the bountiful supply of Louisiana crawfish to permit capitalization on winter and spring fishing seasons in these regions.

Products

Bait crawfish buyers usually speak in terms of numbers per pound (count) or pounds per thousand crawfish. Preferred sizes for live hard crawfish for fish bait are 50 to 200 per pound depending on the target fish species. These crawfish are abundant but usually rejected by crawfish processors for food because of their small size. Depending on target fish species, the whole crawfish, the unpeeled tail, or the peeled tail could be used for bait. Inquiries about frozen crawfish for bait have been received for over a decade in Louisiana but no processors have seriously pursued such a market outlet.

One unique crawfish bait form is preserved in formalin. Very small crawfish, 1 1/4 to 2 inches long, are preserved in 5 percent formalin. This is accomplished by placing live crawfish in a solution of one part of 37 percent formalin (full strength) plus 19 parts of water for about a week, washing them in fresh water, and flavoring them with an attractant like oil of anise. The absolute market potential for such a product is not clear when one considers how many successful soft-bodied artificial crawfish lures are now widely available.

Harvesting

Crawfish are harvested with baited traps or some form of dip net, seine, or trawl. Advanced premolt crawfish which are about to shed their shells (less than three days to molting) will usually not enter baited traps. Therefore, trapping is the best method for obtaining intermolt crawfish that will not be subject to molt stress when handled and moved to market. However, thin-shelled postmolt crawfish readily enter traps seeking food after shedding their shells. Rapidly growing crawfish, regardless of species and size, molt on a 10 to 20 day basis. Therefore, it is wise to know an individual population's molt cycle when planning harvesting and shipping schedules.

Smaller crawfish are more active during the day than larger crawfish. Therefore, day-time trapping produces higher proportions of small crawfish than night-time or overnight trapping. Trap mesh size also affects size of crawfish caught. Large crawfish often keep small crawfish out of a trap even if they cannot get into it themselves. If this is a problem, the larger crawfish need to be captured and removed from a pond.

Fig. 77. Pyramid crawfish trap being checked in typical shallow crawfish pond. Note bait well. Photo, J. Huner.

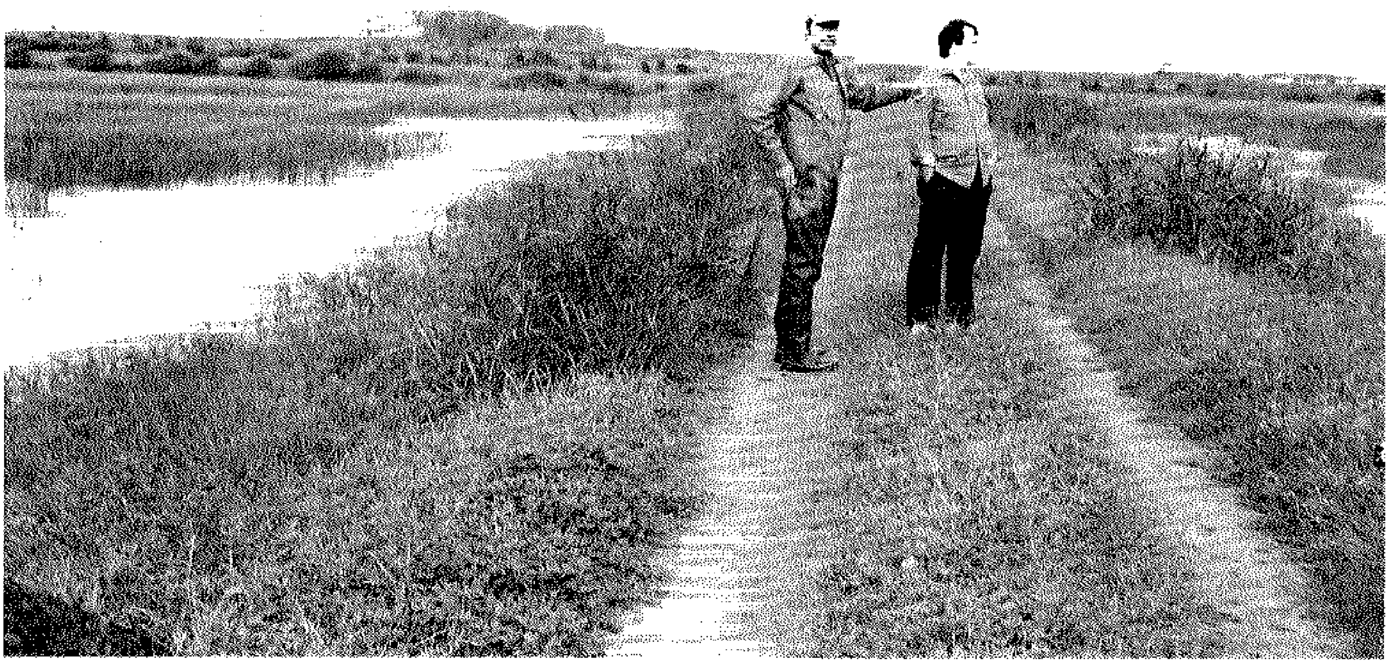


Fig. 78. Pond planted with rice for crawfish fodder. Note the trapping lanes, which also facilitate water flow.

Nets are not selective when it comes to harvesting crawfish. Anything in a net's path is caught. Therefore, one may catch significant numbers of fragile early postmolt, advanced premolt, and soft-shelled crawfish as well as intermolt, hard crawfish. This requires sorting which is not widely practiced in the crawfish industry. Both soft-shelled and late premolt crawfish may be frozen and sold later for bait. These bait forms are not as popular as live animals but are generally much more effective than hard crawfish. The angler can easily remove the old, brittle shell from a late premolt crawfish, live or thawed, and it will be almost as effective as a soft-shelled crawfish. Premolt crawfish can also be kept alive in a bait bucket as one would keep minnows and they will often molt during the fishing trip.

The same concerns about molt cycles in planning the trap-harvesting of bait crawfish must be considered in net harvesting of bait crawfish. Using some form of bait to "chum" an area can reduce the numbers of soft-shelled and late premolt crawfish that are caught. Harvesting at night can usually produce higher numbers of large crawfish, as they tend to be more active than during the day. Some crawfish producers in the midwest tie pieces of bait onto a 20- to 30-foot seine and then lay it in the water along the pond bank with the lead line out the deep end. Many crawfish can then be caught by quickly lifting the two ends after a "set" of 15 to 30 minutes.

Handling and Shipping of Bait Crawfish

Crawfish need to be purged for 24 to 48 hours to allow them to eliminate wastes from their digestive systems. Nonmolting crawfish, as a rule, can be held at a density of about 50 per square foot either submerged with aeration or partially submerged (water 1/2 to 1 inch deep). The water has to be exchanged several times during the first 24 hours to remove wastes and to prevent accumulations of pathogenic bacteria and toxic levels of ammonia. If the crawfish can raise their heads (cephalothoraxes) to the surface in a shallow system, they can use atmospheric air and survive; however, they much prefer to be kept in water with oxygen levels above 3.0 parts per million.

No hard and fast rules can be provided for holding submerged crawfish. Warm water fishes can be held at several pounds per cubic foot of water with heavy aeration after they have been purged. However, crawfish must have vertical partitions in the water column in a deep tank (most holding tanks are about three feet deep) because they cannot suspend themselves in the water column as fish do. Crawfish have no swim bladders and cannot "float."

Obvious premolt, soft-shelled, and tender postmolt crawfish have to be separated from the firm, intermolt hard-shelled crawfish. If this is not done, mortality will be great. These vulnerable crawfish are excellent fish baits but require special handling. Intermolt crawfish can be shipped by air in water-saturated, sealed boxes. Abrupt temperature changes must be avoided and temperature should be in the 60° to 70° F range. Packing material (sphagnum moss, shredded newspaper, etc.) should be saturated with water, but water must not accumulate on the bottom of the container, especially around crawfish on the bottom. Crawfish should be packed one layer at a time (one crawfish deep) with partitions betwen layers to prevent the crawfish from being crushed.

Crawfish can be shipped in oxygen inflated plastic bags (heavy gauge) with wet packing material to minimize weight and jostling. Again, they should be purged before shipping.

Some bait dealers haul live hard-shelled bait crawfish in plastic grape lugs (boxes). These are equipped with wooden "shoulders" so they can be stacked without crushing the crawfish.

Shipping times should be as short as possible although tests have shown that properly packaged, purged hard red swamp crawfish can easily survive 72 hours without major mortality so long as they are in water-saturated air (100 percent humidity). Check with private carriers (including the bus lines) and the U.S. Postal Service for the best rates.

Live soft-shelled crawfish can be shipped as hard-shelled crawfish but they must be chilled, 40° to 45° F. This stops the hardening process. They have to be layered in packing material, one layer thick, to minimize shipping damage. Though they will hold for several days under such conditions, they need to be moved and sold quickly.

SOFT-SHELLED CRAWFISH

Small soft-shelled crawfish (50 to 100 per pound) have long been produced in the northern states for fishbait. Crawfish about to shed their shells are caught with seines in small ponds and held in tanks or troughs for 12-48 hours until they molt. They are then refrigerated and sent to market.

The production of larger soft-shelled crawfish for the gourmet food market began several years ago in Louisiana and surrounding states. Sizes have ranged from 15 to 35 per pound, with the average being about 25 per pound. Most of these crawfish are produced by catching immature crawfish in traps, confining them in shallow trays, feeding them, and, just before they molt, placing them into molting trays. Recommended stocking rate is one pound per square foot at temperatures around 80°F. Recirculating systems are used to conserve water and heat and to maximize efficiency.

Although imminent molt (late premolt) crawfish are periodically abundant in crawfish ponds, no system has been developed that permits their easy capture in ponds for transfer to molting containers. There is generally too much vegetation in ponds to permit conventional seining. However, several machines with trawl devices have been developed for harvesting crawfish (see harvesting section) and should soon have a major impact on the soft-shelled crawfish industry. A discussion of the molting process is presented in the biology section of this text.

Detailed information about soft-shelled crawfish production is available from a number of texts listed in the bibliography at the end of this book. Note that production systems were developed with the red crawfish as the target organism. Although white crawfish molt readily in confinement, they do not molt as rapidly as red crawfish when confined in the intermolt stage and fed at high densities in shallow trays.

OTHER SPECIES OF AMERICAN CRAWFISH SUITABLE FOR CULTIVATION

Crawfish are now grown in earthen ponds by establishing self-perpetuating populations. This effectively limits crawfish culture to a few species, including *P. clarkii* and the white crawfishes (*P. a. acutus*, *P. zonangulus*, and the undescribed species) in much of the United States and *Orconectes immunis* in the midwestern and northeastern U.S. Orconectes im-munis is very similar to red and white crawfish in life cycle and adaptability to earthen ponds with alternate wet-dry periods. But it rarely exceeds 2 1/2 inches in length and is cultured almost exclusively for fish bait.

Several species of *Procambarus* perpetuate in earthen ponds and can probably be cultured. These include *Procambarus fallax* and *Procambarus troglodytes* on the lower east coast; *Procambarus alleni* in Florida; *Procambarus hayi* in the central south; and *Procambarus simulans* in the lower and central south. *P. troglodytes* is very similar to *P. clarkii* and is hard to distinguish from it, but taxonomists insist that it is a separate species. All of the *Procambarus* species mentioned except *P. alleni* reach sizes over four inches.

In the central U.S., three *Orconectes* species, *Orconectes rusticus*, *Orconectes virilis*, and *Orconectes nais*, grow well in fish culture ponds that are dried each year in the winter as a sanitation practice. These species probably warrant further attention if demands for crawfish rise, but O. rusticus, at least, was all but eliminated from one set of Ohio ponds by *P. clarkii*. Thus, in stocking crawfish, care must be exercised to identify the species.

Should hatchery production and stocking become economically viable, *Pacifastacus leniusculus*, the northwestern U.S. signal crawfish, can be cultured, particularly in cooler waters—55 to 70°F. In fact, they are cultured and stocked in Europe where high prices make it profitable to do so.

There are over 350 species of crawfish in North America. It is doubtful that *P. clarkii* and the white crawfishes are the only ones suitable for culture. However, *P. clarkii* has been the most widely publicized and introduced species. Introductions in areas where this species is not native have been made without any real effort to screen native species for suitability for culture. Ecologists and taxonomists speak disparagingly about this because introduced species have eliminated native species. Yet one would never think twice about moving cattle, sheep, and goats about the world, even though native herbivores might be suitable for domestication. Regrettably, time and funds for screening species are rarely, if ever, available, so that prospective farmers are limited to those species that have been successful elsewhere.

Those concerned about introductions and finding suitable crawfish for culture need to identify species already growing in area fish hatchery ponds. They have already been able to adapt to pond life and it might prove profitable to culture them in favor of nonnative species. However, identification is crucial, as *P. clarkii* has become well established in Indiana and Ohio fish hatchery ponds after being introduced with minnows from other states.

AUSTRALIAN CRAWFISH

Australian crawfish belong to the family Parastacidae and over 100 species have been identified. Sizes range from less than one-half ounce to over six pounds. The five largest crawfish include: *Astacopsis gouldi* (to 7 1/2 pounds), *Cherax teniumanus* (to 3 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 marron *C. teniumanus* and yabby *C. destructor* for culture potential. More recently, the Queensland marron, or Queensland red claw, *C. quadricarinatus*, intermediate in size between marron and yabby, has drawn considerable interest in Australian aquaculture circles. The other species, although large, have a small abdomen compared with the head and are slow growing. 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. teniumanus* is naturally found in permanent streams but has promise as a candidate for culture in earthen ponds. One main difference between culturing the Cherax species and culturing *P. clarkii* is that the Australians 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 two pounds per square yard have generated good results. Production has exceeded 2000 pounds per acre in one four- to five-month growing season, but size is roughly two to three ounces—this compared with *P. clarkii* sizes of one ounce.

Many people have inquired about the feasibility of importing various Australian crawfish 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 crawfish are believed to be highly susceptible to the crawfish plague (see disease section), which is known to exist throughout the United States. American crawfish tolerate the plague but a well-established crawfish farm stocked with Australian crawfish might be ruined in a few days.

There are also legal considerations. For example, the Australian government restricts the export of several species of crawfish. In general, most states require that one obtain a permit before importing any nonnative aquatic species, even *P. clarkii*, and failure to do so is a violation of federal law. Penalties can be very stiff and can involve prison sentences. Certainly, anyone contemplating the culture of any Australian crawfish would be well advised to secure reliable counsel such as someone with the local cooperative extension service.

CRAWFISH ASSOCIATIONS

The International Association of Astacology (crawfish biology) publishes an international newsletter, a directory of astacologists, and its periodic symposium proceedings. Its official domicile is the University of Southwestern Louisiana, Lafayette, Louisiana 70504.

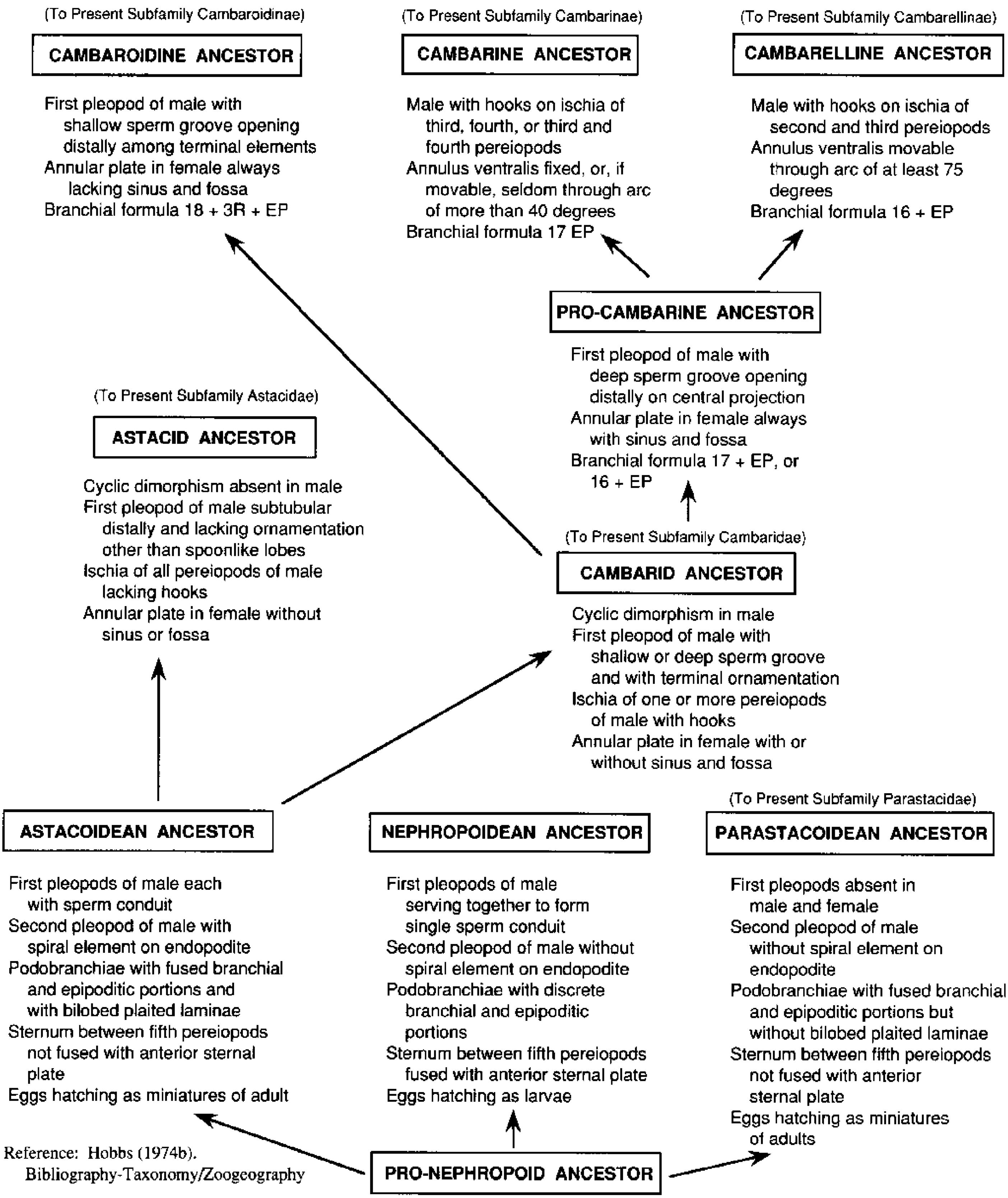
Several states have crawfish associations of various types. These include Louisiana, Texas, Arkansas, South Carolina, North Carolina, and Maryland at this writing. Local Cooperative Extension Service offices can assist in locating addresses. The Louisiana Crawfish Farmers' Association is, by far, the largest of all these associations, and publishes a quarterly magazine entitled *Crawfish Tales*. The LCFA's current address is P.O. Box 9656, New Iberia, Louisiana 70562.

LIST OF FIGURES

LIST OF TABLES

APPENDIX A

OTHER SPECIES OF AMERICAN CRAWFISH SUITABLE FOR CULTIVATION



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	51	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 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 and 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
0	10	5	4	3	8	1	3	1	7	2	1	1	0	4	0	0	0	0	0
50																			
0	(20)	10	8	6	(16)	2	6	2	(14)	4	2	2	0	(8)	0	0	0	0	0
0	0	0	0	0	0	0	0	5	25	10	5	2	5	20	7	5	3	10	3
100																			
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

APPENDIX C

Mark-Recapture

A biologist captured 100 crawfish in a ditch. He marked them and returned them to the ditch. A week later he sampled the ditch again and caught 50 crawfish, of which 25 were marked and 25 were not. How many crawfish were in the ditch?

Formula:

$$\text{Number} = \text{Number marked and released on first sampling day} \times \frac{\text{Total caught on second sampling day}}{\text{Number of marked crawfish recaptured on second sampling day}}$$

Therefore:

$$\text{Number} = 100 \times \frac{50}{25} = 200 \text{ (crawfish in ditch)}$$

Declining Catch Per Unit Effort

A biologist caught crawfish in a small pond three days in a row. She used the same amount of effort each time. Her catch was as follows: Day 1, 100 crawfish; Day 2, 50 crawfish; and Day 3, 25 crawfish. What was the original population in the pond?

You must plot cumulative catch on the x-axis and daily catch on the y-axis of a graph. After all data are graphed, a straight line drawn through all points is extended to the x-axis to give the population estimate.

APPENDIX D

WEIGHT AND MEAT YIELDS

RED SWAMP CRAWFISH

Total Length (in.)	Mature Male			Immature/Sexually Inactive Male			Female		
	#/lb.	lb. Meat w/Fat/ 100 lb.	lb. Meat w/o Fat/ 100 lb.	#/lb.	lb. Meat w/Fat/ 100 lb.	lb. Meat w/o Fat/ 100 lb.	#/lb.	lb. Meat w/Fat/ 100 lb.	lb. Meat w/o Fat/ 100 lb.
2.75	43.2	21.1	19.5	53.4	25.7	25.6	50.4	25.8	23.1
3.00	34.2	19.7	18.0	40.9	24.5	24.3	38.2	24.5	21.8
3.25	24.9	18.5	16.7	32.0	23.4	23.0	29.9	23.7	20.8
3.50	19.7	17.4	15.5	25.5	22.4	21.9	23.8	22.8	19.9
3.75	15.6	16.4	14.6	20.5	21.5	20.9	19.1	22.1	19.0
4.00	12.6	15.6	13.7	16.8	20.7	20.0	15.6	21.3	18.3
4.25	10.3	14.6	12.9	13.8	19.9	19.1	12.9	20.7	17.6
4.50	8.5	14.2	12.3	11.6	19.2	18.4	10.8	20.2	17.0
4.75	7.2	13.6	11.7	9.8	18.6	17.7	9.1	19.7	16.5
5.00	6.1	13.1	11.2	8.4	18.1	17.1	7.8	19.2	16.0

WHITE RIVER CRAWFISH

Total Length (in.)	Mature Male			Immature/Sexually Inactive Male			Female		
	#/lb.	lb. Meat w/Fat/ 100 lb.	lb. Meat w/o Fat/ 100 lb.	#/lb.	lb. Meat w/Fat/ 100 lb.	lb. Meat w/o Fat/ 100 lb.	#/lb.	lb. Meat w/Fat/ 100 lb.	lb. Meat w/o Fat/ 100 lb.
2.75	36.6	19.3	17.5	39.5	21.4	19.6	41.7	23.5	21.5
3.00	27.7	18.0	16.1	32.4	21.5	19.7	32.0	22.7	20.6
3.25	21.4	16.9	15.0	24.9	20.1	18.3	24.5	21.8	19.4
3.50	16.9	15.9	14.0	19.8	18.9	17.2	19.5	21.0	18.5
3.75	13.5	15.0	13.0	15.9	17.9	16.1	15.7	20.4	17.8
4.00	11.0	14.3	12.3	12.9	16.9	15.2	12.8	19.8	17.1
4.25	9.1	13.6	11.6	10.7	16.0	14.4	10.6	19.3	16.4
4.50	7.6	13.0	11.0	8.9	15.3	13.7	8.8	18.8	15.8
4.75	6.4	12.5	10.4	7.5	14.6	13.0	7.5	18.3	15.3
5.00	5.5	11.8	9.8	6.4	13.7	12.2	6.4	17.5	14.5

MEATS PER POUND OF PEELED MEAT

RED SWAMP CRAWFISH

Total Length	Mature Male	Immature/Sexually Inactive Male	Female
(in.)	Meats/lb.	Meats/lb.	Meats/lb.
2.75	227	206	216
3.00	182	168	175
3.25	151	138	142
3.50	126	116	119
3.75	108	99	101
4.00	93	84	86
4.25	80	72	73
4.50	70	63	63
4.75	61	55	55
5.00	55	49	49

WHITE RIVER CRAWFISH

Total Length	Mature Male	Immature/Sexually Inactive Male	Female
(in.)	Meats/lb.	Meats/lb.	Meats/lb.
2.75	206	197	197
3.00	175	162	157
3.25	142	138	126
3.50	123	116	106
3.75	103	99	89
4.00	89	86	76
4.25	78	74	65
4.50	69	65	56
4.75	61	57	49
5.00	55	52	44

APPENDIX E

CRAWFISH FARMER'S CHECKLIST

Under the right circumstances, crawfishing can be very profitable. Like other forms of farming, however, crawfish production involves substantial capital investment (but generally much less than conventional fish farming) and many risks.

Growing crawfish differs from other forms of aquaculture in that ponds are dry from June through September. And harvesting, with 20-30 traps per acre, may extend from November or February through May.

In addition, crawfish may be integrated into crop rotations with rice.

If you are considering crawfish farming, this checklist can help you to determine whether a crawfish enterprise is feasible for your particular situation. The checklist, of course, does not cover all possibilities.

Answering yes to most questions will not guarantee success, just as answering no will not mean automatic failure. The checklist does list the most important considerations, however, and to have a good probability of success, most of your answers should be in the yes column when you begin a crawfish operation.

Your county extension agent can direct you to sources of information for the more technical questions.

ECONOMIC FACTORS

Management

	Yes	No
1. Do you already have rice fields or a site for ponds?	___	___
2. Do you have most of the machinery and equipment needed?	___	___
3. Do you have the necessary financial resources?	___	___
4. Is the crawfish profit potential competitive with that of other possible investments?	___	___
5. Will the expected profit be adequate compensation for your labor, management, and risk?	___	___
6. Will investment and operating capital interest rates permit a reasonable profit?	___	___
7. Is crawfish the best alternative for use of the land?	___	___
8. Can you afford to forego income until you begin to harvest your first crop?	___	___
9. Are you able to absorb occasional losses?	___	___
10. Are you willing to devote the daily time and effort required?	___	___
11. Have you read all pertinent "how to" publications?	___	___

Marketing

	Yes	No
1. Do you know of an established market for your crawfish?	___	___
2. Is there a market for your crawfish throughout the season?	___	___
3. Do you have a suitable arrangement for harvesting?	___	___
4. Are you prepared to purge your crawfish if this is demanded by the market?	___	___
5. Do you have an alternative marketing strategy to fall back on?	___	___
6. Do you know who your competitors are? Can you obtain crawfish from outside sources to maintain supplies in a new market?	___	___
7. Do you know the product form(s) that you will produce: • Food crawfish: Hard or soft shell • Bait crawfish: Hard or soft shell • Scientific specimen: Live or preserved?	___	___

PHYSICAL FACTORS

	Yes	No
1. Does the topography of the land lend itself to pond construction?	___	___
2. Will the soil hold water?	___	___
3. Is the soil fertile?	___	___
4. Is enough water available to fill the ponds and replace losses?	___	___
5. Is your water of the proper quality for crawfish production?	___	___
6. Is the pond area protected from flooding?	___	___
7. Are the drains in existing ponds large enough to quickly drain the pond if it is flooded by rain during the dry season?	___	___
8. Can wild fish be prevented from entering the pond?	___	___
9. Is there all-weather access to the pond for harvesting?	___	___
10. Is your residence close enough to the pond to allow frequent and timely observations and the necessary management adjustments?	___	___

RISKS

Are you equipped to handle the following problems?	Yes	No
1. Poor water quality?	___	___
2. Pesticide contamination?	___	___
3. Poachers and vandals?	___	___
4. Personal stress resulting from risk management?	___	___

PRODUCTION FACTORS

	Yes	No
1. Are you aware of the basic life cycles of the red swamp and white river crawfishes and how they relate to pond management?	___	___
2. Are brood red swamp crawfish available from local suppliers during the spring?	___	___
3. Can you make or purchase the necessary aeration equipment?	___	___
4. Do you have or can you afford pumping and/or recirculation capacity to deliver 100 gallons per minute (gpm) per acre during critical periods of low oxygen?	___	___
5. Do you have a source of fuel for pumps, sacks, traps, bait and chemicals such as rotenone?	___	___
6. Are good quality baits readily available at competitive prices?	___	___
7. Do you have facilities for storing bait?	___	___
8. Is dependable labor available?	___	___
9. Are dependable advisory personnel (county extension agent and Soil Conservation Service agent) available and do you know their function?	___	___
10. Are you aware of appropriate trade associations that can help you?	___	___

NOTE: This checklist is based on one developed for catfish farming by J. Jensen and J.R. Crews, Alabama Cooperative Extension Service, Auburn.

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