Abalone (Genus *Haliotis*) Mariculture on the North American Pacific Coast

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ABSTRACT: First commercial attempts to culture native Pacific coast abalones were undertaken in California in the mid-1960s. These pioneering groups established basic techniques and stimulated the development of a half-dozen abalone production operations, still chiefly in California. Refinements to the culture technology have resulted from research and development by the industry, but also through studies conducted by nonprofit research groups and government and university programs. This paper briefly examines recent trends in world abalone fisheries and the requirement for mariculture, then describes and evaluates the principal elements contributing to the technological advancement of abalone mariculture in North America.

Substantial advances have been made in the artificial propagation of members of the genus *Haliotis* during the past two decades in the United States, Japan, Australia, New Zealand, and France. Faced with the necessity to supplement the fishery catch or to avert anticipated declines in supplies of this valuable marine resource, efforts in several countries are being directed toward development of effective hatchery programs for production of juvenile stock for use directly in fishery enhancement (through seeding) or for grow-out and production by mariculture. Profit incentives alone have spurred the evolution of private sector intensive abalone culture in the United States.

By far the greatest national effort to increase abalone production has occurred in Japan. Over 30 fisheries laboratories and "Fisheries Farming Centers" throughout that country are concentrating efforts on generation of juvenile abalone (seed) for release in the sea (Uki 1981; McCormick and Hahn 1983). Collectively, these facilities produce about 30 million seed annually (Uki 1981; Grant 1981). Authoritative reviews are also provided by Ino (1980) and Saito (1984).

The Pacific abalone, *Haliotis discus hannai*, is the primary species cultured in Japan, China, and Korea (Sheehy and Vik 1981). Recent attempts to culture the pauas (chiefly *H. iris*) in New Zealand (Anon. 1986) as well as *H. ruber and H. laevigata* in Tasmania (D. Cropp 1987[1]) are showing encouraging results. The ormer, *H. tuberculata*, is being produced in initial programs in Britain and France (Flassch and Aveline 1984). Other experimental and incipient commercial attempts to culture native and introduced species are in progress in Canada (Fletcher 1987), Mexico (Aguirre 1988), and Chile (Owen et al. 1984).

On the Pacific coast of the United States several species of abalones have been subjects of experimental and commercial aquaculture for almost two decades, chiefly the red, *H. rufescens*, and the green, *H. fulgens*. The red abalone is the largest member of the genus and, historically, the major fishery species. First attempts to cultivate abalone in the Western Hemisphere involved this species (Owen et al. 1971; Leighton 1977, 1987). The green abalone, native to temperate waters of southern California and northern Mexico, is broadly tolerant of temperature (Leighton 1974). Some new commercial enterprises are focusing on green abalone production to capitalize on its versatility, relatively rapid growth, and ready marketability. Until quite recently, only in the United States have abalone been cultured to adult size (5–10 cm) by intensive methods for direct marketing as seafood products. Operations elsewhere in the world have focused on producing seed for restocking programs, but it is anticipated that newly established operations for full grow-out will soon expand in Japan, Australia, New Zealand, and Canada.

STATUS OF THE FISHERY

Abalones, all in the genus *Haliotis*, are herbivorous marine gastropods which have long

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been utilized as food by man. Nearly 90 species and subspecies are recorded as living in the world today. Paleontological records indicate the presence of the genus since the Cretaceous (Cox 1962). Most extant species live in shallow waters, feeding on marine algae common on rocky substrates from the intertidal to depths over 50 m.

A staple item in the diet of coastal native American tribes, abalone have also been of major importance as food, medicine, and elements of ritual in Asia for centuries. In modern times, extensive exploitation in many countries has resulted in a marked reduction of fishery stocks. Prior to the onset of abalone population decline in California, annual harvests generally exceeded 4.5 million pounds (>2,000 t, see below). In Japan, annual yields have been over 10 million pounds, supplemented now by an intensive nationwide habitat improvement and seeding program (Uki 1981). Production, chiefly from fisheries, has exceeded 44 million pounds (20,000 t) annually (FAO 1975). Worldwide, the market for abalone and abalone products is estimated at more than $300 million (NMFS 1982[2]). Countries most productive in this fishery have been Japan, Mexico, Australia, South Africa, and the United States.

[2]National Marine Fisheries Service. 1982. Southwest Regional Headquarters, Long Beach, CA. (Unpubl. rep.)

In North America, fisheries continue to provide the major supply of abalone, although aquaculture is gaining rapidly as a significant new source, currently estimated at about 5% of the total harvest. Commercial quantities of abalones have been found chiefly along the coasts of California and northern Baja California, Mexico. A small fishery exists in Canada for the pinto abalone, *H. k. kamtschatkana*, (Mottet 1978).

Large-scale exploitation of abalones in California has been in progress for almost a century. Intertidal and shallow subtidal populations were severely depleted by Asian harvesters around the turn of the century. As diving techniques improved and the number of divers increased, especially following World War II, deep-water populations were similarly impacted (Cicin-Sain et al. 1977). An alarming decline was seen in the early 1970s, and annual harvests dropped to less than one million pounds after 1974 (Fig. 1). Comparable declines have been experienced in Mexico, Japan, and elsewhere in the world were intensive fisheries for abalones have developed. However, the demand for abalone remains strong, especially in Asian countries. Japan now imports quantities almost equal to the domestic harvest (Uki 1981).

Circumstances surrounding the decline of the California abalone populations have been unique. Red abalone, once abundant off the central California coast, supported the bulk of the commer-

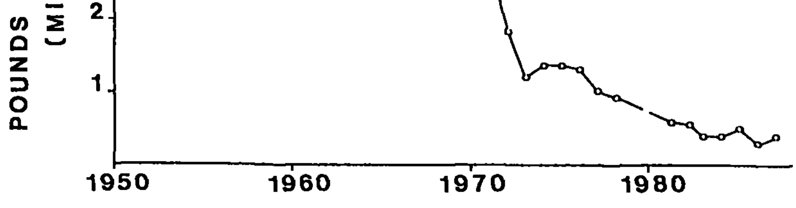

FIGURE 1.—California commercial landings for red, green, and pink abalones, 1951–87. Red abalone predominated in catch until 1975. During 1981–87 average annual landings of red abalone dropped to 329,410 pounds (in-shell) while black abalone take averaged 414,620 pounds. Data from Cicin-Sain et al. (1977) and California Department of Fish and Game, Marine Statistics, Commercial Fish Landings, 1982–87. Other records for 1976–81 from Fish Bulletin 168 and 170, and unpublished logs. Reports for 1979 and 1980 not available.

cial take until about 1965. Thereafter both the toll of increased fishing pressure and increased depredation by the rapidly expanding California sea otter populations significantly reduced red abalone stocks (Cicin-Sain et al. 1977). A combination of pollution, habitat loss, competition with uncontrolled sea urchin population growth, mortalities of undersize abalone due to "bar cuts", and increased harvests by both sport and commercial divers have had a severe impact on stocks of all species of abalones, especially in Southern California (Cicin-Sain et al. 1977). An important additional element in the decline of California abalone populations has been the establishment of seasonal closures which do not adequately protect a large portion of the breeding populations. The midwinter closure for both commercial and sport abalone harvests (mid-January to mid-March) existed for several decades. Since pink (*H. corrugata*), green, and black (*H. cracherodii*) abalones spawn from late spring to late fall (Leighton 1974; Tutschulte 1975), no reproductive protection was afforded by that measure. Only the deep-water, late-winter to spring spawning white abalone, *H. sorenseni*, and a fraction of the year-round spawning red abalone populations, were benefitted by the California abalone "closed season". Currently, a split closure to include one summer month is enforced for the commercial industry, and also for northern California sport divers. The effect of these measures has yet to be assessed. Minimum size limits exist for each species which conserve only the reproductive contribution by young and smaller adults.

THE DEVELOPMENT OF ABALONE MARICULTURE IN CALIFORNIA

It is a commonly held misconception that abalone culture in the United States was modeled after methods established in Japan. However, little technical information on critical aspects of larval and postlarval culture of abalone by Japanese biologists was available to the first entrants into the field in the 1960s. Consequently, the methods developed for culture of all stages of American abalones are quite different from those practiced in Japan (Leighton 1987). More recently, several attempts have been made in California to apply traditional Japanese hatchery methods, but generally the results of these approaches have not been encouraging (see Hatchery Methods, next section).

Pacific Mariculture (Pigeon Point, CA) began to explore possibilities for culture of abalone as seed for reintroduction to native habitat in 1964. Success was achieved in production of juvenile red abalone. Also, spawnings in tanks holding several species yielded hybrid combinations (Owen et al. 1971; Owen and Meyer 1972[3]; Leighton 1987). Experimental planting of juvenile abalone was done, but emigration and mortality at the local offshore site limited returns. At the time, the Department of Fish and Game could not grant exclusive fishery rights to in-sea mariculturists for "undersize native" abalones. Proprietary "nonnatives" (in this case, hybrids) did poorly in the Pigeon Point area. Accordingly, Pacific Mariculture redirected its attention to the production of oyster spat and abandoned further abalone mariculture efforts (B. Owen 1968[4]).

In 1967, California Marine Associates (H. Staton, D. Leighton, and J. Perkins) launched the first large-scale abalone mariculture program in North America with the goal to produce red abalone in land-based tank systems for direct sales to the seafood market. Thousands of seed were provided to the California Department of Fish and Game for their first attempts to plant abalone in the natural environment (Bjornson 1970; Bailey 1973). Commercial quantities of young adult red abalone were soon reared in large concrete raceway tanks. Following an instructive, but problematic, cooperative experimental program with the Atlantic-Richfield Company to conduct containment grow-out of abalone beneath an offshore oil production platform (Gealy and Lindstedt-Siva 1984[5]), California Marine Associates was reorganized to become Estero Bay Mariculture. In 1982, further reorganization occurred and a new company, The Abalone Farm, Inc., was formed. Refinements in the basic culture procedures and expansion of the hatchery and raceway systems have boosted production significantly. In 1986, over 180,000 small adult red abalone (5–10 cm) were marketed, valued at over $400,000 (F. Oakes 1987[6]).

[3]Owen, B., and R. Meyer. 1972. Laboratory hybridization in California abalones (*Haliotis*). Pacific Mariculture, Pigeon Road Point, Pescadero, CA (Unpubl. rep.)

[4]B. Owen, Pacific Mariculture, Pigeon Point Road, Pescadero, CA 94060, pers. commun. 1968.

[5]Gealy, F., and J. Linstedt-Siva. 1984. Containment culture of abalone beneath an offshore platform. Talk presented at Aquaculture Symposium, May 1984, Southern California Academy of Sciences, Los Angeles.

[6]F. Oakes, The Abalone Farm, Inc., P.O. Box 136, Cayucos, CA 93430, pers. commun. 1987.

Ab Lab (J. McMullen, proprietor) began operation in 1972 at Port Hueneme, CA. Initial efforts yielded seed size (2–4 cm) red abalone grown entirely within small tanks. A change to containment culture using mesh-ended polyethylene drums held beneath a dock at the harbor entrance has improved production of larger abalone (4–8 cm). A new market developed in specialty seafood restaurants and sushi bars in the Los Angeles area in the early 1980s. Ab Lab marketed approximately 150,000 young red abalone in 1986 (J. McMullen 1987[7]; Hamilton 1988).

Monterey Abalone Farms began research and development activities for culture of red abalone in 1972. Using an old building on Cannery Row in Pacific Grove, annual production gradually increased, but difficulties stemming in part from what was considered an inordinate volume of governmental restriction and consequent efforts in compliance (Armbrister 1980) prompted a move of the operation to Hawaii. There, an experimental program is underway to apply artificially upwelled seawater to the culture of coldwater mollusks in the tropics (Fassler 1987).

Institutional research efforts related to abalone mariculture have been diffuse. Studies have been based largely at the University of California at San Diego (Leighton 1968, 1972, 1974; Leighton and Lewis 1982) and Santa Barbara (Morse et al. 1977, 1979, 1984), the California Department of Fish and Game laboratory at Carmel (Ebert and Houk, 1984), and World Research, Inc., a San Diego nonprofit research organization (Leighton et al. 1981, Leighton 1985, 1987). Many findings from these studies have added to the fund of knowledge facilitating the development of abalone mariculture.

NORTH AMERICAN SPECIES OF IMPORTANCE TO MARICULTURE

Aside from a single rare and small species occurring in deep water off the Florida Keys (*Haliotis pourtalesii*), North American abalones are to be found only on the Pacific coast. There, seven species and two subspecies of haliotids occur (Fig. 2). In the order of their historical value to California fisheries (prior to 1975) are the red, *H. rufescens*; pink, *H. corrugata*; green, *H. fulgens*; white, *H. sorenseni*; and black, *H. cracherodii*. The remaining species are small and of minor commercial interest.

Descriptions and ranges for the northeastern Pacific abalones are to be found in the literature (McLean 1969; Haaker et al. 1986). An earlier account by Cox (1962) and a later one by Hooker and Morse (1985) contain inaccuracies which make those papers less useful. Generally, the red and black abalones are distributed most broadly, while the green, pink, and white abalones are found only south of the cold-warm transition near Point Conception, CA (Fig. 2.).

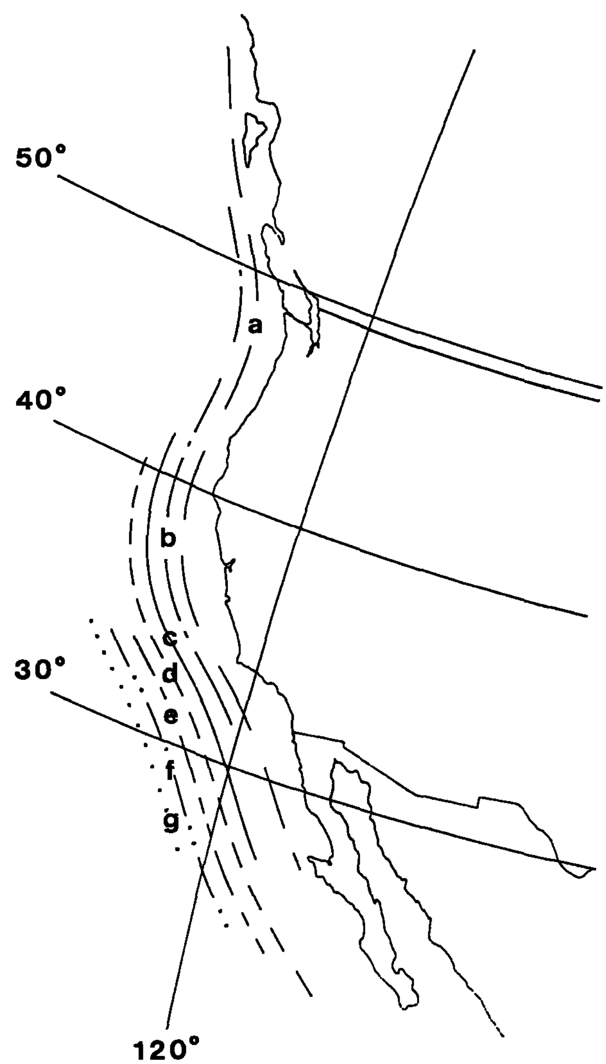

FIGURE 2.—Latitudinal distribution of abalones along the Pacific coast of North America. Range limits are as provided by Haaker et al. (1986). a. *Haliotis kamtschatkana* (two subspecies, *H. k. kamtschatkana* north of Monterey Bay, and *H. k. assimilis* south of that point). b. *H. walallensis*. c. *H. rufescens*. d. *H. cracherodii*. e. *H. fulgens*. f. *H. corrugata*. g. *H. sorenseni*.

[7]J. McMullen, Ab Lab, U.S. Navy Civil Engineering Laboratory, Port Jueneme, CA 93043, pers. commun. 1987.

All California species have now been cultured experimentally, but the red abalone remains as the principal species for mariculture. This cold-water abalone has been the focus of attention chiefly because it thrives along the central California coast where early mariculture operations were most effectively established. Furthermore, most biological information was available for the red abalone and the species was most attractive from the mariculture standpoint, being the largest member of the genus and having the strongest commercial history. It has proved, fortunately, to be the most easily cultured California abalone (Leighton 1987).

The green abalone has shown special potential for mariculture in systems utilizing thermal effluent (Leighton 1974, 1985; Leighton et al. 1981) and other means to provide temperatures in the range 20°–28°C (e.g., thermal enhancement in passive solar or geothermal systems). In the late 1970s, Leighton transported larval and juvenile green abalone to mariculture facilities in Hawaii and Florida, finding survival and growth to be exceptional in those tropical regions (Leighton 1987). The green abalone is especially attractive since its growth rate is significantly increased at higher water temperatures; young adults gain nearly 5 cm/yr in shell diameter (Leighton 1974, 1985; Leighton et al. 1981).

Pink and white abalones have been cultured on a small scale (Leighton 1972, 1974). The black abalone, a shallow-water species of lower commercial grade, is broadly tolerant of temperature in adult stages, but larvae from California races have thermal limits similar to that of the cold-water red abalone. Black abalone have been reared from laboratory-spawned eggs (Leighton 1974, unpubl. data). Flat, *H. walallensis*, and threaded, *H. kamtschatkana assimilis*, abalones have also been cultured in research projects in Southern California. The pinto abalone, *H. k. kamtschatkana*, is receiving attention as a mariculture subject in Washington and British Columbia (Fletcher 1987). All species of eastern North Pacific abalones have been found to hybridize in the laboratory with varying degrees of success. In most cases larvae and subsequent stages are fully viable and young adults fertile (Owen and Meyer 1972 [fn. 3]; Leighton and Lewis 1982). Some hybrids exhibit features which promise to be advantageous to mariculture, including environmental adaptability, improved growth rate and hardiness, and possibly refinements in quality of flesh (Leighton 1987).

AMERICAN ABALONE CULTURE TECHNOLOGY

As stated earlier, methods to culture abalone in California were developed quite independently from those practiced in Japan. Generally, the emphasis by U.S. culturists has been on production of crop animals of small adult size directly marketable in the domestic trade. Abalone are reared to sizes of 7–10 cm either within specialized tanks on shore or in containments held in protected ocean waters. In Japan, however, young abalone are usually released to the natural environment at a size of 2–5 cm for continued growth over periods of 2–4 years until a marketable size (7–10 cm) is reached (Saito 1984). Few attempts have been made in that country to rear abalone to adults under the controlled environmental conditions afforded by appropriate tank systems. However, highly elaborate concrete and plastic structures of many designs to provide protective substrate and improved foraging are now being applied to abalone grow-out in the sea (Sheehy and Vik 1981). Coupled with habitat improvement (i.e., algal afforestation and predator control), these in-sea approaches to increase abalone production are gaining success (see Alternatives for Grow-Out). The economic and other risks associated with such measures have constrained development by private enterprise in the United States.

Hatchery Methods

The requirement of North American species of abalones for rapidly moving, well-aerated seawater led to the early development of culture tanks which provided full circulation. Circular tanks proved most effective, and Leighton (1977) introduced such a tank in which rotary flow was easily maintained by air-lift with minimum energy input. Self-cleaning features accompany the vortical drive, airlift return design (Fig. 3). Originally devised for culture of relatively sessile marine invertebrates, the tank allows maximum control, a rapid circulation, and foam fractionation via the return line. These features are effective for culture of swimming larvae and early settled stages. Following use by us (California Marine Associates), new entrants adopted similar tank designs for postlarval and juvenile culture. Now typical of U.S. hatchery tank arrays, round tanks stand in marked contrast to the "raceways" and immersed plastic panels employed in Japan and elsewhere.

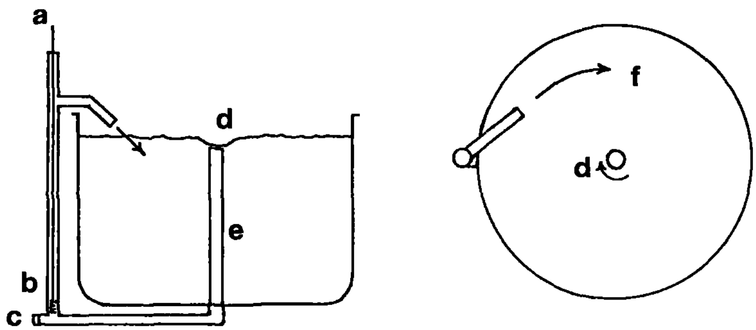

FIGURE 3.—Cylindrical larval and postlarval rearing tank. Vertical drive airlift circulated tank in its simplest form. Tank is self-cleaning and vertical extension for air-lift pipe allows foam fractionation (from Leighton 1965 (unpubl. data), 1977). a. Airline; b. air stone at base of airlift column; c. drain port, normally closed; d. vortex; e. central stand pipe, removable; f. return flow.

Gravid adult abalone may be induced to spawn using several different methods. Thermal shock, still used in some hatcheries in Japan (Ino 1980), was initially used in U.S. abalone culture, but soon abandoned in favor of the method of Kikuchi and Uki (1974) using UV-irradiated seawater. Also available is the hydrogen peroxide method developed by Morse and associates (Morse et al. 1977, 1978). Each approach has its advantages and disadvantages (Ebert and Houk 1984; Leighton and Lewis 1982). Usually broodstock are spawned in separate containers, then gametes are collected and combined to yield the highest fertilization rates. Eggs are subsequently washed and incubated under static conditions at temperatures most appropriate for the species (Leighton 1972, 1974).

Embryos generally hatch from eggs in 12–18 hours as trochophore larvae. Soon after hatching, larvae display a negative geotaxis (Leighton 1972, 1974), swimming at the surface in culture containers for 6–12 hours. This behavior, common to red, green, pink, and white abalones, has been mistakenly regarded as a positive phototaxis in observations with *H. rufescens* by some workers (c.f., Ebert and Houk 1984; Hooker and Morse 1985). Light, however, has a negligible influence on the swimming behavior of these species in the trochophore and pre-eyespot veliger larval stages. Larvae then become increasingly demersal with age. Culture routines, involving water changes and concentration of larvae, take advantage of these behavioral characteristics.

In the hatchery, larvae are generally reared through swimming stages (approximately one week) in culture containers of small volume (5–10 L) with careful attention to water quality, bacterial contaminants, temperature, and density. Highly filtered (ca. 1 μm) seawater, antibiotic treatment, and daily water changes promote maximum survival (virtually 100%) and normal development when larvae are incubated at densities of 2 individuals/mL or less (Leighton 1977). Some laboratories utilize mesh-bottom plastic cylinders immersed in a highly controlled, circulating system similar to that employed in bivalve culture (Ebert and Houk 1984).

The temperature dependency of early development for the principal California species is described by Leighton (1972, 1974). Cold-water species (red, pinto, flat, and white) have thermal optima for larval development in the range of 12°–16°C. The black abalone, while broadly tolerant of temperature in adult stages, is similar to the cold-water species in larval life (optimum 14°–18°C; Leighton 1987). The green abalone is distinctive, having a thermal optimum for larval development in the range of 18°–24°C (Leighton 1974, 1985; Leighton et al. 1981). The pink abalone is intermediate in its thermal requirements. In contradiction to a recent report by Hooker and Morse (1985), only the green abalone among California species may be considered "thermophilic". Hatcheries involved in culture of red, pink, and green abalones must observe the temperature requirements of these species closely.

Advanced larvae are induced to settle and begin metamorphosis using a variety of methods (see Problem Areas). Commonly, larvae at an age of about six days are admitted to small volume tanks supporting thin coatings of benthic microflora (chiefly diatoms and associated bacteria) wherein larvae settle within several hours to two days. It was observed early in red abalone hatchery research that larvae introduced to tanks precolonized by crustose coralline red algae settled promptly. Tanks which had recently held healthy conspecific juveniles, the walls of which presented a well-grazed microfloral substrate, proved especially beneficial to successful settlement and metamorphosis (Leighton 1987). Several sources of "inducers" which effectively prompt settlement and metamorphosis appear to exist (see Problem Areas).

Settled larvae immediately begin feeding on bacteria and other microflora. Metamorphosis commences with loss of the velar cilia and larval operculum. Deposition of peristomial shell is evident within another day, but metamorphosis is a complex and gradual transition. The first respiratory pore is formed at the end of postlarval life (onset of the early juvenile stage), generally as the abalone reaches 1.5–2.5 mm (age about six weeks).

Postlarval attrition continues to remain as the principal "efficiency bottleneck" in abalone culture. Under usual hatchery conditions, survival and normal development for swimming larvae are close to 100% (Leighton 1977, 1985), but mortalities occur in a large percentage of metamorphosing postlarvae with the result that early juveniles represent at best 5–10% of the number of larvae at settling. Declines are most evident during the fourth to sixth week postfertilization. However, when conditions are optimized (usually in small volume containers), survival through postlarval life may be over 25% (c.f., Leighton et al. 1981; Table 1). Losses during critical early benthic stages may thus be reduced significantly by appropriate control and care to include frequent water changes, maintenance of clean conditions, and supplying microalgal foods on a regular basis (see Problem Areas).

Juvenile Culture

Once postlarval abalone begin to form the first respiratory pore, the pallial system (gills and associated structures) and other features of anatomy become more typical of the adult. The juvenile stage commences at this point and extends to young adulthood and onset of sexual maturity. Dietary changes occur in conjunction with development; first-settled metamorphosing postlarvae feed upon smaller microflora (diatoms, sessile flagellates, and bacteria). Early juveniles rely on many larger microalgae, but undergo a dietary transition to include a variety of green, red, and brown macroalgae as advanced juvenile stages are approached. The dietary transition to macroalgae occurs in many species at about 1 cm shell length (4–6 months), but is usually never complete as microalgal films may be ingested and metabolized through adult life (Leighton 1987).

When juvenile abalone reach about 3 mm, they are transferred to larger tanks precolonized by appropriate algae. Transfer is achieved with negligible losses by simple brushing (Leighton

TABLE 1.—Size increase for young adult red and green abalones provided two brown algal diets.

		Mean shell length gain (μm/d)					
		Haliotis rufescens period			*Haliotis fulgens* period		
Alga	Group	I	II	III	I	II	III
Macrocystis	A	64.9	57.7	61.7	33.4	45.9	54.0
pyrifera	B	35.8	71.0	65.9	31.4	17.8	36.8
$\bar{x}$	(S.D.)		59.5	(12.4)		36.6	(12.5)
Egregia	A	76.3	91.9	81.5	86.4	101.6	93.0
menzesii	B	60.5	97.3	78.8	71.4	90.0	66.0
$\bar{x}$	(S.D.)		81.1	(12.9)		84.7	(13.5)

Mean shell length increases (μm/d) for young adult abalone held in duplicate groups (6 individuals/group). Abalone were fed to satiation throughout three feeding periods of 40–50 days each. All abalone were in the size range 5–10 cm; groups were held in 10 L plastic pails receiving ambient seawater at 1 L/min and vigorous aeration. To promote continuous feeding, freshly collected algae were provided in excess (ca. 100 g) weekly. *Haliotis rufescens* observations were made in winter, 13°–17°C; *H. fulgens* in summer and fall, 18°–22°C.

1977, 1985). Some culturists employ chemical relaxants (such as Benzocaine at 100 ppm) to facilitate transfer, but associated losses may be high. The latter method becomes necessary when original culture tanks are large and immovable.

Japanese methods for abalone culture, outlined by several researchers (Kan-no 1975; Ino 1980; Grant 1981; Uki 1981), almost universally employ elongate rectangular "raceway" tanks holding vertically suspended corrugated plastic panels for culture of postlarvae and juveniles. Larvae are allowed to settle directly on the plastic substrates in special tanks prior to transfer to the raceways. Young abalone are reared to 1–2 cm under those conditions. While some hatcheries release the juveniles in the sea for fishery enhancement at that point, others retain the abalone in mesh-bottom drums held upright in larger tanks or supported by rafts in protected marine areas for growth to 3–5 cm (Kan-no 1975).

In the two principal hatcheries for red abalone in California (The Abalone Farm and Ab Lab), culture through early juvenile stages is achieved employing similar systems. However, these groups differ markedly in their approaches for rearing young abalone to market size (4–10 cm). The Abalone Farm practices raceway culture in which juveniles are reared in a series of concrete troughs through which seawater cascades from upper to lower members. Vigorous aeration is supplied intermittently and seawater flow rates vary from 0 to 200 L/min, depending on the pumping schedule. The kelp, *Macrocystis pyrifera*, is the principal food provided, although many species of red, green, and brown algae are available locally in large quantity and are supplied supplementally. Ab Lab transfers juvenile red abalone at about 1 cm to containment structures held in the channel at the entrance to Port Hueneme Harbor. Large polyethylene drums (ca. 55 gal capacity) with plastic or stainless steel mesh capped ends are secured in a horizontal position to braces in racks, all immersed to a depth of a few feet beneath a pier. Each drum receives several thousand individuals initially. *Macrocystis* forms the majority of the diet. Thinned with growth, the young abalone are reared to a size of 4–5 cm and sold live to specialty seafood dealers in the Los Angeles area (Hamilton 1988).

The relatively slow growth rate typical of abalones (ca. 2.5 cm/yr) has been limiting to commercial production by mariculture. However, some species exhibit accelerated development and growth at water temperatures higher than normally experienced in nature. The Pacific abalone has been reared in thermal effluent seawater from an electric power plant in Japan during the cold season (McBeth 1972). Growth rate of the California green abalone was almost doubled when reared at 24°–28°C in power plant effluent in an extensive 4-yr study (Leighton et al. 1981; Leighton 1985). Two new programs in abalone mariculture are being established to utilize thermal energy from coastal power facilities in Southern California for commercial production of this valuable species (see Future Prospects).

ALTERNATIVES FOR GROW-OUT

High costs of grow-out in most land-based systems make methods to rear abalone from juveniles to marketable adult stages in the sea attractive. As discussed earlier, emphasis in Japan has been placed on the design and testing of a diversity of artificial habitats for environmental improvement and partial containment for abalone in the ocean. In that country the largely government-supported hatcheries supply seed abalone to members of fishery cooperatives for planting on improved and controlled areas of sea bottom (Saito 1984; Sheehy and Vik 1981). The introduced abalone are allowed to mature for a period of 2–4 years before final harvest. Much attention has been given means for enhancing survival and growth of these crops by increasing production of kelps and other seaweeds as well as expanding the substrate necessary for concentrated "farming" of abalone. Yields of marketable abalone have been increased appreciably in some areas as these two approaches are coupled with measures to harvest or otherwise reduce numbers of predatory fish and invertebrates (Ino 1980; Uki 1981).

In the mid-1960s, significant advances were made in the United States toward kelp habitat improvement (North 1976). Areas of rocky bottom maintained in minimal algal productivity by large concentrations of sea urchins are often those with the highest potential for algal production and abalone recruitment. A valuable tool for restoration of ecological balance resulted from the finding by Leighton that calcium oxide effectively reduced numbers of overgrazing echinoids, fostering the return of *Macrocystis* and other vegetation with subsequent repopulation by diverse fauna (Leighton et al. 1966; Leighton 1971). Red and pink abalone populations returned to the Point Loma Shelf (San Diego) with unusually heavy recruitment following treatment in 1963–65 of the area with quicklime to reduce sea urchin numbers (Leighton 1968). Interest is gaining in Japan to reclaim vast areas of potentially productive sea bottom limited by sea urchins (e.g., the "isoyake", or "pink rock", coralline algae/echinoid-dominated bottom) for increased abalone production using several approaches of physical habitat improvement, chemical treatment, and algal afforestation (Uki 1986[8]).

Several groups holding leases to areas of offshore California land are engaging in "sea-floor ranching" of abalone. In 1984, a total of about 50 acres had been leased for this purpose in southern California (Leighton 1984[9]). One individual (D. Gilbert, San Diego Mariculture) has liberated many millions of late-stage larvae onto rock bottom within boundaries of his lease holdings. Increases in population densities of seeded species are reported in preliminary surveys. Larval seedings often fail for a number of reasons, including "temporary settlement" (clinging while retaining the ability to swim once again; Leighton 1987), micropredation, and variable viability of different larval stocks. A successful field plant of larval *H. iris* in New Zealand has been reported (Tong et al. 1987). In that experiment, localized recruitment occurred, likely because larvae were released at an advanced age (13 days, Tong 1987[10]), thus reducing the opportunity for emigration.

It appears success of larval and juvenile plantings is dependent on a variety of factors (see Problem Areas). Extremely high losses of red abalone juveniles were reported soon after release off the California coast by Department of Fish and Game biologists (Tegner and Butler 1985). Introduction of young abalone to the marine environment is, however, quite unlike releasing trout fry in freshwater lakes and streams. Using "temporary protective habitats", Leighton (1985, 1987) found greatly improved survival of green abalone through reduced handling during transport and minimized predation during the critical 1–2 days following plants.

[8]N. Uki, National Research Institute of Aquaculture, Nansei, Mie 516–01, Japan, pers. commun. 1986.

[9]Leighton, D. L. 1984. Recent developments advancing aquaculture of abalone in southern California. Paper presented to Marine Aquaculture–Southern California, 1984 Symposium. Annual Meeting, Southern California Academy of Sciences, May 12, 1984, Los Angeles.

[10]L. Tong, Ministry of Aquaculture and Fisheries, Fisheries Research Center, P.O. Box 297, Wellington, New Zealand, pers. common. 1987.

This highly effective and low cost method uses shelters consisting of stacked corrugated PVC sheet (Fig. 4) which allow high density containment during transport and initial protection at the planting site, virtually eliminating "planting mortality". Survival one year after release, based on live recoveries, has been at least 20%; a highly conservative estimate since the planting areas were sampled without destructive approaches to open crevices or upturn large rocks (Leighton 1985, 1987). Likely a combination of controlled planting, habitat improvement, algal afforestation, and predator reduction will prove most effective for the success of seafloor ranching of abalone in California.

Experimental U.S. programs in containment culture carried out by private interests have included buoyed cages (Pacific Ocean Farms, Monterey), cylindrical modular habitats (Atlantic-Richfield Company/California Marine Associates, Santa Barbara), and bottom-secured concrete pipe sections. Containment culture in the sea presents advantages for concentration and protection not inherent in the more extensive approach of seafloor ranching. Under appropriate routines for feeding and maintenance, abalone may be reared at high densities, greatly simplifying the harvesting process. However, containment culture has, to date, proven expensive, not entirely free of predation problems (as young stages of crabs, seastars, etc. enter cages), and subject to destruction by heavy surge and entanglement by drifting kelp. Groups conducting studies in California have not solved all these problems. New designs of containment structures, which incorporate effective feeding systems, are simply monitored and are less susceptable to damage by physical forces are needed to advance technology in this area.

PROBLEM AREAS

The major technological impediments to full development of efficient abalone mariculture in North America appear to fall into three categories: 1) Yields of juveniles under hatchery conditions generally represent less than 10% of the larval stock; 2) conditions for optimization of the culture environment to promote maximum health and growth still require definition for each of the principal species cultivated; and 3) cost-effective methods and associated materials for grow-out, especially in the ocean, remain to be tested and applied on a commercial scale.

Abalone culture technology advanced rapidly

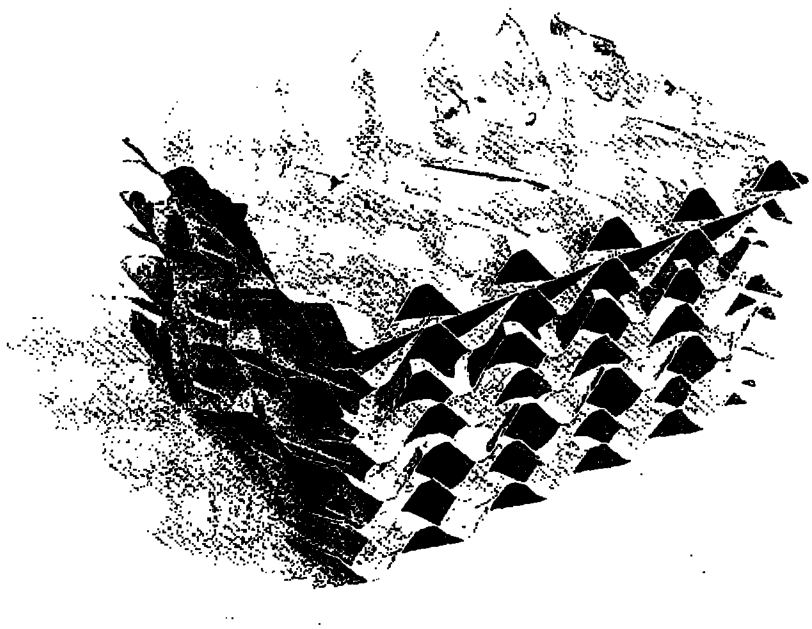

FIGURE 4.—Corrugated PVC sheet "temporary shelter" used to corral juvenile abalone in the hatchery, act as containment structure in transport, and serve as a stocking module and protective habitat for abalone planted in the marine environment. Over 200 juveniles (1–2 cm) may be contained in a single unit 20 × 20 × 30 cm. Abalone planted in these modules move to surrounding natural habitat within 24–48 hours without the high handling and predation mortality experienced with other methods (Leighton 1985). The layered plastic material is manufactured by B. F. Goodrich Company as "Bio-trickling Filter Medium" for use as a high surface to volume bacterial substrate applicable to sewage treatment processes. [Reference to trade name does not imply endorsement by the National Marine Fisheries Service, NOAA.]

in the private sector in the period 1970–75; highly effective methods were found to allow rearing of young red and green abalones through larval and early postlarval stages (ca. days 1–15) with minimal losses (Leighton 1987). These procedures have understandably been closely guarded by the pioneering U.S. abalone culturists. Recently, reports have appeared of new and grand technological advances in abalone culture through research in government (e.g., Ebert and Houk 1984) and academic laboratories (e.g., Hooker and Morse 1985). However, with the exception of the highly useful hydrogen peroxide method for induction of spawning in abalones (see Hatchery Methods), these studies have not, to date, added significantly to the technology for culture of larvae, postlarvae, and juveniles developed by the industry. Certainly, however, the research has contributed valuably to our understanding of basic biological processes (see below).

Interest has focused recently on the facilitation of settlement and prompting of metamorphosis by the addition of bioactive chemicals such as the neurotransmitter, gamma-aminobutyric acid (GABA) and related compounds (Morse et al. 1979). GABA does indeed cause a change in swimming behavior, possibly by affecting the bioelectric potential of cell membranes associated with the velar cilia (Koshtoyants 1960; Baloun and Morse 1984), with active settlement in mature and "competent" larval abalone. Behavior of larvae exposed to GABA, however, differs from that of larvae in the presence of "natural" inducers (see below). Exposure of larvae to GABA at concentrations in excess of 10^{-5} M is in fact lethal (Akashige et al. 1981; Slattery 1987), perhaps a consequence of excessive activation and/or blocking of receptor and transduction sites involving other vital functions. The role of GABA as a neurotransmitter is now well recognized in vertebrate and invertebrate systems. However, induction of settling and onset of metamorphosis in abalone larvae may be more complex than initially proposed (see Trapido-Rosenthal and Morse

1986) and may involve yet unidentified mediators and environmental cues. Further insight regarding use of GABA and other bioactive substances to prompt settlement and metamorphosis may be gained from the analysis and discussion by Pawlik (1988).

The behavior of larvae at settlement is critical to subsequent survival. In the presence of many elements common to the native environment of abalone, including microfloral colonies (diatoms, bacterial films, etc.), biliprotein-containing crustose red algae and cyanobacteria (Morse et al. 1984) and even "mucous trails" of conspecific juveniles (Seki and Kan-no 1981; Leighton 1985; Slattery 1987), advanced larvae of *H. rufescens* and other species examined exhibit a typical swimming behavior consisting of a series of landings and takeoffs as if testing the substrate prior to settlement. Surface acceptance is independent of orientation; settlement may be on container sides, bottom, or even on the undersides of included substrates. In contrast, in the presence of GABA, larvae often settle promptly (usually within 2 hours at 10^{-6} M), but almost exclusively on container bottoms. In the hatchery setting, the tank bottom rapidly becomes a hostile environment and larvae settled there soon succumb to bacterial overgrowth. Using diatom films and other natural substrates, dispersal is optimized and subsequent settling and metamorphosis are normal (Leighton 1977, 1985). GABA is not used routinely in commercial facilities for the reasons cited above.

In California abalone hatcheries, larvae at competence are admitted to tanks appropriately prepared for settling and metamorphosis containing partially cleared diatom coatings (Leighton 1977), other microflora, or traces of mucus and associated substances left by former conspecific occupants (Leighton 1985, 1987; Slattery 1987). In the early stages of red abalone mariculture (Leighton, pers. obs. 1970–75) crustose coralline red algae (*Lithothamnion* and related forms) were cultured within special postlarval culture tanks. Settlement on coralline surfaces was often intense, and subsequent survival and growth of postlarvae was excellent. However, juveniles larger than 5 mm derived decreased nutriment from the coralline-benthic diatom substrate, necessitating their transfer to tanks precolonized by diverse microflora and to which macroalgae were supplied as foods. This observation is in confirmation of results (Leighton 1968: table XXX) showing reduced nutritional benefit of crustose coralline algal substrates for juvenile *H. rufescens*. It was also found in early hatchery operations that larval settling and postlarval success were greatly improved in fiberglass tanks which had recently held conspecific juveniles and adults (Leighton, pers. obs. 1971). More recently, Japanese biologists have found a similar benefit for larval recruitment to exist in *H. discus hannai* (Seki and Kan-no 1981).

As noted earlier, postlarval attrition still limits the efficiency of abalone mariculture, although claims to the contrary appear in the literature (e.g., Hooker and Morse 1985). Losses of 60–80% of postlarvae are commonly experienced during the second to sixth weeks following fertilization (Leighton 1985). While microbial pathogens have not often been demonstrated, a portion of the postlarval attrition may be due to disease. Mortalities may be reduced by providing intensive care to small-scale cultures for which antibiotic prophylaxis or other procedures are followed to minimize epizootic complications. A parasitic protozoan found especially lethal to juveniles younger than 190 days, but not injurious to more mature abalone, was isolated from an abalone hatchery in British Columbia (Bower 1987). Since many potentially deleterious organisms (e.g., *Vibrio* spp.) appear to thrive in decomposing organic matter, the well-managed hatchery is not likely to experience epidemic outbreaks of bacterial and protozoan diseases.

Regardless of the approach, a major portion of the postmetamorphic young eventually succumb before passing early juvenile stages (Leighton 1985). In practice, the high fecundity typical of mature female abalone acts in compensation for the large losses, and spawnings of small numbers of broodstock supply commonly several million larvae on each occasion.

The U.S. species of abalones most produced by mariculture, the red and the green, differ markedly in their requirements of nutrition as well as temperature (Leighton 1987). Kelps commonly used as foods for abalone in California mariculture are *Macrocystis pyrifera* and *Egregia menzesii*. The former is a valuable food for young red abalone, but a relatively poor diet for green abalone (Table 1). *Egregia* is effectively utilized by both species and is the diet of choice for culture of green abalone (Leighton et al. 1981). *Laminaria farlowii*, common in southern California, is also a productive diet, especially for green abalone. Mixed algal diets yield superior growth (Leighton 1968, 1977).

In hatchery systems, holding abalone at high stocking densities and providing satiation feeding, optimization of flow and exchange rates, pH, oxygenation, and other factors is essential for best animal health and growth. Often all requirements appear not to be met in tank rearing systems, however. Growth rate and vitality are generally greatly improved when abalone are matured in the sea in appropriate containments (see Alternatives for Grow-Out).

Growth of the industry in Southern California has been limited by land availability, water quality, and regulatory constraints. Central and northern California offer a far greater extent and variety of coastal sites, but temperature optimization, food availability, salinity reduction, and, at some locations, pollution add to operational limitations. Aside from certain locations within Puget Sound, WA and contiguous areas of Canada, most coastal regions in the Pacific Northwest present similar problems. Failure of some recent mariculture ventures has been due, in part, to inattention to some of these considerations.

FUTURE PROSPECTS

Successes in production and marketing by the existing abalone mariculture concerns in California are stimulating interest among new groups. At least three additional groups are planning shore-based abalone culture operations in the state at this time: Pacific Mariculture, Inc., Santa Cruz (P. Scrivani 1988[11]); Abalone Resources, Inc., Guadalupe; and Marine Bioculture, Inc., Carlsbad. Most will concentrate on production of small adult red abalone. Marine Bioculture will produce green, pink, and red abalones. Total annual production from expanded activities at the Abalone Farm, the Ab Lab, and the newer organizations could reach 100 t by 1995 and 250 t by the year 2000. Harvests from seafloor ranching of red abalone may increase rapidly and match the onshore production by that time. Thenceforth, yields from expanded in-sea programs (both containment culture and seafloor ranching) are expected to gain appreciably as the pertinent technology and cost/benefit factors are improved, and as seed stock becomes more universally available from the land-based hatcheries.

[11]P. Scrivani, Pacific Mariculture, Inc., 100 Shaffer Rd., Santa Cruz, CA 95060. PMI is distinct from PM, Pigeon Point, CA.

The potential for effective abalone mariculture both onshore and in the sea off Baja California, Mexico, is exceptional. To date mariculture of red, pink, green, and black abalones has been largely experimental in that country, but it is expected commercial operations will develop there soon (Aguirre 1987).

A forecast of significant growth in the abalone production industry over the next decade applies to the entire North American Pacific coast from Baja California to Alaska. The frontier now lies in the sea with a promising evolution of effective approaches to both managed cultivation by seafloor ranching and concentrated production within containing structures.

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