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THE REPLACEMENT DECISION

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1.0 INTRODUCTION

Aquaculture is increasingly seen as a means of augmenting the supply of commercially important aquatic species. Under certain conditions, aquaculture may possess a comparative advantage over wild harvest (Shang, 1981). Wild populations may be widely dispersed due to natural ecological dynamics or as a result of harvest pressure. Dispersion affects per unit harvest costs by increasing search time, labor requirements, fuel use, etc. Aquaculture may produce lower per unit costs by concentrating the target species in a confined and more accessible location. Genetic selection combined with controlled feeding and environmental conditions can improve yields relative to natural production. Aquaculture can also allow suppliers to mitigate seasonally fluctuating wild catch and guarantee delivery with greater certainty than when dependent upon wild harvest.

The Florida hard clam aquaculture industry is an example of an emerging aquaculture industry. Two species of hard clam are native to Florida, Mercenaria mercenaria, the northern hard clam, and Mercenaria campechiensis, the southern hard clam (Vaughan et al., 1988). Natural territories of the two species overlap. M. mercenaria is found from the Gulf of St. Lawrence, Canada, to the northern Gulf of Mexico, with the center of abundance from Massachusetts to Virginia. M. campechiensis is found from Cape May, New Jersey, to Campeche, Mexico, with the center of abundance in southwest Florida. Some hybridization occurs where the species overlap, but the two species typically prefer different habitats, with M. mercenaria being an estuarine inter- to subtidal species and M. campechiensis preferring deeper, higher salinity waters (Malouf and Bricelj, 1989). Commercially exploited populations are typically M. mercenaria, as this is the more abundant species and it lives in more accessible waters. Hard clams can live for 23 years or more and achieve a length in excess of 135 millimeters (mm) (Malouf and Bricelj, 1989).

Wild hard clams have historically been found in Florida waters, but large scale harvest and culture have typically been confined to mid-Atlantic and north Atlantic coastal regions (Manzi and Castagna, 1989). As shown in Table 1-1, from 1973 to 1983, annual Florida hard clam landings from wild stocks averaged 107.54 thousand pounds of meat compared to total U.S. average annual landings of 14.362 million pounds (Adams et al., 1991). In the early 1980s, however, a large natural set of clams in the Indian River Lagoon resulted in average annual harvests of 1.366 million pounds of clam meat from 1984 through 1987. Total annual U.S. landings over the same period averaged 13.664 million pounds of meat. This represented an increase in Florida landings as a percentage of total U.S. landings from less than 1% during 1974-83 to almost 10% during 1984-87. Harvests eventually declined to 711 thousand pounds in 1988, due to a combination of harvest pressure and changing environmental conditions. Total U.S. hard clam landings in 1988 were 12.371 million pounds of meat, with Florida production comprising 5.7% of the total.

The ability of Florida waters to support such large wild harvests and the ability of regional markets to absorb the harvests caused many to consider the potential of culturing clams in Florida. Particular note was given to the suitability of Florida's natural environmental conditions relative to

Table 1-1. Hard Clam Landings, 1973-88.

Year	Florida	U.S.	Share of U.S.
	-Thousand pounds of meat-		Percent
1973	139	14,505	0.95
1974	94	14,665	0.64
1975	74	14,995	0.49
1976	61	15,251	0.40
1977	148	14,690	1.00
1978	126	13,295	0.94
1979	72	12,058	0.59
1980	62	13,370	0.46
1981	117	18,118	0.64
1982	145	12,855	1.12
1983	145	14,186	1.02
1984	1377	14,749	9.33
1985	1441	16,697	8.63
1986	1448	11,793	12.28
1987	1197	11,418	10.48
1988	711	12,371	5.47

Source: 1973-84, NMFS; 1985-88, FDNR.

hard clam production. Clam growth is temperature sensitive. Lower water temperatures depress growth while the converse is true, to a point, for warmer water temperatures (Manzi and Castagna, 1989). An accelerated growth rate should allow increased clam biomass production per unit of area and per unit of time.

1.1 The Management Problem: Replacement Under Risk

The decision to undertake hard clam aquaculture requires the evaluation of numerous issues. Hard clam aquaculture is an integrated process consisting of hatchery, nursery and growout phases. A commercial culturist may choose to operate at all levels of production or decide to specialize on a particular level. Hence, a choice of level of integration must be made. Similarly, multiple production technologies exist for each production stage, so a technology adoption decision is required. Next, for each choice of production technology, options exist relative to production scheduling, size of clam seed, planting densities, monitoring schedules, etc. Further, decisions are required on marketing strategy. Specific strategies require decisions concerning whether to target seasonal markets, what size clams to market, and where to market.

The productive capacity, capital requirements and labor intensity of the hatchery and nursery phases of hard clam aquaculture make them less suitable than growout culture for operations owned, managed, and worked by a single individual. The research presented focuses on growout culture. Management options for hard clam growout include the selection of seed size, choice of planting method, clam density and replacement scheduling.

The evaluation of management options is complicated where risk is encountered. Risk is inherent in any system where outcomes are not guaranteed. This applies to both production and financial outcomes. Stochastic production may result in variable output quality and quantity. Variable output produces variable revenue. Stochastic prices further increase the variability of revenue. Consumer preference results in a price structure where a price penalty is incurred for larger size classes. Production uncertainty has particular relevance in hard clam aquaculture as prices are higher in the smaller legal size categories and lower for larger sized clams. Hence, the culturist is concerned that the clams not grow out of the higher-priced size classes.

Research on the costs and returns of hard clam growout aquaculture has been limited to systems and growing conditions representative of the South Atlantic region (Adams et al., 1991). No comprehensive work has been conducted on systems and conditions specific to Florida. Current studies (Adams et al., 1991; Thunberg and Adams, 1990) do not incorporate clam price and yield variability other than through basic sensitivity analysis. Sensitivity analysis simply changes an outcome without examining the likelihood of that outcome actually occurring. The true consideration of risk reflects both its impact and the likelihood of occurrence.

A decision to undertake hard clam growout aquaculture in Florida, therefore, requires knowledge of appropriate production systems, sources of operation risk, the effects of risk on operation design and replacement scheduling, and estimates of the costs and returns of hard clam growout under risk. The specific objectives of this research project were:

1. Develop a bioeconomic model of Florida hard clam growout.
2. Generate cost and return estimates of hard clam growout under different scenarios of growth and price variability to provide insights to optimal operation design and management.

Section 2.0 provides a description of hard clam aquaculture in Florida. Theoretical consideration, data sources, and the bioeconomic model are presented and discussed in section 3.0. The results of the application of the bioeconomic model are given in section 4.0. A summary, conclusions, study limitations and suggestions for future research comprise section 5.0.

2.0 HARD CLAM AQUACULTURE

Hard clam aquaculture consists of three phases--hatchery, nursery and growout (Manzi and Castagna, 1989). Only the first two phases typically entail controlled environments where specific growing conditions are maintained. In the following discussion, current practices and key issues for Florida hard clam aquaculture are described.

2.1 Hatchery Phase

It has been estimated that 40% of hatchery operating costs are for the production of algae or one-celled plants (phytoplankters) for hard clam food (Hartman, 1989). Two primary methods of algal culture, the Glancy and Milford methods, are used for hard clam aquaculture (Castagna and Manzi, 1989). The Glancy Method filters or clarifies seawater to remove predatory zooplankters and large phytoplankters. Treated seawater is kept in shallow, gently aerated tanks, exposed to natural or artificial light. The algae is normally fed to the clams within 48 hours before larger, less digestible phytoplankters dominate. The Glancy Method works best in moderate climates and where an abundance of natural phytoplankton exists.

The Milford Method relies on the controlled production of selected species of phytoplankters using sterile media and growth promotents. Pure cultures of single algal species are produced. Total harvest and replacement of the algae is practiced to prevent contamination.

Since seawater is the medium for both clam and algal growth, the success of a hard clam hatchery is highly dependent upon the availability of water of a suitable quality. The variables of specific concern to the culturist are water temperature, salinity, dissolved oxygen, chemical or bacterial contamination, and algal and zooplankton content. Water quality can be manipulated by the culturist, but it may not be cost-effective to do so. Larval rearing requires water temperatures of 25-30^0 C, salinity of 26-27 parts per thousand (ppt), and dissolved oxygen levels of 6.8-7.4 milligrams per liter (Adams et al., 1991; Eversole, 1987). Larval growth is fastest at 30^0 C, a temperature which also promotes high bacterial contamination (Menzel, 1989). Proper salinity and dissolved oxygen levels are more critical for larval and juvenile clams than for older clams. Older clams are able to remain closed for longer periods and rely on various metabolic mechanisms to reduce oxygen requirements during periods of environmental stress

.

In the hatchery phase, sexually mature hard clams are induced to spawn and produce fertilized eggs. Broodstock are initially selected from wild stock possessing desired characteristics such as large size, or of a special color form or marking pattern called notata. Notata markings are brown zig zag patterns in the shell as pictured in Figure 2-1. Notata patterns are usually present in only 1% of wild populations and are used as a means of cultured product identification (Vaughan et al., 1988). The presence of notata markings can also be used as a marketing tool to help consumers distinguish cultured from wild clams. Also, the use of notata markings discourages poaching as large numbers of notata clams are an indication of cultured origins. The potential marketing benefits of notata breeding may be temporary, though, as escape and breeding by cultured clams increases the presence of notata markings in wild clam stocks.

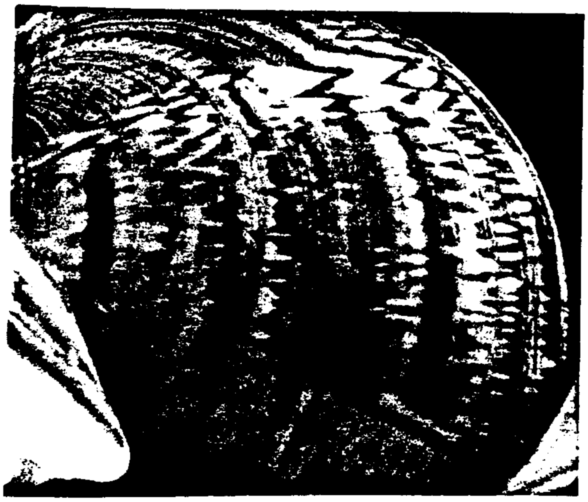

Figure 2-1. Hard Clam Showing Notata Pattern.

Spawning is induced by thermal shock, a process of alternatively raising and lowering the water temperature. Broodstock are placed on a spawning table containing 3-4 inches of clean seawater at 20⁰ C and left undisturbed until all are open and actively siphoning water. The water temperature is then gradually raised to 30⁰ C, left for 30 minutes and then lowered to 20⁰ C for an additional 30 minutes. This process is repeated until all clams spawn. Gonadal material from sacrificed adult clams may be added to the water to further induce reluctant spawners. Egg production ranges from 2-30 million eggs per female (Hartman, 1989).

The fertilized eggs are placed in cone-shaped fiberglass or plastic containers of clean seawater. Within 24 hours of fertilization, the clam larvae, also known as veligers, develop shells and swim freely. Clam larvae do not actively feed for the first 48 hours after fertilization and are not disturbed during this period.

A popular device for rearing clam larvae is the downweller (Castagna and Manzi, 1989). A downweller is a plastic or fiberglass cylinder with an open top and a sieve-covered bottom as pictured in Figure 2-2. Several downwellers are placed in a large fiberglass reservoir filled with clean seawater. The top of the downweller extends above the reservoir waterline. Water flows into the top of each downweller through individual pipes and flows out through the bottom sieves. This system allows the free-swimming larvae to remain in the water column in contact with higher quality food and away from smothering sediment and sick or dead larvae. The larvae are sieved every two days. Sieving allows for the removal of dead larvae and contaminants and permits counting and size sorting.

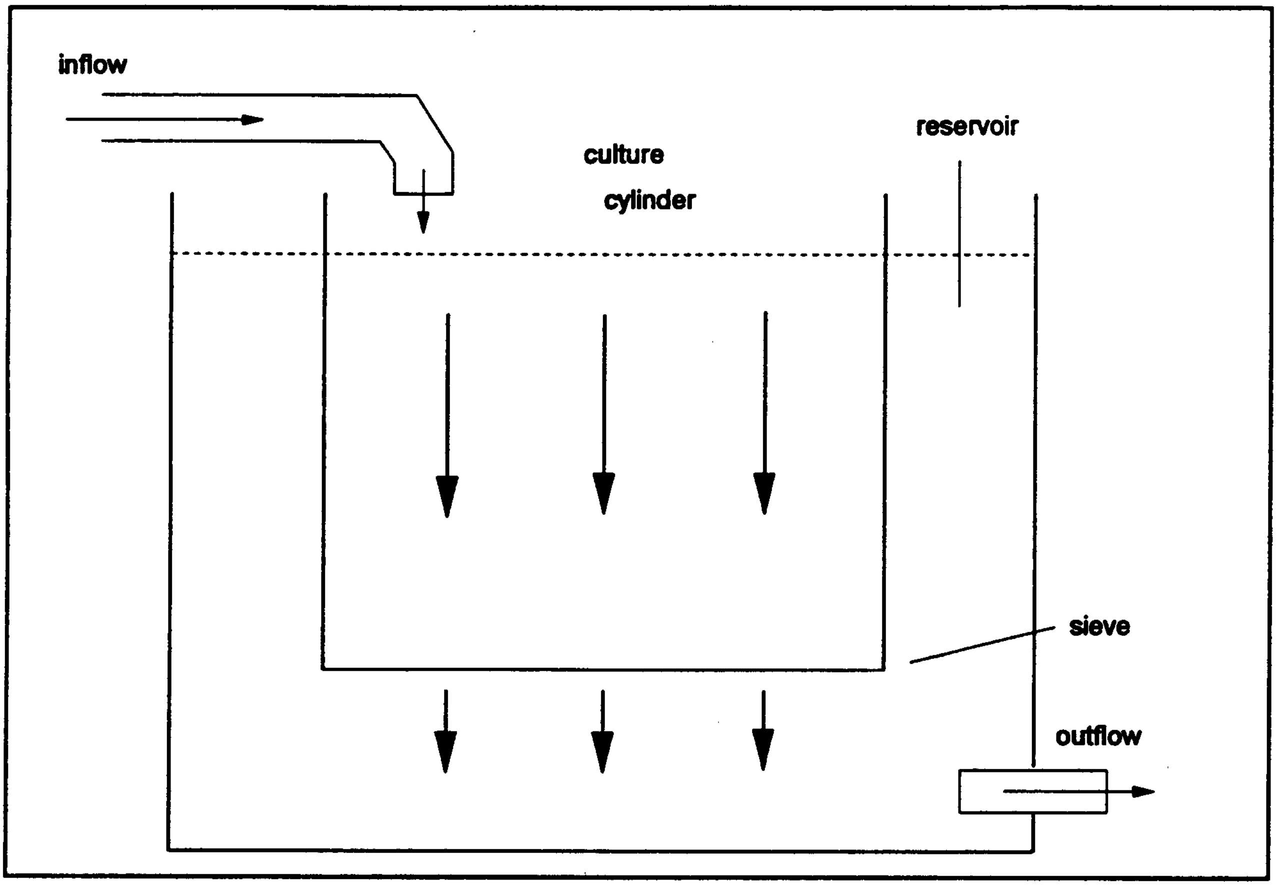

Figure 2-2. Downweller.

Predation and fouling are problems that plague hard clam aquaculture from the earliest stages through harvest. Predation is the consumption of clams by other animals and fouling is the build-up of living organisms on the culture equipment, resulting in smothering, impeded water flow and reduced food access. As mentioned previously, hatchery seawater is filtered, clarified or sterilized to remove predatory zooplankters. Fouling is controlled through reducing water contaminant content, frequent water changes and regular equipment cleaning.

Between 8 and 14 days after fertilization, the clam larvae develop a muscular foot and reach the final larval or pediveliger stage. The larvae lose the ability to swim, but remain mobile through the use of their foot. The clam larvae are called set or post-set and enter the nursery phase.

2.2 Nursery Phase

The goal of the nursery phase is the production of sufficient quantities of seed for final growout. Most growout methods require 7-10 millimeter (mm) or larger seed (measured along the longest axis) (Manzi and Castagna, 1989). Growth rates vary with clam genetics, culture method and growing conditions. Post-set can be expected to reach 1-3 mm at three months, 3-9 mm at six months and 10-15 mm at nine months (Vaughan et al., 1988).

Both onshore and field nursery systems exist. Onshore systems provide the greatest amount of access, control and predator protection, but may do so at considerable land and facility costs. Ambient temperature seawater is used for onshore systems. Water temperature adjustments may be made, however, to maintain optimal temperatures of $20-28^0$ C. Food requirements may be met solely by natural seawater or through a combination of natural sources and cultured supplements. Field nursery systems are generally cheaper, but allow for less access and control as the clams are exposed to ambient water temperatures, algal content, etc. Field nursery systems are preferred because of cost by Florida hard clam culturists (Vaughan and Cresswell, 1989).

A substantial degree of control is required in the nursery phase, especially to reduce predation. The costs of seed production and the subsequent value of clam seed make high survival and rapid growth economic imperatives. Land-based nursery systems use methods similar to those used by hatcheries to control predation. Field systems require a different approach and typically rely on some type of physical barrier between young clams and predators. Dominant hard clam predators in Florida include rays (*Dasyatis* spp. and *Gymnura micruva*), sheepshead (*Archosargus probatocephalus*), blue crabs (*Callinectes* spp.), and various mollusc species (*Melongena corona*, *Fasciolaria* spp., *Euleura cadata* and *Thais haemostoma*). Unprotected hard clam plots in a Florida and Georgia study suffered 100% mortality, of which, 90% was attributed to blue crabs. Vulnerability to predation is inversely proportional to age, as young clams lack the size or shell thickness to prevent crushing, opening or boring by predators.

Fouling also requires special attention. Major fouling organisms in Florida are sponges (*Cliona* spp., *Haliclonia* spp., and *Halochondria* spp.), sea squirts (*Molgula occidentalis* and *Styela plicata*), hydroids (*Obelia* spp.), barnacles (*Balanus* spp.), algae (*Gracilaria* spp.), and various mollusc species (*Crepidula fornicata*, *Crassotrea virginica*, *C. rhizophorae*, *Modiolus* spp. and *Branchiodontes* spp.). Control methods vary with the culture method used and include various combinations of scrubbing, sun drying and turning the equipment over to smother the fouling organisms.

In many operations, the nursery and hatchery phases overlap as hatcheries retain the post-set in their larval rearing containers. This reduces stress and allows greater control over growing conditions. Both downwellers and upwellers are used. Upwellers differ from downwellers in the direction of water flow, with water flowing from the reservoir to the rearing cylinder rather than from the cylinder to the reservoir, as in downwellers. See Figure 2-3. Upwellers vary according to whether seawater is pushed (active flow) or pulled (passive flow) through the clams. Water exits each cylinder through a top drain. Upwellers are more common than downwellers in nursery culture.

Active upwellers are recommended for clams less than 3 mm (Manzi and Castagna, 1989). With proper flow rates, the post-set are suspended just above the sieve by the force of the flow and exposure to algae is maximized. Post-set must be evenly distributed over the sieve for equal food access.

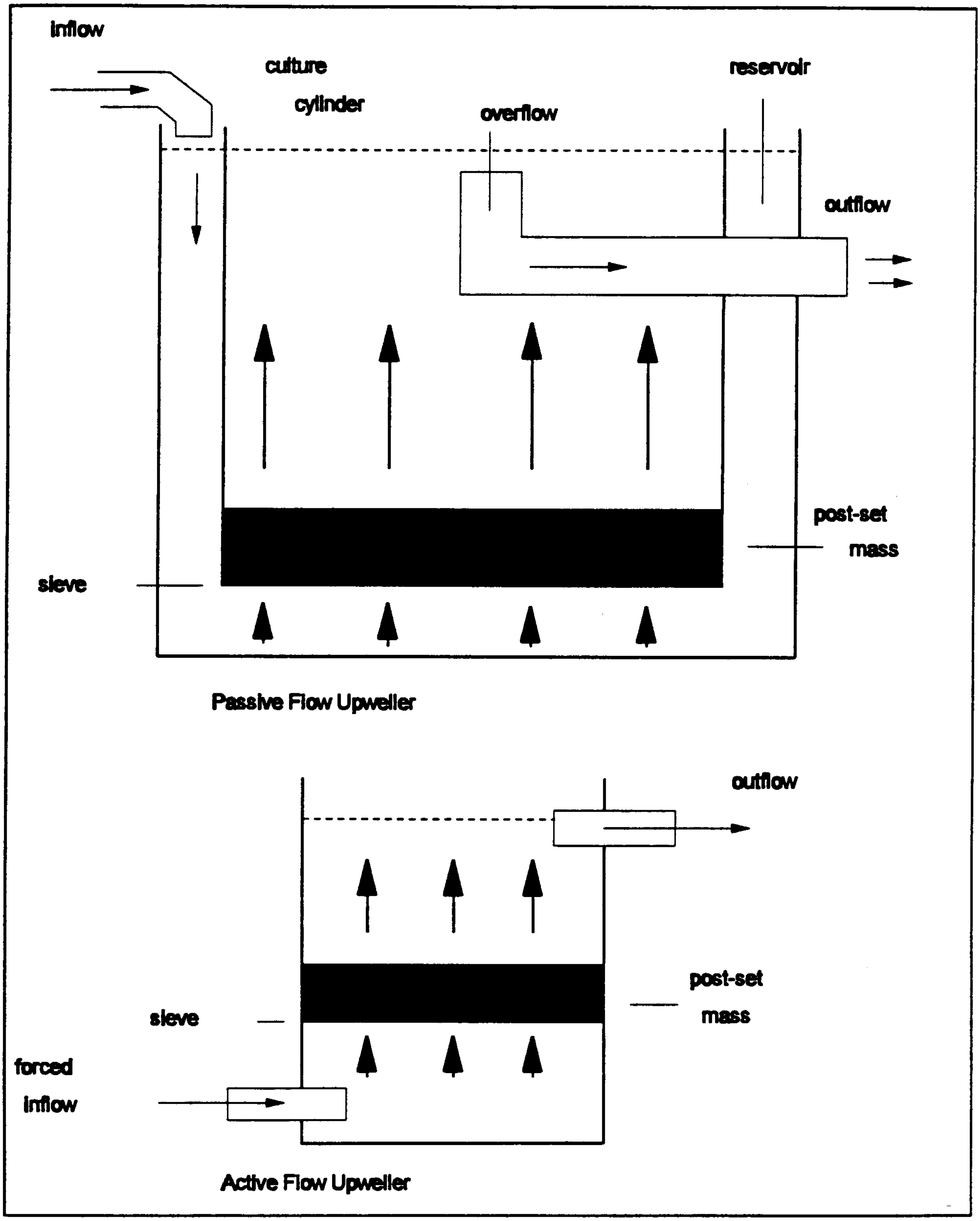

Figure 2-3. Upwellers.

Raceways are a traditional land-based nursery method. Raceways are long tanks or troughs of epoxy-coated wood, fiberglass or concrete. Seawater is pumped into one end of the raceway and exits from the other end. Both shallow and deep raceway systems exist. A shallow system consists of a single layer of clams with just enough water to cover the clams. Deep systems use racks or tiers of trays to create multiple clam layers. A continuous flow of seawater is required. Water quality decreases as the distance from the point of inflow increases. Water algal content is highest at the point of inflow and lowest at the point of outflow. Elevated sediment and waste levels at the end of the raceway (point of outflow) may impede feeding and respiration. Hadley and Manzi (1984) showed a correlation of clam growth with the distance from the inflow, with highest growth occurring in clams nearest the inflow and lowest growth occurring the farthest from the inflow. Flow problems may restrict raceway systems to small post-set culturing.

Post-set under 3 mm are best raised in a land nursery system due to potential predation and smothering problems. Larger post-set perform well in field systems (Castagna, 1983; Castagna, 1986; Vaughan and Cresswell, 1989; Vaughan et al., 1989). Field nursery systems depend on the ability of natural water systems to support post-set growth. This eliminates the need to pump seawater or provide cultured algae. Vertical field systems are multi-tiered structures that place post-set in the water column near higher concentrations of phytoplankton and away from silt and benthic predators (Manzi and Castagna, 1989). Excessive fouling can be problematic. System examples are rafts, cages and racks of suspended trays or nets. A rack support structure is shown in Figure 2-4. Vertical systems are the most space efficient methods for culturing large post-set. The use of vertical systems may be restricted, though, as they may be a navigational hazard. Horizontal field systems rely on culturing post-set on the water bottom. Greater attention must be given to siltation and predation. Fouling can similarly be a problem. Examples of horizontal systems are trays, bottom bags and the flexible belt system. A bottom bag and flexible belt are shown in Figure 2-5. Tray systems use shallow plastic, fiberglass or wooden trays filled with 2 inches of sand or gravel. A mesh covers the tray to exclude predators. Excessive fouling is scraped off the tray and mesh.

Bottom bags are mesh bags held in place by metal stakes. The mesh weave varies with clam size. The bags may be sewn shut or have one side closed with PVC pipe to allow easier access to the clams. A flotation device may be placed in the bag to aid sedimentation, after which the float is removed. Fouling is controlled by turning the bags over.

The flexible belt system consists of a pair of parallel plastic ropes holding individual plastic mesh bags in a pod or modular arrangement attached with PVC pipe closures. Post-set are placed in small mesh bags which are then placed into the individual plastic mesh units. Each bag unit is removable for maintenance or harvest. The entire belt is anchored to the substrate and fouling is reduced by turning the belt over, as with bottom bags.

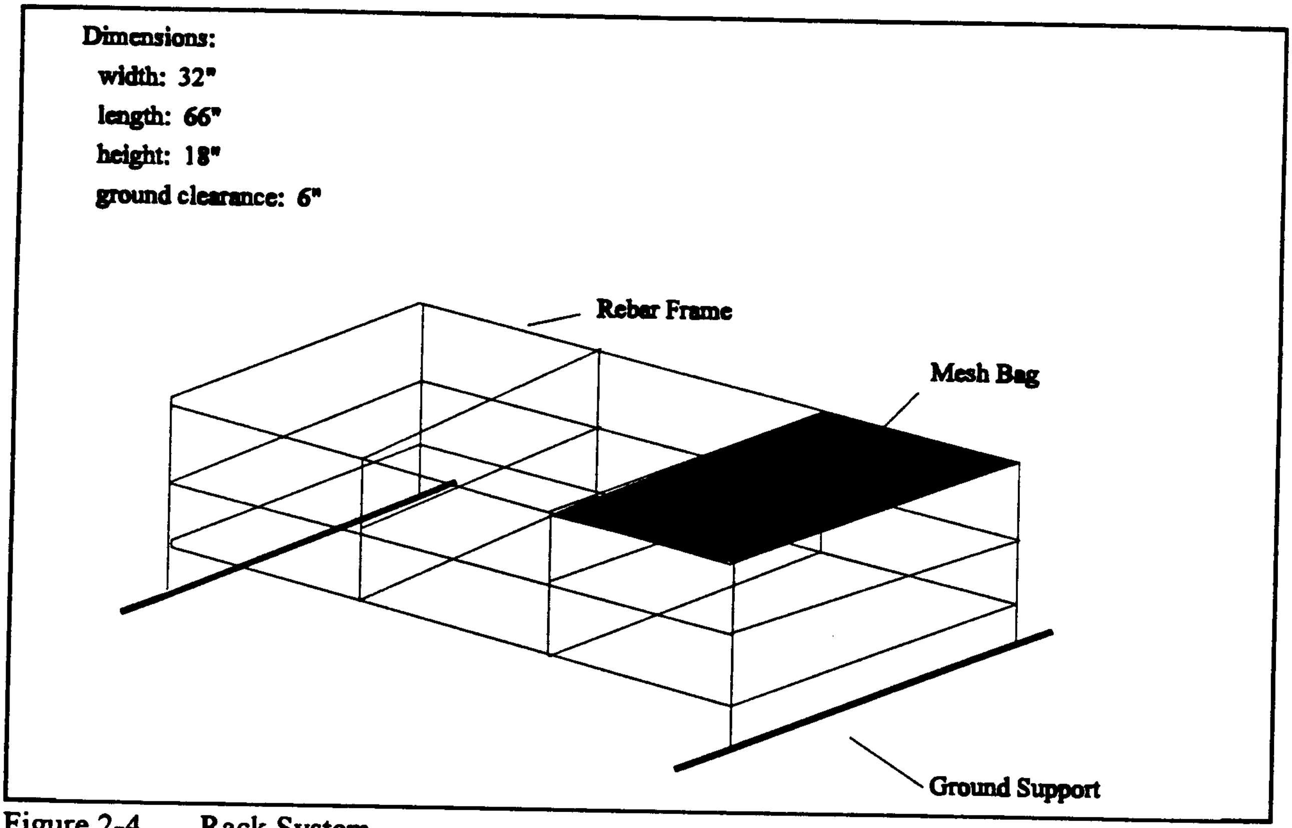

Figure 2-4. Rack System.

Growth trials in Florida (Vaughan and Cresswell, 1989) using 3-9 mm post-set cultured at 1,800 clams per square foot showed trays to be superior to bottom bags and cages, with bottom-bag and flexible-bag culture growth intermediate to that of bottom nets and cages. Choice of tray substrate, sand versus gravel, showed no effect on growth, but resulted in survival rates of 95% for sand and 45% for gravel. The length of the nursery phase varies with stock genetics, culture method, environmental conditions, food abundance and desired seed size.

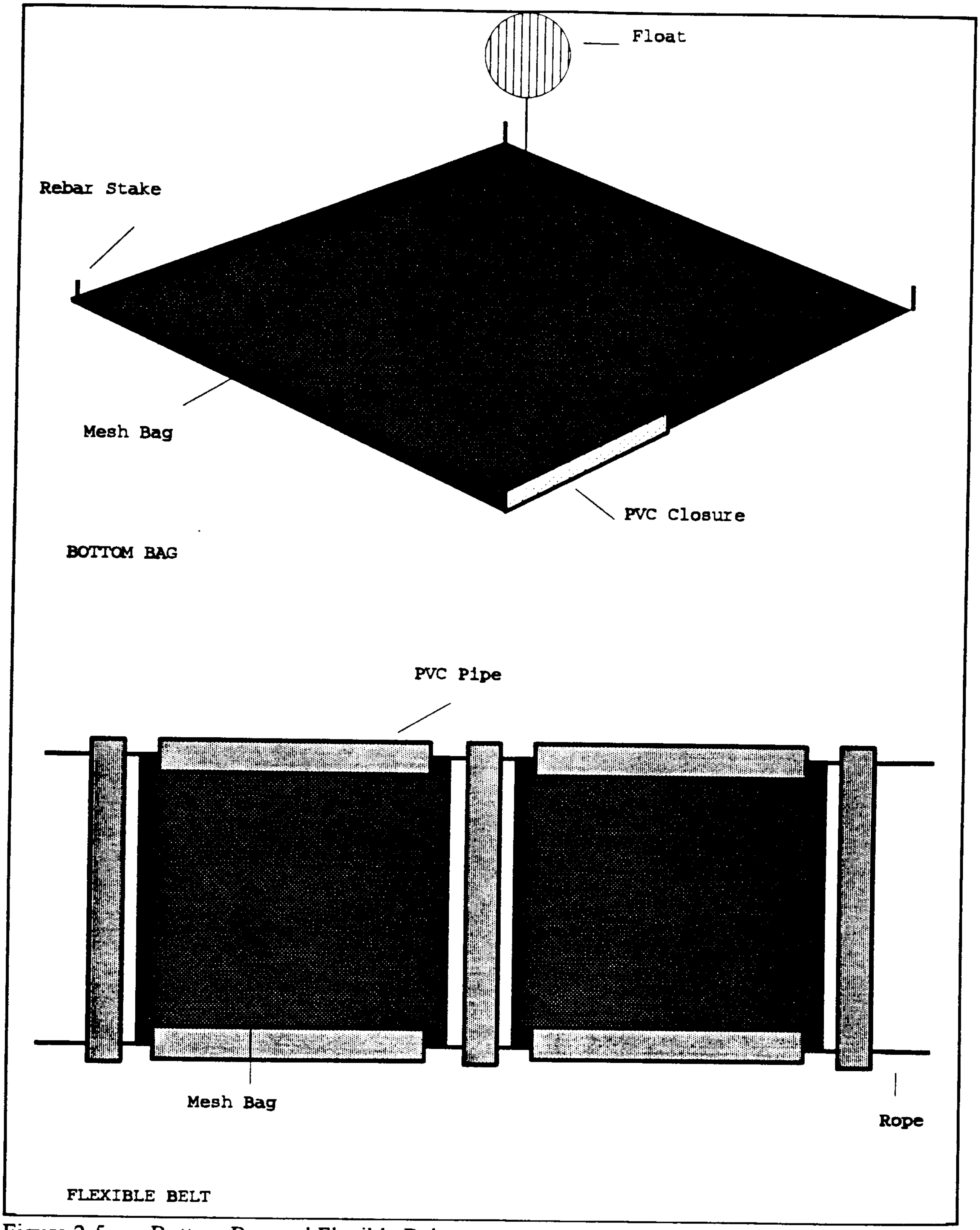

Figure 2-5. Bottom Bag and Flexible Belt.

2.3 Growout Phase

The growout phase takes seed clams and raises them to market size. Increasing water and food demands makes land-based clam growout systems economically impractical. Instead, culturists rely upon natural water systems to meet clam requirements. During growout, culturists are primarily concerned with providing protection from predation while not impeding water flow or food access. Containers, meshes and densities are selected such that adjustments are not required during the growout phase.

The predominant growout methods are tray, bottom net and soft tray or bag culture. Growout trays are similar to those used in field nursery systems except tray dimensions and mesh sizes change to reflect the larger clam size. Sand is the preferred substrate and clams are generally planted at 50-100 clams per square foot (Vaughan et al., 1988). The mesh is kept clean by periodic scrapping to remove fouling organisms.

Bottom nets are the least expensive growout method in both material costs and maintenance (Vaughan et al., 1988). Clams are broadcast in plots over the water bottom and then covered with mesh nets. The nets may be held by an iron frame or staked. Net or plot dimensions vary according to preference, location, management ability, etc., but are usually 25-50 feet long and 8-12 feet wide. Occasionally, mesh is laid under the clams to reduce escape and facilitate harvesting. Bottom nets must be regularly checked for over siltation, fouling and predation. Fouling must be physically removed or the nets periodically replaced with clean nets. Fouled nets are sun-dried to kill the fouling organisms.

Soft-tray or soft-bag growout is similar to soft-bag nursery culture. Clams are placed into mesh bags which are then staked to the bottom. A larger mesh size and bag are used for growout than for nursery culture. Bags are usually four feet square or four feet by eight feet. Fouling is again controlled by flipping the bags over.

The flexible belt system can be used for hard clam growout. Mesh size is larger than for nursery use, and a bag insert is usually not required. The belt is serviced and maintained in the same manner as in nursery use.

Equipment durability is an important consideration in the choice of a particular growout method as growout may take from 3-4 years in cold northern waters, and 1.5 to 2.5 years in warmer waters (Eversole, 1987). Bags, trays and nets must be chosen such that they are capable of extended use and not require frequent repair or replacement.

2.4 Harvest

For harvest and sale purposes, hard clams are measured across the hinge as indicated in Figure 2-6. At the time of this research, Florida hard clams could be legally harvested for consumptive sale when they measured 7/8 inches in width for sale outside the state and one inch for sale inside the state. A one-inch-hinge-measurement equates to a two-inch or 50-mm-long clam. Current Florida law allows the sale of 5/8-inch cultured clams (Marine Fisheries Commission, 1994). This research, assumes a one-inch minimum legal size.

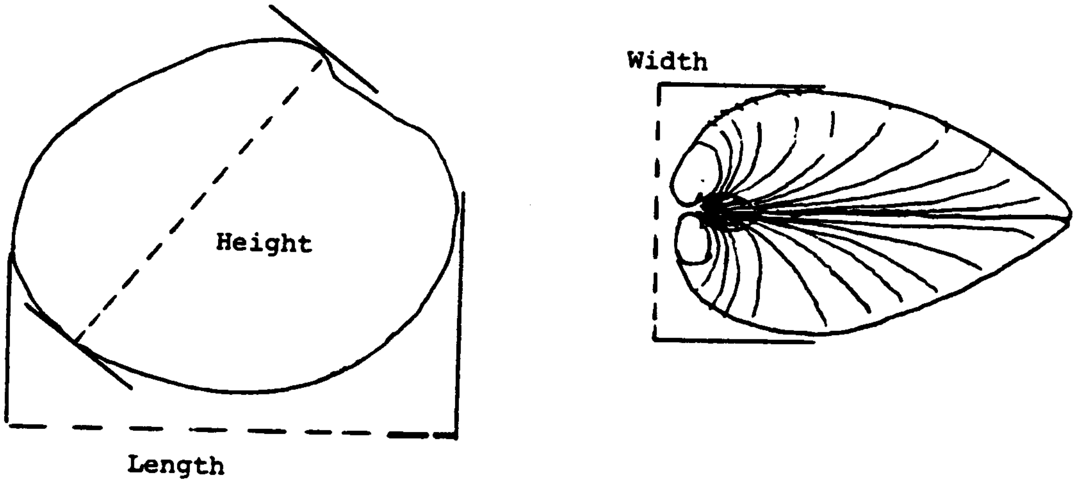

Figure 2-6. Hard Clam Measurement Axes.

The harvesting method used is dictated by the growout method practiced. Tray and bag culture allow for total harvest of the containment device. The tray or bag is manually or mechanically lifted from the bottom and legal clams removed. Bottom-plant methods require a different approach, as the clams are not in any container. Some form of rake, tong or mechanical harvest is required. State law may restrict the use of specific harvest methods, thereby determining the choice of growout method. Mechanical harvest requires a special permit in Florida.

3.0 BIOECONOMIC MODEL

3.1 Economic Model

The objective of a hard clam aquaculture operation is assumed to be profit maximization. Management options for hard clam growout include the selection of seed size, choice of planting method and clam density, and replacement scheduling. The task confronting the aquaculturist is to select a seed size, planting method, clam density, and planting and harvest schedule that maximizes net revenue.

The first three decision options are typically single incident decision choices--an option is selected at planting time and remains fixed throughout the production process. Clam density may be altered through periodic culling. Replacement scheduling, however, is a decision requiring periodic evaluation. At each stage of the growout process, a dichotomous decision choice is faced: to sell the existing stock and replant with new seed, or to keep the existing stock for another period.

Economic principles dictate that the decision to replace or keep existing stock be based on a comparison of the gains from keeping existing stock an additional period with the opportunity gains from replacement stock during the same period (Perrin, 1972). If the gains associated with retaining existing stock exceed the average net returns from harvesting and replacing with new clam stock, then current stock should be retained. Otherwise, immediate harvest and replacement is warranted.

A hard clam is an appreciating asset (to a point) that generates a single, point-of-harvest return in period s. Hard clams provide no stream of revenues prior to harvest. Future hard clam growth and prices cannot be forecast with total accuracy due to the inherent uncertainty of the various processes being examined. Growth and death processes are at best imperfectly describable, and their dependence on stochastic environmental conditions increases the uncertainty of achieving specific future outcomes. Price movements are likewise uncertain. As a result the decision variable is the age, or period s (in days or months), to harvest the hard clam. However, future outcomes or states at any particular age or period s can be predicted only in a probabilistic manner. Hence, rather than having a single net revenue state, F_s, in each period s, there exist k net revenue states in each period s, $F_{k,s}$. Also, each net revenue state k in period s is realized with the probability $\beta_{k,s}$.

Given the above considerations, the discrete-time net present value of hard clams replaced every s periods is:

$$R(s,\infty) = \frac{1}{1-(1+r)^{-s}} \left[\sum_{k \in k^*} (1+r)^{-s} \beta_{k,s} F_{k,s} - M\right] \qquad (3.1)$$

where:

$R(s,\infty)$ = net present value of an infinite stream of revenues from an asset replaced every s period;

r = discount rate;

$F_{k,s}$ = net revenue from asset in state k in period s;

$\beta_{k,s}$ = the probability of having state k in period s;

M = asset replacement cost;

K^* = the set of all possible states.

The term in brackets is the net present value of a single asset cycle and the term outside the brackets converts this to an infinite chain. Equation 3.1 computes the net present value of an infinite annuity received every s period.

Replacement literature uses the term "defender" to refer to the asset already in use and the term "challenger" to refer to the replacement asset (Perrin, 1972). If a single challenger exists, (3.1) is maximized with respect to replacement age s and the maximum present value R^* calculated. At each production period, the culturist has the choice of replacing the defender with the challenger or allowing the asset to grow an additional period. Crane (1979) shows that the replacement decision is based on a comparison of the infinite net revenue streams of each alternative, or:

$$\begin{aligned} &\textbf{replace} \text{ if } R^* > \frac{1}{1-(1+r)^{-1}} \Big[\sum_{j\in j^*} (1+r)^{-1}\, \delta_{j,1}\, D_{j,1}\Big] \\ &\textbf{keep} \text{ if } R^* < \frac{1}{1-(1+r)^{-1}} \Big[\sum_{j\in j^*} (1+r)^{-1}\, \delta_{j,1}\, D_{j,1}\Big] \end{aligned} \tag{3.2}$$

indifferent otherwise,

where:

$\delta_{j,1}$ = the probability of having net revenue j if the defender's life is extended 1 period;

$D_{j,1}$ = net revenue j from the defender if its life is extended 1 period.

Equation 3.2 constitutes the replacement decision policy for the hard clam aquaculturist. The decision space defines the set of all possible options available to the producer. Assuming that the operation will continue production in some manner, the decision space has two elements: to keep existing stock (allow continued growth), or to harvest and replace with new seed.

Dynamic programming is a useful optimization procedure for problems involving a sequence of interrelated decisions. Most frequently, time is the periodic division unit at which the system is evaluated and a policy decision required. State variables are observable or measurable conditions such as clam size, mortality, prices, etc. These provide the basis for periodic evaluation.

The action chosen at each period allows the system to change from state to state according to the processes driving changes in the state variables. A harvest decision prompts restocking and next period's stock is then replacement seed. A decision not to harvest allows additional stock growth, mortality, and market risk. Dreyfus and Law (1977) further develop the general dynamic programming problem, has presented in our case by equations 3.1 and 3.2, and prove that the solution is optimal.

3.2 Hard Clam Growth and Mortality Models

Expected or future hard clam revenue is determined by clam size, price, and quantity of clams. Knowledge of hard clam growth and survival is therefore necessary to predict expected revenues. Growth models simulate the movement of clams across size categories, while mortality models determine survival and, hence, clam quantities available for sale.

Hard clams have seasonal growth. Seasonal environmental variations include changes in air and water temperatures, salinity, dissolved oxygen, and other parameters. The moderate temperatures of the spring and fall produce the fastest growth. High summer temperatures result in the slowest growth and severe winter temperatures similarly depress growth. Changes in the environmental parameters affect hard clams directly by altering metabolic, feeding and respiration rates and indirectly through affecting phytoplankton availability (Eversole, 1987; Van Heiningen, 1992; Malouf and Bricelj, 1989) .

Seasonal growth imposes a degree of production risk on hard clam growout as clam growth becomes dependent upon uncertain environmental conditions. Knowledge of the impacts of specific environmental parameters would allow the incorporation of production risk into the bioeconomic model through the estimation of growth given probabilistic environmental conditions.

Despite the recognition of environmental impacts on clam growth, little empirical work exists on quantifying these impacts. Some authors acknowledge the importance of environmental influences in determining clam growth, but make no attempt to quantify these effects. Askew (1978) and Loesch and Haven (1973) model growth simply as a function of initial size. Lough (1975) uses a linear function to specify the effects of temperature and salinity on the percentage growth of hard clams and two other bivalve species. Parameter estimates were made for only two and ten-day-old clam larvae. Results indicated a cessation of growth at temperatures and salinity above 32.5°C and 27 ppt, respectively. Metabolic changes in older clams raise questions on the applicability of these results to larger clams. As clams mature, optimal temperature and salinity ranges change, and tolerance levels increase as older clams are able to remain closed under adverse conditions (Eversole, 1987). The increased tolerance to adverse conditions may allow clams to continue to grow during periods of environmental stress. Growth would, however, likely be less than under favorable conditions.

In a paper describing Virginia private oyster culture, Bosch and Shabman (1989) model growth as a function of initial weight, season and salinity. Their model has the form $W_t = W_0 e^{abc}$, where W_t and W_0 are final and initial oyster weights, e is the base of the natural logarithm, and a, b and c are the seasonal, salinity and instantaneous growth rate (a function of initial weight) effects, respectively. The paper does not attempt to validate the growth function, focusing instead on using it as a tool in simulation modelling of oyster production. Results, though, indicate that improved knowledge of salinity effects holds great promise for increasing oyster culture profitability. Parameter estimates in this model were independently determined from different studies and combined for application to Virginia oyster culture. The linear form of the model is $\ln(W_t/W_0) = abc$. The model is unsuitable for estimation of the individual effects of the various environmental parameters. At best, a single coefficient could be estimated, representing the combined effects of season, salinity and initial weight.

Food (phytoplankton) is discussed by several authors as a major factor in determining clam growth (Epifanio, 1979; Menzel, 1989; Malouf and Bricelj, 1989). Most researchers focused on the growth effects of specific diets, showing that certain algal diets were more beneficial than others. Malouf and Bricelj (1989) discussed the impact of clearance rates--the volume of water filtered completely free of food particles per unit time--on clam growth. Growth was shown to be a function of clearance rate which, in turn, was affected by water temperature, food concentration and food quality. Phytoplankton quality and abundance is also affected by various environmental conditions such as atmospheric temperature, rain, or excessive run-off (Ryther, 1986). These factors influence algal growth and, hence, its availability as food.

3.21 Growth Model

Clam growth can be described as:

$$G - f(I, A, S, T, D, N, C, M) \tag{3.3}$$

where:

G = clam growth or final size;
I = initial clam size;
A = clam age;
S = water salinity;
T = water temperature;
D = water dissolved oxygen;
N = food profile or algal content of the water;
C = water flow or current characteristics;
M = other factors.

The selection of specific independent variables included in the growth model regression was based on considerations of data availability. Specifically, data on food availability (N) and water flow characteristics (C) were unavailable, thus these factors could not be included in the regression analysis. Techniques exist for measuring these parameters and other factors (M) --water speed and direction can be measured, chlorophyll levels are an indication of algal abundance, light refraction meters can measure turbidity or sediment load--but monitoring of such parameters is currently not undertaken with any regularity.

Hard clams are measured by shell size (height or length) and not by total weight or meat mass. Although clam weight or meat mass may decrease under adverse growing conditions, shell size only decreases as a result of shell blunting in extremely old and large clams. Thus, clam growth is nonnegative and an acceptable hard clam growth function is required to mimic this condition. This was accomplished through the use of a log-linear growth function.

The regression model for clam growth in period i was:

$$\ln Y_i = \beta_0 + \beta_1 \ln A_i + \beta_2 \ln S_i + \beta_3 \ln T_i + \beta_4 \ln D_i + \epsilon_i \tag{3.4}$$

where :

$\ln Y_i$ = clam growth (G) measured as the natural log of the ratio of a clam's final size at the end of period i over its initial size at the beginning of period i;
β_0 = a constant;
$\ln A_i$ = natural log of the clam's age at the beginning of period i;
$\ln S_i$ = natural log of the mean water salinity over period i;
$\ln T_i$ = natural log of the mean water temperature over period i;
$\ln D_i$ = natural log of the mean water dissolved oxygen over period i;
ϵ_i = residual for period i.

Non-decreasing shell size results in the ratio "final size/initial size" to be no less than 1, the natural log of which is 0. Thus, the dependent variable, Y_i, is 0 or positive and preserves the nonnegative growth requirement. The model is also similar in form to the linear form of the Bosch-Shabman model but allows for estimation of the individual effects of different environmental parameters.

Production data were obtained from a commercial hard clam operation located in the Indian River Lagoon near Melbourne, Florida, and used to estimate the hard clam growth function coefficients. The data covered production from June 1990 to October 1992 and contained 729 observations of monthly growth and mortality averages. Size measurements were made along the longest axis (length) of the clams. There were an average of 25 observations per month. Individual plantings ranged from 360,000 to 5 million clams. Clams ranged in age from 1 to 37 months old (post-plant age). All seed were 10 mm. New plantings occurred monthly and in any given month 23-30 different plants existed simultaneously on the lease. Planting densities prior to January 1991 were 80 clams per square foot and 60 clams per square foot during and after January 1991.

The production data also included environmental data from June 1990 to October 1992 and consisted of daily observations of water temperature, salinity and dissolved oxygen. Monthly averages were computed from the daily figures. The production data set is given in Holiman (1993).

The coefficients of the model were estimated by ordinary least squares (OLS) regression[1] and the results are shown in Appendix 1. Separate regressions were run for 60 and 80 clams per square foot. The OLS estimates were used to simulate 30 months of clam growth for both 60 and 80 clam density. A comparison of the performance of the 60-clam and 80-clam models, with plants in each of the 12 calendar months, is shown in Table 3-1. The 60-clam-density model produced larger but more variable clam growth. The difference in the performance of the two models is likely a demonstration of crowding effects. Higher densities reduce mobility, access to food, and access to fresh water, thereby negatively affecting growth. The net effect of crowding, however, might not be uniform across all months due to monthly variations in water quality. The simulation results provide evidence of the positive/negative effects specific months have on the growth performance of clams. Specifically, a growth bias toward fall and winter conditions and away from spring and summer conditions is indicated. Timing is apparently at issue, with clams unable to overcome the negative effects of planting in less favorable months.

Hard clam growth was simulated using equation (3.4) and environmental data collected from the St. John's River Water Management District (SJRWMD). The SJRWMD data consisted of daily water temperature, salinity and dissolved oxygen readings from different locations in the Indian River Lagoon. To test the robustness of the growth model, three sites were selected from which monthly averages were computed. The selection of the three sites was based on comparison of site conditions, with the selected sites representing mean, above mean, and below mean conditions. Mean monthly values for each site are listed in Appendix 2. Each environmental parameter was assumed to have a normal distribution. Using parameter means and standard deviations, monthly averages were assumed to take on three possible values: the mean, greater than mean and less than mean. The extreme values were calculated by adding or subtracting two standard deviations to or from the mean, respectively. Exposure to a mean value had a 68% probability, while exposure to each of the extreme values had a probability of 16%. A given environment consisted of some combination of mean, above mean and below mean values for the three parameters of interest. For example, environment $E1_m$ consisted of mean values for temperature, salinity and dissolved oxygen in month m, where m = 1, 2,..., 12. Environment $E2_m$ had mean temperature and salinity and greater than mean dissolved oxygen in month m, etc. Given three parameters, 3^3 or 27 possible environments existed each month.

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[1] To correct for heteroskedasticity, the model was also estimated using weighted least squares procedures, and since Y is a limited dependent variable, a heteroskedastic tobit estimation was conducted. The three models were used to simulate clam growth for 30 months. Only OLS procedures produced parameter estimates that adequately reflected observed data on growth performance. Thirty-month final clam sizes were 50.567 mm at 80 clams per square foot and 56.114 mm at 60 clams per square foot using OLS parameter estimates. Comparative sizes for WLS and heteroskedastic tobit were 36.602 mm and 30.721 mm, respectively, for clams planted at 80 clams per square foot. The OLS estimation produced the best model and was therefore used to simulate hard clam growth. The results are shown in Holiman (1993).

Table 3-1: Average Expected 30-month Sizes (mm) from Simulation Model Testing using 10 mm Seed.

Planting Month	Density: 60 clams/sq. ft.	Density: 80 clams/sq. ft.
January	65.92	56.16
February	59.09	54.19
March	55.26	52.91
April	50.28	51.19
May	47.33	50.25
June	48.45	50.41
July	51.16	51.13
August	56.87	53.21
September	63.76	56.74
October	70.88	58.36
November	73.15	58.53
December	70.78	57.62

The environmental probabilities for the 27 environmental states are given in Table 3-2. The probability of exposure to a particular environment in any month was determined by the product of the probabilities of receiving each individual parameter. Environmental states were defined in mean, above mean and below mean terms. For example, the probability of having E1, indicating mean temperature, salinity and dissolved oxygen, was 0.68^3 or 31.44%. The probability of having environment $E2_m$ was $0.68^2*0.16$ or 7.4%. The probability of exposure to a given environmental state was the same regardless of which stage or month transition occurred from. The probability of receiving mean values for all three parameters in the current or future growing periods was 31.44% regardless of which month the production process was in. Actual parameter values for a given environmental state, however, and their impact on clam growth, varied from month to month. Mean water temperature for environmental state $E1_1$ was not the same as mean water temperature for $E1_2$, etc. January temperatures are typically different than February temperatures. The probability of exposure to a mean, above mean or below mean value in each month, however, remains the same.

Growth simulation began with a clam or bag of clams of a specific initial size, either 10 mm or 15 mm, and an age of 1, indicating the first growout month. Simulation began with a January plant. January growth simulation produced a new clam or unit with 27 possible profiles or sizes. Although the first step began with seed of equal size, 27 (potentially) alternative final sizes were possible, the result of 27 different environments. The second step required that each of the 27 alternative units produced by step 1 be exposed to each of the 27 February, or period 2, environments. The outcome of an exposure defined by E1 (mean values for all three environmental parameters) in period 2 was calculated as the average size of the 27 period 1 clams transitioning through E1 in period 2. Similarly, the outcome of exposure to E2 (mean dissolved oxygen and salinity and above mean temperature) was the average of those same 27 period 1 units exposed to E2 in period 2, etc. Thus, the outcome of each sequential growth period was 27 "new" clams, where each clam represented an average of 27 potentially different clams transitioning through a given environment.

It is important to note that the 27 clams produced each period need not be of different sizes. The zero growth outcome of certain environments often produced identical representative clams. An example of the outcome of growth simulation is given in Table 3-2. Growth was simulated for 34 months. This produced a 27*34 matrix of ending clam sizes for each period. Each cell or entry in the matrix represented the average of 27 clams exposed to the environment designated by that particular row. For a given site, this procedure was repeated with each of the 12 calendar months as the initial growth period. This process was repeated for each initial seed size (10 and 15 mm) and planting density (60 and 80 clams per square foot). This produced 2*2*12 or 48 growth simulations per growout site.

Final monthly expected clam sizes were computed using the results of the growth simulation and the environmental probabilities. The expected size of a clam at the end of period i equaled the sum of the expected outcome of a clam exposed to environment j in period i times the probability of encountering environment j. Thus, each 27*34 matrix of final clam sizes, where each row represented a different environment, was reduced to a 1*34 vector of expected final sizes. Each outcome represented an expected mean clam size. Size standard deviations were then calculated from the equation:

$$\mathrm{STD} - 2.151 \bullet 0.0603\ \mathrm{FINS} \qquad (3.5)$$

where:

STD = standard deviation of hard clam size;
FINS = hard clam mean size.

Equation 3.5 was estimated using the commercial production data previously described.

3.22 Mortality

Little empirical work exists on developing mortality models for estimating bivalve mortality rates. In situations where populations are modelled from the postlarval stage without consideration of reproduction, the numbers of surviving individuals is due to mortality only. Mortality of seed clams is often many times that of adults (Eversole, 1987). In the absence of adverse environmental conditions, predation is the major cause of hard clam mortality. Susceptibility to predation decreases with increasing clam size and commercial growout methods utilize effective physical barriers to reduce predation. Exposure to environmental conditions outside tolerance ranges also produces increased mortality. As discussed previously with reference to growth conditions, tolerance ranges as they relate to mortality increase for older clams, however, as they are able to maintain closure longer, effectively shutting out certain adverse conditions, and are able to utilize various metabolic mechanisms undeveloped in juvenile clams.

Most models describing populations with an absence of reproduction are usually expressed in terms of an instantaneous mortality rate (Allen et al., 1984) which, despite the name, computes an annual or monthly mortality. Askew (1978) links oyster mortality to size and computes monthly mortality from annual data, using the assumption that short term rates concur with long term rates. Data showed mortality peaks in winter and early summer. Askew acknowledged the potential impact of season on mortality, but concluded insufficient evidence existed to warrant inclusion in his analysis. The observed association of mortality with size implied an inverse relationship as mortality rates decreased with increasing size.

Evaluation of the mortality data used in this research did not produce a workable model of environmentally-dependent mortality. Hard clam mortality was thus calculated in a deterministic manner based on age. First, a cumulative 30-month mortality was identified from discussions with hard clam research specialists (David Vaughan, Harbor Branch Oceanographic Institute, Ft. Pierce, Florida, and Leslie Sturmer, Project Ocean, Cedar Key, Florida, personal communications). Next, a weighting system for mortality was determined from examination of available mortality data linking mortality with age. The resulting weight system placed greater weights on younger clams, indicating greater early mortality and lower mortality of older clams.

Table 3-2. Environmental Probabilities Used in Hard Clam Growth Simulation.

Environment	Dissolved Oxygen	Salinity	Temperature	Probability
E1	X	X	X	0.3144
E2	X	X	+	0.0739
E3	X	X	-	0.0739
E4	X	+	X	0.0739
E5	X	+	+	0.0174
E6	X	+	-	0.0174
E7	X	-	X	0.0739
E8	X	-	+	0.0174
E9	X	-	-	0.0174
E10	+	X	X	0.0739
E11	+	X	+	0.0174
E12	+	X	-	0.0174
E13	+	+	X	0.0174
E14	+	+	+	0.0040
E15	+	+	-	0.0040
E16	+	-	X	0.0174
E17	+	-	+	0.0040
E18	+	-	-	0.0040
E19	-	X	X	0.0739
E20	-	X	+	0.0174
E21	-	X	-	0.0174
E22	-	+	X	0.0174
E23	-	+	+	0.0040
E24	-	+	-	0.0040
E25	-	-	X	0.0174
E26	-	-	+	0.0040
E27	-	-	-	0.0040

Code: X = mean value, (-) = mean minus two standard deviations, (+) = mean plus two standard deviations.

Table 3-3: Example of Hard Clam Growth (Ending Size) Simulation Results for a January Plant Using 15 mm Seed Planted at 80 Clams per square foot.

	Period								
Environment	1	2	...	13	14	15	...	33	34
	Size (mm)								
1	18.60	21.97		53.26	56.55	60.22		85.02	85.08
2	18.26	21.55		52.28	55.45	59.15		85.02	85.08
3	19.06	22.57		54.59	58.09	61.68		85.02	85.63
4	18.78	22.27		53.78	57.31	61.19		85.02	85.50
5	18.44	21.84		52.80	56.20	60.11		85.02	85.08
6	19.25	22.88		55.13	58.87	62.68		85.51	86.70
7	18.38	21.60		52.64	55.59	58.94		85.02	85.08
8	18.05	21.18		51.68	54.51	57.89		85.02	85.08
9	18.84	22.19		53.96	57.10	60.37		85.02	85.08
10	18.54	21.94		53.10	56.46	60.14		85.02	85.08
11	18.20	21.51		52.13	55.36	59.07		85.02	85.08
12	19.01	22.54		54.44	58.00	61.59		85.02	85.40
13	18.72	22.24		53.62	57.22	61.11		85.02	85.26
14	18.38	21.81		52.65	56.11	60.02		85.02	85.08
15	19.19	22.84		54.97	58.78	62.59		85.33	86.46
16	18.33	21.57		52.49	55.50	58.86		85.02	85.08
17	17.99	21.15		51.53	54.43	57.81		85.02	85.08
18	18.79	22.16		53.81	57.01	60.28		85.02	85.08
19	18.68	22.02		53.49	56.66	60.33		85.02	85.08
20	18.34	21.59		52.51	55.56	59.25		85.02	85.08
21	19.15	22.62		54.83	58.20	61.79		85.02	85.99
22	18.86	22.31		54.01	57.42	61.30		85.14	85.86
23	18.52	21.88		53.03	56.31	60.21		85.02	85.08
24	19.33	22.92		55.37	58.99	62.79		85.77	87.06
25	18.46	21.64		52.87	55.70	59.04		85.02	85.08
26	18.12	21.23		51.91	54.62	57.99		85.02	85.08
27	18.92	22.23		54.20	57.22	60.47		85.02	85.08

Table 3-4: Periodic (Monthly Growout Age) Mortality Conversion Factors.

Period	Conversion factor
1	0.10
2	0.08
3	0.06
4-11	0.04
12-17	0.03
18-34	0.02

The weight system was then used to generate periodic (monthly) conversion factors that produced the given cumulative 30-month mortality. The monthly conversion factors are given in Table 3-4. The factors sum to one over 30 months and actual periodic monthly mortality is computed by multiplying the cumulative 30-month mortality by the respective conversion factor.

The periodic and cumulative mortalities used in the production simulation are shown in Table 3-5. Early mortality rates are higher than later ones, reflecting the higher natural mortality of younger and smaller clams. When 15-mm seed clams were used, the first two months of the mortality series were eliminated, reflecting the increased survival expectation of larger clams.

Table 3-5: Monthly and Cumulative Mortality Used in Hard Clam Growth Simulation.

	Mortality (%)	
Month	Monthly	Total
1	2	2
2	1.6	3.6
3	1.2	4.8
4	0.8	5.6
5	0.8	6.4
6	0.8	7.2
7	0.8	8
8	0.8	8.8
9	0.8	9.6
10	0.8	10.4
11	0.8	11.2
12	0.6	11.8
13	0.6	12.4
14	0.6	13
15	0.6	13.6
16	0.6	14.2
17	0.6	14.8
18	0.4	15.2
19	0.4	15.6
20	0.4	16
21	0.4	16.4
22	0.4	16.8
23	0.4	17.2
24	0.4	17.6
25	0.4	18
26	0.4	18.4
27	0.4	18.8
28	0.4	19.2
29	0.4	19.6
30	0.4	20
31	0.4	20.4
32	0.4	20.8
33	0.4	21.2
34	0.4	21.6

4.0 ECONOMIC EVALUATION

The results of the hard clam growth simulation were used to determine optimal production design and expected returns. Two production scenarios were modelled. The first scenario treated a lease as a single unit. The entire lease was planted at one time and all clams were harvested in a single month. Hereafter, this scenario will be referred to as single plant production. The second scenario imposed a monthly marketing requirement. Producers might require or prefer a monthly harvest and revenue stream in order to meet labor restrictions or expenditure requirements. Similarly, market outlets might require monthly supplies from growers to satisfy monthly consumer demand. Therefore, some positive quantity of clams was required to be sold monthly. Planting restrictions were not imposed, so an entire lease could still be planted at one time as a single unit. The lease must be harvested, however, in monthly units or plots, so this method is termed multiplot production. Production assumptions are based on Adams et al. (1993). Assumptions common to both scenarios were:

(a) The operation lease consisted of a two-acre submerged tract. The site is situated such that it is never exposed during low tide. Each acre is identical in terms of productive capacity.

(b) A staggered production schedule is followed. Each acre is planted and harvested successively. The first acre is planted the first year and the second acre planted the next. Expected growout periods under a given production regime are identical, thus producing harvests in successive years.

(c) 750 4-foot-square growout bags are planted per acre.

(d) Clam seed is stocked at 1000 (62.5 clams per square foot) or 1200 (75 clams per square foot) clams per bag. These represent recommended average and maximum densities (Adams et al., 1993).

(e) The current month is January and the operation has the option of beginning production (making the initial plant) in the current month or in any of the future 11 months.

Information on hard clam prices was required to determine the expected returns of growing clam stock. Hard clam price data were obtained from the Florida Department of Natural Resources (FDNR) and a commercial fish house in the Indian River Lagoon area. The combined data set consisted of monthly average wholesale (dockside) prices from January 1986 to April 1993 for littleneck, topneck, cherrystone and chowder clams. Although the data covered a span of eight years, relatively few price observations were available as price reporting was voluntary. Price forecasts for subsequent portions of this research were based on average monthly prices for the four size categories. This research assumed a 50-mm-long (one inch across the hinge) minimum legal size. All undersized clams were assigned a price of zero. Mean monthly prices for the various size categories are given in Appendix 3.

4.1 Single Plant Production Optimal Rotations

The results of the hard clam growth simulation were combined with seed quantities and mortality rates to estimate expected revenues. The prescribed densities translated to initial seed plants of 750,000 and 900,000 clams per acre. Surviving clam numbers were determined using initial plant quantities and the previously described mortality rates.

Sixty-eight percent of surviving clams were assumed to possess mean size, 16% mean plus two standard deviations, and 16% mean minus two standard deviations. Hard clam prices are size dependent. Applying the standard deviation to the mean expected size generated a size spread within each age group, thus allowing surviving clams of a given age class to potentially fall into different size categories. Expected gross revenues were then calculated from total clam numbers within each size category times the expected price.

Next, expected net discounted revenues were computed by subtracting periodic maintenance costs and using an annual real discount rate of 4%. These revenues were then examined to identify the growout period that produced maximum expected net discounted revenues. Each production method (density and seed size) and planting month (January through December) was evaluated independently. Hereafter, the term "production method" should be understood to refer to a specific seed density (clams per square foot) and seed size (mm). Thus, optimal growout periods were identified for 10 and 15 mm seed planted at 62.5 and 75 clams per square foot beginning in January, February, March, etc. Revenues over the course of the 34-month growout followed general patterns of first increasing and then decreasing in value. This was due to stocks first growing into and then out of more valuable size categories. Changes were not uniformly up or down, though, as mortality or price movements often offset the effects of growth gains. The revenues produced by these optimal growout periods represented the best potential revenues possible given expected growth, mortality and price movements. Optimal growout periods are listed in Tables 4-1, 4-2 and 4-3.

The next step required connecting consecutive production cycles so that optimal rotations could be identified. A rotation is defined as a pattern of sequential plant, growout, harvest, replant, etc., decisions. A given production schedule or cycle (as defined by the plant month and growout period) resulted in the next cycle beginning in a particular month. Unless the optimal growout period was 23 months, each growout schedule resulted in the next plant beginning in a different month than the previous cycle. For example, a January-Year 1-plant growing for 23 months would be harvested in December, Year 2, allowing replanting in January, Year 3. Simultaneous harvest and replant was not allowed in the model due to the time and labor requirements of harvesting an entire acre, so the effective turnaround time was the growout period plus one month. If planting occurred in January and the growout period were 24 months, harvest would occur in January of the third year and replanting would occur in February. Then, the optimal February-plant growout period would be followed.

Table 4-1. Site 1 Optimal Growout Periods (Months) for Single Plant Production by Production Method and Planting Month.

Planting Month	Seed density/size 62.5/10	62.5/15	75/10	75/15
January	28	19	25	16
February	34	22	31	19
March	30	23	30	21
April	29	23	29	20
May	33	23	31	21
June	34	22	30	20
July	33	21	31	19
August	32	20	28	18
September	30	18	24	17
October	28	17	26	16
November	27	16	25	16
December	27	16	24	16

Table 4-2. Site 2 Optimal Growout Periods (Months) for Single Plant Production by Production Method and Planting Month.

Planting Month	Seed density/size 62.5/10	62.5/15	75/10	75/15
January	32	23	32	19
February	31	24	31	19
March	33	24	33	21
April	34	32	34	22
May	28	31	33	21
June	34	30	32	20
July	33	29	31	14
August	32	25	30	19
September	29	20	29	18
October	34	26	28	17
November	34	18	27	17
December	33	21	26	17

Table 4-3. Site 3 Optimal Growout Periods (Months) for Single Plant Production by Production Method and Planting Month.

Planting Month	Seed density/size 62.5/10	62.5/15	75/10	75/15
January	32	20	32	19
February	31	24	31	19
March	30	23	33	21
April	34	24	34	22
May	33	27	33	21
June	32	26	32	20
July	31	26	31	14
August	34	28	30	19
September	33	20	29	18
October	31	26	28	17
November	29	17	27	17
December	29	17	26	17

This "second-cycle" start was identified for each starting month. Consecutive plants were then strung together. An example might be: January plant, 28-month growout, May harvest, June plant, 32-month growout, February harvest, March plant, 24-month growout, etc. In all cases stabilization or a repetitive cycle emerged. This occurred when any subsequent planting month was the same as any previous planting month. For example, any 23-month growout produced immediate stabilization. As indicated above, a January-plant growing for 23 months resulted in a December harvest and subsequent January replant. The effective turnaround time is 24 months, hence replanting always occurs in the same month. Some repetitive cycles involved multiple plants, while others eventually attained a 24-month repetitive cycle, but required several plants before falling into the cycle.

Once planting patterns were identified, expected revenues were examined to determine optimal rotations. This required comparing the revenue potential of all combinations of immediate replacement and delayed cycles. A cycle with immediate replacement would be that as described in the previous paragraph. Immediate (next month) replacement would follow any harvest. A delayed cycle would include varying quantities of down months. A down month is one in which the acre is empty; no growing clams exist on the acre and neither harvest nor planting occurs. A down month was indicated if revenues could be increased by waiting. For instance, February conditions may be more conducive to rapid growth than January conditions. Hence, a new operation would make initial plants in February and, if harvest ever occurred in December, would delay replanting one month until February. Multiple down months were also a possibility.

An example of an optimal rotation might be to plant in January, grow for 18 months, harvest in August, wait two months until November, plant, and then follow the optimal November cycle. Or, the optimal decision might be to wait four months after the August harvest and replant in January. Hence, although actual growout lasts only 18 months, the effective turnaround time is 24 months and the acre is empty for four months.

Evaluation of the returns of all possible combinations of delayed and immediate replacement production allows the identification of the rotation that produces maximum expected net revenues. Optimal rotations were identified for each production method for each month of the year. Then, these 12 rotations (distinguished by the 12 calendar months) were compared to determine, given the opportunity to begin production in any month, the rotation that produced maximum expected net revenues. Optimal rotations for each production method are given in Table 4-4. Production results generated by the optimal rotations are given in Table 4-5. The production of undersized clams is indicated where the number of clams sold is less than the number of clams that survive. Undersized clams are discarded.

The difference between the procedures described in the above paragraphs is subtle yet significant. The first procedure addresses the question of, if the operation somehow finds itself in a given month with a planting option, what planting schedule should be initiated. Unexpected growth and harvest, mortality, natural disaster, etc. might result in an empty acre in any month. The second procedure addresses the question of when a new lease should begin operation. For example, at Site 1 using 10 mm seed planted at 62.5 clams per square foot, a February plant requires a 34-month growout to maximize net revenue. See Table 4-1. If expected conditions occur, however, the grower should never be faced with a planting decision in February as the optimal planting rotation is January-November-April-November. See Table 4-4. Once optimal rotations are determined, rotations not included in the optimal design are relevant only if unexpected conditions occur.

4.2 Multiplot Production Optimal Rotations

A simple management adjustment to a monthly marketing constraint would be to follow the rotation pattern determined for single plant production and harvest over a 12-month period rather than in a single month. To do so, however, would incur additional mortality and produce potential revenue losses as clams grew into less profitable size categories. Additionally, as the acre is planted as a unit, replanting would be affected as insufficient space would exist for the new seed.

Correct determination of proper management strategy when faced with a monthly harvest requirement, however, requires a change in perspective since the production or management question is now different than that with single plant production. With single plant production the question is, given both planting and marketing freedom, what is the best rotation to follow. All seed is assumed essentially identical with respect to growth potential. Optimal plant and growout times are therefore identical for all seed. When given the freedom or option to plant and harvest

Table 4-4. Optimal Planting Rotations for Single Plant Production by Production Method.

	Plant month/growout period (months)						
Seed density/size (mm)	1	Wait	2	Wait	3	Wait	4
Site 1							
62.5/10	Jan/28	5	Nov/27	1	Apr/29	no	Nov repeat
62.5/15	Feb/22	1	Feb repeat				
75/10	Sep/24	3	Jan/25	6	Sep repeat		
75/15	Feb/19	no	Oct/16	3	Jun/20	3	Jun repeat
Site 2							
62.5/10	Feb/31	2	Dec/33	2	Dec repeat		
62.5/15	Jan/23	no	Jan repeat				
75/10	Feb/31	4	Feb repeat				
75/15	Feb/19	4	Feb repeat				
Site 3							
62.5/10	Jan/32	3	Jan repeat				
62.5/15	Jan/20	3	Jan repeat				
75/10	Feb/31	4	Feb repeat				
75/15	Feb/19	4	Feb repeat				

Table 4-5. Optimal Rotation Production Results for Single Plant Production.

Seed density/size		Age (months)	Average Size (mm)	Size STD	# Clams Start	# Clams Survive	# Clams Sold
Site 1	Plant month						
62.5/10	January	28	63.96	6.01	750,000	606,000	606,000
	November	27	64.47	5.92	750,000	609,000	609,000
	April	29	50.16	5.17	750,000	603,000	506,520
62.5/15	February	22	61.79	5.88	750,000	624,000	624,000
75/10	September	24	50.39	5.19	900,000	741,600	622,944
	January	25	51.84	5.28	900,000	738,000	619,920
75/15	February	19	63.99	6.01	900,000	759,600	759,600
	October	16	62.12	5.90	900,000	772,200	772,200
	June	20	64.37	6.03	900,000	756,000	756,000
Site 2							
62.5/10	February	31	53.07	5.35	750,000	597,000	501,480
	December	33	62.05	5.89	750,000	591,000	591,000
62.5/15	January	23	62.91	5.94	750,000	621,000	621,000
75/10	February	31	51.15	5.23	900,000	716,400	601,776
75/15	February	19	61.80	5.88	900,000	759,600	759,600
Site 3							
62.5/10	January	32	61.77	5.87	750,000	594,000	594,000
62.5/15	January	20	62.11	5.90	750,000	630,000	630,000
75/10	February	31	51.09	5.23	900,000	716,400	601,776
75/15	February	19	61.77	5.87	900,000	759,600	759,600

all clams simultaneously, the correct decision would be to do so. All clams are allowed to attain economic maturity. The correct production question now, however, is given that clams must be marketed each month, when is the best time to plant seed such that they will be available for sale in each calendar month. The intuitive impact of this restriction is that clams will be planted and harvested in months other than those prescribed by the single plant production analysis.

The monthly marketing constraint imposes 12 harvests annually. No restriction was placed on when clams were planted; all clams could be planted during the same month, or any other combination. Actual planting schedules depend upon revenue comparisons of the various options. The clams would be harvested, however, in monthly units. Thus, the production unit, as driven by the harvest unit, is now a fraction of an acre. This requires that the acre be subdivided into units or plots, each representing a separate harvest and, possibly, a separate plant. To simplify the analysis, it was assumed that all plots be equal in size and, hence, planted with equal numbers of clam seed. As previously mentioned, the monthly harvest constraint did not specifically impose quantity restrictions, but rather only required positive monthly sales. All plots were therefore identical and the analysis did not address the question of optimal monthly planting quantities subject to minimum or maximum sales constraints. The analysis could be modified to account for specific volume sales restrictions.

Planting schedules are driven by harvesting requirements since, as previously stated, the economic question is when is the best time to plant seed for harvest in month i. The clam growth simulation results and net revenue estimations used in the first analysis were appropriate for use in determining when harvests began and, hence, when plants were required. An initial harvest rule was selected such that harvest began (given the option of planting in each of the 12 calendar months) when the expected net revenues from a given plant exceeded all other potential revenues for that month from any other plant. This determination required a comparison of not only all potential revenues for that month in that year, but also for that month in all future years. Future year evaluations incorporated a consideration of the revenue potential of not only a given plant 12 months later, but also that of other plants that might not have been planted when the initial observation is made. Since production or growth potential was repetitive, only one set of simulation results had to be examined to encompass all future years. With growout simulated for 34 months using 12 different starting months, the simulation results covered a 45-month period. At one site with a particular production method, a January plant (the first possible plant) with a 28-month growout was determined to be the best way to produce clams for harvest in May. Harvest therefore began in May and the harvest cycle or year was May to April. Harvest was not begun in April because April revenues were maximized by an August plant (with a 32-month growout). Since January was the reference or first possible planting month, an August planting opportunity had yet to occur. April revenues were therefore maximized by waiting until August. This relationship repeated for all other months prior to the first May harvest month: revenues could be increased by waiting. May revenues were greatest, however, with a January plant and, thus, production began in January and produced a first harvest two years later in May.

The initial harvest therefore began when revenues were greatest relative to all other production options for that particular month (year neutral). Determination of the best planting time for the next and all subsequent monthly harvests was then based on comparison of potential revenues for that specific month and year. The distinction between the first step--that of identifying the initial harvest--and this step is important. The first step determined both the month and the year of initial harvest. Harvest then became anchored to that year and the subsequent identification of maximum revenues became year-specific. Revenue comparison thus considered only clams present at that point in time and not clams in future years. Despite the narrowing of focus, once harvest began, revenues chosen represented overall maximums similar to the initial harvest.

Maximum revenues were identified and then tracked back to determine planting schedules. This identified an annual planting schedule consisting of 12 plants. These were then linked to determine the required acre-subdivision by requiring identical annual planting schedules and comparing planting requirements with plot availability as determined by harvests. Same-month harvest and replanting was allowed with multiplot production due to the reduced labor requirements. With 750 bags per acre and a minimum of 12 plots per acre, at most 63 bags would be harvested in any month. Replanting during the same month would not be a problem. The number of required plots per acre are given in Table 4-6. Total plot requirements were determined on a lease or 2-acre basis. Per acre plot requirements were then computed by dividing this total by 2. Fractional per acre plot numbers were indicative of one production unit (plot) spread over two acres. The number of bags per plot are given in Table 4-7. This was computed by dividing the number of bags per acre, 750, by the number of plots per acre. In some instances, rounding requirements in the computation of the number of bags per acre resulted in more than 750 bags planted per acre. Per acre bag totals are given in Table 4-8. The number of required plots were then used to scale production and revenues to reflect the decrease in the unit of analysis from one acre to one plot. The multiplot production numbers are given in Tables 4-9, 4-10 and 4-11. Tables 4-9, 4-10 and 4--11 are arranged by the plant month and not by the harvest month. Thus, the harvest months are not in sequential order. In all instances, however, a full 12-months harvest-year is described.

Table 4-6. Number of Required Plots per Acre for Multiplot Hard Clam Production.

	Seed density/seed size			
	62.5/10	62.5/15	75/10	75/15
Site 1	17	12	14	12
Site 2	17	12.5	17	12
Site 3	16.5	12	16.5	12

Table 4-7. Number of Growout Bags per Plot for Multiplot Hard Clam Production.

	Seed density/seed size			
	62.5/10	62.5/15	75/10	75/15
Site 1	45	63	54	63
Site 2	45	60	45	63
Site 3	46	63	46	63

Table 4-8. Total Bags Planted per Acre for Multiplot Hard Clam Production.

	Seed density/seed size			
	62.5/10	62.5/15	75/10	75/15
Site 1	765	756	756	756
Site 2	765	750	765	756
Site 3	759	756	759	756

Table 4-9. Site 1 Multiplot Production Results.

Seed density/size		Growout (months)		Average Size (mm)	Size STD	# Clams Start	# Clams Survive	# Clams Sold
	Plant month		Harvest month					
62.5/10	January	28	May	63.95	6.00	45,000	36,360	36,360
	January	29	June	65.65	6.10	45,000	36,180	36,180
	January	30	July	65.91	6.12	45,000	36,000	36,000
	January	31	August	66.17	6.13	45,000	35,820	35,820
	January	32	September	66.49	6.15	45,000	35,640	35,640
	January	33	October	66.62	6.16	45,000	35,460	35,460
	January	34	November	66.94	6.18	45,000	35,280	35,280
	February	34	December	61.83	5.87	45,000	35,280	35,280
	August	32	April	63.78	5.99	45,000	35,640	35,640
	November	27	February	62.47	5.91	45,000	36,540	36,540
	December	25	January	53.86	5.39	45,000	36,900	30,996
	December	27	March	61.85	5.87	45,000	36,540	36,540
							Total annual sales:	425,916
62.5/15	January	17	June	63.46	5.97	63,000	53,676	53,676
	January	18	July	64.09	6.01	63,000	53,424	53,424
	January	19	August	64.72	6.05	63,000	53,172	53,172
	January	20	September	65.25	6.08	63,000	52,920	52,920
	January	21	October	65.59	6.10	63,000	52,668	52,668
	January	22	November	66.37	6.15	63,000	52,416	52,416
	February	22	December	61.78	5.87	63,000	52,416	52,416
	February	23	January	66.19	6.14	63,000	52,164	52,164
	March	23	February	67.06	6.19	63,000	52,164	52,164
	April	23	March	64.14	6.01	63,000	52,164	52,164
	December	16	April	63.83	5.99	63,000	53,928	53,928
	December	17	May	66.97	6.18	63,000	53,676	53,676
							Total annual sales:	634,788

Table 4-9--continued.

Seed density/size	Plant month	Growout (months)	Harvest month	Average Size (mm)	Size STD	# Clams Start	# Clams Survive	# Clams Sold
75/10	January	25	February	51.83	5.27	64,800	53,136	44,634
	February	25	March	50.89	5.21	64,800	53,136	44,634
	February	28	June	53.80	5.39	64,800	52,358	43,981
	February	30	August	54.18	5.41	64,800	51,840	43,546
	March	25	April	50.95	5.22	64,800	53,136	44,634
	March	26	May	51.82	5.27	64,800	52,877	44,417
	April	27	July	50.54	5.19	64,800	52,618	44,199
	September	24	September	50.39	5.18	64,800	53,395	44,852
	October	24	October	50.44	5.19	64,800	53,395	44,852
	October	27	January	53.82	5.39	64,800	52,618	44,199
	November	24	November	50.26	5.18	64,800	53,395	44,852
	December	24	December	50.00	5.16	64,800	53,395	44,852
						Total annual sales:		533,652
75/15	January	16	May	62.80	5.93	75,600	64,714	64,714
	January	17	June	64.84	6.05	75,600	64,411	64,411
	January	19	August	67.20	6.20	75,600	63,806	63,806
	February	17	July	62.42	5.91	75,600	64,411	64,411
	February	19	September	63.99	6.00	75,600	63,806	63,806
	February	20	October	65.21	6.08	75,600	63,504	63,504
	February	21	November	66.52	6.16	75,600	63,202	63,202
	April	20	December	62.65	5.92	75,600	63,504	63,504
	May	20	January	62.97	5.94	75,600	63,504	63,504
	June	20	February	64.37	6.03	75,600	63,504	63,504
	August	19	March	64.80	6.05	75,600	63,806	63,806
	December	16	April	63.70	5.99	75,600	64,714	64,714
						Total annual sales:		766,886

Table 4-10. Site 2 Multiplot Production Results.

Seed density/size	Plant month	Growout (months)	Harvest month	Average Size (mm)	Size STD	# Clams Start	# Clams Survive	# Clams Sold
62.5/10	January	27	April	53.25	5.36	45,000	36,540	30,694
	January	29	June	57.83	5.63	45,000	36,180	30,391
	January	31	August	58.15	5.65	45,000	35,820	30,089
	February	27	May	50.48	5.19	45,000	36,540	30,694
	February	29	July	52.44	5.31	45,000	36,180	30,391
	February	31	September	53.06	5.34	45,000	35,820	30,089
	February	32	October	53.28	5.36	45,000	35,640	29,938
	February	33	November	53.42	5.37	45,000	35,460	29,786
	February	34	December	54.31	5.42	45,000	35,280	29,635
	March	34	January	52.63	5.32	45,000	35,280	29,635
	November	28	March	55.40	5.49	45,000	36,360	30,542
	December	26	February	50.52	5.19	45,000	36,720	30,845
							Total annual sales:	362,729
62.5/15	January	23	January	62.91	5.94	60,000	49,680	49,680
	January	24	February	66.32	6.14	60,000	49,440	49,440
	February	24	March	64.31	6.02	60,000	49,440	49,440
	March	24	April	62.74	5.93	60,000	49,440	49,440
	March	25	May	67.12	6.19	60,000	49,200	49,200
	August	25	October	62.76	5.93	60,000	49,200	49,200
	November	18	June	63.79	5.99	60,000	50,880	50,880
	November	21	September	67.20	6.20	60,000	50,160	50,160
	December	18	July	62.88	5.94	60,000	50,880	50,880
	December	19	August	63.20	5.96	60,000	50,640	50,640
	December	22	November	64.86	6.06	60,000	49,920	49,920
	December	23	December	65.29	6.08	60,000	49,680	49,680
							Total annual sales:	598,560

Table 4-10--continued.

Seed density/size	Plant month	Growout (months)	Harvest month	Average Size (mm)	Size STD	# Clams Start	# Clams Survive	# Clams Sold
75/10	January	26	March	50.28	5.18	54,000	44,064	37,014
	January	27	April	51.71	5.26	54,000	43,848	36,832
	February	27	May	50.52	5.19	54,000	43,848	36,832
	February	28	June	50.74	5.20	54,000	43,632	36,651
	February	29	July	50.88	5.21	54,000	43,416	36,469
	February	30	August	51.04	5.22	54,000	43,200	36,288
	February	31	September	51.15	5.23	54,000	42,984	36,107
	February	32	October	51.18	5.23	54,000	42,768	35,925
	March	32	November	50.17	5.16	54,000	42,768	35,925
	March	33	December	50.47	5.19	54,000	42,552	35,744
	March	34	January	51.21	5.23	54,000	42,336	35,562
	December	26	February	50.41	5.18	54,000	44,064	37,014
						Total annual sales:		436,363
75/15	January	17	June	62.70	5.93	75,600	64,411	64,411
	January	18	July	63.97	6.05	75,600	64,109	64,109
	January	19	August	64.78	6.05	75,600	63,806	63,806
	January	21	October	66.12	6.13	75,600	63,202	63,202
	January	22	November	67.18	6.20	75,600	62,899	62,899
	February	19	September	61.79	5.87	75,600	63,806	63,806
	March	21	December	63.23	5.96	75,600	63,202	63,202
	April	21	January	62.74	5.93	75,600	63,202	63,202
	June	20	February	62.35	5.90	75,600	63,504	63,504
	June	21	March	67.20	6.20	75,600	63,202	63,202
	November	17	April	63.86	6.00	75,600	64,411	64,411
	December	17	May	63.77	5.99	75,600	64,411	64,411
						Total annual sales:		764,165

Table 4-11. Site 3 Multiplot Production Results.

Seed density/size		Growout (months)		Average Size (mm)	Size STD	# Clams Start	# Clams Survive	# Clams Sold
	Plant month		Harvest month					
62.5/10	January	26	March	51.89	5.27	46,000	37,536	31,530
	January	32	September	61.77	5.87	46,000	36,432	36,432
	January	33	October	62.75	5.93	46,000	36,248	36,248
	January	34	November	62.75	5.93	46,000	36,064	36,064
	February	26	April	50.00	5.16	46,000	37,536	31,530
	February	27	May	52.33	5.30	46,000	37,352	31,376
	February	28	June	54.19	5.41	46,000	37,168	31,221
	February	30	August	54.81	5.45	46,000	36,800	30,912
	March	28	July	50.85	5.21	46,000	37,168	31,221
	March	33	December	53.42	5.37	46,000	36,248	30,448
	March	34	January	56.68	5.56	46,000	36,064	30,294
	December	26	February	50.00	5.16	46,000	37,536	31,530
							Total annual sales:	388,806
62.5/15	January	20	September	62.11	5.89	63,000	52,920	52,920
	January	21	October	63.25	5.96	63,000	52,668	52,668
	January	22	November	63.28	5.96	63,000	52,416	52,416
	January	23	December	64.18	6.02	63,000	52,164	52,164
	February	23	January	62.14	5.89	63,000	52,164	52,164
	March	23	February	62.43	5.91	63,000	52,164	52,164
	March	24	March	65.28	6.08	63,000	51,912	51,912
	July	24	July	62.77	5.93	63,000	51,912	51,912
	September	21	June	62.21	5.90	63,000	52,668	52,668
	November	17	April	62.13	5.89	63,000	53,676	53,676
	December	17	May	62.47	5.91	63,000	53,676	53,676
	December	20	August	66.33	6.14	63,000	52,920	52,920
							Total annual sales:	631,260

Table 4-11--continued.

Seed density/size	Plant month	Growout (months)	Harvest month	Average Size (mm)	Size STD	# Clams Start	# Clams Survive	# Clams Sold
75/10	January	26	March	50.11	5.17	55,200	45,043	37,836
	January	27	April	51.53	5.25	55,200	44,822	37,650
	February	27	May	50.30	5.18	55,200	44,822	37,650
	February	28	June	50.60	5.20	55,200	44,602	37,466
	February	29	July	50.80	5.21	55,200	44,381	37,280
	February	30	August	50.98	5.22	55,200	44,160	37,094
	February	31	September	51.09	5.23	55,200	43,939	36,909
	March	31	October	50.07	5.16	55,200	43,939	36,909
	March	32	November	50.13	5.17	55,200	43,718	36,723
	March	33	December	50.41	5.18	55,200	43,498	36,538
	April	33	January	50.08	5.16	55,200	43,498	36,538
	December	26	February	50.60	5.20	55,200	44,043	37,836
							Total annual sales:	446,429
75/15	January	17	June	62.31	5.90	75,600	64,411	64,411
	January	18	July	63.82	5.99	75,600	64,109	64,109
	January	19	August	64.58	6.04	75,600	63,806	63,806
	January	21	October	66.13	6.13	75,600	63,202	63,202
	January	22	November	67.02	6.19	75,600	62,899	62,899
	February	19	September	61.76	5.87	75,600	63,806	63,806
	March	21	December	63.07	5.95	75,600	63,202	63,202
	April	21	January	62.82	5.93	75,600	63,202	63,202
	June	20	February	62.45	5.91	75,600	63,504	63,504
	June	21	March	64.54	6.04	75,600	63,202	63,202
	November	17	April	63.57	5.98	75,600	64,411	64,411
	December	17	May	63.55	5.98	75,600	64,411	64,411
							Total annual sales:	764,165

4.3 Production Performance Comparison

Stabilized production results were used to make performance comparisons between single plant and multiplot production. An operation reached stabilization when both acres had been brought into production, production cycles had achieved optimal patterns (as described in previous sections) and operating loan requirements were zero (as determined by the full economic evaluation discussed in the next section). Optimal repetitive cycles varied by site, production method and marketing constraint. Optimal cycles defined when plants and, more importantly, harvests occurred. Multiplot production specifically required monthly and, once begun, annual harvests. Hence, although individual plants might grow for up to 34 months, optimal repetitive cycles were annual in nature. Single plant production had no such restrictions and, thus, allowed cycle length to be determined by growth and economic dynamics. It was therefore possible to have years where no harvest (or plant) occurred. For example, all single plant production scenarios using 10 mm seed produced cycles that included years in which no harvest occurred due to the length of the growout periods. Site 1 cycles covered a 5-year period of four harvests followed by one year with no harvest. Cycles at sites 2 and 3 using 10 mm seed covered three years with two harvests followed by a year of inactivity. All scenarios using 15 mm seed produced annual harvests.

Cycle length considerations were used in the determination of summary statistics for model comparison. The consideration of average production allows more direct comparison between the different production methods as it incorporates the negative effect of inactive years due to extended growout times. Not all summary statistics required averaging of this type. Average clam size and growout time were actual performance values and did not require consideration of cycle length.

Average clam size and growout times for both single plant and multiplot production are given in Table 4-12. No consistent patterns emerged when comparing single plant and multiplot results; a given seed size and density might produce larger clams under single plant production than under multiplot production at one site and smaller clams at another site. Average growout times were similarly nonconsistent. Within a given method (single plant versus multiplot) using a given seed size, increased growout times produced larger clams. Five of the 12 multiplot scenarios (three sites and four production options per site) had longer average growout times yet produced larger clams in seven scenarios. Thus, in two occasions, shorter multiplot average growout times produced larger average clams. This could be explained by, as the multiplot production mix typically included both shorter and longer growout periods for different plants, the impact of the larger clams (produced by the longer growout periods) was greater than that of the smaller clams (produced by the shorter growout periods). A comparison of the annual number of clams planted, surviving and sold is shown in Table 4-13. Patterns were again difficult to discern. Multiplot production generally resulted in greater numbers of clams planted (10 of 12 situations) and sold (9 of 12 situations). Plant quantities varied due to differences in total bags per acre and the effects of extended growout periods and plot subdivision. Percentage survival, however, could be higher/lower yet produce fewer/greater sales. The production of undersized clams was indicated when the quantity of clams sold was less than the quantity survived. With only one exception, undersized clams were harvested with the same production methods in both single plant and multiplot productions.

It should be noted that the above comparisons are intended to simply describe some of the production results. Since determinations of preferred or optimal cycles were based on economic criteria, explanations and an understanding of why specific results might occur require considerations of the cost and revenue impacts of the various production options.

4.4 Economic Performance

The hard clam growth simulation and the identification of optimal rotations described in the previous sections identified and described potential challengers. A logical application of this information and the simulation models employed would be to take an existing growout operation, identify the profile of existing stock, and determine harvest and replacement schedules for existing stock given knowledge of challengers and the expected revenues from existing stock. Despite being extremely situation specific, such an application would be descriptive of the use to which this research might be applied as a management or extension tool.

A second application, however, involves applying the previously described optimal rotations to a new growout operation and determining the expected returns and accrued benefits of the resultant operation. This second application was chosen for the remainder of the research. The rationale for this selection was that, if expected conditions occurred, such an evaluation provided more insight into what an optimally managed operation might be worth. With the first application, once existing stock is replaced and expected conditions again occur, an existing operation would likely fall into an identical new-operation production pattern. The onset of the pattern would, however, be delayed according to the continued growout requirements of existing stock. If expected conditions do not occur, i.e. expected environmental conditions fail to occur, expected conditions fail to produce expected growth, or expected prices fail to be realized, then the system is in a constant state of flux requiring continuous evaluation, and the system likely never attains repetitive patterns.

The optimal rotations for both production methods described both planting and harvesting patterns for one half of the lease (one acre). This pattern was then repeated on the second acre, thereby determining planting and harvest management of the entire lease. These management patterns were used to determine asset replacement and operating expenditure requirements. The expenditure requirements were then used to

Table 4-12. Average Final Clam Size (mm) and Growout Time (Months) for Single Plant and Multiplot Hard Clam Production.

	Seed density/ Seed size	Average Size	Average Growout time
Single plant production			
Site 1	62.5/10	57.32	28
	62.5/15	61.79	22
	75/10	51.12	24.5
	75/15	64.37	20
Site 2	62.5/10	62.05	33
	62.5/15	62.91	23
	75/10	51.15	31
	75/15	61.80	19
Site 3	62.5/10	61.77	32
	62.5/15	62.11	20
	75/10	51.09	31
	75/15	61.77	19
Multiplot production			
Site 1	62.5/10	63.79	30.2
	62.5/15	64.95	20.1
	75/10	51.58	25.8
	75/15	64.29	18.7
Site 2	62.5/10	53.73	30.1
	62.5/15	64.45	22.2
	75/10	50.81	29.6
	75/15	64.14	19.4
Site 3	62.5/10	55.12	29.8
	62.5/15	63.22	21.3
	75/10	50.56	29.4
	75/15	63.80	19.4

Table 4-13. Average Annual Numbers of Clams Planted, Surviving and Sold for Single Plant and, Multiplot Production.

	Seed density/ Seed size	# Planted	# Surviving	# Sold	% Survival	% Sold (of plant)	% Sold (of survive)
Single plant production							
Site 1	62.5/10	600,000	484,800	446,208	80.8	74.4	92.0
	62.5/15	750,000	624,000	624,000	83.2	83.2	100.0
	75/10	720,000	591,840	497,146	82.2	69.1	84.0
	75/15	900,000	756,000	756,000	84.0	84.0	100.0
Site 2	62.5/10	500,000	394,000	334,320	78.8	66.9	84.9
	62.5/15	750,000	621,000	621,000	82.8	82.8	100.0
	75/10	600,000	477,600	401,184	79.6	66.9	84.0
	75/15	900,000	759,600	759,600	84.4	84.4	100.0
Site 3	62.5/10	500,000	396,000	396,000	79.2	79.2	100.0
	62.5/15	750,000	630,000	630,000	84.0	84.0	100.0
	75/10	600,000	477,600	401,184	79.6	66.9	84.0
	75/15	900,000	759,600	759,600	84.4	84.4	100.0

Table 4-13--continued.

	Seed density/ Seed size	# Planted	# Surviving	# Sold	% Survival	% Sold (of plant)	% Sold (of survive)
Multiplot production							
Site 1	62.5/10	540,000	431,640	425,916	79.9	78.9	98.7
	62.5/15	756,000	634,788	634,788	84.0	84.0	100.0
	75/10	777,600	635,299	533,652	81.7	68.6	84.0
	75/15	907,200	766,886	766,886	84.5	84.5	100.0
Site 2	62.5/10	540,000	431,820	362,729	80.0	67.2	84.0
	62.5/15	720,000	598,560	598,560	83.1	83.1	100.0
	75/10	648,000	519,480	436,363	80.2	67.3	84.0
	75/15	907,200	764,165	764,165	84.2	84.2	100.0
Site 3	62.5/10	552,000	442,152	388,806	80.0	70.4	87.9
	62.5/15	756,000	631,260	631,260	83.5	83.5	100.0
	75/10	662,400	530,465	446,429	80.1	67.4	84.0
	75/15	907,200	764,165	764,165	84.2	84.2	100.0

determine fixed and variable costs according to guidelines described in Adams et al. (1993). The operation described in Adams et al. and modelled here assumes that the owner-operator is employed full time in some other occupation and that the culture operation exists as a part-time activity. Alternative income activities are assumed limited to minimum wage jobs. Asset and production requirements were combined with expected revenues in a cashflow model to determine annual loan requirements, finance payments, taxes, net positions, etc. Financial assumptions common to both production scenarios were:

(a) Sixty-five percent of initial investment requirements and asset replacement is financed by borrowed capital.
(b) All operating loans are fully financed by borrowed funds.
(c) All debt capital has a 9.5% real annual rate of interest over a ten-year loan period.
(d) Depreciation on capital assets is computed using straight-line depreciation.
(e) The wage rate is $4.10 per hour.
(f) Monitoring costs are $120 per acre per month.
(g) Growout bags are harvested at the rate of two bags per hour. This includes pulling, grading and bagging (sales bags).

The debt capital interest rate assumes a 4% real interest rate and a 5.5% risk premium. Initial investment costs are listed in Appendix 4 and production costs are listed in Appendix 5.

4.5 Income Statements

Income statements are developed using the results of the cashflow analysis. Average expectations of stabilized production, as described in the previous section on production comparisons, were determined. Again, an operation reached stabilization when full production of the lease had begun, production cycles had achieved optimal repetitive patterns and operating loan requirements were zero. Values used in the income statements thus represented averages over the repetitive cycle.

Returns net of variable and fixed costs represent the returns to the land and owner labor, management and capital. The opportunity cost of owner labor was calculated by determining the annual number of labor hours required and assuming the next best alternative was a minimum wage job. The opportunity cost of capital was calculated at 11.5% of owned equity. This interest rate included a 2% premium over the loan rate.

The next step, required identifying the residual claimant and quantifying the residual. The residual claimant is that component to which final net returns or residual accrues. Both management and land might be considered valid residual claimants. Selection of the residual claimant requires a thorough understanding of the productive process examined, and consideration of the goals of the research and the ability to realistically isolate the contributions of specific inputs. Although management of a small hard clam growout operation is a new endeavor, precedent exists for estimating management fees in other agricultural fields as a endeavor, precedent exists for estimating management fees in other agricultural fields as a percentage of gross or net returns. Management fees ranging from three to 10 percent are used in grain, vegetable and citrus operations with the higher percentages usually awarded for the more labor intensive crops (various personal communications). Most management payments likely include base salaries with performance incentives. The lack of a history of hard clam management and the difficulty of the identification of available alternatives, however, makes detailed estimation of management fees difficult. Percentage calculation is, therefore, appealing.

Valuation of the land is equally problematic. The argument could be made that, since a lease fee structure already exists, these costs should be deducted, thereby attributing the residual to management. Current lease fees, however, are only $20 per acre per year, and thus likely represent only filing or paperwork fees. This fee thus fails to represent the unique productive capacity of the land. Considerations of alternative commercially productive use values is likely limited to oyster culture, an emerging operation similar to clam culture and one in which evaluations of economic potential are similarly incomplete.

Given the above considerations, the decision was made to make the land the residual claimant. Production results indicated that returns were driven by site specific characteristics. The same management philosophy or decision rules were applied across all production options at all three sites. Actual management in terms of specific planting and harvest schedules varied across sites, but the rules determining or identifying optimal rotations were identical. Returns, however, varied by site. Thus, the land was chosen as the residual claimant. Returns to management were calculated as 3% of gross revenues. Residual returns represented the returns to the lease or two acres of water bottom. The results of this evaluation for single plant production are shown in Tables 4-14, 4-15 and 4-16. Multiplot production financial results are shown in Tables 4-17, 4-18 and 4-19.

Examination of the income statements showed that, while differences in performance existed, all scenarios produced significant residual returns ranging from a low of $4,000 per lease under multiplot production at Site 2 using 10-mm seed planted at 62.5 clams per square foot, to a high of $33,400 per lease at Sites 2 and 3 under single plant production using 15-mm seed planted at 75 clams per square foot.

4.6 Net Present and Annualized Values

The figures presented in the income statements represented expected performance of the operation after operating loans are retired and the planting schedules achieve an optimal cycle. Thus, the income statements fail to incorporate performance information prior to the achieved stability. Two other measurements, the net present value and the annualized value, capture these off-year effects and are therefore more descriptive. The net present value represents net returns--calculated from initial start-up--discounted over 20 years at 10.2%. The present value per acre represents the amount a person should be willing to pay to obtain a 2-acre 20-year lease. The

Table 4-14. Site 1 Single Plant Production Income Statement.

	Production method (seed density/seed size)			
	62.5/10	62.5/15	75/10	75/15
Revenue	$56,000	$75,900	$62,100	$97,100
Expenses				
Variable cost	13,200	19,700	15,100	22,800
Fixed cost				
Overhead	1,000	1,000	1,000	1,000
Debt interest	3,100	2,200	3,000	2,300
Depreciation	8,300	6,200	7,800	6,200
Taxes	8,400	13,100	11,200	17,900
Net return to labor, management, capital and land	22,000	33,700	24,000	46,900
Opportunity cost of labor	2,900	3,600	2,900	3,600
Opportunity cost of capital	7,300	5,000	5,700	15,700
Opportunity cost of management	1,700	2,300	1,900	2,900
Net return to land	10,100	22,800	13,500	24,700

Table 4-15. Site 2 Single Plant Production Income Statement.

	Production method (seed density/seed size)			
	62.5/10	62.5/15	75/10	75/15
Revenue	$50,600	$75,500	$52,200	$97,500
Expenses				
Variable cost	11,500	19,700	13,000	22,800
Fixed cost				
Overhead	1,000	1,000	1,000	1,000
Debt interest	2,900	2,200	2,700	2,200
Depreciation	7,200	6,200	7,200	6,200
Taxes	9,100	13,000	10,500	18,300
Net return to labor, management, capital and land	18,900	33,400	17,800	47,000
Opportunity cost of labor	2,400	3,600	2,400	3,600
Opportunity cost of capital	6,600	4,900	3,700	7,100
Opportunity cost of management	1,500	2,300	1,600	2,900
Net return to land	8,400	22,600	10,100	33,400

Table 4-16. Site 3 Single Plant Production Income Statement.

	Production method (seed density/seed size)			
	62.5/10	62.5/15	75/10	75/15
Revenue	$50,800	$80,900	$52,200	$97,500
Expenses				
Variable cost	11,500	19,700	13,000	22,800
Fixed cost				
Overhead	1,000	1,000	1,000	1,000
Debt interest	2,900	2,200	2,700	2,200
Depreciation	8,300	6,200	7,200	6,200
Taxes	10,100	14,500	10,500	18,300
Net return to labor, management, capital and land	17,000	37,300	17,800	47,000
Opportunity cost of labor	2,400	3,600	2,400	3,600
Opportunity cost of capital	3,600	5,600	3,700	7,100
Opportunity cost of management	1,500	2,400	1,600	2,900
Net return to land	9,500	25,700	10,100	33,400

Table 4-17. Site 1 Multiplot Production Income Statement.

	Production method (seed density/seed size)			
	62.5/10	62.5/15	75/10	75/15
Revenue	$48,400	$72,100	$60,400	$89,600
Expenses				
Variable cost	11,100	21,300	14,700	21,400
Fixed cost				
Overhead	1,000	1,000	1,000	1,000
Debt interest	2,800	2,200	3,100	2,200
Depreciation	7,600	6,200	8,500	6,200
Taxes	7,300	12,400	9,300	16,500
Net return to labor, management, capital and land	18,600	28,800	23,800	42,300
Opportunity cost of labor	3,000	3,700	3,300	3,700
Opportunity cost of capital	7,600	6,800	8,300	11,400
Opportunity cost of management	1,500	2,200	1,800	2,700
Net return to land	6,500	16,200	10,400	24,500

Table 4-18. Site 2 Multiplot Production Income Statement.

	Production method (seed density/seed size)			
	62.5/10	62.5/15	75/10	75/15
Revenue	$41,400	$69,500	$49,100	$88,700
Expenses				
Variable cost	11,000	17,500	12,700	21,400
Fixed cost				
Overhead	1,000	1,000	1,000	1,000
Debt interest	2,800	2,300	2,800	2,200
Depreciation	7,600	6,100	7,600	6,200
Taxes	5,300	11,900	7,000	16,300
Net return to labor, management, capital and land	13,700	30,700	18,000	41,600
Opportunity cost of labor	3,000	3,500	3,000	3,700
Opportunity cost of capital	5,500	9,600	6,700	9,300
Opportunity cost of management	1,200	2,100	1,500	2,700
Net return to land	4,000	15,500	6,700	25,900

Table 4-19. Site 3 Multiplot Production Income Statement.

	Production method (seed density/seed size)			
	62.5/10	62.5/15	75/10	75/15
Revenue	$44,300	$72,800	$50,200	$88,700
Expenses				
Variable cost	11,200	18,300	12,900	21,400
Fixed cost				
Overhead	1,000	1,000	1,000	1,000
Debt interest	2,900	2,300	2,900	2,200
Depreciation	7,700	6,200	7,700	6,200
Taxes	6,000	12,600	7,200	16,300
Net return to labor, management, capital and land	15,500	32,400	18,500	41,600
Opportunity cost of labor	3,000	3,700	3,000	3,700
Opportunity cost of capital	5,500	8,900	6,900	9,300
Opportunity cost of management	1,300	2,200	1,500	2,700
Net return to land	5,700	17,600	7,100	25,900

annualized value represents an average annual return to the lease over the same 20-year period and is comparable to the annual lease fee--$40 for two acres--for performance evaluation. The annualized value is the amount a person should be willing to pay annually for the 2-acre lease. The discount rate used represented an average of the loan rate and the opportunity cost of capital rate weighted by the capital asset financing ratio previously specified. The present value of the land for all production scenarios is given in Table 4-20 and the annualized values are given in Table 4-21.

A comparison of the present value per lease (2 acres of land) for single plant and multiplot production show values from single plant production to exceed those from multiplot production in all cases. Differences are minor, however, at Site 1 planting 15-mm seed at 75 clams per square foot. An examination of the income statements of the two scenarios shows that, while the gross revenues for single plant production exceed those of multiplot production, $97,100 to $89,600, a considerable portion of this difference, $4,300, is negated when the opportunity cost of capital is accounted for. Further evaluation of the two situations using production information not presented here attributed the higher opportunity cost of capital with single plant production to a faster rate of equity build-up. Specifically, on January 1 of any given year, the date on which evaluations were based, both acres were fully planted under single plant production whereas only 1.33 acres were planted under multiplot production. At this particular site, there was a concentration of monthly plants early in the year. Three plants were scheduled for January and four for February. Thus, seven plots were empty at the point of evaluation.

The results confirm expectations that harvest restrictions impair the economic performance of the operation. Imposing harvest restrictions leads to either or both planting and harvesting clams other than when otherwise prescribed in the absence of such restrictions. This can produce economically immature and overage clams as well as increased mortality. Monthly marketing reduced revenues sufficiently that in only one instance, at Site 1 planting at 75 clams per square foot, were 10-mm seed profitable. Revenues were never sufficient to overcome initial negative net balances.

Larger seed always outperformed smaller seed, while higher planting densities almost always outperformed lower planting densities. The one exception occurred at Site 1 where the lower density using 15-mm clams outperformed the higher density. Reasons can again be traced to equity build-up. See Table 4-14. The greatest returns were achieved by using the largest seed planted at the highest density at Sites 2 and 3. The major cost impact of using larger seed came from higher seed costs. These costs are more than recouped, though, through faster turnover of stock. Similarly, although growth was affected by planting density with higher densities producing more conservative growth, the negative effects of the higher density were not sufficient to offset the gains attributed to larger volume sales.

Table 4-20. Present Value of a Two-Acre Lease Across All Sites and Production Options.

		Seed density/seed size			
		62.5/10	62.5/15	75/10	75/15
Site 1					
	Single plant	$19,700	$145,200	$42,300	$141,300
	Multiplot	-9,600	83,300	13,800	140,900
Site 2					
	Single plant	11,900	143,400	51,000	220,300
	Multiplot	-21,300	39,100	-5,500	147,900
Site 3					
	Single plant	47,400	166,100	51,000	220,300
	Multiplot	-8,400	74,100	-3,900	147,900

Table 4-21. Annualized Value of a Two-Acre Lease Across All Sites and Production Options.

		Seed density/seed size			
		62.5/10	62.5/15	75/10	75/15
Site 1					
	Single plant	$1,700	$12,200	$3,600	$11,900
	Multiplot	-800	7,000	1,200	11,800
Site 2					
	Single plant	1,000	12,000	4,300	18,500
	Multiplot	-1,800	3,300	-500	12,400
Site 3					
	Single plant	4,000	14,000	4,300	18,500
	Multiplot	-700	6,200	-300	12,400

Selection of the best site varied with production method. Each site represented physically distinct locations possessing unique environmental profiles in terms of expected water temperature, salinity and dissolved oxygen. The results indicate that site selection is an important factor to consider in hard clam growout. How to effectively incorporate this information in management decisions is less clear. While ambient environmental conditions varied from site to site, determination of combinations that can be classified as productively similar or different is difficult. Also, identical productive or economic potential depended upon both production method and harvest restriction. Sites 2 and 3 produced identical economic outcomes under single plant production at 75 clams per square foot, but not at 62.5 clams per square foot. Further, under multiplot production, Sites 2 and 3 produced identical returns using 15-mm seed planted only at the higher density. Thus, the incorporation of environmental considerations is difficult. Trends evidenced by the net present values of the various production options are repeated in the annualized values. The primary benefit of the annualized values is the ease of comparison with current lease fees. As can be seen from Table 4-20, with the exception of the plantings under multiplot production using 10-mm seed, all other scenarios produce values much larger than the current fee of $40 (for two acres).

A final analysis examined the impact of lower prices. Prices were uniformly (across all size categories) reduced 10, 20 and 30%. The evaluation was performed on Site 2, single plant production. Net present value and annualized value results are given in Table 4-22. As can be seen from the results, the price reduction eventually totally erodes the profitability of production using 10-mm seed. Production using 15-mm seed, however, still produces considerable returns, though net present value decreases with price reductions at a rate of two-to-one or greater.

Table 4-22. Net Present Value (NPV) and Annualized Value (AV) of a Two-Acre Lease at Site 2 Under Uniform Price Reduction.

Price Reduction		Seed density/seed size 62.5/10	62.5/15	75/10	75/15
10 %					
	NPV	-$9,100	$107,700	$28,400	$174,500
	AV	-800	9,000	2,400	14,700
20 %					
	NPV	-30,200	72,100	5,700	128,100
	AV	-2,500	6,100	500	10,800
30 %					
	NPV	-51,100	37,700	-17,500	82,900
	AV	-4,300	3,200	-1,500	7,000

5.0 SUMMARY AND CONCLUSIONS

5.1 Summary

The determination of optimal hard clam growout production design incorporating the selection of seed size, planting density, plant scheduling and replacement timing depends on consideration of the complicated interactions of monthly clam growth and price relationships. Optimal scheduling depends on the ability to predict future conditions of growth, mortality and price. Growth prediction for this research was accomplished through the development of a hard clam growth function modelling periodic growth as a function of initial clam size, age, and water temperature, salinity and dissolved oxygen. Growth function parameter estimates were made for two planting densities. Stochastic hard clam growth was simulated for two sizes of seed clam planted at two densities using environmental values from three sites in the Indian River area of Florida. Monthly mortality was imposed in a deterministic manner using a terminal base mortality and weight system such that the mortality of younger clams was greater than that of older clams.

The results of the hard clam growth simulation were used to estimate expected net revenues by incorporating average monthly clam prices for four size categories. Clam prices were determined from time series price data. The expected revenues were then examined to determine optimal planting months and growout times. Two marketing arrangements were examined, the first allowing all clams to be planted and harvested as a single unit (single plant production), and the second requiring monthly harvests (multiplot production). Evaluations of the results produced specific plant, harvest and replacement schedules that varied with production method (seed size and density) and site location. Optimal rotations determined total operational input requirements and cost and revenue flows. These were then used to determine the residual value of the lease, the present value of the residual stream and an annualized value of the residual stream.

Comparison of the economic performance of each production method at each site showed single plant production to always outperform multiplot production. Larger seed planted at the higher density outperformed all other options in all but one case. Single plant production allowed clams to be planted and harvested such that expected net returns were maximized. Multiplot production caused clams to be planted and/or harvested in months other than those indicated by less restrictive optimization. The higher returns to larger seed planted at greater densities were attributed to a shorter growout period generating faster turnover and higher volume sales. The one case where the lower density outperformed the higher density was attributed to higher opportunity costs resulting from faster equity build-up with the higher density.

5.2 Conclusions and Implications

The results of this study must be put in proper perspective. Various assumptions were required to construct a representative operation. Individual features are presented as neither concrete absolutes nor unrealistic options. They are reasonable assumptions as determined by scholarly research and through contacts with industry professionals. Actual values or requirements for individual producers are expected to be both higher and lower. The purpose of the research is not to determine precisely what can be accomplished, but rather to provide a foundation for establishing and directing further areas of emphasis and consideration. Where consideration has not been given to seed density, planting month, site location, etc., this research provides justification for such. It is in this context that the results should be viewed.

The economic potential of hard clam growout is a complicated interaction of growth, as dictated by various environmental factors, and variable prices, as determined by clam size and month of harvest. Higher/lower densities may produce slower/faster growth while smaller/larger seed produce longer/shorter growout times. These only have economic relevance when combined with cost and revenue considerations. It is inaccurate and insufficient to say that a faster growth rate or a larger seed is preferred without knowledge of what effect the growth rate or seed size has on when clams reach market size and what prices might be expected. Further, while prices might be uniform across a region, growth conditions likely vary from site to site making optimal operation design specific to a given site.

Comparisons of the results of this study with others is difficult because of differences in production and financial assumptions. Thunberg and Adams (1990) estimate fifth-year net returns for two million seed (one million clams sold), a 3-year growout, and a $0.14 market price at $71,840. The comparable result from the current research is $17,800 to $24,000 for single plant production using 10-mm clams planted at 75 clams per square foot (900,000 clams planted and 602,000 to 623,000 sold) and sold at $0.10 per clam (see Tables 4-6, 4-17, 4-18 and 4-19). Ignoring the clam volume differential of the two studies, the results by Thunberg and Adams include $40,000 attributable to the higher price and do not subtract taxes which would be in excess of $20,000 under the assumptions of the current study. A more direct comparison is possible with Adams et al. (1993), as they assume a 2-year growout and $0.10 per clam. Net returns from clams planted at 75 clams per square foot are $32,807 for 765,000 clams sold. The comparable results from this study are $47,000 for single plant production (756,000 to 760,000 clams sold) and approximately $42,000 for multiplot production (764,000 to 767,000 clams sold), both using 15-mm seed planted at 75 clams per square foot (see Tables 4-12, 4-17, 4-18, 4-19, 4-20, 4-21 and 4-22). Thus, comparisons of this research with other studies indicate that returns can be increased by careful attention to production method and timing.

The results of this study also indicate that, in the absence of mitigating circumstances, the grower should plant larger seed and at the highest recommended density. Fifteen-millimeter seed may not be available in all areas, or it may be available, but only at prohibitive prices. While this research did not conduct seed price sensitivity analysis, the magnitude of difference between 10-mm and 15-mm results would indicate that some upward leeway on larger seed prices still exists. Limitations on planting density will be dictated by site-specific environmental conditions. The grower must determine maximum planting densities for his particular site from either research recommendations or personal test trials.

The residual values attributed to the lease computed in this study indicate that current lease fees substantially undervalue the productive capacity of the land. Given the complexity of the determination of residual values and their variability from site to site, it is unlikely that the full residual value could ever be recaptured as rent. The failure to properly value the land nevertheless represents a substantial revenue loss to Florida residents, the true owners of the land. Further, the variability of residual values by site provides justification for variable lease fees based upon the productive capacity of each specific site. The identification of productively unique sites, however, remains a problem. The costs of such a determination may not justify the benefits. A uniform lease fee arrangement may be the preferred option. This research suggests, however, that the lease fee be greater than current requirements.

The magnitude of the difference between existing lease fees and the residual values estimated by this research raise interesting policy implications. Current fees may be low due to ignorance of the true value of the land, or they may be set intentionally low so as to allow access by low income groups residing in coastal communities. If the intention were to allow access by low income groups, increased lease fees based on the productive capacity of the lease could reduce access by increasing start-up costs, thereby erecting a barrier to entry. This problem could be eliminated, however, and increased revenues captured through the imposition of a royalty or production tax. The culturist would pay a fee based upon the actual output of the operation. Start-up costs would remain the same, thus allowing continued access by original target groups, and the public would reap increased benefits from its ownership of the resource.

The effects of the marketing constraint, as demonstrated by multiplot production, provide evidence of the practical management and economic implications of such a constraint. The results indicate that restrictive marketing requirements may have considerable impact on the economic performance of a hard clam growout operation as evidenced by Site 2 and Site 3. Market restrictions may also have little impact, as evidenced by Site 1. Actual marketing constraints might be less restrictive than those modelled, requiring less frequent sales, or more restrictive, such as requiring both monthly sales and volume commitments. Less restrictive marketing requirements would be expected to produce returns approaching single plant production, while more restrictive marketing requirements would be expected to further erode the profitability of hard clam culture. Nevertheless, in the event of such restrictions, a production option might be linkage with producers at other "environmentally unique" sites producing clams on different harvest cycles. Through cooperative agreements, supply requirements might be met while allowing production to more closely follow less restrictive site specific optimal plant and replacement schedules.

Although environment-related loss can be severe, the relatively low start-up costs and rapid turnover time from plant to market allow fairly rapid recovery from adverse events. Of greater concern to the industry is market stability. The clam market has seen prices decrease from $0.17 per littleneck clam in the 1980's (Adams et al., 1991) to $0.10 in 1993 (Adams et al., 1993). This research allowed price to vary by month as determined by historical data, with littleneck prices varying from $0.10 to $0.13 per clam. As recently as October, 1993, however, littleneck prices were $0.08 in the Indian River, Florida, area and were $0.08 to $0.10 in the Cedar Key, Florida, area (various personal communications). While current studies have been incapable of keeping abreast of the downward price movements, the price sensitivity analysis in the previous chapter demonstrates the potential impact of reduced prices on the value of a lease. In the absence of increased market demand or supply disruptions in other productive regions, the influx of additional cultured supplies by Florida producers will likely exert additional downward price pressure. The hope is that these problems can be offset through increased marketing efforts directed towards increasing consumer awareness and demand.

Recent developments with respect to legal size categories raise further questions about market stability. At the time of this research, Florida hard clams could be legally harvested for consumptive sale when they measured 7/8 inches in width for sale outside the state and one inch for sale inside the state. Current Florida law allows the sale of 5/8-inch cultured clams (Marine Fisheries Commission, 199_). This research, assumes a one-inch minimum legal size. The impact of the smaller size is unclear and will depend upon how the marketplace reacts in terms of demand for both the new legal size categories. Without question, Florida producers would be capable of producing the smaller clams in shorter growout periods than that required to produce larger clams. What is less clear, however, is whether prices would dictate that the smaller clams be produced. Current prices do not uniformly decrease with size. Topnecks occasionally command higher prices than littlenecks, depending upon the season and supply. Each size category serves a particular market niche. A specialty market targeting the smaller clams may develop such that higher prices are commanded. Also, demand for the smaller clams would likely absorb a portion of existing demand for larger clams. Markets will still exist, however, for larger clams. Price dynamics would determine the ultimate production mix, as in this research where it was occasionally indicated that topnecks, a larger clam, be produced rather than littlenecks, the smallest legal clam.

5.3 Limitations and Suggestions for Further Research

While the growth function developed for this research performed satisfactorily, additional work is required in further developing and refining the hard clam growth function. Of specific concern is the fact that in some instances larger clams (70-90 mm) exhibited 5 and 6-mm monthly growth spurts, a phenomenon not supported in literature (Eversole, 1987). While clams this large never factored into economic decisions due to harvest indications at smaller sizes, these growth spurts indicate a potential flaw in the growth function. While the flaw may or may not be relevant to the size stage or growth window of concern to culturists, its existence nevertheless begs attention. Thus, considerations of functional form and/or the incorporation of additional independent variables would be beneficial. The effects of current, tidal orientation, phytoplankton abundance, suspended solids, etc., warrant investigation. Also, a density variable would be useful so that a single growth function could be applied to multiple plant densities.

Once environmentally-dependent growth relationships are defined, additional work is required in identifying environmental profiles that can be expected to produce similar growth, thus allowing classification of lease sites by growth and, hence, economic potential. This would allow the creation of variable lease fees, differing by economic potential.

The development of a hard clam mortality function would allow stochastic mortality to be incorporated in a manner similar to growth, thus more realistically depicting stock changes. This was an intended component of this research, but an examination of the available data failed to identify any concrete relationships. While the impact of severe cold weather is unlikely in Florida, the results of this research indicated a bias against clam planting and growout in warmer months. The negative impact of warm weather planting and growout took the form of stagnant growth and increased mortality as determined by extended growout times. This is likely a simplistic summation of the environmental impact on mortality and more explicit linkage needs to be identified.

Existing price data were insufficient to allow sophisticated incorporation of price expectations. This research was forced to use average monthly prices which were derived from relatively few field observations. Additional data would allow more accurate predictions.

Certain risks exist for the prospective hard clam aquaculturist. This research assumed a specific familiarity with both the methods of clam culture and with marine environments as a whole. In the absence of such familiarity, a learning curve is expected such that mistakes will be made leading to decreased economic performance due to increased mortality, mishandling of clams, and misreading of economic signals.

The results of this research were based on the assumption of stable expected environmental conditions. These conditions are long term phenomena and actual conditions may expose clams to less favorable growing environments. Of specific concern is exposure to extreme conditions such as might exist in the event of a storm or hurricane. The method of culture described provides protection from predation. Bag anchoring is a guard against mild current and tidal flow. Hurricane conditions, however, are capable of extensive clam mortality and equipment damage. The possibility of severe weather should be appreciated and incorporated into site selection. Further environmental threats exist from sewage contamination, excessive rain and run-off effects, natural toxic algal blooms, etc. Excessive rain creates multiple problems in that it reduces salinity levels and increases pollutant run-off into bays. The likelihood of adverse conditions will vary from location to location and should be considered when selecting a site.

A final point of consideration deals with the issue of replanting undersized clams. It is not unusual for growers to periodically harvest legal clams and replant those clams that have yet to attain market size. This research did not allow replanting undersized clams. The production assumption was that all clams in a given plant be harvested simultaneously as a single unit. When the harvest of undersized clams was indicated, the undersized clams were discarded. Undersized clams were produced when specific conditions produced stunted or slow growing clams such that either a marketable size was not achievable for all clams under the time constraints established by the models or additional growout produced net losses from current market-sized. In most instances, replanting would likely not allow greater numbers of clams than those described in this research to flow through the system. Some undersized clams may be sufficiently slow growers or stunted as a result of a particular production method that market size is not attainable in any reasonable timeframe. Some production scenarios simulated by this research failed to produce marketable clams in 34 months. Further, the existence of replanted clams may impede replanting with new seed by monopolizing an already limited growing space. Also, the added costs of culling and replanting may exceed any increased revenues. Culling and replanting undersize clams is a costlier, more time consuming process than simply harvesting and discarding. Replanting is similarly more time consuming than initial planting. The gains from eventual sales of undersized clams may, therefore, not justify the costs. It is unlikely, then, that replanting undersized clams would significantly improve the results of this research.

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APPENDIX 1

HARD CLAM GROWTH MODEL PARAMETERS

Estimates from OLS, WLS and heteroskedastic tobit regressions. Standard errors are in parentheses.

Estimation Procedure	Density	Standard Error	β_0	β_1	β_2	β_3	β_4
1^a	60	0.0664	0.6577	-0.0507	0.1736	-0.2742	-0.1019
			(0.1755)	(0.0068)	(0.0409)	(0.0458)	(0.0245)
	80	0.0415	0.2316	-0.0550	0.0629	-0.0718	-0.0085
			(0.0699)	(0.0029)	(0.0161)	(0.0154)	(0.0079)
2^b	60	0.0685	0.9751	-0.0681	0.1267	-0.3063	-0.1324
			(0.0963)	(0.0061)	(0.0319)	(0.0422)	(0.0190)
	80	0.0455	-0.0154	-0.0377	0.1018	-0.0492	-0.0083
			(0.0610)	(0.0037)	(0.0107)	(0.0127)	(0.0044)
3^c	60	0.3489	1.0137	-0.0770	0.3007	-0.4489	-0.2161
			(0.1546)	(0.0070)	(0.0490)	(0.0682)	(0.0300)
	80	0.3344	0.0422	-0.0724	0.2417	-0.1820	-0.0210
			(0.1432)	(0.0053)	(0.0349)	(0.0324)	(0.0156)

a - OLS; b - WLS; c - heteroskedastic tobit.

APPENDIX 2

ENVIRONMENTAL VALUES USED IN GROWTH SIMULATION

Temperature (^{0} C)

	Site 1		Site 2		Site 3	
Month	Mean	STD	Mean	STD	Mean	STD
January	18.14	2.65	18.92	2.15	17.52	1.79
February	20.98	3.28	20.27	2.70	20.85	2.79
March	19.17	2.72	19.04	2.38	19.45	2.47
April	23.30	1.69	23.15	1.16	23.30	1.53
May	26.40	1.44	26.27	1.02	26.63	1.23
June	28.12	2.39	28.92	2.56	28.23	2.64
July	30.30	0.60	30.40	0.46	30.14	0.61
August	30.15	1.20	29.83	0.65	29.37	0.57
September	29.20	1.41	29.53	1.55	30.35	0.49
October	24.67	2.17	25.14	2.10	26.87	0.15
November	21.32	3.28	22.67	2.31	22.67	2.31
December	18.07	2.70	18.60	2.37	18.25	3.18

Salinity (parts per thousand)

	Site 1		Site 2		Site 3	
Month	Mean	STD	Mean	STD	Mean	STD
January	27.70	2.33	28.50	2.04	26.25	2.06
February	26.75	3.18	26.00	4.11	25.05	2.81
March	27.20	3.94	25.80	3.70	26.12	3.17
April	26.42	2.08	26.42	2.20	26.17	2.34
May	26.50	2.38	25.37	1.06	26.33	2.08
June	26.12	1.93	25.95	2.42	26.67	1.53
July	24.25	6.40	23.83	5.78	23.60	5.81
August	20.25	8.84	20.17	5.80	20.07	5.59
September	25.50	2.78	25.33	1.53	26.50	3.54
October	24.82	2.69	24.76	2.74	25.23	3.22
November	25.25	3.23	25.33	0.58	24.83	0.29
December	25.17	4.75	23.62	4.96	24.50	6.36

Dissolved Oxygen (milligrams per liter)

	Site 1		Site 2		Site 3	
Month	Mean	STD	Mean	STD	Mean	STD
January	7.92	1.59	8.20	1.36	8.73	1.72
February	7.33	0.75	7.52	1.09	7.43	1.56
March	7.40	0.68	7.20	0.43	7.20	0.94
April	7.77	3.03	7.85	3.46	8.15	3.56
May	6.75	0.66	7.25	0.63	7.93	1.10
June	6.53	0.69	6.65	0.87	6.57	1.37
July	5.98	1.23	5.82	1.55	6.24	1.13
August	7.45	1.34	6.67	1.90	6.80	2.98
September	6.87	1.01	6.60	0.36	7.40	0.28
October	7.35	1.42	7.56	1.48	7.07	0.59
November	6.80	0.43	6.73	0.81	7.10	0.10
December	8.93	1.37	8.20	0.29	7.65	0.35

APPENDIX 3

HARD CLAM EXPECTED MEAN PRICES

Month	Littleneck 50-64 mm	Topneck 64-77 mm	Cherrystone 77-89 mm	Chowder > 89 mm
January	$0.11	$0.12	$0.07	$0.05
February	0.12	0.13	0.07	0.05
March	0.11	0.12	0.07	0.04
April	0.12	0.12	0.07	0.04
May	0.12	0.11	0.07	0.05
June	0.11	0.12	0.08	0.04
July	0.11	0.10	0.08	0.05
August	0.10	0.12	0.08	0.05
September	0.13	0.12	0.07	0.05
October	0.10	0.12	0.07	0.06
November	0.10	0.13	0.07	0.07
December	0.12	0.13	0.08	0.06

APPENDIX 4

INITIAL INVESTMENT REQUIREMENTS FOR HARD CLAM BOTTOM BAG GROWOUT

Equipment	Years of Life	#	Year 1	Year 2
Bags	a	750/acre	$6000	$6000
Stakes	a	1500/acre	210	210
Wet Suit	3	2	500	
Boat	7	1	3000	
Motor	2	1	3000	
Trailer	5	1	500	
Winch	3	1	500	
Truck	5	1	3000	
Miscellaneous	5	1	700	
Initial Site Survey		1	500	
Total			$17,910	$6,210

a - Bag life varies with the length of the hard clam growout period. If the growout period is two years or less, then bags last for two growouts or approximately 4 years. If the growout period is greater than two years, then the bags last for only one growout.

APPENDIX 5

PRODUCTION COSTS FOR 2-ACRE HARD CLAM BOTTOM BAG GROWOUT

Year	1	2	3
Variable Costs			
Seed	a		
Supplies/expendables	120	120	120
Fuel/oil			
Boat	900	1,100	1,100
Truck	300	300	300
Maintenance			
Boat/truck	1,000	1,000	1,000
Bags	65	130	130
Harvest Bags	b		
Wages	c		
Overhead Expenses			
Insurance	400	400	400
Permits	200	0	0
Bookkeeping/Acct. Fee	500	500	500
Licenses	140	140	140

a - Variable. Seed prices are $1.50 per 100 clams for 10-mm seed and $2.00 per 100 clams for 15-mm seed. Seed numbers vary with production method.
b - Variable. Harvest bags hold 250 clams and cost $0.20 each.
c - Variable. For single plant production, $1500 per year if harvest occurs and $0 otherwise. For multiplot production, $0 in all years.