2008

A Bio-Economic Feasibility Model for Remote Setting: Potential for Oyster Aquaculture in Virginia

Michael Spohn Congrove
College of William and Mary - Virginia Institute of Marine Science

Recommended Citation

Congrove, Michael Spohn, "A Bio-Economic Feasibility Model for Remote Setting: Potential for Oyster Aquaculture in Virginia" (2008). *Dissertations, Theses, and Masters Projects.* Paper 1539617864.
https://dx.doi.org/doi:10.25773/v5-dpen-ek98

A Bio-Economic Feasibility Model for Remote Setting: Potential for Oyster Aquaculture in Virginia

---

A Thesis
Presented to
The Faculty of the School of Marine Science
The College of William and Mary in Virginia

In Partial Fulfillment
of the Requirements for the Degree of
Master of Science

---

by
Michael Spohn Congrove
2008

Approval Sheet

This thesis is submitted in partial fulfillment of
the requirements for the degree of
Master of Science

Michael S. Congrove

Approved, by the Committee, 12/15/2008

Standish K. Allen Jr., Ph.D.
Committee Chairman/ Advisor

Romuald N. Lipcius, Ph.D.

Mark W. Luckenbach, Ph.D.

Roger L. Mann, Ph.D.

Donald W. Meritt, Ph.D.
University of Maryland
Cambridge, Maryland

TABLE OF CONTENTS

Page

SECTION I

Estimating the Biological Variables Affecting Remote Setting Success

SECTION II

Bio-Economic Feasibility of Remote Setting

ACKNOWLEDGEMENTS

I would like to first thank my advisor, Dr. Stan Allen for the opportunity to come to VIMS. Your support and guidance throughout my time here, both school related and in other realms, has been invaluable. You have successfully shown me the bigger oyster picture and the industry has gained an advocate because if it. I must also thank my committee, Dr. Roger Mann, Dr. Mark Luckenbach, Dr. Rom Lipcius, and Dr. Don Meritt for their advice and guidance during the construction and completion of my thesis work. A special thanks to Dr. Don Meritt for all the conversations concerning eyed larvae and remote setting rate- hopefully there will be many more to come. I must also thank Tom Murray who helped guide the economic side of this research.

Thank you to Dr. Jim Wesson, who I probably spoke to on a day-to-day basis more than anyone else, likely sometimes too often. Your understanding of the Virginia oyster industry is unparalleled and all your help and support is much appreciated. Also from VMRC I must thank Adam and Vernon for their support during planting.

I must thank everyone in the Aquaculture Breeding and Technology Center for their help and support through my time at VIMS. Specifically I must thank Katie Blackshear and Brian Callam who were integral in data collection during my first and second seasons respectively. Without you two this project could not have been accomplished. Thank you to the ABC hatchery crew, past and present, for tolerating my persistent presence in the hatchery and allowing me to arrange, re-arrange, and re-re-arrange my squatted space. Also, thanks to Karen Hudson who has given me help and guidance both before and during my graduate school days, and hopefully after.

I must also thank Andy Drewer, Tommy Kellum, Rufus Ruark, AJ Erskine, Rich Harding, Ron Sopko, Kevin Wade, John Vigliotta, and Robby Johnson for their participation in the remote setting program.

Finally I must thank family. During my time at VIMS I bought my first house, renovated that house, became a husband, and became a father. Without the love and support of my entire family I never could have accomplished all this. To my parents, thank you for all your love and support over these last 26 years. What you have taught and continue to teach me has brought me to where I am today. To my wife, Heather, thank you for believing in me (and supporting us) and allowing me to accomplish this goal. Now it is your turn. To my daughter, Ellie, the last eleven months have been the most amazing time in my life. Thank you for opening my eyes to a whole new level of living and reminding me to operate in the present.

LIST OF TABLES

Table Page

LIST OF FIGURES

ABSTRACT

A bio-economic model in the form of an interactive enterprise budget was constructed and tuned using empirical data to assess, practically, the feasibility of extensive oyster culture in Virginia using remote setting production techniques to produce spat-on-shell. Data was collected from ten sites located in various areas of the Virginia portion of Chesapeake Bay. If data collected during this study are typical, remote setting based oyster culture is biologically and economically feasible.

Remote setting success, as measured by the ratio of surviving spat at planting to the quantity of larvae used at setting, was highly variable with a range from 0-24% and a mean of 7%. Setting rate over 5% is sufficient for economically viable spat-on-shell production.

Growout duration to harvest size was estimated by fitting the Bosch and Shabman growth function to empirical estimates of growth from planting to approximately 13 months of age. This function predicts that 80% of surviving oysters reach market size (>76mm) in approximately 30 months. Survival to harvest size (30 months) was estimated by fitting the Weibull function to empirical estimates of survival from planting to 13 months of age, and estimated a mean of 21% with a range from 9-33% among growout sites. Wiebull parameter estimates were $\lambda=0.67\pm0.14$ and $\gamma=0.44\pm0.01$ (±SE) with $R^2=0.80$. Survival to one year was found to be density dependent with lower survival significantly correlated ($\alpha=0.1$) with higher spat count per shell (-0.469, p=0.09).

Infrastructure costs for a remote setting facility capable of producing approximately 3,000 bushels annually were modest with a mean of $9,750 and a range from $8,300 to $17,750. Labor requirements for producing one bushel of spat-on- shell ranged from 0.18 to 1.05 with a mean of 0.45 man hours per bushel. Cost distribution predicted by the bio-economic model was as follows: 1% for facility set-up, 6% for site preparation, 30% for larvae purchase, 12% for setting labor and materials, and 51% for harvest. Given the most probable parameterization of the model, and using empirical estimates derived in this study, the predicted cost of producing, planting, and harvesting one bushel of market size oysters was $21.40. Assuming a market value of $35.00 for a bushel of market size oysters, this is a return of $13.60 per bushel.

A Bio-Economic Feasibility Model for Remote Setting: Potential for Oyster Aquaculture in Virginia

THESIS INTRODUCTION

Crassostrea virginica

The eastern oyster, *Crassostrea virginica* is a remarkably tolerant organism with an extensive range that covers nearly the entire eastern seaboard of North America as far north as Nova Scotia, the entire Gulf of Mexico and Yucatan coasts, many islands of the Caribbean Sea, and a small portion of the northern South American Coast as far south as Venezuela. This impressive range includes water temperatures from zero to greater than 30°C and salinities from near zero to greater than 35ppt (Galtsoff 1964). A fishery exists or has existed in the past for nearly every area where *C. virignica* occurs in sufficiently large quantities (Kirby and Linares 2004).

C. virginica is a filter feeder capable of filtering upwards of 200L of water per day as an adult in optimal conditions (i.e. optimal salinity, temperature, and food availability) (Newell 1988; Newell and Langdon 1996). This filtration is important to the oyster for food, phytoplankton, but is also important environmentally in helping to affect eutrophication through removal of phytoplankton and, so indirectly, nutrients, in addition to increasing water clarity through removal of suspended sediments (Officer et al 1982). During feeding, sediments and other unwanted particles are separated, food is ingested and egested as feces, while unwanted particles like sediments are rejected and expelled as pseudofeces (Galtsoff 1964). Nutrients (nitrogen and phosphorus) that are not assimilated by the oyster arrive at the benthos in feces and pseudofeces. Once there, phosphorus is either buried or immobilized as phosphate. Nitrogen is buried and nitrified in oxic conditions and returned to the water column as inorganic nitrogen, or denitrified in anoxic conditions and released as nitrogen gas. It has been suggested, that removal of these organic nutrients from the water column can help to limit eutrophication (Newell et al 2002, Dame et al. 2002, Porter et al. 2004).

C. virginica, in many parts of its range, is (or was) the primary player in benthic-pelagic coupling. *C. virginica* plays a critical role in transferring biomass from primary production in the water-column to the benthos (Dame et al. 2002 and Porter et al 2004).

As a reef-building species, *C. virginica*, also provides habitat and forage areas to many other species, including commercially important ones such as *Callenectus sapidus* and *Marone saxatallis*. In many areas reefs were extensive, paralleling vast lengths of shoreline in shallow water as "fringing reefs", or as standalone three-dimensional structures extending from the bottom to above mean low water (Hargis 1995). These extensive reefs have been accreting since the beginning of the last period of sea level rise with recruitment and growth maintaining and increasing the reef both in diameter and height, each subsequent year creating net accretion upward from previous seawater levels (Hargis 1995). The end result of this process in many cases was prominent reefs extending into the intertidal even in areas of relatively deep water (greater than 4 or 5 meters).

As a result of the function of oysters in estuaries, in many they are considered keystone species and are critical to the productivity of these systems. Unfortunately, *C. virginica* populations throughout its range are a fraction of what they were historically with accounts of reef destruction recorded as early as 1880: "... once famous for its oyster beds, but now these are practically exhausted", written about the York River in Chesapeake Bay (Wheatley et al 1959).

The Fishery

Crassostrea virginica is fished throughout the majority of its natural distribution and is even cultured in areas outside of this range. Its highly sought-after meat, both along the Atlantic coast and west across the country, supported booming fisheries in the late nineteenth and early twentieth centuries (NMFS). High demand, however, led to reckless fishing that has been linked, at least in part, to collapse after collapse of local wild fisheries. Kirby and Linares (2004) identified a sequential pattern of expansion and collapse of these local wild fisheries from basins in the North, southward down the east coast and subsequently around Florida into the Gulf of Mexico. As fisheries collapsed, the industry moved progressively southward in search of more productive beds. Each move south led to a swelling of the industry followed by over-fishing of that basin and the next subsequent move south (Kirby and Linares 2004). This pattern has led to overfished *C. virginica* populations along the entire eastern seaboard with the only relatively viable wild (though highly privatized) fishery left in the Gulf of Mexico. Attention here is focused on the Virginia portion of Chesapeake Bay.

While overfishing is often considered the precursor to the collapse of the wild oyster fishery in Chesapeake Bay, there were a number of other players including disease, substrate removal, water quality degradation, decreased demand, and more recently increased predation from cownose rays (Kemp et al 2005, Kirby and Miller 2004, Merriner and Smith 1979, Meyers et al. 2007, Rothschild et al 1994, Wheatley et al 1959).

Compounding overfishing was a substrate limitation caused by the removal of huge amounts of oyster shell with comparatively miniscule amounts replaced (Rothschild et al. 1994). With a deficit of appropriate recruitment substrate, *C. virginica* recruitment was reduced not due to less larvae in the water, but less chance of surviving larvae locating appropriate recruitment substrate (Hargis and Haven 1995).

Despite overfishing in the late 1800's and early 1900's and reduced demand for oysters in the early and mid 1900s (Wheatley 1959), by the 1930s, the fishery was relatively stable. Then in the late 1960's MSX-disease (caused by *Haplosporidium nelsoni*), and Dermo-disease (caused by *Perkinsus marinus*) in the 1980's caused significant disease related mortalities (National Research Co)ncil 2004). Note that *P. marinus* has been known to exist in the Bay since the 1950's (though originally misclassified as a fungus). (National Research Council 2004).

Starting in the 1970s and becoming more of a problem in recent years, cownose rays began feeding more intensely on oysters, particular seed oysters (Merriner and Smith 1979). An increase in cownose ray population size in conjunction with the unavailability of more traditional prey such as razor and soft clams (*Tagelus plebius* and *Mya arenaria* respectively) also suffering from depressed populations, has led to a significant increase in ray predation (Dungan et al. 2002, Merriner and Smith 1979, Meyers et al. 2007).

Anthropogenic changes in water quality have also been cited as exacerbating the decline of oysters in the Bay (Kirby and Miller 2004). Increased eutrophication leads to hypoxic and anoxic conditions, which may limit suitable habitat for oysters, while toxic algal blooms can cause larval mortality further hampering recruitment.

The Virginia fishery, starting as early as the 1930's, was primarily a private fishery with approximately two thirds of landings coming from privately leased ground. This was in direct contrast to Maryland, which was primarily a public fishery with only about 5% of the fishery coming from private ground in the1930's. The private fishery in Virginia operated under a leasing system through which an oysterman could lease "unproductive ground", assessed as such by the Baylor survey (Baylor 1870). In 1892, section 2137 of the Code of Virginia made it possible for private industry to occupy these grounds for the purpose of "planting or propagating oysters." Oystermen paid a nominal fee per acre to lease the ground, and in return had exclusive rights to any oysters on their leased ground. This ground could now be planted with oyster shells to "catch" naturally occurring larvae (propagating), or be planted with oyster shells and oyster seed to be grown there until of harvestable size (planting). The latter method of oyster production is generally referred to as transplanting.

Initially, oysters planted on private ground were obtained from seed beds managed by the Commonwealth of Virginia. Later, starting around 1945 and as a result of compromised profitability due to rising Commonwealth seed (seed oysters from Commonwealth managed beds) prices, private planters began producing their own seed via shell plantings (Wheatley 1959). For example, in 1959, the cost per bushel for Commonwealth seed was approximately $1.50, whereas the cost of planting shell, including the cost of shell, was only $0.25. Meanwhile the market value per bushel was $3.00 to 3.50 with harvest costs ranging from $0.15 to $0.20 per bushel if dredged, and $0.50-$1.00 if tonged by hand (The difference in cost between methods stemmed from the relative efficiency of dredging over tonging. The large range in cost of tonging was a function of the variance in oyster density among reefs) (Wheatley et al. 1959).

In the early 1960s there was a shift in the Virginia oyster fishery from primarily private landings to primarily public landings. This shift was a result of several factors making planting oysters more risky. There was a period of intense disease-induced mortality (generally attributed to MSX-disease, National Research Council 2004) in Chesapeake Bay starting in the early 1960s. By the late 1960s, total landings in

Maryland rebounded to levels nearly equivalent to pre-mortality levels (though this level was not maintained for long, diminishing in the early 1980s). In Virginia however, landings did not rebound. The decline in total landings in Chesapeake Bay in the 1960s (from approximately 35 million bushels annually in the 1950s to approximately 23 million bushels in the late 1960s) is solely the result of a lack of recovery in Virginia landings following the mortality event beginning in 1960, and more specifically, the result of a drastic reduction in the level of private plantings in Virginia. With disease now a debilitating problem, and coupled with increased seed costs, as well as increased threat of significant cownose ray predation (rays becoming a significant nuisance in the late 1960s, Merriner and Smith 1979)), the risk involved in planting oyster seed on private ground had increased sharply and was sufficient to severely reduce private production. Without substantial private production, the Virginia fishery was a fraction of what it was prior to 1960 with less than half (approximately 0.9 million bushels) of total landings (approximately 2 million bushels) coming from private ground in the late 1960s, down to just 36% (approximately 0.22 million bushels) of total landings (approximately 0.6 million bushels) by 1988 (Alford 1975, Bosch and Shabman 1990). Compare these landings to pre-disease levels in the late 1950s where greater than 80% (approximately 4 million bushels) of total landings (approximately 5 million bushels) came from private ground (Alford 1975, note: landings in pounds converted to bushels using bushels = pounds/4.4743 as per Bosch and Shabman 1990).

The range of oyster related problems in the Bay (substrate limitation, reduced recruitment, disease, water quality degradation, cownose ray predation, and increased seed costs) has all but ended the wild and private fisheries in Virginia. Total Virginia landings in 2005 were only 136,300 bushels (Virginia Marine Resources Commission [VMRC] Landings Bulletin 2006). The majority of oysters processed in Virginia now come from outside Virginia, primarily the Gulf of Mexico (500,000 to 600,000 bushels annually) (Dr. James Wesson, Head of Conservation and Replenishment Division, VMRC). The majority of oysters marketed as true Chesapeake Bay oysters and sold out of Virginia are actually purchased from Maryland. Virginia producers would benefit from a supply of Chesapeake Bay oysters as they have historically been a product that demands a higher price than oysters from the Gulf of Mexico. The deflated mean value of Chesapeake Bay oyster meat from 1950 to 2005 was $3.8 per pound. Gulf oysters had a value through this same period of $3.2 per pound (NMFS 2007). This lack of locally available, in-state product makes for a precarious and inconsistent supply of oysters and hampers the growth and sustainability of the Virginia industry. The need for a more consistent and self-sufficient source of oysters in Virginia has led industry members to aquaculture.

Aquaculture in Virginia

Aquaculture is certainly not new to Virginia as the method of private production, i.e. transplanting, previously described is undoubtedly a form of culture. A key distinction between transplanting culture and what is most often thought of as oyster culture today is the addition of a hatchery phase in today's culture practices. The addition of a hatchery phase removes reliance on the variability of natural recruitment for acquiring seed oysters. Hatcheries focus on producing oyster larvae from broodstock (adult oysters used to propagate a generation of oysters for culture) and rearing them under controlled conditions to maximize survival. Hatchery reared larvae are then used to produce seed oysters for culture. There are two general categories of oyster aquaculture currently employed in Virginia: 1) intensive culture and 2) extensive culture.

Intensive oyster aquaculture is on the rise in Virginia with nearly five million cultured oysters sold in 2007. This is up six times from less than one million sold in 2005 (Murray and Oesterling 2008). Intensive aquaculture consists of hatchery production of individual oysters, referred to as "singles", which are grown in nursery systems until large enough to be "planted" in the water in some sort of containment unit. These containment units include mesh bags or mesh lined cages and are either placed on the bottom, just off the bottom, or floated just beneath the waters surface. This method provides protection from predation, particularly cownose rays, and produces an esthetically appealing oyster good for the half shell market. Contained culture has had variable success and shows promise as a means of producing a quality half-shell oyster. The high labor demands, however, of handling the containment units and the shear number and associated cost of containment units required, may limit the scale at which it can be done profitably (Weiland 2006, Dr. James Wesson, VMRC pers. comm.). The industries biggest current need is for a large, consistent supply of oysters for the shucking market which it seems cannot be met by intensive aquaculture, but might be by extensive aquaculture.

The extensive culture category includes the transplanting method and is defined by a hands-off approach where oysters are planted on the bottom, usually unprotected, for later harvest. A relatively new twist (circa 1970 on the US west coast and in the 1980s in Virginia) on this approach is the use of hatchery reared larvae to produce seed, dubbed "spat-on-shell" (many newly attached oysters on old oyster shell), via a process called remote setting (Lund 1972). This seed can then be planted on the bottom similar to the seed transplanting methods used historically.

To be clear, remote setting only includes the actual setting process where larvae are allowed to attach to shells. Remote setting in addition to grow-out of spat-on-shell for future harvest will be referred to here as remote culture.

Gear and labor for remote culture are much less than for intensive culture, however survival is generally much lower since they are not protected by containment units and are at higher risk to sedimentation. In this case oysters are attached to shell and eventually one another, therefore, this product much more resembles wild-caught oysters with various shapes and sizes and therefore can be processed in ways similar to wild oysters, where during the culling process some may be set aside for half shell that meet standards, whereas the majority are shucked for meat.

In Virginia the method of remote culture was first evaluated in the early 1980s by Virginia Sea Grant (VASG) at the request of the Virginia oyster industry and as a result of worry over the *P. marinus* related mortalities occurring during this same period. Several remote sets and spat-on-shell plantings were successfully completed at various industry sites via a remote setting tank constructed by VASG and towed by trailer to the respective sites. The production method failed to catch on however and was attributed to several factors: 1) survival of planted oysters was extremely low due to the same high disease pressure that was killing wild oysters, 2) early mortality of planted spat-on-shell, particularly in the high salinities was extremely high because of *Stylocus ellipticus*, known to prey heavily on newly set oysters (Newell 2000), 3) there were no large hatcheries in Virginia capable of producing enough larvae to support any sizeable scale-up of production and there was little interest in new hatcheries as a result of two, recent and high profile hatchery failures in the 1970s still fresh in the minds of industry, and 4) a resurgence of the natural population during the VASG remote setting experiment reduced what little interest was left in the technique and the program was abandoned (Mike Oesterling, VA Sea Grant).

The primary problem with remote culture when it was first tried in Virginia was that disease affected hatchery produced oysters the same way it did wild oysters and therefore offered little benefit. Today however, this is not the case as selective breeding programs have been domesticating oysters in the effort to breed disease resistance and fast growth into oyster stocks. Oysters selectively bred to better resist disease relative to wild stocks have been documented to show resistance to both MSX-disease and Dermo-disease (Calvo et al. 2003). Another product of domestication, also not available during the VASG trial, is triploidy. Triploid oysters are bred to be sterile by mating a tetraploid male that has four sets of chromosomes with a diploid female that has the normal two sets of chromosomes (Guo et al. 1996). Approximately 99.99% of the resulting offspring have three sets of chromosomes rendering them sterile (S. Allen, unpublished data, Aquaculture Genetics and Breeding Technology Center (ABC), VIMS). With dramatically reduced gonadal development, more effort is directed into somatic growth, making triploid oysters grow faster than diploids (Allen and Downing 1986, Shpigel et al. 1992, L. Degremont et al., ABC, in prep. In addition, condition of triploid oysters is not compromised by spawning since gonad production is minimal and therefore quality product is available to a producer when diploid oysters are not marketable (Allen and Downing 1986). With triploid technology, the ability to produce fast growing, disease resistant oysters with year round marketability now exists in remote setting based production.

Remote Setting

Oysters were first produced and allowed to metamorphose in a hatchery in 1920 by W.F. Wells (Wells 1920). Remote setting, however, is relatively new to the oyster production game, and was pioneered by industry members in the Pacific Northwest. The first mention of the technique in the literature was in 1972 with Lund's Master's Thesis at

Oregon State (Lund 1972). In 1973, Budge developed a method for packaging and shipping oyster larvae that was used to complete the first remote set (Budge 1973). Since remote setting is traditionally done in an area "remote" from the hatchery, an integral step in successful production is getting the larvae from the hatchery to the setting site with minimal mortality and degradation. Budge pioneered this technology.

In the 1980s there were a number of practical publications on remote setting (Jones and Jones 1983, Jones and Jones 1988, Henderson 1983). These works were primarily instruction manuals for remote setting. The Jones and Jones manuals are probably the most referenced manuals for remote setting and focus on the Pacific oyster, *Crassostrea gigas*. These manuals take the reader step by step through the remote setting process pointing out pitfalls and areas that require special attention. They are thorough, explaining biology, suggested methods of tank design, tank setup, and record keeping. With the aid of these manuals, someone with relatively little culture experience can complete a remote set. Most of the remote setting that is done in the United States currently is modeled after techniques presented in these practical manuals.

Remote culture consists of four typical phases: 1) hatchery production of eyed larvae (eyed larvae being metamorphically competent larvae), 2) remote setting and planting, 3) grow-out, and 4) harvest. Larvae are grown in hatcheries until ready to settle and metamorphose at which time they are removed from culture and sent to a remote site for setting. At the remote site, tanks of clean and containerized cultch (usually oyster shells) and conditioned seawater receive larvae, add them to the tank and allow them to settle on the shells. The end product is "spat-on-shell" seed that is similar to wild caught spat (except for the genetics), where several to many spat are attached to each shell. In Virginia spat-on-shell is typically removed from the tanks after 10 days and transported to the plant site where spat-on-shell grow-out closely resembles the traditional method of seed transplanting. Oysters are then left in place until ready for harvest. The remote setting method of oyster production has worked successfully for many years on the Pacific Northwest Coast and is the primary product source for large producers there. Remote culture, given its ability to produce disease resistant, triploid oysters, using minimally labor and gear intensive methods, appears to be the most feasible method to approach the scale of oyster culture necessary to return Virginia's primary source of shucking product back to the Commonwealth.

The Study

The purpose of this thesis research was to perform a feasibility analysis of remote culture using remote setting techniques to assess its cost-effectiveness in Virginia. The objectives of this study are as follows:

1. Obtain empirical estimates of mean and range for rate of remote setting for various regions in Virginia.
2. Obtain empirical estimates of post-deployment mortality for spat-on-shell in various regions of Virginia.
3. Estimate a mean and range of survival to market size of spat-on-shell oysters for various regions of Virginia.
4. Obtain empirical estimates of the costs associated with spat-on-shell production including investment and operating expenses.
5. Estimate a mean and range of the revenues associated with spat-on-shell production and compare to costs, to assess feasibility.
6. Construct a customizable, predictive model that will allow a user to assess his or her potential for spat-on-shell production given user-specified conditions.

The results of this study will be beneficial to those interested in getting started in spat-on-shell oyster production both here in Virginia, as well as in other coastal areas. The customizable model will empower its user to make informed decisions concerning financial feasibility and gear, labor, and larval requirements given a specified level of production. It will also allow the user to forecast production with expected or "what-if" levels of mortality and growth.

Section 1

Estimating the Biological Variables Affecting Remote Setting Success

INTRODUCTION

The purpose of Section I is to provide estimates of the biological parameters that influence the success of remote setting including setting, growth, and survival. This information is used in Section II to inform and tune the bio-economic model.

Settlement of oysters takes place in two sequential steps: settlement followed by metamorphosis. Settlement occurs when a larva leaves the water column for the benthos in response to stimulus from a cue associated with suitable attachment substrate (Burke 1983). If suitable substrate is found, the larva will attach and undergo metamorphosis. If suitable substrate is not found the larva can resume swimming for settlement again elsewhere. Metamorphosis occurs after settlement, when the larva has found suitable substrate, and consists of permanent cementation and the rearrangement of internal organs for the subsequent sedentary life (Bonar 1991 Burke 1982, Kennedy 1996, Cranfield 1973). Immediately following metamorphosis there is also likely to be some level of post-metamorphic mortality due to reduced feeding and depletion of energy reserves during metamorphosis. Settlement rate as it is measured in this study includes all of these events: settlement, metamorphosis and post metamorphic mortality into one measure referred to here as "remote setting rate". Remote setting rate is effectively a measure of survival from eyed larvae added to the setting tank to post-metamorphic spat removed from the tank approximately 1-3mm in size after seven to ten days in the setting tank.

Remote setting rate can be thought of as the largest single mortality event encountered in the remote culture process, and therefore has the greatest effect on cumulative survival from setting to harvest. Therefore, higher remote setting rate leads non-proportionally to more product and therefore higher returns. Setting rate is affected by various factors including larval competence (Carriker 1961, Baker 1994), lipid reserve (Gallagher and Mann 1986), temperature (Hidu and Haskin 1971 and Lutz et al. 1970), salinity (Hidu and Haskin 1971), light (Nelson 1953, Ritchie and Menzel 1969, water quality (absence of toxins, excessive waste products) (Jones and Jones 1988), cultch condition (clean, grit-free cultch is preferred) (Jones and Jones 1988), available settlement cues (substrate and conspecific) (Burke 1983, Bonar et al. 1990, Crisp 1967, Hidu et al 1978, Keck et al. 1971, Hidu 1969, Weiner et al. 1985), toxins (Jones and Jones 1988), and possibly others. Larval competence is generally under the direct control of the hatchery, as the hatchery decides when larvae are ready to be removed from culture for setting and it is at this point that development to competence is truncated. One commonly employed method of determining larval competence is size of eyed larvae, where large and uniform larvae are generally preferred. Therefore, size (shell height) of eyed larvae can be used as a rough proxy for competence. For this study, setting rate was calculated for all sets to derive a mean and range for the model. Some potentially influential parameters were tracked including temperature, salinity, and a proxy for competence (larval shell height).

Growth and survival of spat-on-shell are affected by similar factors at work in natural populations. Growth, for example, is affected by factors such as salinity, temperature, and, food availability (Galtsoff 1964, Wang et al. 2008). In nature, and probably for remote culture, initial survival of post-metamorphic spat (planted spat in the case of remote culture) is low primarily due to predation. Primary predators of newly set spat in the Chesapeake Bay include xanthid crabs (primarily *Panopeus herbstii* and *Eurypanopeus depressus*), *C. sapidus*, and *Stylocus ellipticus* (Krantz and Chamberlin 1978, Abbe 1986, Bisker and Castagna 1987, Newell 2000). Survival increases significantly with size as oysters obtain a size refuge from xanthids and *S. ellipticus* (*C. spapidus* predation continues, though at a reduced rate). *S. ellipticus* are known to be ravenous predators of newly set spat and are considered a nuisance in oyster culture (Newell 2000, Andrews 1973).

Growth was tracked in this study at ten sites to estimate the length of time required to grow spat-on-shell oysters to market size. Survival was also tracked at the same intervals to estimate a survival curve for spat-on-shell oysters. With this information, an estimate of the number of oysters remaining at the time of harvest, and the period of time necessary for spat-on-shell oysters to reach market size can be estimated. From a production standpoint this information estimates revenue as a function of size of the harvest, determined by the associated survival, and time to harvest determined by growth.

Three of the six main objectives are covered in this section:

1) Obtain empirical estimates of remote setting rate for various regions in Virginia.
2) Obtain empirical estimates of post deployment mortality for various regions in Virginia.
3) Estimate a mean and range of survival to market size of spat-on-shell oysters for various regions of Virginia.

METHODS

Site Descriptions

Ten setting facilities were used in this study. Six of these were operational in both 2006 and 2007, four additional sites operated in 2007 only (Table 1.1). These sites were spread around the Virginia portion of Chesapeake Bay including the western, southern, and eastern shores over a mid-summer mean salinity range of approximately 10ppt – 22ppt. From north to south down the western shore the setting facilities include one each in Kinsale (Yecomico River), Lottsburg (Coan River), Burgess (Little Wicomico River), Weems (Carter's Creek), Urbanna (Lagrange Creek), Gwynn's Island (Milford Haven-north), Hudgins (Milford Haven-south), Mobjack (Ware River), Suffolk (Chuckatuck Creek) and one on the bayside eastern shore: Saxis (Saxis Bay). These facilities will be referred to be their location name (e.g. the Saxis facility).

Spat produced over the course of the two year study were planted at various locations around the Bay. In 2006, spat were planted in close proximity to the respective setting facility on six sanctuary reefs chosen by the VMRC (Table 1.2). Each setting facility planted exclusively on their specific designated site. In contrast, in 2007, in most cases the planting sites were not near the setting facility and in many cases multiple setting facilities planted on the same plant site (Table 1.2). Plant sites in 2007 included both sanctuary reefs and temporarily closed public oyster ground. Locations of all setting facilities and plant sites for 2006 and 2007 are displayed in Figure 1.

Table 1.1: Location of each of the 10 remote setting facilities and their respective number of sets completed. Sites are arranged by salinity. NP denotes stations that were not participating in 2006 and had no production. R. is river. * Mean salinity is the mean of salinity recorded at the time of each set, not over time.

			Number of Sets Completed	
Location	**Water Body**	**Mean Salinity* (ppt)**	***2006***	***2007***
Lottsburg	Coan R.	11.7	NP	3
Kinsale	Yecomico R.	13	2	3
Burgess	Little Wicomico R.	13.5	NP	2
Saxis	Saxis Bay	15.5	4	5
Weems	Carter's Cr.	15.7	3	5
Urbanna	Lagrange Cr.	16.2	NP	2
Hudgins	Milford Haven	17.2	2	3
Gwynn's Island	Milford Haven	18.5	4	3
Mobjack	Ware R.	19.6	NP	1
Suffolk	Chuckatuck Cr.	22.5	3	2

Table 1.2: Remote setting facilities and their corresponding planting sites for 2006 and 2007. Latitude/ longitude are in decimal degrees. The map column lists the letter that denotes the plant site on the study map (Figure 1.1). The spat-on-shell planted column is the number of spat-on-shell planted at each plant site by the corresponding remote setting facility. NP denotes stations that were not participating in 2006 and had no production. R. is river. Cr. is creek. Sanc. is sanctuary reef.

Location	Plant Site 2006	Map	Latt. (N)	Long. (W)	SOS planted	Plant Site 2007	Map	Latt. (N)	Long. (W)	SOS planted
Lottsburg	Coan River Sanc.	A	37.969	76.465	292,000	Barn Point (PG #112)	G	38.030	76.536	4,400,000
Kinsale	NP					Honest Point (PG #77)	H	37.992	76.467	4,000,000
Burgess	NP					Hilly Wash	J	37.852	76.328	3,300,000
Weems	Drumming Ground	B	37.654	76.463	6,700,000	Little Wicks/ Big Wicks	L	37.691	76.573	4,700,000
Saxis	Pungoteague Cr.	F	37.671	75.859	4,000,000	Pocomoke Sound (PG #9)	N	37.946	75.718	1,300,000
Urbanna	Temple Bay	C	37.590	76.425	7,400,000	Little Wicks/ Big Wicks	L	37.691	76.573	2,900,000
Gwynn's Island	NP					Rogue Point	K	37.847	76.332	3,000,000
						Shell Bar	I	37.828	76.332	681,000
Hudgins	Palace Bar	D	37.528	76.374	1,800,000	Rogue Point	K	37.847	76.332	335,000
						Shell Bar	I	37.828	76.332	1,500,000
Mobjack	Ware River Sanc.	E	37.369	76.457	4,900,000	Shell Bar	I	37.828	76.332	2,000,000
Suffolk	NP					Nansemond R. (PG #6)	M	37.822	76.318	344,000

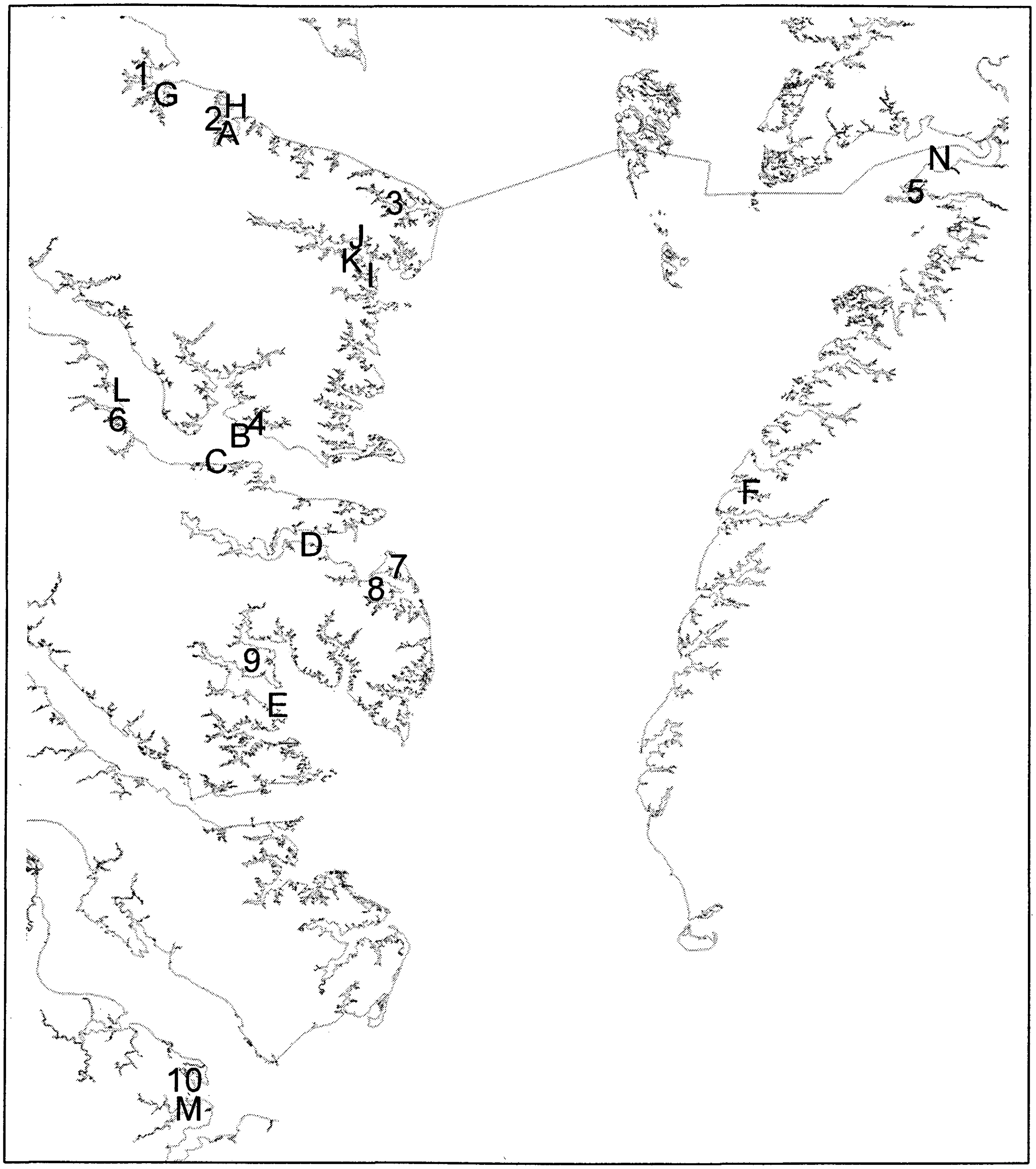


Figure 1.1: Virginia portion of Chesapeake Bay. Labels 1-10 are setting facilities, Table 1.1 matches label to site. Labels A-N are plant sites (see table 1.2 for corresponding plant site name. A-F are 2006 plant sites. G-N are 2007 plant sites.

Yecomico River

Oyster were planted in the Yecomico River in 2007 on public ground number 112, also known as Barn Point (G). (The letter following any plant site references that particular site on the map in Figure 1). Barn Point is in approximately 2 meters of water and is located at 38.030N, 76.536W. Barn Point received three deployments of about 4.4 million oysters.

Coan River

Oysters planted in the Coan River in 2006 went on the state constructed 3-dimensional sanctuary reef (A) located at 37.969N, 76.465W in approximately 1-2 meters of water. The sanctuary reef received two deployments totaling approximately 292 thousand oysters. In 2007 oysters were planted on public ground number 77, also known as Honest Point (H). Honest Point is in approximately 3-4 meters of water and is located at 37.992N, 76.467W. Honest Point received three deployments of about 4 million oysters.

Great Wicomico River

Oysters were planted in the Great Wicomico River in 2007 only and went on three different areas: 1) Shell Bar (I), 2) Hillywash (J), and 3) Rogue Point (K). Shell Bar is located at 37.828N, 76.332W in approximately 1-2 meters of water. Hillywash and Rogue Point are both located in approximately 2-3 meters of water at 37.852N, 76.328W and 37.847N and 76.332W respectively. Shell Bar received six deployments totaling approximately 4.2 million oysters, Hillywash – two deployments of about 3.3 million oysters, Rogue Point – two deployments of about 3.3 million oysters.

Rappahannock River

Oysters planted in the Rappahannock River in 2006 went on two state-sanctuary reefs, Drumming Ground (B) and Temple Bay (C). Both reefs are located in approximately 2-3 meters of water at 37.654N, 76.463W and 37.590N, 76.425W, respectively. In 2007 oysters were planted on two areas of public oyster ground known as Little Wicks (L) and Big Wicks (L), both in approximately 3-4 meters of water located adjacent to one another at 37.691N, 76.573W . Drumming ground received four deployments totaling approximately 6.7 million oysters, Temple Bay – three deployments of about 7.4 million oysters, Little Wicks – four deployments of about 2.9 million oysters, Big Wicks –five deployments of about 4.6 million oysters.

Piankatank River

Oysters were planted in the Piankatank River in 2006 only and went on Palace Bar (D) located at 37.528N, 76.374W in approximately 1-2 meters of water. Palace Bar received two deployments of about 1.8 million oysters.

Ware River

Oysters were planted in the Ware River in 2006 only and went on the state sanctuary reef (E) located at 37.369N, 76.457W in approximately 2-4 meters of water. This reef received four deployments of about 4.9 million oysters.

Nansemond River

Oysters were planted in the Nasemond River in 2007 only and went on public ground number 6 (M) and is located at 37.822N, 76.318W in approximately 2-4 meters of water. This reef received one deployment of about 344 thousand oysters.

Pocomoke Sound

Oysters were planted in Pocomoke Sound in 2007 only and went on public ground number 9 (N), located at 37.946N, 75.718W in approximately 3-4 meters of water. This reef received two deployments of about 1.3 million oysters.

Pungoteague Creek

Oysters were planted in Pungoteague Creek in 2006 only and went on the state constructed 3-dimensional sanctuary reef (F) located at 37.671N, 75.859W in approximately 1-2 meters of water. This reef received three deployments of about 4 million oysters.

Design

Setting

At each setting facility and for each set, remote setting rate was determined by first calculating the mean number of spat per shell resulting from a set. This measure was performed at the time of planting, generally 7-10 days after larvae was released into the setting tank. One hundred shells were randomly selected from various areas and depths in each of two tanks set (taking no more than 5 shells from any one shell bag), enumerating the number of spat alive on each shell to obtain a mean number of spat per shell for the tank. The mean number of spat per shell was then multiplied by the number of shells in the setting tank to obtain an estimate of the total number of spat produced. This estimate was divided by the number of larvae that went into the setting tank to obtain remote setting rate. The number of larvae that went into the tank was calculated by the hatchery supplying the larvae. This calculation was done for each of the 18 sets completed in 2006. Water temperature and salinity at the time of setting were also collected at each site for each set.

In 2007, the method for calculating the setting rate was altered slightly because spat were transported, in many cases, by truck to a dock where they were loaded onto a boat for deployment. In this case, rather than taking 100 shells from each of two set tanks, 300 shells were randomly selected and counted from each cohort planted as they were being loaded from the truck to the deployment vessel (again taking no more than 5 shells from any one bag), otherwise the method remained the same. Three hundred were taken instead of two hundred because in 2007, 300 bushels were planted at a time as opposed to 200 bushels planted at a time in 2006. The number of sample shells was increased to maintain the same ratio of 1 sample shell per planted bushel as was the precedent in 2006. This calculation was done for each of the 29 sets completed in 2007. Water temperature and salinity at the time of setting were again collected at each site for each set.

In both years, for each set performed at a setting station, a parallel larval setting assay was also performed at constant temperature (27±2°) and at site specific salinity at the Virginia Institute of Marine Science oyster hatchery. The purpose of the assay was to assess the quality of larvae in a more controlled setting than was possible in the remote field sets. By completing these assays, the relative performance of the larvae was known, and could be ruled out, or implicated, as a factor in poor setting. The setting assay was imperative to objectively evaluate the remote setting rates at the sites to ensure that they were primarily a function of the setting process and not the quality of larvae.

Larval setting assays were performed in a downweller setting apparatus using micro-cultch (crushed oyster shell approximately 300μm in size), commonly used for the production of single spat. Each assay consisted of triplicate setting boxes in a common 40 liter tank. Each screened box received 25ml of micro-cultch that was spread as settlement substrate evenly on the bottom. Tanks were filled with filtered seawater and adjusted with deionized fresh water to match the salinity of the setting facility. Water treatment consisted of sand, ultraviolet, and charcoal filtration.

Larvae for use in the setting assays were obtained by retaining a small portion from each cohort set in the field. For transport, larvae were rapped in a Nytex screen and moist paper towel, put into a Ziploc bag and maintained in a cooler at 4-7°C until setting at the hatchery, usually within 2-4 hours of field setting. Prior to setting, assay larvae were allowed to acclimate, split into three equal volumes, counted, then added to the prepared downwellers. Twenty five milliliters of micro-cultch was added to each downweller as a settlement substrate. In 2006 approximately fifteen thousand larvae were added to each downweller screen. Using fifteen thousand larvae often resulted in a large number of spat (~3,000-5,000) to be counted. In 2007, because of approximately 45 scheduled sets compared to 18 in 2006, the number of eyed larvae per downweller was decreased to approximately five thousand to reduce the number of resulting spat (~500-1,000) to be counted.

Spat were grown to a size sufficient for counting in triplicate upwellers (sieved on a 2mm screen). Upwellers are a commonly used nursery for oyster spat consisting of a number of cylinders with screened bottoms contained within a large common tank. The upweller cylinders hold small oyster seed on the appropriately sized screen and are plumbed such that water entering the common tank travels up through the screen, past the spat, and then out of the system. The directed flow of water past the spat provides nutrition for the growing spat. Food was that which occurred in ambient water and therefore may have fluctuated between cohorts each season. Spat were in the upweller system from approximately 750µm to 2mm in size for a period of one to three weeks.

In 2007, mean shell height of each larval cohort was measured at the time of the control set.

Growth

Growth data were collected at 2006 plant sites only. Of the six sites, three were replicated and three were not. Whether sites were replicated or not was determined by ease of access to sampling apparatus. The replicated sites were in relatively shallow water (1-2 meters) and could be accessed by wading. The non-replicated sites were in deeper water (>3 meters) and could only be accessed by diving. Dive sampling was conducted by a third party (VMRC). The non-replicated plant sites include the Ware River reef, Drumming Ground, and Temple Bay. Replicated plant sites included a low (9-11ppt), medium (13-15ppt) and high (15-18ppt) salinity reef, respectively: the Honest Point reef (Public Ground #77) in the Coan River, the Pungoteague Creek reef, and Palace Bar in the Piankatank River (Table 1.2).

At the three replicated plant sites, three, one-meter square open-top sampling cages were placed on the bottom with approximately 1000 randomly selected shells per cage for each set planted at that site. At Pungoteague Creek a total of nine cages were placed, three cages for each of three separate sets. At Honest Point, a total of six cages were placed, three cages for each of two sets. At the Coan River reef, a total of six cages were placed, three cages for each of two sets. At the three non-replicated sites, only one cage per set was placed. At Temple Bay and Ware River, four cages were placed, each site receiving four sets. At Drumming Ground three cages were placed for three sets planted there.

Growth was measured at four intervals: 1) deployment, 2) post-deployment (one – two weeks after planting), 3) pre-winter (late November to early December), and 4) one year (late summer 2007). At each sampling interval shell height of 100 oysters from each planted cohort was measured.

Survival

Survival was measured at three intervals: 1) post-deployment (one – two weeks after planting), 2) pre-winter (late November to early December), and 3) one year (late summer 2007). Survival data were collected for all sampling intervals in 2006. In 2007 survival was only measured at the post-deployment interval. Estimates of survival were calculated from spat per shell counts from the same cages described above from which growth was measured. At each sampling interval, the number of spat alive on each of 100 cultch shells from each sampling cage was enumerated. Therefore the number of spat per shell was counted on 300 shells for the replicated sites, and 100 shells for the non-replicated sites.

Data analysis

Setting

Basic descriptive statistics were calculated including mean, range, standard deviation, and confidence interval for setting data. Site specific setting performance was assessed using a setting performance indicator (SPI) defined as the mean of the site specific remote setting rate (RSR) divided by the mean of its appropriate assay setting rate (ASR) the latter being the rate at the VIMS hatchery.

$$SPI = \frac{RSR}{ASR} \qquad (1)$$

The setting performance indicator allows for a relative comparison of the effective setting performance among sites taking into account variation in overall larval quality between larval cohorts. Assuming the control represents the maximum potential of a larval cohort, SPI=1 is perfect setting performance. Note that SPI does not necessarily measure competency since larvae used for controls had more time to settle – by virtue of dwelling in the setting boxed for, on average, 14 days, than did larvae in field tanks. Therefore variation in performance among sites may be confounded by the competence of a larval cohort. The level of competence of larvae coming from commercial hatcheries, however, will always be variable, so the data here represent likely estimates of "industry setting" at this point in the evolution of spat-on-shell.

Effect of temperature and salinity on setting rate was assessed using regression analysis. Correlation between control setting rate and field setting rate was analyzed using Pearson product-moment correlation to consider the effect of larval quality on remote setting rate. The effect of larval size, a loose proxy for competence, on field setting rate was analyzed using Pearson product-moment correlation.

Growth

In an effort to put observed growth in a useful context for the feasibility model, growth data were used to fit three models as a means to predict the approximate time oysters will reach harvestable size. Models used include von Bertalanffy (1938), simple linear, and Bosch and Shabman (1990). The von Bertalanffy and simple linear were used for comparison to other studies on oyster growth utilizing these same models (Southworth et al. in prep, Rothschild et al. 1994, Cardenas and Aranda 2007, Coakley 2004). The Bosch and Shabman model was used because it was parameterized using Virginia oyster data and is able to incorporate seasonal growth.

Combined (all sites) mean population growth curves (age in years, shell height in mm) were fitted using the von Bertalanffy (1938) shell height-at-age model with nonlinear least squares regression. The von Bertalanffy model equation is:

$$SH_t = SH_{\max}(1 - e^{-k(t-t_0)}) \qquad (2)$$

where SH_t is shell height at time t, SH_{max} is maximum shell height, t_0 is shell height at time zero, and k is the rate at which maximum shell height is approached.

A simple linear model was also fit to observed growth data using linear least squares regression. The model equation is:

$$SH_A = mA + a_0 \qquad (3)$$

where SH_A is shell height at age A, m is the slope of the line, A is the age in years, and a_0 is the shell height at age zero.

Finally, the Bosch and Shabman (1990) monthly growth model was adapted to the observed growth data. The model equation is:

$$W_t = W_0 e^{a_i b_j c_k} \quad (4)$$

Where W_t is the weight of the oyster at the end of month t, W_o is the weight at the beginning of month t, e is the base of natural logarithms, a_i represents one of twelve monthly growth parameters, b_j accounts for salinity regime, and c_k reduces growth rate as the weight at the beginning of the season increases (parameter value in Table 1.3). Shell height was transformed to weight using the following equation:

$$LN(W)=-6.9944+2.53526LN(SH) \quad (5)$$

where W is the weight predicted by the model, LN is the natural logarithm and SH is the predicted shell height (Bosch and Shabman 1990).

Survival

Interval and cumulative survival were calculated using the mean number of spat per shell at each sampling interval. To predict cumulative survival out to the time of harvest for use in the feasibility model, exponential and Weibull survival functions were fit using the observed survival data. A one parameter exponential function is not able to adequately incorporate the large mortality observed during the post-deployment interval and therefore includes an intercept. The exponential model equation is:

$$S_t = S_0 e^{-\lambda t} \quad (6)$$

where S_t is survival at time t, S_0 is survival at time zero, e is the base of natural logarithms, λ is the scale parameter, and t is the age of the oyster. Because of the inability of the exponential function to adequately incorporate the large post-deployment mortality, the Wiebull function was also used. The Wiebull model equation is:

$$S_t = e^{-\lambda t^{\gamma}} \quad (7)$$

where S_t is survival at time t, e is the base of natural logarithms, λ is the scale parameter, and γ is the shape parameter (Wiebull 1951).

RESULTS

Setting

Exploratory frequency distribution analysis was performed on settled spat per shell data using Anderson-Darling (A-D) goodness of fit tests. Prior to analysis, spat per shell data were transformed by adding one to each data point for distribution testing. In 2006, the data best fit a lognormal distribution ($A^2=14.591$, $p<0.005$), though it did not meet the critical value for a lognormal distribution ($A^2=0.752$ at $\alpha=0.05$) (Unless otherwise stated, $\alpha=0.05$). In 2007, the data best fit a Weibull distribution ($A^2=123.594$, $p<0.010$), though they were not substantially different from a lognormal distribution ($A^2=127.675$, $p<0.005$). Similar to 2006, the critical value for the Weibull function was not satisfied ($A^2=0.757$ at $\alpha=0.05$). The combined data set for both years best fit a lognormal distribution ($A^2=121.561$, $p<0.005$) with a Weibull having the second best fit ($A^2=170.260$, $p<0.010$) (Figure 1.2). Despite a non-significant fit to the lognormal distribution, it is the best relative fit. This distribution suggests that there are many more shells with few or no oysters on them than shells with many oysters on them. Given the

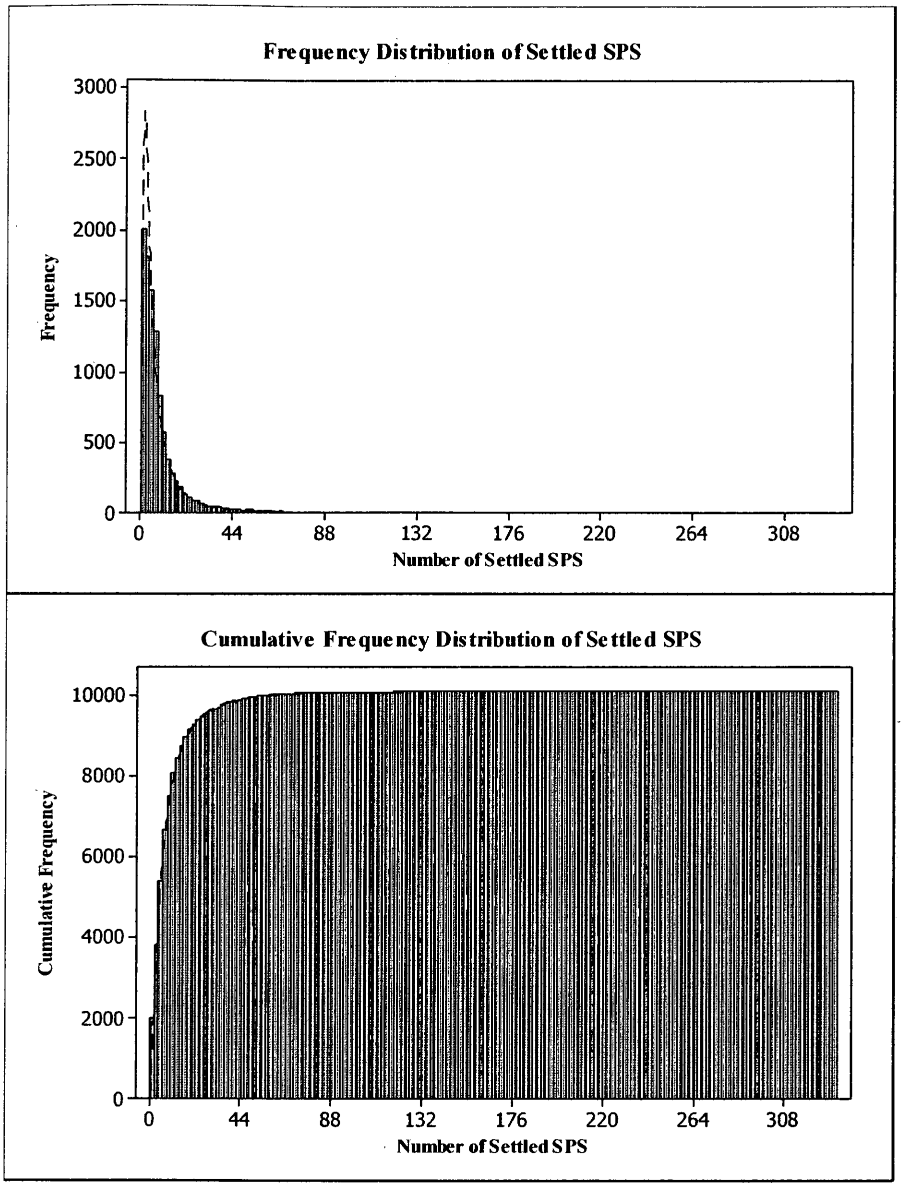


Figure 1.2: Regular (top) and cumulative (bottom) frequency distribution of spat of *C. virginica* per shell at planting. SPS is spat per shell. Plotted data are for all sets at all sites (n=10,109 from 47 sets).

relatively low setting rates observed in this study, this is expected as poor remote sets are characterized by many shells with no spat attached.

Remote setting rate range was large 0-24% with a mean of 7% for both years. Assay setting rate range was also large, 1-80% with a mean of 24% for both years. Mean setting rate in 2006 was 9±6% (mean ± standard deviation, SD) with a 95% confidence interval of ±3%, whereas in 2007 it was lower at 6±3% with a 95% confidence interval of 1% (Figure 1.3). The range among remote setting rates was large, from 1% to 24% in 2006 and 0% to 12% in 2007. Assay setting rates differed significantly between years (t=-2.89, p=.006). In contrast to field setting rate however, assays were higher in 2007 than 2006 with a mean and confidence interval of 18±3% in 2006 and 28±6% in 2007 (Figure 1.3). Assay setting rate ranged from 2% to 35% in 2006 and 1% to 80% in 2007.

There was no significant correlation between assay setting rate and remote setting rate (PPMC=0.068, p=0.656); however, larval cohorts that performed poorly (<5% set) in the setting assay always performed poorly (<5% set) in the respective remote set. Larval cohorts that performed well in the setting assay, however, did not always perform well in the respective remote set (Figure 1.4).

The setting site performance indicator (SPI) was calculated for 2006 and 2007 (Figure 1.5). In 2006, the Urbanna facility performed best (SPI=0.97) while the Lottsburg facility performed worst (SPI=0.06). The best performance in 2006 was coupled with moderate salinity of 15-16ppt. In 2007, the Weems facility performed the best (SPI=0.49) with the Suffolk station performing the worst (SPI = 0.11). As in 2006, the best performance was in moderate salinities, however, this relationship is not as pronounced in 2007.

Regression analysis of the effect of temperature on remote setting rate in 2007 yielded no significant relationship (R^2=0.042, p=0.287. Regression analysis of the effect of salinity on remote setting rate suggests a weak negative relationship (R^2=0.151%, p=0.037) in 2007 (Figure 1.6). In 2006 this relationship was positive, but much weaker and not significant (R^2=0.066, p=0.303).

In 2007, larval shell height was measured as an approximation of larval competency. There was a significant positive correlation between larval shell height and remote setting rate (PPMC=0.502, p=0.008 (Figure 1.7).

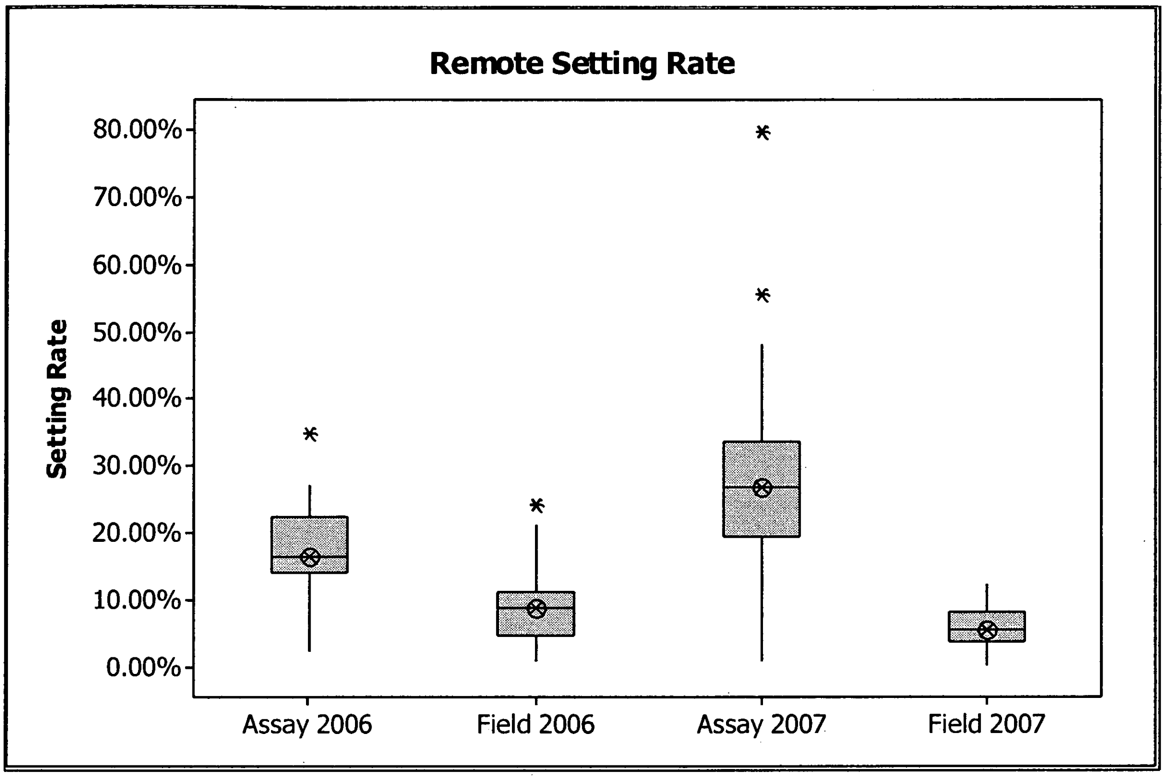


Figure 1.3: Box plot of remote setting rate (Field) and assay setting rate (Assay) of *C. virginica* for 2006 and 2007. Boxes represent interquartile range, symbol inside box is the mean, and whiskers represent range minus any outliers denoted by the asterisks.

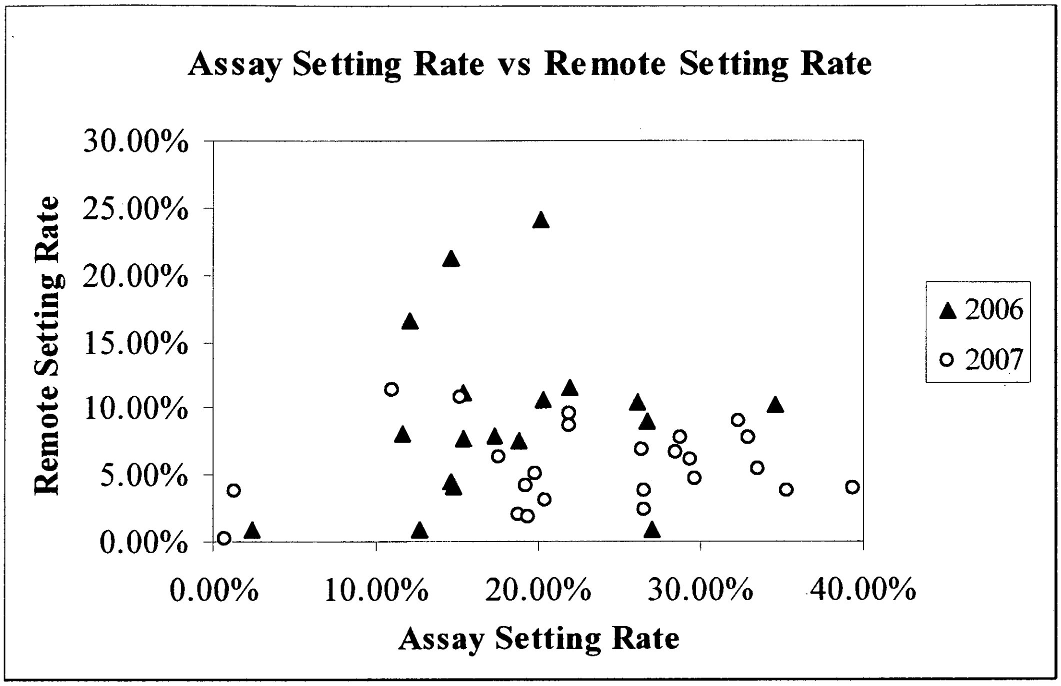


Figure 1.4: Remote setting rate vs. assay setting rate of *C. virginica* for 2006 and 2007.

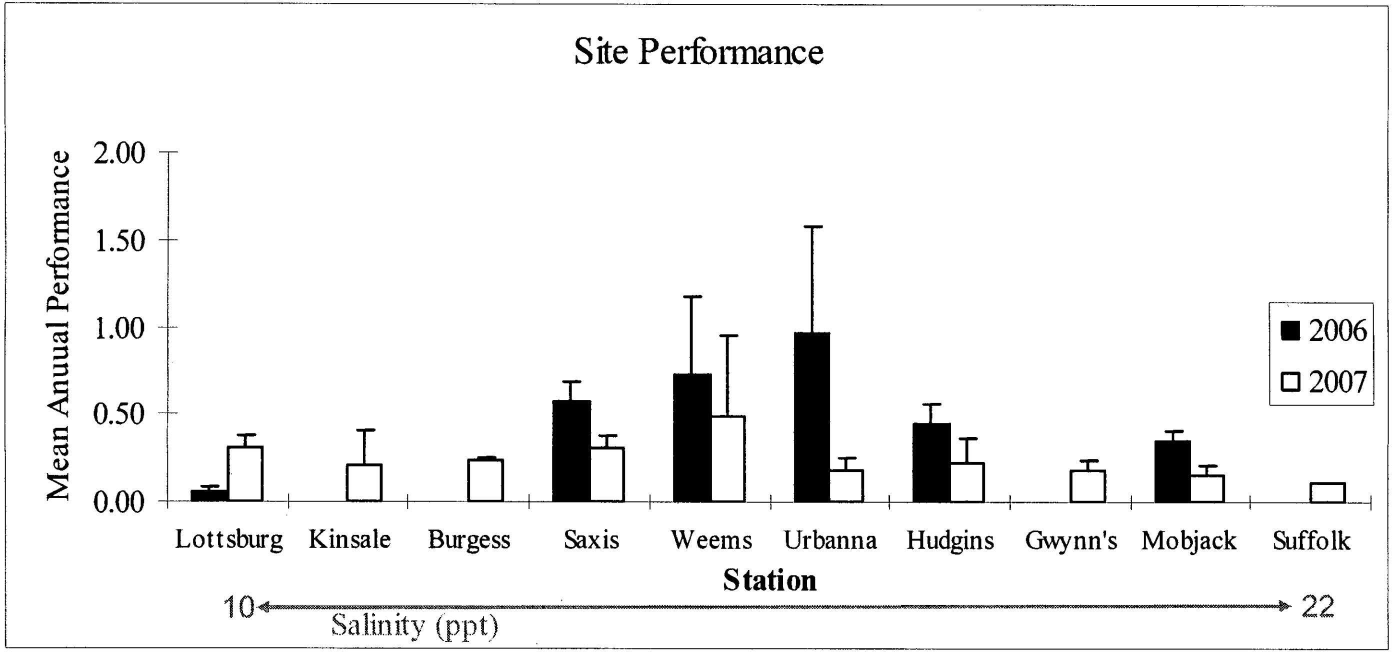


Figure 1.5: Performance indicator by site; calculated by dividing the remote setting rate by the assay setting rate for 2006 and 2007. Sites are ordered left to right based on mean salinity at time of setting. Error bars are standard deviations.

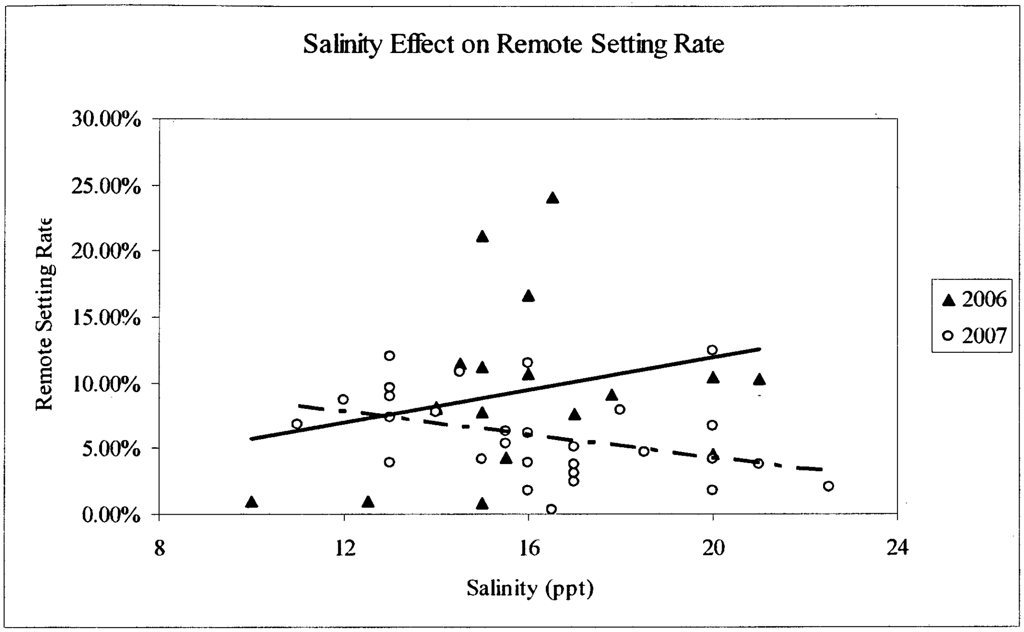


Figure 1.6: Effect of salinity on remote setting rate of *C.virgincia*. Lines represent trends in respective data sets for 2006 (solid line) and 2007 (broken line). In 2006 there was a non-significant, weak, positive relationship between higher salinity at time of setting and higher remote setting rate (R^2=0.07). In 2007 there was a non-significant, weak, negative relationship between higher salinity at time of setting and lower remote setting rate (R^2=0.15).

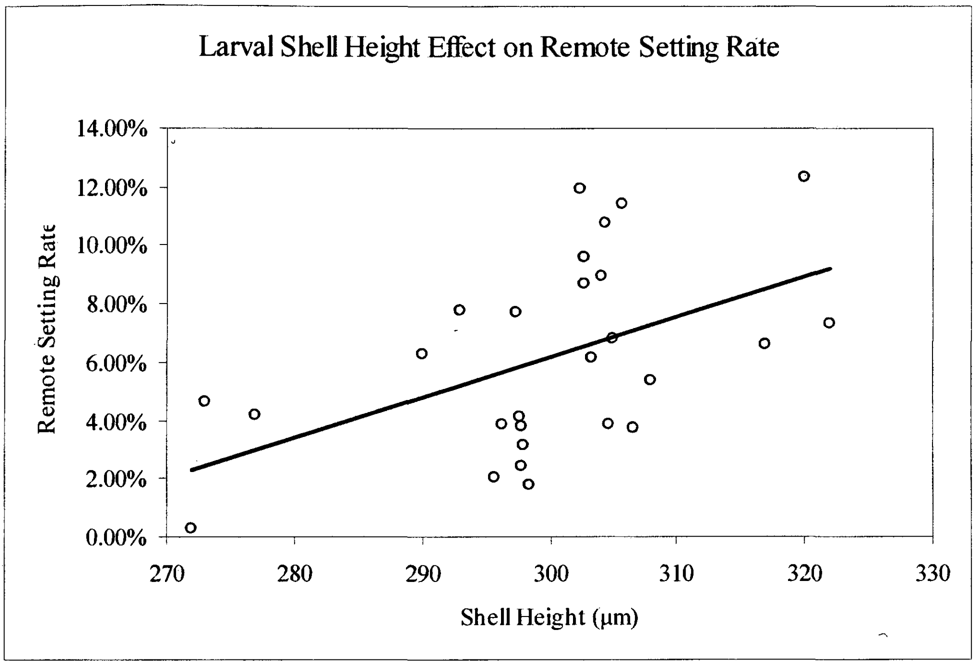


Figure 1.7: Effect of larval shell height on remote setting rate of *C. virignica*. Larval shell height is used here as a proxy for larval competency. Line represents linear trend (R^2=25%). Significance of regression can not be estimated since there is error in the dependent variable. There was however a significant Pearson product moment correlation (0.502, p=0.008).

Growth

Of the six sites where growth was measured, only four were analyzed in depth. Coan River growth was omitted from analysis due to unmatched, fast growth during the period prior to pre-winter sampling (mean growth of 0.30±0.08 [SD] mm per day relative to a mean of 0.16±0.09mm per day across all other sites) followed by extremely slow growth between the pre-winter and one year sampling intervals (mean growth of 0.08±0.01mm per day relative to a mean of 0.13±0.01mm per day across all other sites).

Also omitted was the first planted cohort at Temple Bay. After production of this cohort, set oysters were found to be triploid. Triploid, rather than diploid, larvae were sent to the station by mistake by the hatchery. Interestingly, this triploid cohort had a mean shell height more than 10mm greater after one year than the mean of the other two cohorts (~55mm) planted on the same ground. Note that the triploid cohort was planted first and may have gained some growth advantage as a result.

Ware River growth data were omitted from certain analyses due to the lack of data at year one. Sometime after the pre-winter sampling interval, the sampling cages were buried by shifting sediments, destroying the oysters contained within.

Mean shell height of all planted cohorts was between 1mm and 6mm at the time of planting. By one year mean shell height for all planted cohorts was 50mm with a range of 47mm to 58mm (Figure 1.8). Mean growth rate was measured as millimeters of growth per day across the four sampling intervals and across all sites (Figure 1.9). There was no significant difference in growth rate among sites and therefore shell height–at-age analysis was performed on the combined data set.

Shell height at age analysis was performed using the von Bertalanffy (1938) model. The Porch et al. (2002) model was also attempted because of its ability to accommodate change in k (the rate at which the organism approaches its maximum or asymptotic size) and its ability to account for seasonally dependent growth, both of which make it an exceptional candidate for use on oyster growth. However, there was limited

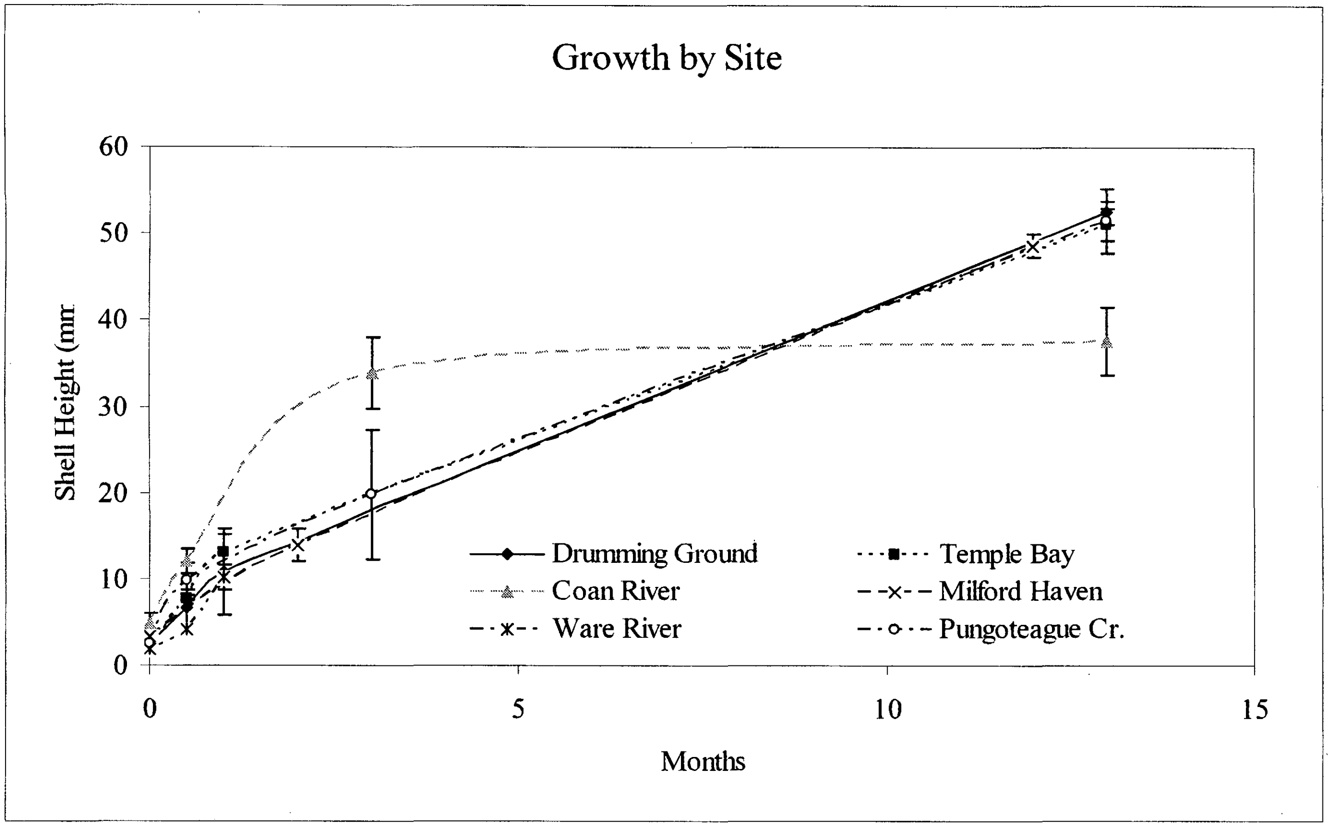


Figure 1.8: Mean shell height of all planted cohorts for each site at each of the four sampling intervals. Sampling intervals were as follows: planting, post-deployment (1-2 weeks after planting), pre-winter (2-3 months after planting), and one year (aproximately 13 months after planting). Cohorts were planted at various times throughout the summer of 2006, but here, the x-axis is age, not time, and therefore all curves begin at zero. Error bars are standard error.

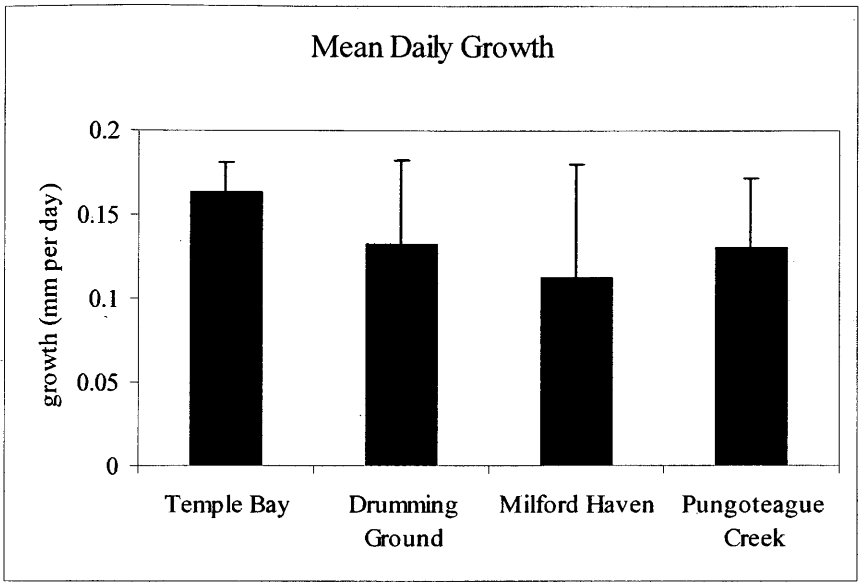


Figure 1.9: Mean daily growth of oysters at sites with complete (planting to one year) data sets. Data sets with missing or suspect data (incomplete data sets) were excluded from this analysis. There was no significant difference in growth rate among sites. Error bars are standard deviation.

data for shell height in older age classes and, therefore, data were insufficient for estimating Porch parameters with confidence. Truncated age distribution (lack of old, large animals), also confounds the von Bertalanffy (1938) estimation because the predicted maximum size (L_∞) relies heavily on the oldest animals within the data set. Using the combined data set, estimated von Bertalanffy parameters were: L_∞=66.93±5.78 (parameter estimate ± standard error), k=1.44±0.29, t_0=0.048±0.01 (R^2=96.2%) and are plotted in Figure 1.10. Estimates are unrealistic however, as L_∞ is ten millimeters shy of even a market size animal (76mm).

A linear model was also used to estimate shell height at age analysis. The linear model can be considered a high estimate, as it does not accommodate any slowing in growth rate with age. Using the combined data set, estimated linear parameters were: m=45.18±0.99 and a_0=0.99±0.52 (R^2=97.5%) and are plotted in Figure 1.11. This model suggests a planted cohort would reach mean market size in one year and eight months. The mean shell height at two years of age would be approximately 90mm relative to the von Bertalanffys prediction of approximately 60mm. The true mean size at age two likely falls between these two estimates.

The Bosch and Shabman (1990) model was adapted to fit the planting time, size, and salinity regime of the observed data. Parameter values are displayed in table 1.3. Planting time was set to be July 1 for all cohorts. The model does not have c_k parameter values for oysters weighing less than 3.0g or less than 24mm in shell height, but mean starting shell height here is 3mm. To account for this a larger c_k value was used that allowed the growth curve to follow observed data below 24mm shell height. The parameter value used when shell height was less than 24mm was c_k=10.82. It was also necessary to increase b_j (0.7) beyond that which was suggested for salinities greater than 13ppt (0.595) in order to adequately fit the observed data. While in this case the observed data were not used statistically to estimate the parameters of the Bosch and Shabman function, it was developed in the Virginia portion of Chesapeake Bay for wild caught seed, which approximates conditions for spat-on-shell. Predicted growth using this function, given the parameters described above is displayed in figure 1.12.

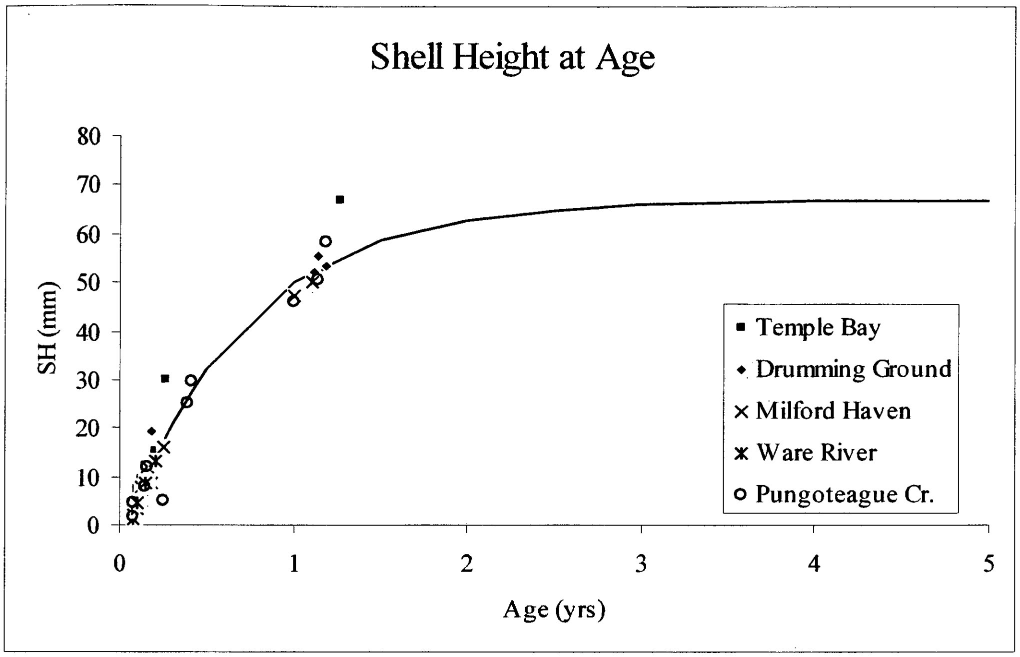


Figure 1.10: Von Bertalanffy shell height-at-age curve for all sites combined. Shell height is predicted to 5 years. Parameter estimates ±SE: L_∞=66.93±5.78, k=1.44±0.29, t_0=0.048±0.01 (R^2=96.2%).

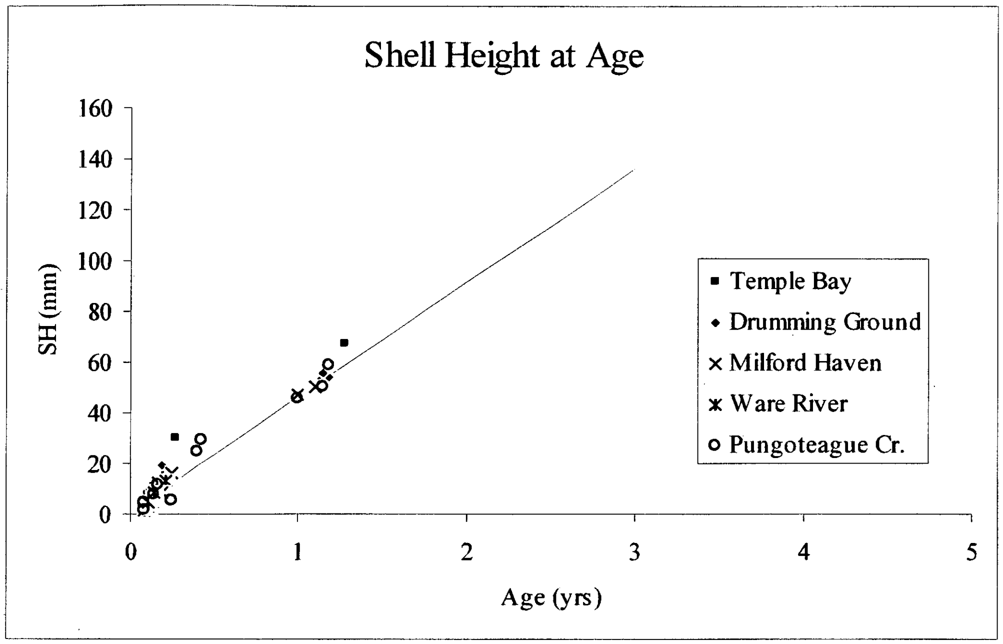


Figure 1.11: Linear shell height at age estimation, predicted to 3 years. This is assumed to be an over-prediction as it is not plausible to assume linear growth to age 3. Parameter estimates ±SE: m=45.18±0.99 and a_0=0.99±0.52 (R^2=97.5%).

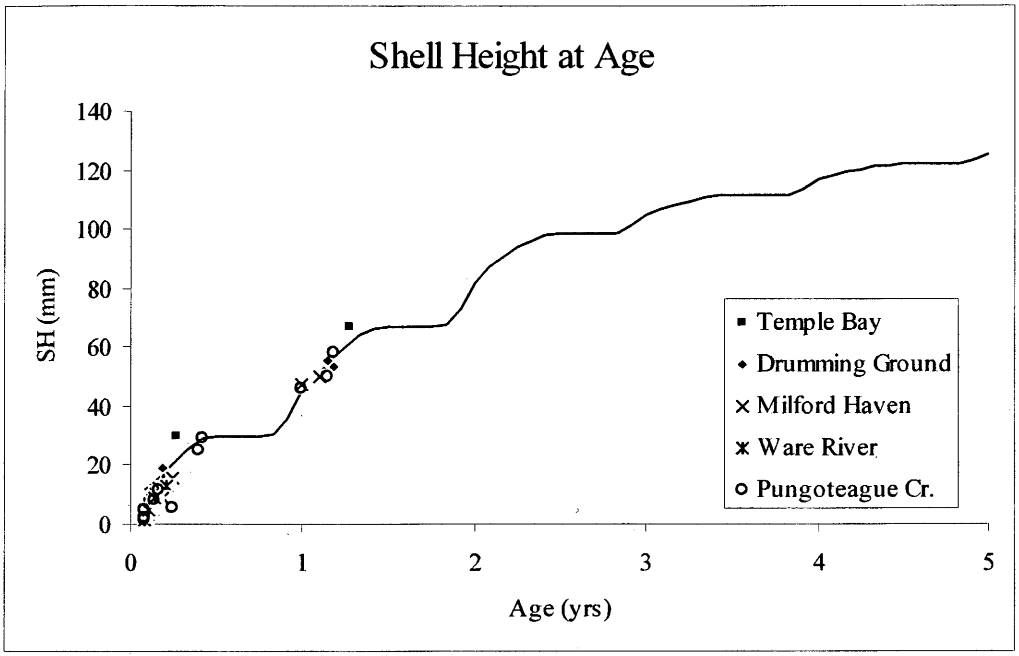


Figure 1.12: Bosch and Shabman growth curve parameterized to fit observed growth data. Parameter values were used as defined by Table 1.3. c_k=10.82 was used for animals less than 3 grams.

Table 1.3. Parameter tables from Bosch and Shabman 1990 for use in the growth model derived in figure 1.12. Weight is grams wet weight.

Month	**Parameter value (a_i)**
January	0
Febuary	0
March	0
April	0.021
May	0.221
June	0.323
July	0.178
August	0.108
September	0.106
October	0.077
November	0.052
December	0.012

Weight	**Annual Growth Rate (c_k)**
3.0-4.9	2.82
5.0-9.99	2.32
10.0-19.99	1.82
20.0-29.99	1.4
30.0-39.99	1.11
40.0-49.99	0.83
50.0-59.99	0.75
60.0-69.99	0.62
70.0-79.99	0.54
80.0-89.99	0.41
≥90.0	0.36

Survival

Interval and cumulative survival were measured at each of the 2006 plant sites with the exception the Ware River, for which data only exists until the pre-winter sample when sampling cages were buried. Post-deployment survival (PDS) was important because at times it was low. Mean PDS was measured in 2006 and 2007 with a combined mean of 62±29% (±SD). PDS was highly variable both within and among sites and ranged from greater than 100% (obviously a result of sampling error) to 1%. There was a substantial, though non-significant difference between mean PDS in 2006 (41±21%) and in 2007 (74±26%).

Mean cumulative survival across sites was modeled using exponential and Weibull functions (Figure 1.13). Parameter estimates for the exponential function were $s_0=0.41\pm0.11$ and $-\lambda=0.44\pm0.01$ (±SE) with $R^2=0.13$. The Weibull function more accurately fit the data ($R^2=0.80$) due to its ability to accommodate low survival during the post-deployment interval. Weibull parameter estimates are $\lambda=0.67\pm0.14$ and $\gamma=0.12\pm0.05$. The Weibull model was also used to estimate site specific cumulative survival for all sites. Site specific Weibull parameter estimates and R^2 values can be found in Table 1.4 and are plotted in Figure 1.14. Whereas growth did not vary greatly among sites, site specific Weibull estimates for survival do.

Initial observations of the data suggested that survival was related to spat density, and exhibited density dependent survival to one year. Specifically, although counts of spat per shell were highly variable at planting, spat per shell at one year was similar across all sites (Figure 1.15). Lower survival was found to be significantly correlated ($\alpha=0.1$) to higher planting density per shell (-0.469, $p=0.09$). To evaluate the possibility of density dependence, mean oysters per shell at one year was plotted against mean spat per shell at planting (Figure 1.16). If survival was density independent a linear function with a y-intercept near zero would have the best fit; however, the best fit for the complete data set is a logarithmic function ($R^2=0.54$, linear function: $R^2=0.44$), suggesting that plantings with low density of spat per shell have disproportionately higher survival than those with high density at planting. The Rappahannock River (Drumming Ground and Temple Bay) plantings were assessed separately with the most appropriate fit a linear function with a y-intercept of 4.07 ($R^2=0.05$, or 0.85 after removal of a single

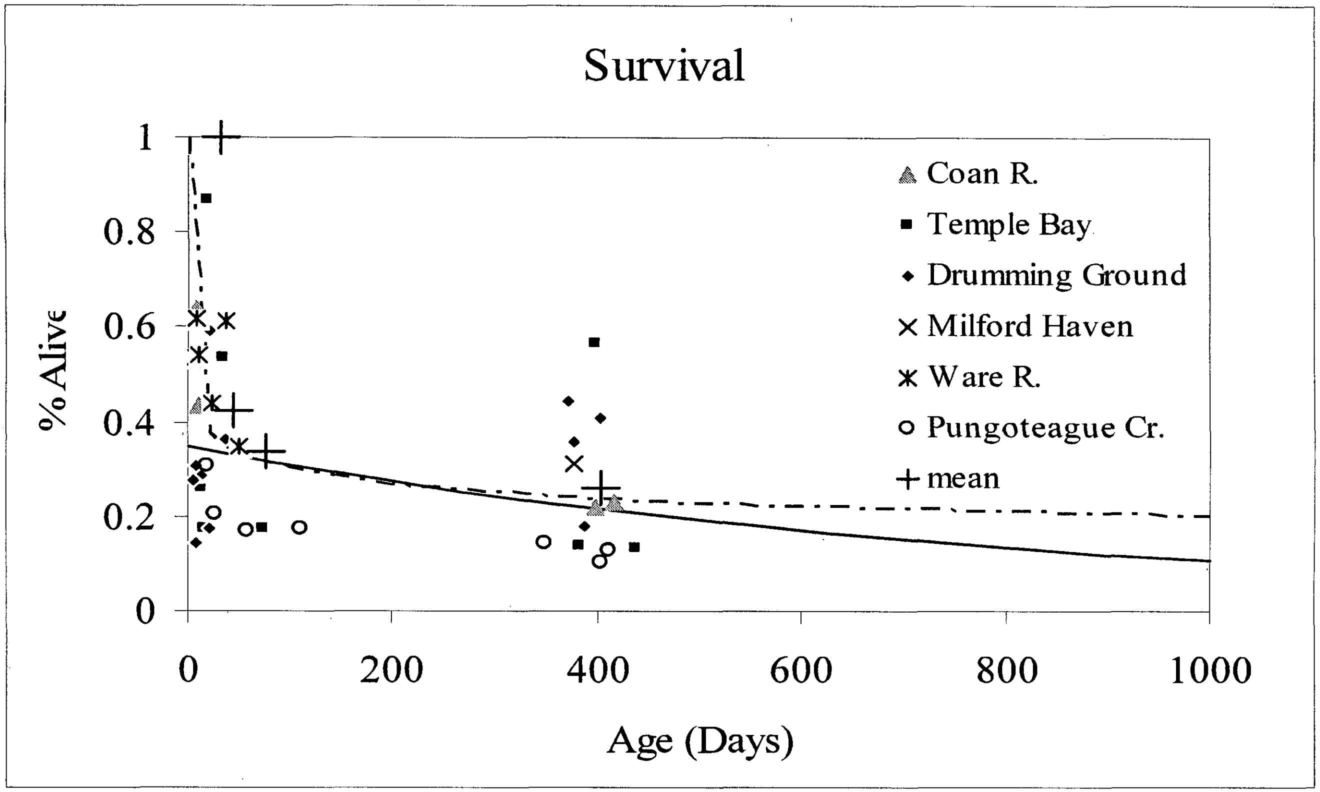


Figure 1.13: Survival data was used to estimate an exponential function (solid line) and a Weibull (broken line) function for all sites and predict survival to 1000 days in age. Exponential parameter estimates ±SE: $s_0=0.41\pm0.11$ and $-\lambda=0.44\pm0.01$ ($R^2=13\%$). Weibull parameter estimate ±SE: $-\lambda=0.67\pm0.14$ and $\gamma=0.12\pm0.05$ ($R^2=80\%$). Exponential predicts 12% survival at 30 months. Weibull predicts 21% survival at 30 months.

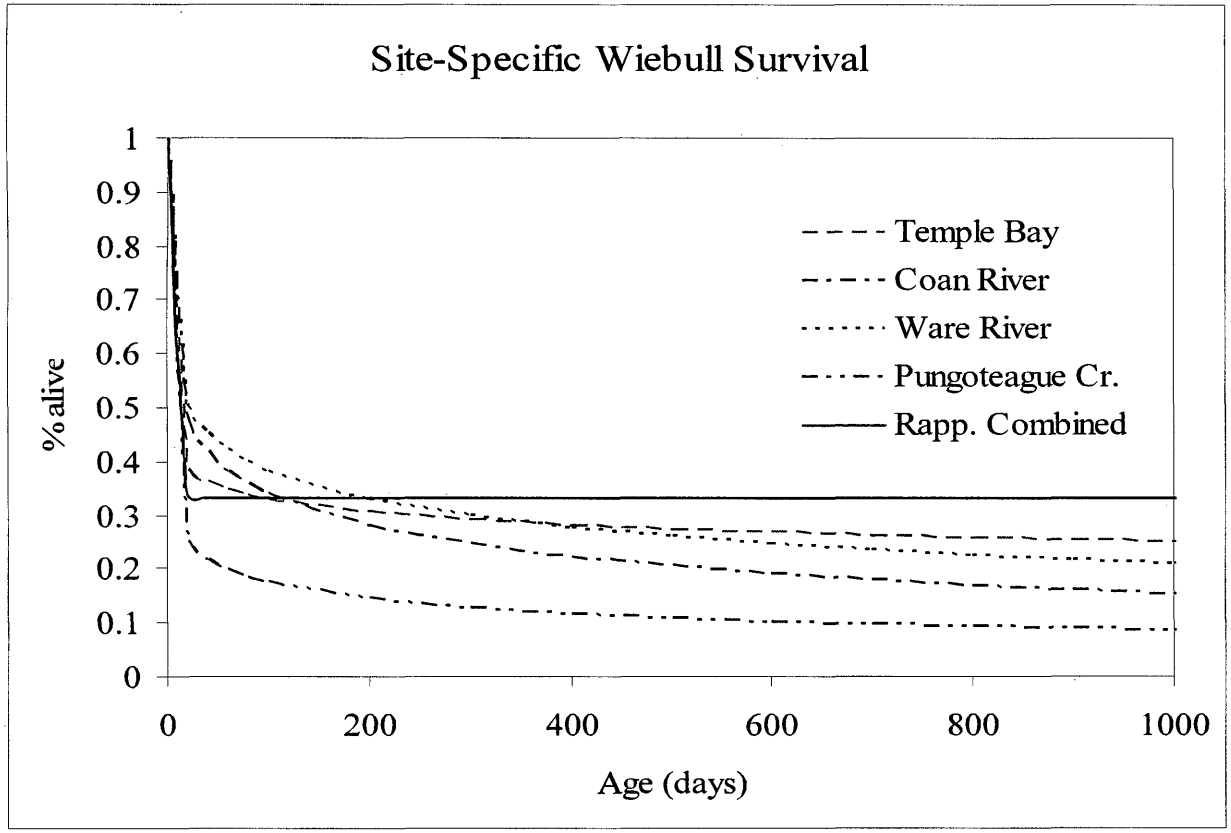


Figure 1.14: Weibull survival estimation for all sites individually and predicted to 1000 days in age. Drumming Ground is excluded because parameters would not converge. Rapp. Combined includes cohorts planted at both Drumming Ground and Temple Bay.

Table 1.4: Weibull parameter estimates for curves displayed in Figure 1.14, standard errors and R^2 for each site individually.

Plant Site	λ	λ **SE**	γ	γ **SE**	R^2
Temple Bay	0.7143	0.4440	0.0960	0.1454	66.59%
Coan R.	0.3635	0.0950	0.2375	0.0576	97.51%
Drumming Ground	did not converge ------------------------------------				
Ware R.	0.3652	0.1373	0.2103	0.1254	92.92%
Pungoteague Cr.	0.8813	0.1146	0.1488	0.0288	99.71%
Rappohanock R. (Temple Bay and Drumming Ground)	1.0902	0.2958	0.0020	0.0642	76.85%

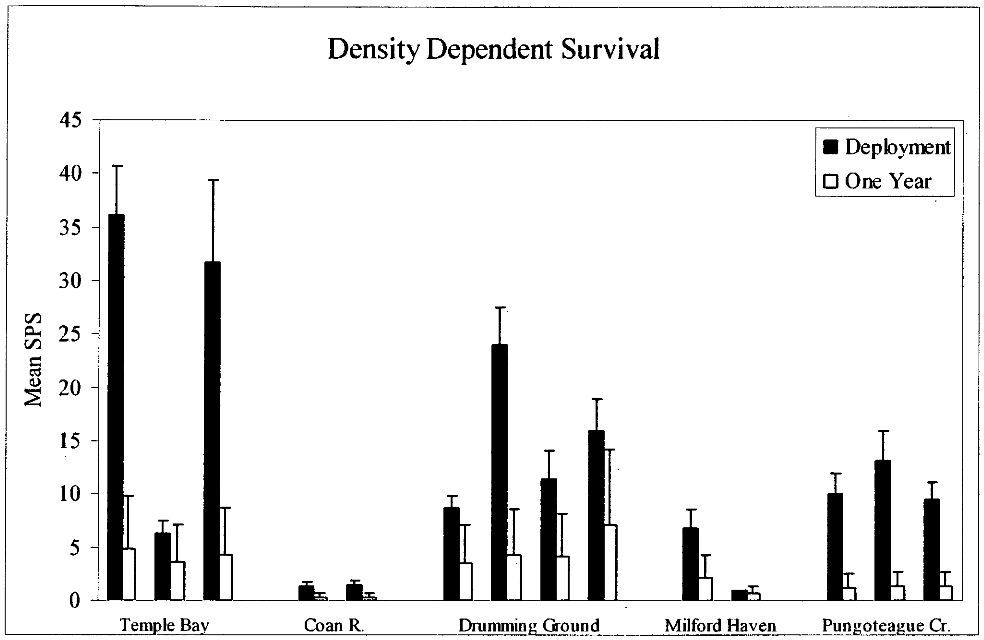


Figure 1.15: Mean number of spat per shell at planting and at one year sampling intervals. Survival is low on shells where spat density is high. Data are for the 2006 cohort. Error bars are one standard deviation.

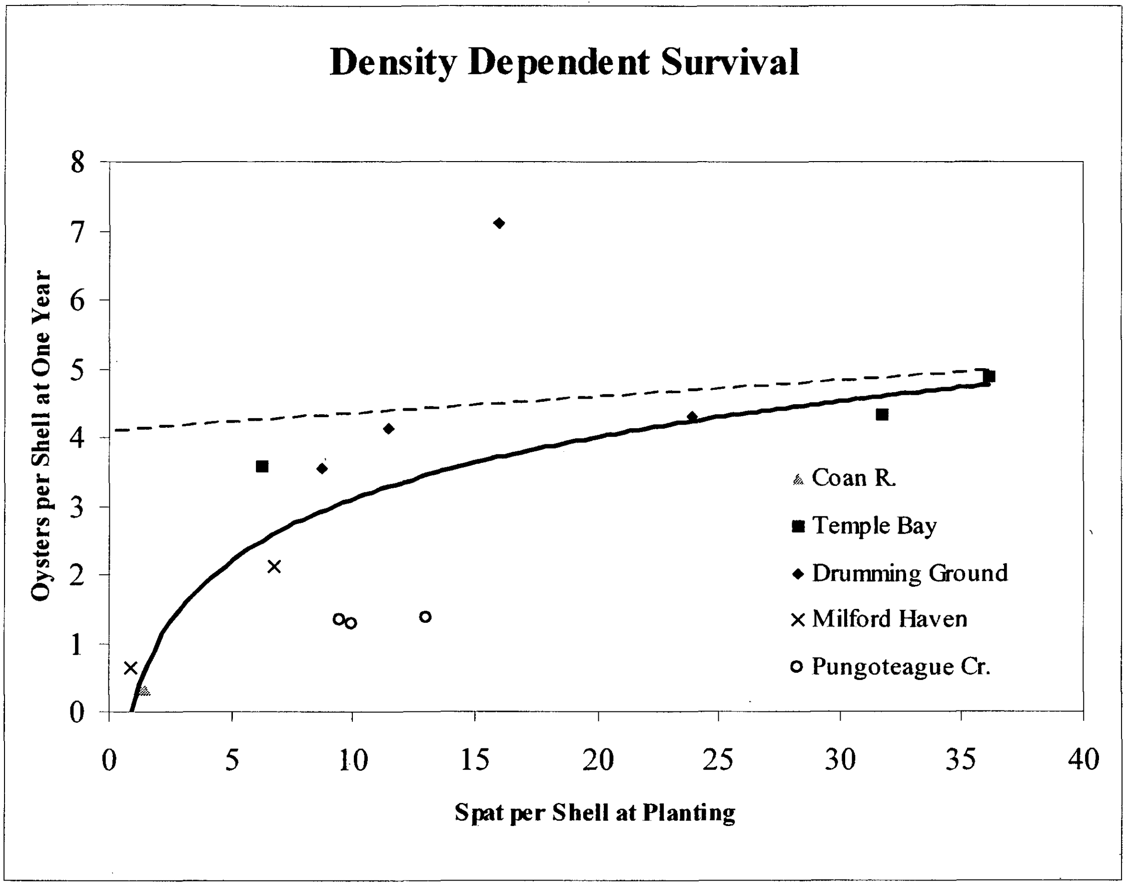


Figure 1.16: Oysters per shell at one year vs. spat per shell at planting. The solid line is a logarithmic function fit to all sites combined (R^2=53%). The broken line is a linear function fit to Temple Bay and Drumming Ground only, both located in the Rappahannock River (R^2=5%, 85% without the outlier). Data are for the 2006 cohort.

outlier). A non-zero y-intercept and minimal slope (0.02) suggest that an increase in spat per shell at deployment does not translate to an equal increase in oyster per shell at one year, and therefore survival is lower with higher spat per shell densities at planting. The observed data for the Pungoteauge Creek follows a similar trend as the Rappahannock. In summary, the inability of these data to fit a linear function with a near zero intercept, suggests that survival of spat-on-shell to one year may by dependent on inter-shell density (i.e. the density of spat on a single shell) with higher survival associated with lower inter-shell density. This relationship may be the result of an underling adult-size, inter-shell carrying capacity that is approached with age.

DISCUSSION

Setting

Remote setting rate was highly variable. The mean for remote setting rates observed in this study was 7%±5% (SD), ranging from 0%-24%. Mean remote setting rate for *C. gigas* generally falls in the range of 15-25% (Jones and Jones 1988, Nosho and Chew 1991, Henderson 1983). Mean remote setting rate for *C. virginica* at a small setting facility in New Hampshire for one year was 16.65% (Greene and Grizzle 2005). The University of Maryland's Horn Point Laboratory has a large scale *C. virginica* remote setting operation in Cambridge Maryland, which had a mean remote setting rate of approximately 8% in 2006 and 14% in 2007, but greater than 20% in 2008 (Tobash-Alexander unpublished data). Clearly, greater success is possible with *C. virginica* but currently remains low for Virginia.

An unpublished study completed at the University of Maryland's Horn Point Laboratory oyster hatchery facility suggests that spat-on-shell counted without microscopic aid at sizes smaller than 3-4mm is subject to significant error (Don Meritt, Hatchery Program Director, Univ. of MD, pers. comm.). In some cases, three times as many spat were counted with the use of a microscope as were counted using the nakedeye. In light of this recent study it is possible that enumeration of spat per shell at planting was underestimated. This would mean that survival values are also lower than the true value. This however does not affect the feasibility conclusions drawn in the next section, and suggests that remote setting rate in Virginia may be higher than is reported here.

Frequency distribution of spat per shell most closely resembled a log normal distribution (Figure 1.2). This is due to the high frequency of shells with few spat per shell and relatively infrequent occurrences of high numbers of spat per shell. Jones and Jones (1988) report frequency of a typical set of *C. gigas* as 7% of shells with 0-5 spat, 14% with 6-10, 26% with 11-20, 40% with 21-60, and 13% with greater than 61 spat per shell. This is certainly not typical of sets observed in this study where 47% of shells had 0-5 spat, 21% had 6-10, 16% had 11-20, 15% had 21-60 and 1% had greater than 61 spat per shell.

Low assay setting rate (<5% set) was able to predict low remote setting rate (<5% set), however, high assay setting rate was not able to predict high remote setting rate. The assay setting rate was, however useful in assessing relative site performance. The setting performance indicator (SPI), measured how the remote setting rate at any given station compared to the assay setting rate of larvae used. This was useful in comparing performance of sites despite variation in the performance among larval cohorts. While the variation in remote setting rate across sites made it impossible to discern any significant patterns, there was a tendency toward higher site performance at medium salinities around 15ppt, particularly in 2006 (Figure 1.5). Larvae produced came from hatcheries with salinity generally between 15ppt and 20ppt and therefore the increased success at medium salinities may be due to reduced osmotic shock of larvae set there.

In 2007, mean shell height of eyed larvae at the time of setting was measured for each larval cohort. This measure was used as a practical proxy for competence. This is the measure used in hatcheries to manage "harvest" of eyed larvae, typically by employing a particular screen size corresponding to a particular shell height to harvest larvae from the culture. In the case of *C. virginica* in Chesapeake Bay this is often a 212μm screen for diploid larvae which translates to retention of larvae exceeding 300μm shell height. The mean shell height of larvae set in 2007 was 299.7μm. There was a significant positive correlation between larval shell height and remote setting rate (Pearson Product Moment Correlation (PPMC)=0.502, p=0.008 (Figure 1.7) suggesting that competency as assessed by size is important to remote setting rate and larger larvae generally set at higher rates. In all cases where mean larval shell height was below 300μm, remote setting rate was below 8%. This underscores the importance of producing healthy, highly competent eyed larvae for remote setting to obtain consistently high remote setting rates.

Growth

Growth observed in this study fell within the range reported by other growth studies in Chesapeake Bay. Four studies were compared to the data in this study, including two from the Maryland portion of the Chesapeake Bay (Rothschild et al. 1994 and Coakley 2004), one from the Mexican portion of the Gulf of Mexico (Cardenas and Arandas 2007), and one study similar to this study, where triploid spat-on-shell produced via remote setting were grown out in an area very near the station 1 plant site in the Yecomico R. (Southworth et al. in prep). Growth observed in this study falls somewhere in the middle with faster growth than the two Maryland studies and slower growth than the Gulf of Mexico and triploid studies. It is expected that growth estimates in Maryland are reduced by lower salinity and a shortened growing season compared to Virginia, and growth is faster in the Gulf of Mexico due to higher salinity and an extended growing season. Faster growth also is expected in triploids spat because of inherently faster growth in triploid oysters (Allen and Downing 1986, Shpigel et al. 1992, Frank-Lawale, ABC in prep). Figure 1.17 compares these functions to the linear, von Bertalanffy and Bosch and Shabman functions derived from this study. Linear models (Southworth et.al and this study) are truncated as it is nonsensical to assume linear growth of oysters over a five year time period. The Southworth et al. linear model is truncated at 1.5 years as this is when sampling stopped. The linear model from this study is truncated at two years, and even then is likely to be an overestimate of shell height at age two.

From the growth analyses performed in this study, and compared to the models above, spat-on-shell planted in 2006 is likely to reach harvestable size in two and a half years or three growing seasons. This estimate is based on the mean shell height of a harvestable cohort being approximately 90mm. Legal harvest size of oysters in Chesapeake Bay is three inches or 76mm, however, a planted cohort of spat-on-shell, with a mean shell height of 76mm, consists of roughly only 50% of market size oysters assuming a normal distribution of shell heights. By considering 90mm the mean size at which a cohort is deemed harvestable, given a standard deviation of 17mm at least 80% of that cohort is market size, at SD=11mm, 90% of that cohort is market size.

The possibility exists to harvest from a planted cohort multiple times and only taking the market size animals each time. In this scenario, a producer could likely harvest approximately 25% of a cohort at the end of the second growing season or one and a half years given a mean of 68±12mm (±SD) assuming a normal distribution. At two years assuming a mean of 80±14mm another 37% would be market size, and at 2.5 years assuming a mean of 90±17mm another 18% would be market size leaving approximately 20% still on bottom. In this hypothetical scenario standard deviation is made to increase with time assuming that the spread of the distribution increases over time. These calculations do not however, account for mortality throughout grow-out or affects from multiple harvests.

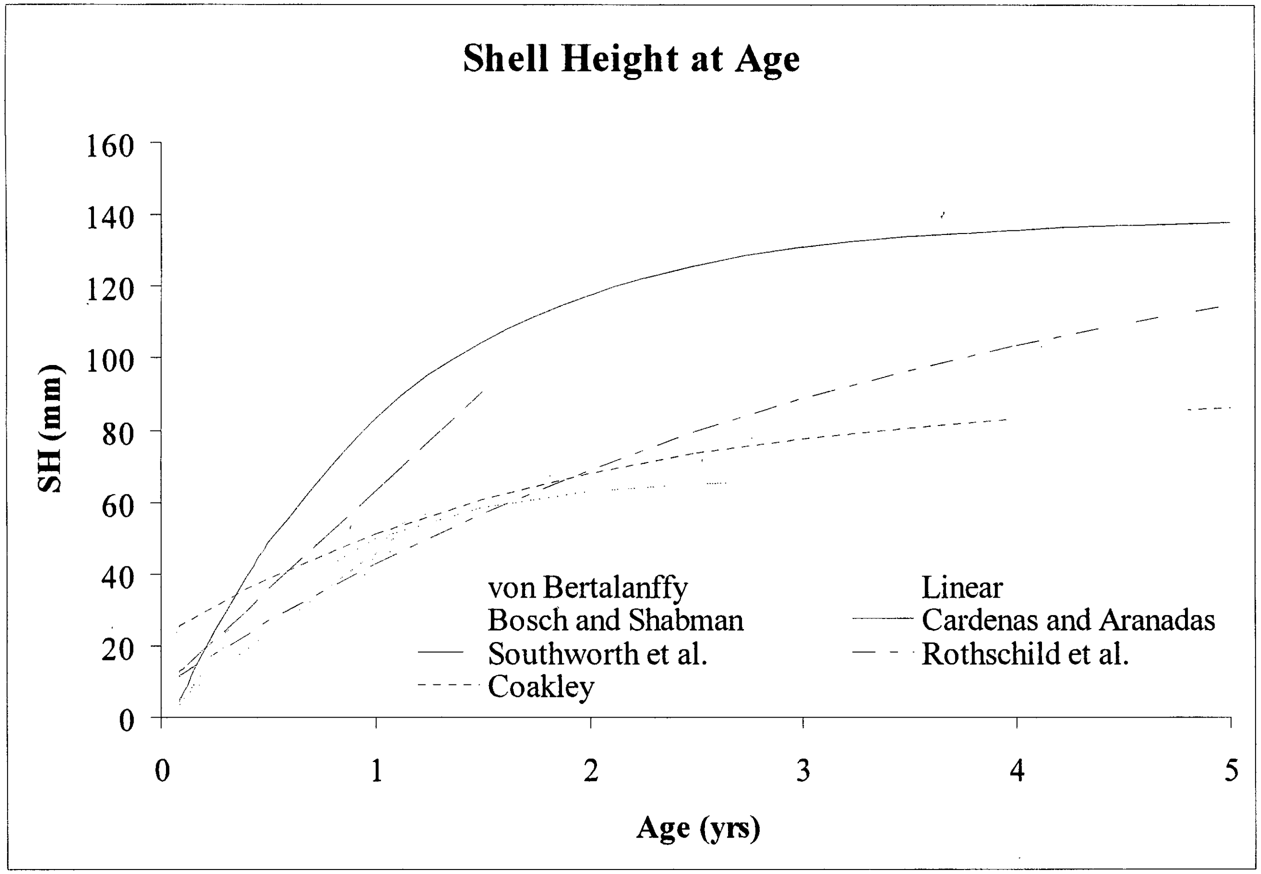


Figure 1.17: Shell height-at-age models from this study and others including Cardenas and Aranadas (2007), Southworth et al. (In Prep), Rothschild et al (1994), and Coakley (2004). Parameter estimates: Cardenas and Aranda (L_∞=139, k=0.96, t_0=0.05), Southworth et al (m=55.13, a_0=7.85), Rothschild et al. (L_∞=150, k=0.28, t_0=-0.2), Coakley (L_∞=90.85, k=0.55, t_0=-0.51).

Survival

Post-deployment survival (PDS), measured at 1-2 weeks after planting was significant with a project mean of 63%. One week survival reported in the literature for spat attached to shell ranges from 0-64% (Roegner 1991, Roegner and Mann 1995, Newell 2000, Wallace et al. 1999, Southworth et al. in prep). Note that survival is subject to the accuracy of initial spat- per-shell counts and may be have been underestimated as discussed previously.

Survival at post-deployment is critical in that it has a disproportionately large affect on cumulative survival. There was a substantial, though not statistically significant difference in mean PDS in 2006 (41%) relative to 2007 (74%). This was at first assumed to be density dependent survival where the higher mean number of spat per shell in 2006 (12.5) had a negative effect on survival, which was subsequently relaxed in 2007 given the lower mean number of planted spat per shell (5.7). If the mean number of spat per shell at the post-deployment sampling interval is plotted versus the mean number of spat per shell at planting however, data sets for both years best fit a linear function with a y-intercept near zero suggesting that they are encountering differing survival in respective years, but without any density dependent effect (Figure 1.18). A more plausible explanation may be the change in planting sites between years (Figure 1.1). All planting sites, with the exception of the Nansemond R. site (at which only one cohort was planted) were located further north in 2007. The more northern, lower salinity plant sites may have incurred less xanthid crab predation as these planting areas are approaching the xanthid lower salinity limit of 10ppt (Schwartz and Cargo 1960). There is no reason however to suggest that *S. ellipticus* and *C. sapidus* should be present in dissimilar densities relative to that at the 2006 sites.

Cumulative survival was predicted using the Weibull function. When data from spat per shell at one year was plotted on oysters per shell at one year, each site seemed to be following an independent trajectory and therefore survival was also predicted using the Weibull function for each site separately (Figure 1.14). The variation among sites was used to obtain a mean and range of survival at market size. At two and a half years,

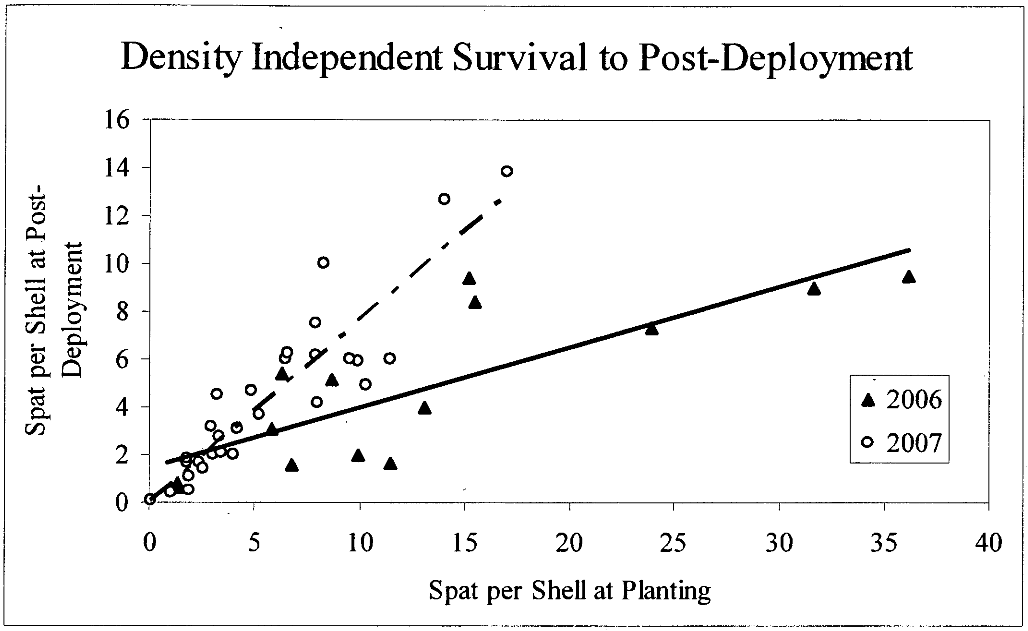


Figure 1.18: Density independent survival to 1-2 weeks of age for all planted cohorts. Solid trend line is for 2006, broken trend line is for 2007. Because linear functions intercept the y-axis near zero, survival is density independent.

or three growing seasons, predicted cumulative survival of planted spat-on-shell ranged from 33.0% in the Rappahannock R. to 8.8% in Pungoteague Cr. with a mean of 21.0%. Southworth et al. (in prep) observed 25% survival of 16 month old triploid spat-on-shell in the Yecomico River. Bosch and Shabman (1990) estimated survival for wild seed planted in the Virginia portion of Chesapeake Bay at 14% in the 1960s, 16% in the 70s, and 19% in the 80s.

Density dependent survival to one year was examined after observation of similar counts of spat per shell at one year with very dissimilar spat per shell counts at planting (Figure 1.15). For example, considering just those cohorts planted in the Rappahannock R. (Temple Bay and Drumming Ground, n=7), mean spat per shell (±SD) at planting was 19.1±11.6, whereas mean spat per shell at one year was 4.5±1.2. Notice in particular, the disproportionately lower standard deviation in the one year mean compared to the planting mean suggesting that there may be an underlying carrying capacity of oysters per shell that is being approached. This may not necessarily be a specific carrying capacity in terms of individuals per shell, but may vary negatively with increasing biomass upon a single shell.

It is apparent that sites are experiencing differential survival. Figure 1.16 plots oysters per shell at one year on spat per shell at planting. Particularly interesting are the cohorts planted in the Rappahannock R. and Pungoteague Cr., which appear to be incurring density dependent survival. If survival was density independent, points would fall on a straight line with an intercept near zero. This is not the case for the Rappahannock R. or Pungoteague Cr. data which plot along nearly horizontal lines with non-zero intercepts and depict similar inter-shell spat density at one year whether inter-shell spat density was high or low at the time of planting. Therefore, survival is density dependent with higher survival associated with lower initial (planting) density. This is important to the economics of remote setting in that using more larvae to set more oysters per shell may actually be disadvantageous as with higher number of oysters per shell comes lower survival and therefore proportionally less resulting spat for the money spent.

CONCLUSION

Remote setting rate was highly variable with a range of 0-24% and a mean of 7%. Of those factors measured that affect remote setting, competency (by proxy of shell height of eyed larvae) was the most highly correlated. The availability of large quantities of highly competent eyed larvae will be essential to high and consistent remote setting rate.

Grow-out of oysters to market size oysters (>76mm) of about 80% of a planted cohort was estimated to be approximately 30 months for diploid spat-on-shell. As an alternative to harvesting an entire cohort at one time, market size oysters could likely be harvested according to the following schedule: 25% at 18 months, 37% at 24 months, and 18% at 30 months for a total of 80% harvested by 30 months. Growth to one year did not vary significantly among sites.

Estimates of survival to market size did vary among sites with a range of 8-30% and a mean of 21% across all sites. Post-deployment mortality was often high with a project mean of 64% and a range of 14% to greater than 100% (assumed sampling error). There was a non-significant difference in post deployment survival with a mean in 2006 of 42% relative to a mean of 74% in 2007. Density dependent survival is suspected in at least the Drumming Ground, Temple Bay, and Pungoteague Creek planting sites where higher spat per shell densities at planting was correlated with lower survival to one year. In addition, despite very dissimilar densities of spat per shell at planting among cohorts, densities of oysters per shell among cohorts at one year were very similar suggesting possible site-specific carrying capacity of oysters per shell.

If the results of this study are typical for other years and places, then remote culture is possible in Virginia. The next step is to assess whether remote culture is economically feasible given the constraints imposed by the biology.

FUTURE WORK (pertaining to the biology of remote setting)

While this study has shed light on the possibility of remote culture as an oyster production method in Virginia, it has also raised several questions that warrant attention. First, the variable nature of remote setting rate adds risk to the prospects of remote setting as a private venture. Hatcheries producing larvae for the purpose of remote setting must be able to produce, with consistency, highly competent eyed larvae. Once there is a large and consistent supply of highly competent larvae, experimentation focusing on other aspects of the process (at the level of the setting facility) can be manipulated to optimize production. Treatment of larvae or the addition of some settlement cue to the setting tanks are good starting points for this research. For example, cultchless oyster production often utilizes a chemical treatment (epinephrine bath) of larvae to increase the setting rate of oysters produced as singles (Coon et al. 1986). This treatment is not applicable to spat-on-shell because it triggers metamorphosis without settlement behavior and therefore may result in spat not attached to shell. The use of L-dopa however, has been shown to induce settlement only, with subsequent metamorphosis when adequate substrate is present (Bonar et al. 1990). This larval treatment has been shown to increase remote setting rate by as much as 20% (Nosho and Chew 1991).

Post-deployment mortality is the second most significant loss of oysters produced for spat-on-shell; however, relatively little is known about what is causing this mortality. Studies addressing this point would be beneficial to producers so that they could work at maximizing survival during those first few weeks following planting. For example, in this study higher survival was observed on plant sites located further north in less saline waters. In this less saline water, two of the three primary small oyster predators (*S. ellipticus* and *C. sapidus*) should still be present in similar quantities to the more saline waters. Xanthid crabs, however, may be limited by lower salinity at the 2007 sites suggesting that xanthid crab predation may control post-deployment mortality. There is also the question of handling of spat-on-shell between removal from the setting tanks and planting on the grow-out site and what affect, if any, this has on post-deployment survival.

Although there is some information concerning the use of a nursery for spat-on-shell (Wallace et al. 1999, Dr. Don Merritt University of Maryland, Horn Point Laboratory., Jones and Jones 1988), this has not been done in Virginia, and considering the high variation in survival across sites, it may not be appropriate to rely on data from outside of Virginia to determine if this would be a beneficial step.

There is evidence in this study to suggest that spat-on-shell survival is density dependent. Observation of this trend is limited by a relatively small data set in this study (n=7 for the Rappahannock R.). Verifying and determining to what extent this is widely occurring would be very beneficial to a producer. If the density dependent trends observed in this study are typical, it would seem that production efficiency could be increased by reducing the number of larvae added to the setting tank (assuming a consistent supply of highly competent eyed larvae is available). Without more consistent setting however, (i.e. similar numbers of spat on each shell) adding fewer larvae to a setting tank may result in too many shells with too few spat. These issues must be considered in future spat-on-shell work.

Section II

Bio-Economic Feasibility of Remote Setting

INTRODUCTION

The purpose of Section II is to assess economic feasibility of the remote culture method of oyster production given the constraints of the biological parameters estimated in Section I. This was accomplished by constructing an interactive enterprise budget for remote culture in order to evaluate, practically, feasibility of remote culture.

Numerous enterprise budgets exist for various forms of agriculture (Virginia Cooperative Extension 2001, Center for Integrated Agricultural Systems 2003, Penn State Cooperative Extension 1994), and are not uncommon for aquaculture (Riepe et al. 1993, Engle and Stone 1996). Currently, no such enterprise budgets exist for oyster aquaculture, although there is currently an enterprise budget under construction for intensive, contained oyster aquaculture (Miller in prep).

This analysis will use the results reported in Section I, in addition to results reported in this section, pertaining to investment and operating costs for remote culture to parameterize the enterprise budget and examine the feasibility of remote culture based on those results. The enterprise budget was constructed with emphasis on flexibility, so that it might be useful also to interested parties outside of Virginia.

A remote setting facility consists of only a handful of items. Essenital equipment includes tank(s), water pump(s), air blower(s), PVC plumbing, a shell cleaner, machinery to move shell, and a vessel to plant and harvest oysters. (Reusable shell containers could also be included here). A satisfactory site for this equipment would typically include an area in close proximity to seawater with plenty of room for cleaning and storing shell.: however, considering the current price of waterfront property (>$200,000 per acre in Virginia), ideal sites may be limited to those that already have established operations on the water. For newcomers, or perhaps entrepreneurial waterman interested in remote setting, but with only a slip for his boat and a bottom lease, there are other options. While waterfront is certainly advantageous, it is not absolutely necessary because tanks could, with some work be setup on a barge, or modified to float in the water. Setting equipment, a site, in addition to an area of leased bottom for planting spat-on-shell are all considered investment costs in this analysis.

Once a facility is set up, commodities necessary for production include eyed larvae, shell (or other form of cultch), cultch containers, electricity, and labor. These items are all classified as operating costs.

The objectives of this section are the following:

1. Define a mean and range of the costs associated with remote culture including investment and operating.
2. Construct a customizable, predictive model in the form of an enterprise budget for remote culture.
3. Compare estimated returns to estimated costs of remote culture to assess feasibility.

METHODS

Cost Estimation

The same ten setting facilities described in Section I were also used to estimate costs. Costs of remote culture are broken into two main categories: investment and operating. Itemized cost estimates were obtained from each site in order to calculate a mean and range of those costs. This will allow for feasibility assessment given best-case, worst-case, and plausible scenarios.

Investment Costs

Investment costs were measured via producer interviews, a mailed survey (Appendix 2), and from literature. Investment costs include fixed costs for items necessary to accomplish remote culture. These items included tanks, pumps, blowers, plumbing, shell washer, and any other items associated with the facility. Bottom lease and vessel lease costs would also be included here, however, they were not assessed in this study because all participants already had these items on hand. It is likely that the vast majority of parties interested in remote culture will already have leased bottom and vessel(s).

Operating Costs

Operating costs were measured via observation, interview, survey, and literature review. Operating costs included eyed larvae, setting cultch, disposable cultch containers, electricity, and labor. Cost estimates are also provided for centrifuged algae supplementation even though it was not used by participants in this study. Electricity use was estimated based on equipment wattage and duration of use using the following equation:

$$EC = \frac{W \times h}{1000} \times kWh \qquad (1)$$

where EC is the total electricity cost in dollars, W is the wattage of the equipment in question, h is the number of hours the equipment is used, and kWh is the cost of electricity per kilowatt hour.

Labor can be divided into 5 main components: 1) Cultch cleaning and containerization, 2) tank loading, 3) tank unloading, 4) planting, and 5) harvest. The actually setting process, where larvae are physically added to the tank is negligible. Tank loading, tank unloading, and planting were all observed in this study allowing for calculation of labor by multiplying the number of men by the number of hours required to complete the task. Cultch containerization was not observed and was therefore determined through survey and interviews. Oysters planted in this study were not for harvest and therefore there are no direct estimates of harvest cost. Most participating producers, however, actively harvest oysters from the bottom and therefore were asked to estimate this parameter.

Eyed larvae, cultch, algae and disposable cultch containers (plastic-mesh sleeve bags) costs are considered fixed and therefore only vary with level of production.

Enterprise Budget Construction

The bio-economic feasibility model was constructed in the form of an annualized enterprise budget for remote oyster culture integrating, among others, the biological and economic parameters estimated in this study. In general terms, the measure of feasibility is positive annual net revenue.

The formulation of the enterprise budget begins with the general formulation:

$$ANR = AR - AC \tag{2}$$

where ANR is total annual net revenue, AR is total annual revenue, and AC is total annual cost.

Total annual revenue is defined by:

$$AR = R_m + R_s \tag{3}$$

where R_m is revenue from marketed oysters, and R_s is revenue from spat-on-shell sold as seed. The separation of these two terms allows for accounting of spat-on-shell sold immediately as seed separately from that planted and harvested later as market oysters. Seed revenue (R_s) is defined by:

$$R_s = B_p P_s mv_s \tag{4}$$

where B_p is the predicted number of bushels of seed planted, P_s is the proportion of the total quantity of spat-on-shell produced that were sold as seed, and mv_s is the market value of spat-on-shell seed per bushel. Market oyster revenue (R_m) is defined by:

$$R_m = B_h mv_m \tag{5}$$

where B_h is the number of bushels harvested, and mv_m is the fair market value of those oysters harvested per bushel. Market oyster revenue is dependent on the predicted number of bushels harvested (B_h) which is defined by:

$$B_h = \frac{O_p P_m Vj}{d_B} \tag{6}$$

where O_p is the number of spat-on-shell oysters produced, P_m is the proportion of the total quantity of spat-on-shell produced that was planted on the bottom for future harvest, V is the estimated cumulative survival of spat-on-shell from planting to harvest, j is the harvest efficiency or ratio of oysters surviving at harvest to oysters captured during harvest, d_B is the count of oysters per bushel at harvest. The count of oysters per bushel at harvest (d_B) is a proxy for harvested oyster size as count varies inversely with size. While this size of harvested oysters will likely have an effect on price, the extent of this effect is not predicted by the model, but is left to the discretion of the user.

Total annual cost (AC) is defined by:

$$AC = F + L + E + S + H \tag{7}$$

where F is annual facility cost, L is annual lease preparation cost, E is annual eyed larvae cost, S is annual setting cost, and H is annual harvest cost. Facility cost (F) is defined by:

$$F = \sum_{\zeta = t,b,p,h} \zeta q_{\zeta} l_{\zeta} + \sum_{\zeta = z,w} \zeta l_{\zeta} \tag{8}$$

where t, b, p, h, z, and w are per item costs respectively, for a setting tank (t), blower (b), water pump (p), heater (h), appropriate plumbing (z), and a shell washer (w); q is the quantity of an item, and l is the life of an item. Annual lease preparation (L) is defined by:

$$L = (600sac) + v_L + f_L \tag{9}$$

where s is the number of inches of base shell desired, a is the number of acres to be planted, c is the cost one bushel of shell, v_l is the cost of vessel use if applicable, and f_l is the cost of fuel. The number of acres (a) is determined by:

$$a = O_p \div d_p \tag{10}$$

where O_p is the total number of bushels of oysters produced and d_p is the planting density in bushels per acre. The cost of eyed larvae (E) is defined by:

$$E = \left(\frac{B_p d_y c}{1{,}000{,}000}\right) mp_y \tag{11}$$

where B_p is the number of bushels of spat-on-shell to be produced, d_y is the density per cultch shell that larvae are to be stocked at in the setting tanks, c is the number of shells (or cultch) that comprise one bushel, and mp_y is the market price for eyed larvae. The cost of setting (S) is defined by:

$$S = \big((M + N + X + f_S + v_S + a)k\big) - \big((k - k_n)C_n\big) \tag{12}$$

where M, N, and X are the costs of materials, labor, and electricity, respectively, and are defined further later, f_S and v_S are the costs of fuel and vessel use associated with planting spat-on-shell, a is the cost of algae fed to larvae in the setting tanks, k is the number of sets completed annually, k_n is the number of sets during which heaters were in use, and C_n is the cost of heater use for one set. Material costs (M) are defined by:

$$M = \sum_{\zeta = c,x} \zeta \lambda \tag{13}$$

where c and x are the costs of cultch and container material for one set respectively and λ is the bushel per set capacity of the setting facility. Labor costs are defined by:

$$N = \sum_{\zeta = \alpha,\beta,\chi,\delta} \zeta \lambda \theta \tag{14}$$

where α, β, χ, and labor costs per set for cultch containerization, tank loading, tank unloading, and planting respectively, λ is the bushel per set capacity of the setting facility, and θ is the labor rate. Electricity costs (X) are defined by:

$$X = \sum_{\zeta = b,p,h} \frac{24 W_\zeta \tau_\zeta}{1000 \psi q_\zeta} \tag{15}$$

where b, p, and h are wattage (W) estimates for the blower(s), pump(s), and heater(s) in use during the setting process, τ is the number of days the equipment is running for each set, ψ is the electric rate in kilowatt hours, and q is the quantity of each type of equipment in use. Cost of feeding centrifuged algae in the setting tanks is defined by;

$$a = \frac{\tau_a \varepsilon}{\phi} \tag{16}$$

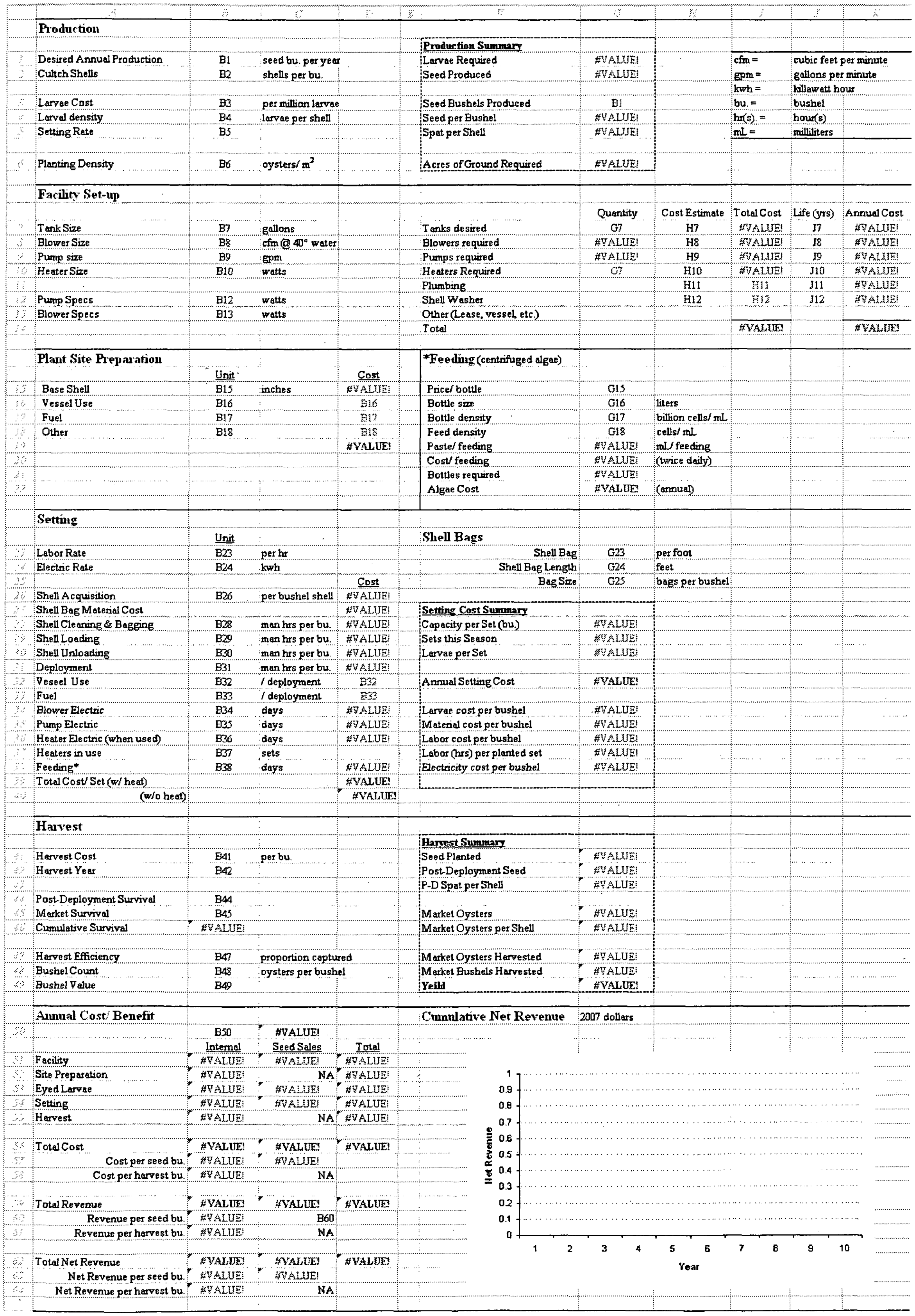
where τ_a is the number of days algae is put into the setting tanks, ε is the amount of paste added per feeding in milliliters, and φ is the price of centrifuged algae paste per liter. Harvest cost (H) is defined by:

$$H = iB_h \tag{17}$$

where i is estimated cost of harvest per bushel, and B_h is the estimated number of bushels harvested. Note that B_h accounts for survival and harvest efficiency (Equation 6). The combined equation for the enterprise budget is defined below: (18)

$$ANR = \left[\left(\frac{O_p P_m Vj}{d_B} mp_m\right) + \left(B_p P_s mp_s\right)\right] - \left[\begin{array}{l} \left(\sum_{\zeta = t,b,p,h} \zeta q_\zeta l_\zeta + \sum_{\zeta = z,w} \zeta l_\zeta\right) + \left((600 sac) + v_L + f_L\right) + \left(\left(\frac{B_p d_y c}{1{,}000{,}000}\right) mp_y\right) + \\ \left(\left(\left(\sum_{\zeta = c,x} \zeta \lambda\right) + \left(\sum_{\zeta = \alpha,\beta,\chi,\delta} \zeta \lambda \theta\right) + \left(\sum_{\zeta = b,p,h} \frac{24 W_\zeta \tau_\zeta}{1000 \psi q_\zeta}\right) + f_g + \frac{\tau \varepsilon}{\phi}\right)\right) \\ k - ((k - k_n)C_n) + iB_h \end{array}\right]$$

The enterprise budget described above can be found on the attached CD in Excel and PDF formats. The budget user guide can be found in Appendix 2. The model



Production

Desired Annual Production	B1	seed bu. per year
Cultch Shells	B2	shells per bu.
Larvae Cost	B3	per million larvae
Larval density	B4	larvae per shell
Setting Rate	B5	
Planting Density	B6	oysters/ m^2

Production Summary

Larvae Required	#VALUE!
Seed Produced	#VALUE!
Seed Bushels Produced	B1
Seed per Bushel	#VALUE!
Spat per Shell	#VALUE!
Acres of Ground Required	#VALUE!

cfm = cubic feet per minute
gpm = gallons per minute
kwh = killawatt hour
bu. = bushel
hr(s). = hour(s)
mL = milliliters

Facility Set-up

Tank Size	B7	gallons
Blower Size	B8	cfm @ 40" water
Pump size	B9	gpm
Heater Size	B10	watts
Pump Specs	B12	watts
Blower Specs	B13	watts

	Quantity	Cost Estimate	Total Cost	Life (yrs)	Annual Cost
Tanks desired	G7	H7	#VALUE!	J7	#VALUE!
Blowers required	#VALUE!	H8	#VALUE!	J8	#VALUE!
Pumps required	#VALUE!	H9	#VALUE!	J9	#VALUE!
Heaters Required	G7	H10	#VALUE!	J10	#VALUE!
Plumbing		H11	H11	J11	#VALUE!
Shell Washer		H12	H12	J12	#VALUE!
Other (Lease, vessel, etc.)					
Total			#VALUE!		#VALUE!

Plant Site Preparation

	Unit		Cost
Base Shell	B15	inches	#VALUE!
Vessel Use	B16		B16
Fuel	B17		B17
Other	B18		B18
			#VALUE!

***Feeding** (centrifuged algae)

Price/ bottle	G15	
Bottle size	G16	liters
Bottle density	G17	billion cells/ mL
Feed density	G18	cells/ mL
Paste/ feeding	#VALUE!	mL/ feeding
Cost/ feeding	#VALUE!	(twice daily)
Bottles required	#VALUE!	
Algae Cost	#VALUE!	(annual)

Setting

	Unit		Cost
Labor Rate	B23	per hr	
Electric Rate	B24	kwh	
Shell Acquisition	B26	per bushel shell	#VALUE!
Shell Bag Material Cost			#VALUE!
Shell Cleaning & Bagging	B28	man hrs per bu.	#VALUE!
Shell Loading	B29	man hrs per bu.	#VALUE!
Shell Unloading	B30	man hrs per bu.	#VALUE!
Deployment	B31	man hrs per bu.	#VALUE!
Veseel Use	B32	/ deployment	B32
Fuel	B33	/ deployment	B33
Blower Electric	B34	days	#VALUE!
Pump Electric	B35	days	#VALUE!
Heater Electric (when used)	B36	days	#VALUE!
Heaters in use	B37	sets	
Feeding*	B38	days	#VALUE!
Total Cost/ Set (w/ heat)			#VALUE!
(w/o heat)			#VALUE!

Shell Bags

Shell Bag	G23	per foot
Shell Bag Length	G24	feet
Bag Size	G25	bags per bushel

Setting Cost Summary

Capacity per Set (bu.)	#VALUE!
Sets this Season	#VALUE!
Larvae per Set	#VALUE!
Annual Setting Cost	#VALUE!
Larvae cost per bushel	#VALUE!
Material cost per bushel	#VALUE!
Labor cost per bushel	#VALUE!
Labor (hrs) per planted set	#VALUE!
Electricity cost per bushel	#VALUE!

Harvest

Harvest Cost	B41	per bu.
Harvest Year	B42	
Post-Deployment Survival	B44	
Market Survival	B45	
Cumulative Survival	#VALUE!	
Harvest Efficiency	B47	proportion captured
Bushel Count	B48	oysters per bushel
Bushel Value	B49	

Harvest Summary

Seed Planted	#VALUE!
Post-Deployment Seed	#VALUE!
P-D Spat per Shell	#VALUE!
Market Oysters	#VALUE!
Market Oysters per Shell	#VALUE!
Market Oysters Harvested	#VALUE!
Market Bushels Harvested	#VALUE!
Yeild	**#VALUE!**

Annual Cost/ Benefit

	B50	#VALUE!	
	Internal	Seed Sales	Total
Facility	#VALUE!	#VALUE!	#VALUE!
Site Preparation	#VALUE!	NA	#VALUE!
Eyed Larvae	#VALUE!	#VALUE!	#VALUE!
Setting	#VALUE!	#VALUE!	#VALUE!
Harvest	#VALUE!	NA	#VALUE!
Total Cost	#VALUE!	#VALUE!	#VALUE!
Cost per seed bu.	#VALUE!	#VALUE!	
Cost per harvest bu.	#VALUE!	NA	
Total Revenue	#VALUE!	#VALUE!	#VALUE!
Revenue per seed bu.	#VALUE!	B60	
Revenue per harvest bu.	#VALUE!	NA	
Total Net Revenue	#VALUE!	#VALUE!	#VALUE!
Net Revenue per seed bu.	#VALUE!	#VALUE!	
Net Revenue per harvest bu.	#VALUE!	NA	

Cumulative Net Revenue 2007 dollars

Figure 2.1: User interface for the remote culture enterprise budget. See Appendix 1.

Table 2.1: Parameter values for the three scenarios under which the enterprise budget was run. Worst-case, best-case, and plausible scenario parameters were based respectively on the minimum, maximum, and mean results of this study. Scenario budget configurations were constructed to demonstrate both the utility of the model and a range of possible outcomes of remote culture in Virginia. The location column displays the location of each variable in the model interface.

Scenario Parameter Values	**Location**	**Worst-Case**	**Best-Case**	**Plausible**
Biologic				
Setting Rate	*C5*	5%	15%	7%
Harvest Year	*C59*	4	2	3
Post-Deployment Survival	*C44*	15%	85%	64%
Cumulative Survival	*C45*	8%	33%	21%
Economic				
Labor				
Cultch Containerization	*C28*	0.80	0.14	0.32
Tank Loading	*C29*	0.05	0.01	0.03
Tank Unloading	*C30*	0.10	0.02	0.04
Planting	*C31*	0.11	0.01	0.06
Infrastructure	*J13*	$17,750.00	$8,300.00	$9,750.00
Harvest	*C41*	$20.00	$2.50	$11.00

Table 2.2: Parameter defaults for the enterprise budget. These values represent the plausible scenario and the mean results obtained in this study. For that reason they are a good starting point for budget parameterization. Unless otherwise noted this is the parameterization of the enterprise budget throughout this document. The location column displays the location of each variable in the model interface.

Parameter Defaults

Production	**Value**	**Unit**	**Location**	**Feeding**	**Value**	**Unit**	**Location**
Desired Annual Production	2,400	bushels	*B1*	Price	$36.89	bottle^{-1}	*H15*
Cultch Shells	700	shells bushel^{-1}	*B2*	Bottle size	0.9464	liters	*H16*
Larvae Cost	$200.00	million^{-1}	*B3*	Bottle density	2	billion cells ml^{-1}	*H17*
Larval Density	100	larvae per shell^{-1}	*B4*	Feed density	100,000	cells ml^{-1}	*H18*
Planting Density	1000	oysters m^{-2}	*B6*				
Facility Set-up				**Facility Set-up**			
Tank Size	3,000	gallons	*B7*	Tank Cost	$3,000	each	*I7*
Blower Size	50	feet^{3}minute^{-1}	*B8*	Blower Cost	$900	each	*I8*
Pump Size	200	gallons minute^{-1}	*B9*	Pump Cost	$500	each	*I9*
Heater Size	15,000	watts	*B10*	Heater Cost	$0	each	*I10*
Pump Specs	2760	watts	*B12*	Plumbing Cost	$300	total	*I11*
Blower Specs	900	watts	*B13*	Shell Washer Cost	$2,050	total	*I12*
Plant Site Preparation				**Facility Life**			
Base Shell	3	inches	*B15*	Tank Cost	10	years	*K7*
Vessel Use	$1,000		*B16*	Blower Cost	5	years	*K8*
Fuel	$100		*B17*	Pump Cost	5	years	*K9*
Other	$0		*B18*	Heater Cost	10	years	*K10*
				Plumbing Cost	3	years	*K11*
Setting Costs				Shell Washer Cost	10	years	*K12*
Labor Rate	$7.73	hour^{-1}	*B23*				
Electric Rate	$0.10	kilowatt-hour^{-1}	*B24*	**Shell Bags**			
Shell Acquisition	$1.00	bushel^{-1}	*B26*	Shell Bag	$0.05	foot^{-1} of material	*H23*
Shell Cleaning & Bagging	0.32	bushel^{-1}	*B28*	Shell Bag Length	4.0	feet	*H24*
Shell Loading	0.03	bushel^{-1}	*B29*	Bag Size	2	bags bushel-1	*H25*
Shell Unloading	0.04	bushel^{-1}	*B30*				
Deployment	0.06	bushel^{-1}	*B31*	**Harvest**			
Veseel Use	$0.00		*B32*	Harvest Efficiency	75.00%	percent recovered	*C47*
Fuel	$50.00		*B33*	Bushel Count	350	oysters bushel^{-1}	*C48*
Blower Electric	10.0	days	*B34*	Bushel Value	$35.00	bushel^{-1}	*C48*
Pump Electric	7.0	days	*B35*				
Heater Electric	10.0	days	*B36*	**Annual Cost/ Benefit**			
Heaters in use	2	sets	*B37*	Proportion Internal	100%		*C50*
Feeding	0.0	days	*B38*	Spat-on-Shell Seed Price	$25	bushel^{-1}	*D60*

Table 2.3: Summary of setting costs estimated via producer interviews, observation, and survey. Listed is the minimum, maximum, and mean of each parameter. These values were used in the parameterization of the worst-case, best-case, and plausible enterprise budget scenarios.

Setting Costs Summary	Min	Max	Mean
Total Men	3	9	5.1
Labor Rate	7	7.96	7.37
Man Hours per Bu.			
Bagging	0.14	0.80	0.32
Loading	0.01	0.05	0.03
Unloading	0.02	0.10	0.04
Deployment	0.01	0.11	0.06
Total Man Hours per Bu.	0.18	1.05	0.45
Infrastructure Cost	$8,300.00	$17,750.00	$9,750.00

interface is displayed in Figure 2.1. To assess remote culture feasibility given various scenarios, a worst-case, best-case, and plausible run of the model was performed using the minimum, maximum, and mean, respectively, parameter estimates calculated from the biological and economic results. The parameter inputs used for these model runs are displayed in Table 2.1. Model runs are available in Appendix 4. Parameters not listed in Table 2.1 remained the same for the three model runs.

Those parameters that did not vary among the three model runs are not necessarily fixed but will vary among sites and with different production levels. In the case of the model runs to generate scenarios, default values were used that reflect the set-up of a typical facility as observed in this study and are used throughout this section unless otherwise noted. The default parameters are displayed in Table 2.2.

Enterprise Budget Sensitivity

A sensitivity analysis was completed to rank relative sensitivity of all model parameters. Parameter values for the plausible scenarios were used as initial values for the sensitivity analysis. Parameter values were changed individually by intervals of 25% from 50% to 150% of the initial value. The gain or loss of net revenue resulting from this change in each parameter was calculated and used as the measure of sensitivity. A negative value means that as the parameter increases, revenue is lost. Conversely, a positive value means revenue is gained as the parameter increases. The absolute value was used to rank relative sensitivity. The larger the absolute value, the more sensitive the model is to that parameter.

RESULTS

Cost Estimation

Investment Costs

As setting sites were equipped in this study and assuming a four month (mid-May to mid-September) setting season with one set every two weeks for a total of eight sets per season, seasonal production capacity is approximately 2400 bushels. A modest investment cost of approximately $8,300 to $17,750 covered the infrastructure necessary for production at this capacity (Table 2.3). This included necessary infrastructure such as tanks, water pumps, air blowers, plumbing, a shell washer, and in some cases heaters. The variation among sites was due primarily to difference in size or quality of individual equipment and the purchase, or not, of tank heaters, which cost approximately $1,100 (2007 dollars) for a unit sufficient to heat one 3,000 gallon tank.

Infrastructure costs are similar to those reported by Southworth et al (in prep) that estimated the cost of a similar setting facility, capable of approximately the same seasonal production, at $7,838. This estimate does not include a shell washer or tank heaters.

Proportional investment costs for infrastructure elements are approximately as follows: 62% for tanks 21% for a shell washer, 9% for blowers, 5% for pumps, and 3% for plumbing. The addition of tank heaters changes this to 50% for tanks, 18% for heaters, 17% for a shell washer8% for a blower, 4% for a pump, and 3 % for plumbing. 25% for tanks, 7% for blowers, 4% for water pumps, 9% for heaters, 2% for plumbing, and 19% for a shell washer. Setting facility infrastructure costs are minimal, relative to remote culture costs, at only 1%. If more mechanized methods were used (i.e. loaders, fork lifts, conveyors, etc.) they would also be included here.

Investment costs not included in this analysis are waterfront property, vessel cost, or annual lease costs. The cost of waterfront property in Virginia is currently approximately 200,000-$300,000 per acre (AndersonBay.com 2008), which may be even higher for a site appropriate for remote setting. The minimum cost for a vessel capable of transporting spat-on-shell efficiently in calm water is approximately $5,000 to $10,000. This estimate is for a large skiff with a working load of 50-75 bushels, however, more appropriate spat-on-shell vessels are Chesapeake Bay style deadrise workboats (150 bushels per load), and bow-deck seed boats (300+ bushels per load depending on vessel size). The cost of maintaining a private oyster lease in Virginia is $1.50 per acre annually with an initial cost of approximately $600 for application processing and surveying (VMRC lease application 2006).

The possibility of equipping a barge for remote setting is plausible to avoid waterfront property costs if available water access is sufficient to load and unload a vessel capable of transporting cultch to the setting barge. Note that this adds to the labor loading costs. Non-waterfront property would still be necessary for storing equipment and cultch, as well as cleaning and containerizing cultch. Associated setting barge costs would likely be near $40,000 for new items that would include the barge itself and a sufficient generator, in addition to normal setting facility costs described above.

Operating Costs

Operating costs include eyed larvae, cultch, disposable cultch containers, electricity, algae, setting labor, and harvest. Of these, the most variable among sites is labor. Labor rate among sites had a mean of $7.37 with a range from $7.00 to $7.96. Labor associated with the main elements of remote setting includes cultch containerization, tank loading and unloading, and planting.

Labor estimates are reported as man-hours per bushel here, and in Table 2.3 and 2.4. Containerization labor had a mean of 0.32 with a range from 0.14 to 0.80. Tank loading labor had a mean of 0.03 with a range from 0.01 to 0.05. Tank unloading had a mean of 0.04 with a range from 0.02 to 0.10. Planting labor had a mean of 0.06 with a range from 0.01 to 0.11. Total mean setting labor was 0.45 with a range from 0.18 to 1.05. Given the mean labor rate, labor cost of remote setting ranged from $1.26 to $7.35 per bushel with a mean of $3.15.

Operating costs with associated fixed material prices include eyed larvae, cultch, cultch containers, and algae. Eyed larvae costs in Virginia are currently $200 per million with larvae added to setting tanks in this study at a ratio 100 larvae per cultch shell. Eyed larvae cost varies with production level accordingly. Given 700 pieces of cultch per bushel and larvae added at a rate of 100 per piece of cultch, eyed larvae costs are $14 per bushel.

Oyster shell was the primary cultch used in remote setting observed in this study. The cost of oyster shell was estimated at $1 per bushel. Plastic mesh bags used to containerize cultch in this study were purchased from Conwed Plastics at approximately $52 per 1000 foot roll. Unfinished bag length was approximately 3 to 4 feet for a

Table 2.4: Setting costs for each participating setting facility. These values were used to create the summary of setting costs found in Table 2.3. Setting facilities are in random order to remain anonymous. nd = no data collected. Plant or deliver refers to whether a setting facility planted produced spat-on-shell themselves, or whether it was delivered to another location by truck for subsequent planting by a third party.

Setting Costs by Site	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Planted or delivered	plant	deliver	plant	plant	deliver	plant	plant	deliver	deliver	plant
Total Men	7	6	4	9	3	5	5	3	3	4
Labor Rate	$7.96	$7.50	$7.00	$7.00	nd	nd	nd	nd	nd	nd
Man Hours per Bu.										
Bagging	0.1880	0.8000	0.1429	0.1429	nd	0.1600	nd	nd	nd	nd
Loading	0.0458	0.0278	0.0133	0.0505	0.0200	0.0200	0.0200	0.0133	0.0200	0.0200
Unloading	0.0467	0.0278	0.0533	0.1011	0.0267	0.0200	0.0200	0.0200	0.0250	0.0300
Deployment	0.0667	0.0080	0.0133	0.0667	0.0933	0.0583	0.0500	0.0933	0.0933	0.1067
Total Man Hours per Bu.	0.3472	0.8636	0.2228	0.3611	0.1400	0.2583	0.0900	0.1266	0.1383	0.1567
Infrastructure Cost	$12,200.00	$8,320.00	$17,750.00	$750.00	nd	nd	nd	nd	nd	nd

container cost of $0.15 to $0.20 per bag. Given the mean labor rate and the range for containerization of 0.14 to 0.80 man hours per bushel, labor cost of bag construction ranged from $0.98 to $5.60 per bushel with a mean of $2.24. Assuming a four foot unfinished bag length, the complete cost of an unset shell bag ranged from $2.38 to $7.00 per bushel with a mean of $3.64. Note that costs reported per bushel are actually for two half bushel bags. Total mean cost of a set shell bag is $10.18 with a range from $9.11 to $12.75

Though disposable cultch containers were used by all setting facilities in this study and are included in operating costs, the possibility of re-useable cultch containers exists and would be considered an investment cost. A simple analysis suggests that, in the long run, re-usable cultch containers in conjunction with increased mechanization would reduce the costs associated with spat-on-shell production and planting (Table 2.5). Using labor values from the plausible scenario for bag production, and best-estimates for cage production, total cost per set for labor was $1,470 for bags and $160 for mechanized cage production. Total mechanization costs were estimated at $45,500, primarily for the construction of enough stainless steel cages to contain 300 bushels of cultch ($32,000). Other mechanization costs were those for conversion of a vessel to plant loose shells ($5,000), a small, stationary, used crane to move cages in and out of the setting tanks ($3,500), and a used forklift to move cages as needed ($5,000). Given a life span of 10 years for the cages and 5 years for the other equipment, annualized cost of cage production is $7,180. Annualized bag production is $12,720. Despite initially lower costs for bag production, by the fourth year cumulative costs for both production modes is approximately equal, and after the fourth year cumulative cost will be lower using cage production as a result of reduced labor costs.

Centrifuged algae were not used in this study; however, associated costs were estimated. The cost of centrifuged algae is approximately $36.80 for a liter bottle. At a feeding density of 100,000 cells per milliliter twice a day and feeding for the first two and a half days, the cost of algae per set is around $150 or $0.50 per bushel.

The mean cost of producing and planting spat-on-shell seed is $20.46 per bushel with a range from $18.22 to $25.49.

Table 2.5: Comparison of containerization using cultch bag or cultch cage. Mechanization of the setting process was portrayed given a hypothetical situation where cages were used to containerize cultch instead of bags, as observed during the course of this study.

Mechanized Cultch Containerization	Bags	Cages
Material Cost	$120.00	
Labor		
Shell Cleaning and Containerization	114	8
Tank Loading	6	2
Tank Unloading	9	2
Planting	18	4
Labor Subtotal ($10hr^{-1})	$1,470	$160
Cost of 1 300 bu. Set	$1,590	$160
Annual Cost (8 set season)	$12,720	$1,280
Mechanization		
Cages		$32,000
Seed Boat Conversion		$5,000
Crane		$3,500
Forklift		$5,000
Annualized Cost	$12,720	$7,180
Cumulative Total Cost		
Year 1	$12,720	$33,280
Year 2	$25,440	$48,060
Year 3	$38,160	$49,340
Year 4	$50,880	$50,620

Costs of spat-on-shell harvest (per bushel) estimated by participants ranged from \$2.50 to \$20.00. The middle of this range was used in the plausible model run and was set at \$11.00 This cost cannot simply be added to the per bushel cost of seed production, but must first be multiplied by yield as yield determines the number of harvested bushels resulting from the number of planted seed bushels. Incorporating harvest costs, the total cost for a bushel of harvested market size spat-on-shell including cost of production, planting and harvest (and given a yield of 2.22:1) is \$21.40. Yield is a traditional measure of oyster planting success and is the ratio of the number of bushels of market oysters retrieved from every bushel of seed oysters planted.

Operating costs comprise about 99% of the total cost. Although dependent on remote setting rate, survival, and production variables, and given the model parameters used in the plausible scenario, 30% of total cost is for eyed larvae; 6% for site preparation; 12% for setting costs including setting labor, electricity, algae, and cultch containers; and 51% for harvest.

Enterprise Budget

Scenarios

The worst-case, plausible, and best-case model runs (Appendix 4) returned annual net revenue of -\$44,147, \$72,526, and \$525,751, respectively, given an annual production level of 2400 bushels (Table 2.6). These results suggest feasibility of remote culture given the best-case and plausible scenarios but not the worst-case. Total annual cost was \$95,177, \$100,784, and \$113, 752 for worst-case, best-case, and plausible model runs. Not necessarily intuitive, the plausible scenario has a higher cost than the worst-case scenario because the low setting rate and low survival of the worst-case scenario results in fewer oysters to be harvested, thus reducing harvest costs. The planted bushel cost of spat-on-shell for these three runs was \$18.22, \$25.49, and \$20.46 for the best-case, worst-case, and plausible scenarios respectively. Cost per bushel of seed, however, does not take into consideration setting performance and therefore seed costs are often expressed in units of 1000 seed. In this case, mean cost per thousand spat-on-shell is \$4.16 (plausible) with a range from \$1.74 (best-case) to \$7.28 (worst-case).

Table 2.6: Summary of results from the three scenario runs. Yield represents the number of bushels of market oysters harvested for every bushel of spat-on-shell planted. Annual costs are broken down into four main components. The cost of eyed larvae is excluded here as it is the same for each of the three scenarios.

Scenario Results			
	Worst-Case	**Best-Case**	**Plausible**
Yeild	0.61	7.46	2.22
Annual Costs			
Facility	$2,172	$1,040	$1,185
Site Preperation	$4,836	$12,308	$6,331
Setting	$25,409	$9,083	$14,092
Harvest	$29,160	$44,753	$58,545
Total Annual Cost	$95,177	$100,784	$113,752
Annual Revenue	$51,030	$626,535	$186,278
Annual Net Revenue	($44,147)	$525,751	$72,526
First Year Positive Cumulative Net Revenue	NA	2	6

The annual cost of the worst-case run is lower because of relaxation of harvest costs as a result of low production due to poor setting rate, exacerbated by low survival, and despite a higher harvest cost. High setting rate and survival in the best-case run does not increase harvest cost dramatically because the cost of harvesting is set lower in the best-case ($2.50 per bushel) than in the plausible case ($11.00 per bushel).

Positive cumulative net revenue is never achieved, because net revenue is negative in the worst-case scenario. In the best-case and plausible scenarios positive cumulative net revenue is achieved in year 2 and in year 6 respectively. The lag in positive cumulative revenue is a function of the lag between product planting and product harvest. Less time to harvest and increased annual net revenue decrease the time necessary to reach the first year of positive cumulative net revenue. The shorter the period to positive cumulative net revenue, the more attractive start-up of a remote setting operation will be.

Budget Sensitivity

Input parameters were analyzed for sensitivity given their affect on annual net revenue over a range of values between 50% and 150% of initial parameter values used in the plausible scenario. The total increase or decrease in net revenue over this range is displayed in Table 2.6. The higher the absolute value associated with each parameter, the more sensitive the model is to that specific parameter. A positive value indicates that as the parameter increases, annual net revenue increases. A negative value indicates that as the parameter increases, annual net revenue decreases.

The value of a bushel of harvested oysters has the most affect on annual net revenue, followed closely by the size at which oysters are harvested. The next greatest effect on annual net revenue is from survival, followed closely by setting rate (which is essentially just a measure of survival from larvae to spat). The next greatest effect comes from the number of cultch shells in a bushel and the density at which larvae are added to the setting tanks. Harvest efficiency has the next greatest effect, followed by harvest and larvae costs, the latter two being negative relationships (those that decrease annual net

Table 2.7: Sensitivity analysis of remote culture enterprise budget. Budget parameters were adjusted individually from 50% to 150% of default values. The resulting change in net revenue is represented by the value listed for each parameter. The absolute value for each parameter represents the relative sensitivity of the budget to that parameter. Higher absolute values represent higher sensitivity. Parameters with positive values are those that increase net revenue as they increase. Parameters with negative values are those that decrease net revenue as they increase.

	Sensitivity		
Parameter		**Negative Relationship**	
Bushel Value	266112	Harvest Cost	-65406
Harvest Size	238741	Larvae Cost	-36000
Post-Deploymnet Survival	134291	Labor Rate	-9090
Survival to market	133721	Cultch Containerization	-7050
Cumulative Survival	133529	Base Shell	-5604
Setting Rate	128688	Shell Cost	-2400
Cultch Shells	94688	Electricity Rate	-1984
Larval Density	92688	Number of sets heaters used	-1440
Harvest Efficiency	89527	Days per set heaters on	-1440
Planting Density	7472	Annual Infrastructure Cost	-1297
		Larval Feeding Density	-1180
		Days Larvae Fed	-1180
		Planting Labor	-1113
		Cultch Container Price	-960
		Bag Size	-720
		Tank Unloading Labor	-557
		Shell Bag Length	-480
		Tank Loading Labor	-371
		Days Water Pump On	-371
		Days Blower On	-173

revenue as they increase). The remainder of the parameters control labor and setting costs and have little effect on annual net revenue relative to those mentioned previously.

DISCUSSION

Cost Estimation

Given the most plausible scenario, constructed from the results of this study, the per capita cost of remote setting is approximately $22.00 per bushel to produce and harvest a bushel of market size oysters derived from spat-on-shell. It is possible to further reduce this cost via mechanization beyond that observed in this study and through increased economy of scale. The cost estimate above is based on a yield of 2.22:1 and a cumulative survival of approximately 21% and will quickly increase as survival or yield decreases.

Southworth et al. (in prep) reported a similar cost for producing remote set market oysters of $23.58. It is likely that the cost here is higher as a result of only 280 bushels of seed being produced compared to the estimate in this study based on 2400 bushels of seed.

Supan et al. (1995) outlines a hypothetical remote setting operation for the purposes of re-seeding public oyster ground and therefore has no production estimates that include harvest costs. Supan et al. (1995) estimates seed production costs at $2.16 per thousand seed given the scenario most similar to this study. Given the plausible scenario in this study, seed cost per thousand is $4.16. The reason for this discrepancy is that Supan et al. sets remote setting rate at 20% compared to the plausible scenario in this study of 7%. If remote setting rate in Supan et al. is reduced to 7% the resulting cost per thousand seed increases to $6.16.

A 3% return of market sized oysters from larvae is common in remote setting using shell bags and on-bottom growout (Supan et al. 1995). Given a 21% survival in Supan et al., this return is approximately 2.7%. Given the plausible scenario in this study, the return from larvae is 1.1%. This discrepancy is again due to the higher remote setting rate in Supan et al. of 20% compared to 7% in this study. Also, there is no mention of any harvest efficiency in Supan et al., whereas in this study only 75% of surviving oysters are considered in calculation of harvested oysters. Excluding the harvest efficiency, return from larvae increases to 1.5%. To achieve a return of 3% from larvae in this study leaving all other parameters the same, a remote setting rate of greater than 14% must be achieved.

Model Utility, Limitations, and Accuracy

The enterprise budget for remote culture is a useful tool for assessing feasibility given user-specified conditions. It can also be used for forecasting labor and material demands in the future given a specified level of annual production. Estimates of labor, cost, and revenue, however, are just that, and should be treated as such.

Care should be taken to parameterize the model specifically to a site and operation, because certain items that may be initially viewed as trivial have a large effect on the model output. Predictions made by the model are only as accurate as the information provided. Take for example the number of cultch shells per bushel. According to the sensitivity analysis (Table 2.7) the number of cultch shells per bushel has a relatively large effect on the model output. Time should be taken to count several bushels of cultch to get a reasonable average of the number of cultch shells per bushel. More accurate site-specific parameter values will give a user more accurate predictions.

This enterprise budget does not account for a crop being harvested over multiple years, but assumes that the entire crop, excluding that not harvested according to the harvest efficiency parameter, is harvested in the year specified by the years to harvest parameter.

The Southworth et al (in prep) study was used to test the accuracy of the remote culture enterprise budget. Important parameters enumerated in the Southworth et al. study were facility costs, eyed larvae cost, total production, remote setting rate, planting and cumulative survival, and time to harvest. The remainder of the parameters are left as the default with the exception of harvest efficiency, which was estimated to be 50% (Southworth person. comm.). Total annual facility cost of the Southworth et al. (in prep) study was $2,894, eyed larvae cost was $167.50 per million, total production was 280 bushels, remote setting rate was 7.25%, planting and cumulative survival was 37% and 25% respectively, and time to harvest was approximately two years for all oysters harvested. These parameter values were entered in the remote culture enterprise budget using the budget defaults for parameters not enumerated above. Initially, yield was higher than that reported by Southworth et al. (3.4) at 3.69. To account for this, the number of oysters per bushel was increased to 375 from the default of 350 (still a reasonable count) reducing yield to 3.44. Given this change, and the parameter values described above, predicted annual net revenue was $10,893 by the remote culture enterprise budget compared to $10,776 in Southworth et al. (in prep).

Remote Culture Feasibility

Using the results of this study and current typical remote setting practices in Virginia, the plausible scenario was created to assess feasibility of remote culture in Virginia given the most likely case. This scenario estimates annual net revenue at $72,526 beginning in the third year, after approximately 2.5 years of growing time. Total investment, prior to the first year of revenue is approximately $230,000. Given this, and excluding any interest on start-up capitol that may have been borrowed, the first year of positive cumulative net revenue will be in year 6. Total cost per *planted* bushel of spat-on-shell, including future harvest costs is $47.40. Given the associated yield of 2.22 in this scenario, total cost per *harvested* bushel is $21.37.

Yield (the ratio bushels of market oysters harvested to bushels of seed planted) has been a traditional measure of seed planting success. Southworth et al (in prep) observed a yield of 3.37:1 for 280 bushels of triploid spat-on-shell. Bosch and Shabman (1990) estimated yield on private ground using wild seed and transplanting culture methods at 1.98:1 in the 1960s, 1.44:1 in the 1970s, and 1.01:1 in the 1980s. There are also several estimates of yield using transplanting techniques from Louisiana waters including 1.1:1 by Melancon and Condrey (1992), 0.4:1 to 1.68:1 by Melancon (1990), 0.89:1 to 1.52:1 by Mackin and Hopkins (1961), 3:1 to 4:1 by Perret and Chatry (1988), and 1.21:1 as an overall average for Louisiana by Dugas (1977). The plausible scenario estimates a yield of 2.22:1 and seems to fall somewhere in the middle of all these estimates.

While annual net revenue is high, negative cumulative net revenue must be incurred prior to year six, and is at its highest at the end of year two, before the first year of positive annual net revenue in year three. The ability to absorb an investment loss of $228,000, not to be returned in full until year six is likely to be a hindrance in entry of new participants into this industry. While this start-up money could be borrowed, the risk involved and the interest associated do not make it an attractive option. Shortening the time to positive cumulative net revenue would likely allow more entrance into the market.

There are, however, other ways to reduce this initial loss. The plausible scenario starts out with a production level of 2400 bushels and maintains this for a period of ten years to produce the cumulative net revenue figure in the plausible model run. One, way to reduce this initial loss would be to reduce the number of bushels that were produced in the first few years, building up to a production level of 2400. For example, if a remote culture firm was to produce 900 bushels in the first year, 1800 bushels in the second year and 2400 bushels every year after that, all other things being equal, the investment to be absorbed is reduced to approximately $175,000, however, because of less annual revenue in year three and four, the first year of cumulative net revenue is pushed back to year 7. While the option of an initially lowered production level will reduce initial loss, because of the lowered production, it will also push back the first year of positive net revenue.

Another option to reduce initial loss is the diversification of a remote culture firm by selling spat-on-shell produced as seed. By doing this, net revenue can be made in the first and second years to help offset initial loss. For example, given a spat-on-shell seed price of $25 per bushel and 75%, 50%, and 25% of total annual production (2400bu) sold as spat-on-shell seed in years 1, 2, and 3, respectively, the total initial loss can be reduced to approximately $128,000 with the first year of positive cumulative net revenue occurring in year 7.

In order to reduce the time to positive cumulative net revenue, seed must be sold for a longer period of time. For example if 50% of total production (2400bu.) is sold as spat-on-shell seed indefinitely, time to positive cumulative net revenue is reduced to 5 years and total initial loss is reduced to $100,000.

Given the potential of a spat-on-shell seed market, the original enterprise budget was adjusted to create a second budget (Appendix 3) that is tailored for use by an individual interested in purchasing and planting, for later harvest, spat-on-shell seed from a remote setting facility. Empirical estimates were used in the default parameterization of the budget where possible to give users a starting point. As with remote culture, there is a significant period of time (7 years in the default case) before positive cumulative net revenue is realized. This may be prohibitive to those not able to secure financing making a spat-on-shell seed market dependent on the availability of subsidy. The spat-on-shell seed planting enterprise budget can be found on the compact disc included with the original remote culture enterprise budget. The budget interface and user guide can be found in Appendix 3.

The possibility of a more direct way to reduce time to positive cumulative net revenue does exist however, but requires moving outside of the confines of the plausible scenario by reducing the time to harvest. This is likely possible through the use of triploidy which may reduce harvest time to the second year, rather than the third year. Southworth et al (in prep) observed harvest of triploid spat-on-shell in 21 months. By changing only the harvest year in the plausible scenario to year two, the first year of positive cumulative net revenue is reduced to year three. Cutting in half the time it takes to break even will undoubtedly make remote culture more accessible to more parties.

While the above approaches can reduce the time to first positive net revenue and total initial loss, it also significantly reduces the total cumulative net revenue. This is because of the much lower profit margin of seed sold compared to oysters grown to harvest. Given the plausible scenario, net revenue for harvested oysters is $13.63 per bushel, whereas the net revenue per bushel of seed is only $4.63. For example given 0% spat-on-shell seed sold, under the plausible scenario total cumulative net revenue is $353,000 over a 10 year time period. Given 25%, 50%, and 75% spat-on-shell seed sales in years 1, 2, and 3, total cumulative net revenue after 10 years is reduced to $261,000. Given 50% spat-on-shell seed sales over the entire ten year period, total cumulative net revenue is reduced to $232,000.

The end-point of this model is with a harvested bushel of market size oysters, however, it is likely that many remote culture firms will be vertically integrated and processing harvested oysters. Given this case, after the first year of cumulative net revenue, a firm may be interested in only breaking even in terms of remote culture annual net revenue as they are simply supplying themselves with a product to process and add-value. Given the plausible scenario, per bushel value can be reduced to $27 and still return $30,000 annually. This annual net revenue would likely be a sufficient return for management and maintenance costs associated with the remote culture operation while providing the processing portion of the business with a relatively low-cost, landed product.

Sensitivity

Sensitivity analysis suggests that the model is most sensitive to harvested bushel value and oyster size at harvest. Considering this, it may be beneficial for a grower to leave oysters in the water for an extra year to attain a larger size as this will effectively increase the number of harvested bushels per planted bushels (yield), as well as have some affect on price per bushel. The effect on price per bushel is not accounted for by the model however, and must be changed manually to a more appropriate value by the user.

Survival to market and remote setting rate were the next most sensitive parameters. Optimization of remote setting rate would increase the efficiency with which eyed larvae are used. For example, if remote setting rate was increased, fewer larvae could be used per set which would lower overall eyed larvae costs. It may also be possible to manipulate survival given the density dependent relationship theorized in Section I. If a relatively consistent remote setting rate could be obtained, the number of larvae added to the setting tanks per piece of cultch could be manipulated to maximize efficiency of larval use. If cultch shells planted at 20 spat per shell, and those planted at 7 spat per shell both reach 3 oysters per shell at the time of harvest, the larvae used to obtain a spat per shell count greater than 7 were essentially wasted. To maximize efficiency in this case, given an optimized and relatively consistent setting rate of 15%, the number of larvae added per piece of cultch could be reduced to 47.

The model was found to be relatively insensitive to labor and other setting costs. Years of growth until oysters were market size had the greatest affect on the time until first positive cumulative net revenue. An unsuspected highly sensitive parameter was the quantity of cultch per container. Since this metric is a multiplier used to estimate the total number of seed produced from the number of spat per shell, it is important to estimate it as accurately as possible.

CONCLUSION

Investment costs are minimal for a remote culture facility ($8,300 to $17,750), comprising only about 1% of total annual costs. Not included here is the cost of waterfront property ($200,000 to $300,000 per acre), which could limit remote culture to those already in possession of waterfront property. A possible alternative to waterfront property is non-land based remote setting either in floating tanks or on a barge.

Operating costs comprise the majority at about 99% of total cost. Operating costs include bottom-lease preparation, eyed larvae, and harvest and vary with production level, remote setting rate, and survival. Given the plausible scenario, distribution of operating costs is as follows: site preparation is 6%, eyed larvae is 30%, setting is 12%, and harvest is 51%. This distribution varies depending on model parameterization.

Annual setting costs can be reduced by nearly 50% through mechanization of setting and deployment. Annual setting costs (for an eight set season) for a non-mechanized facility using disposable cultch containers was $12,720, relative to $7,180 for a mechanized facility using reusable cultch cages. Investment costs associated with mechanization can be recouped by the end of the fourth year of use.

The remote culture enterprise budget was developed with the intention of releasing it to industry for their own use in gauging economic feasibility; estimating larvae, material, and labor needs; and forecasting potential production. Using the minimum, maximum, and mean results from both sections of this study, three budget scenarios were developed to assess the feasibility of remote culture given a worst-case, best-case, and plausible scenario. Remote culture was found to be feasible given the best-case and plausible scenarios, but not feasible given the worst-case scenario. Given the plausible scenario run and all other parameters unchanged, when remote setting rate drops below 3%, annual net revenue is negative. Remote setting rate values below 5% likely do not provide enough return for effective operation. Annual net revenue also goes negative when cumulative survival drops below 10%, all other parameters unchanged.

A remote setting seed market has potential to offset remote culture start-up costs. To encourage this secondary market of spat-on-shell, a second enterprise budget (Appendix 3) was constructed for use buy potential buyers of this product. This budget is tailored to those interested in planting spat-on-shell, but will buy it rather than produce it themselves. It is important to note here, that as with starting a remote culture operation, there is a significant start-up cost that must be incurred during the time before the first planted cohort is ready for harvest. It is likely that many of these spat-on-shell planters will be one man or very small operations and will not have the capitol available for start-up costs. The budget will be useful in a business plan to secure financing or to justify the need for subsidy.

By increasing remote setting rate and reducing the spat per shell density at planting, eyed larvae costs can be reduced. A prerequisite for this manipulation is a higher and more importantly, a consistent setting rate than has been observed to date.

Future Work (pertaining to the economics of remote setting)

Mechanization of cultch handling and containerization has potential to reduce operating costs involved in setting. This work will likely fall on the private sector to pioneer given its practical nature. However, Federal and State funding agencies could promote these advancements by making available grant monies for research and development of more mechanized techniques.

As mentioned in section I, research in the area of remote setting rate is key to optimizing remote culture. Development of techniques and/or technologies that will increase and stabilize remote setting rate will allow for more cost-effective remote culture. Given the current state of remote culture in Virginia, the most gain can be made with advances in remote setting rate.

Lacking in the Virginia remote culture sector is an adequate supply of eyed larvae. Oyster culture operations in Virginia often have trouble getting enough single oyster seed for their intensive culture and often seek out and purchase seed from out of state. Given that remote setting takes significantly more eyed larvae than single seed setting, Virginia hatchery capacity is obviously inadequate to allow development of the remote culture industry. Significant increase in Virginia hatchery capacity will be necessary to fuel the scale-up of remote culture.

THESIS SUMMARY AND OUTLOOK

For more than a century the eastern oyster, *Crassostrea virginca* has been commercially harvested from Chesapeake Bay. Over time, the level of this harvest has dwindled as a result of multiple factors including overfishing, removal of recruitment substrate, disease, reduced demand, increased cownose ray predation and water quality degradation (Rothschild et al 1994, Meyers 2007, Kirby and Miller 2004). Unique to Virginia was a primarily private fishery where Bay bottom was leased by the Commonwealth to oystermen who prepared the bottom for oysters by adding old oyster shell. The leased bottom was then either stocked with oyster seed transplanted from public or private seed beds, or allowed to catch naturally occurring oyster larvae if in an appropriate area. This type of privately held fishery has recently been regarded as better than a fully public fishery as private ownership often promotes more sustainable harvest practices (Anderson 2002, Crowley 1996). The level of risk associated with a private fishery however, is often higher than a public fishery, because in the case of private oyster production an investment (preparation of lease and purchase of seed) in addition to fuel and vessel maintenance must be made in order to realize a return. There is a much higher monetary risk relative to the public fisherman who must only fuel and maintain a vessel. In the eyes of the private oysterman, after the disease epidemics of the 1960s, the risk of planting oysters outweighed the potential benefit and is reflected in the concurrent, drastic reduction in oyster landings (Bosch and Shabman 1990, Alford 1975).

The late 1960's marked the end of significant oyster landings in Virginia, after which the majority of oysters landed in Chesapeake Bay came from Maryland (a primarily public fishery). In the 1980s another round of disease induced mortality significantly reduced oyster landings in Maryland, after which there has been comparably miniscule harvest from Chesapeake Bay with landings at about 1% of the 1890s peak of around 18 million bushels (Newell 1988).

Without any significant level of landings in Virginia, or for that matter, Chesapeake Bay, the Virginia oyster processing industry has been forced to go out of state for product. The majority of oysters brought into Virginia are shipped from the Gulf of Mexico. In fact, some processors have gotten into the bait business primarily to avoid sending an empty truck to the Gulf. In this case, bait is shipped down to the Gulf and oysters are shipped back. Approximately 500,000 – 600,000 bushels of oysters are shipped to Virginia from the Gulf each year (James Wesson, VMRC). While not optimal, this practice has to date been feasible. With the cost of diesel exceeding $4.00/ gallon in May 2008 and projected to continue its increase, it is becoming less so. Rising fuel costs also have potential to limit the purchase of non-essential items, like shellfish, by the public as budgets are constrained by the increase in price of other, more essential items. Therefore any increase in the price of oysters due to increasing fuel costs may further reduce oyster demand. In addition to becoming increasingly expensive, shipping oysters from the Gulf also requires a large expenditure of time and energy by a processor to track down and secure product. Storms and closures that disrupt product stream make the Gulf market inconsistent and sometimes unavailable.

The largest current need for the Virginia processing industry is a consistent supply of locally available oysters. Could this not be met by remote culture? After all, the Virginia fishery was primarily a private one prior to the 1960s and was at that time capable of landing 2-3 million bushels annually (NMFS). A return to culture with the replacement of wild seed by hatchery produced domesticated and disease resistant seed has potential to revitalize the oyster processing industry in Virginia. If the average results of this study can be achieved with relative consistency, remote culture is biologically and economically feasible in Virginia and capable of producing a landed bushel of market size oysters at a cost of $21.37 given a yield of 2.22:1. Given a market value per bushel of $35 and prior to any added value associated with post-harvest processing, this is a return of $13.63 per bushel. Given a shucking yield of 6 pints to a bushel, the dockside product cost (excludes processing cost) of a gallon of shucked oyster meat is $29.24.

Currently, there are ten remote setting facilities in Virginia capable of producing at least 2,400 bushels of seed annually. Given a yield of 2.22:1, this is 5328 bushels of market size oysters annually for a combined total, including all ten sites, of 53,280 bushels. This potential annual production from just ten sites exceeds the total Virginia landings during the period from 1999 to 2004 (VMRC Landings Bulletin). Recall that 500,000 – 600,000 bushels of oysters are shipped into Virginia from the Gulf States each year. A one order of magnitude increase in remote culture capacity in Virginia could possible take the place of Gulf oyster import.

Let us consider for a moment the Virginia hard clam (*Mercenaria mercenaria*) culture industry. In 2006, 211 million cultured clams were sold (Murray and Oesterling 2008). If these were oysters, this would be approximately 600,000 bushels of oysters assuming 350 oysters per bushel. This level of clam production has been obtained over a time period of less than 10 years. The clam culture industry in Virginia is a testament to the fact that the goal of offsetting Gulf of Mexico oyster import is not unobtainable.

It is not necessarily plausible to envision another 90 remote setting facilities exactly like those in place to sprout up all over the Bay to accomplish the necessary order of magnitude increase. If the goal is to reduce dependence on Gulf oysters and, to do this, Virginia needs to be capable of landing, e.g., 500,000 bushels of oysters annually, there are a couple of ways that the industry could reach this goal. One scenario would be that oyster processors vertically integrate remote setting facilities, produce their own seed, plant on their own bottom, and harvest their own oysters. In this case, if 10 processors set up large scale facilities, each would have to produce 25,000 bushels of spat-on-shell annually and harvest 50,000 bushels annually. A more reasonable scenario might be one of 10 vertically integrated processors producing 10,000 and harvesting 20,000 bushels annually with another 100 oystermen turned remote culturists and using much smaller, possibly cooperative remote setting facilities, producing 1500 bushels of spat-on-shell and harvesting 3000 bushels of oysters annually for a grand total of 500,000 bushels harvested annually. There is also the potential for spat-on-shell seed to be sold by either processor or cooperative remote setting facilities to oystermen interested in on-bottom growout, but not seed production. Recall that this market also benefits the remote setting facility by helping to offset production costs with an immediate form of revenue.

There are three potential obstacles still not adequately addressed that have the potential to hold back remote culture in Virginia. First, while processors and other entrepreneurs seem excited by the prospect of remote culture, will average public waterman share this excitement? To truly revolutionize the industry, it will take participation of the entire industry, not just a select few, and therefore public waterman must be included in this process. Optimistically speaking, remote culture should prove to be less drastic of a change to the average watermen than the alternative mode of intensive contained culture. The similarities of remote culture to historical transplanting will be key to selling this aquaculture method to the masses. The romanticized oyster fishery defined by deadrise workboats, oyster dredges, and hand tongs does not have to disappear with aquaculture. Remote culture can be accomplished undercover of the Bay with oystermen working in the same capacity as they have for a century.

Second, cownose ray predation has become a significant problem in Virginia. Rays often travel in large schools and if they happen across a bed of loose oysters, can decimate the bed. Theoretically, spat-on-shell, due to its clumped nature and many spat per shell will be more resistant to cownose ray predation than single oysters or those with only a few per shell. Transplanted wild seed is often broken up when collected for transplanting elsewhere and therefore does not provide the same resistance. The larger diameter of a clump of spat-on-shell requires a ray's mouth to be opened wider and therefore is left with less leverage to crush the oyster (Bob Fisher, Virginia Sea Grant, pers. comm.). However, if cownose rays prove to be as efficient at eating spat-on-shell as loose oysters, remote culture may not to be feasible in the form described here, or it will be restricted to certain areas where ray predation is limited.

Third, spat-on-shell production via remote setting requires an immense supply of eyed larvae. To reach the previously proposed goal of 500,000 bushels of harvested oysters would require approximately 35 billion eyed larvae annually. Demand for the 2007 season was in excess of 1 billion eyed larvae, however, less than 500 million were produced and set. Currently, eyed larvae production capacity in Virginia is barely a billion, with two hatcheries capable of, but not proven to, produce about 500M each. There is only one hatchery in Virginia dedicated exclusively to oyster production, and others that shift from clams to oysters mid-season. The majority of shellfish hatcheries in Virginia focus on hard clam larvae production. To reach the 500 thousand bushel goal would require at least three hatcheries capable of producing about 5 billion eyed larvae annually. It seems that eyed larvae production capacity will be the limiting factor of any remote culture scale-up for the immediate future.

Considering how far away the Virginia oyster hatchery industry is from 35 billion eyed larvae annually, the focus of funding to benefit aquaculture should be on hatcheries. For the remote culture industry to develop to its potential will take tremendous investment by the private, public, academic, and political arenas. With cooperation, however, among these groups, a self-sustaining culture based oyster industry in Virginia seems plausible and has potential to revitalize not only the oyster processing sector, but the entire Virginia oyster fishery.

APPENDIX 1

Mailed Setting Costs Survey

2008 Spat on Shell Cost Survey

General

Average labor rate ________ *$/hr*

Total number of men involved in SOS operation ________ *men*

Estimated harvest cost/ bu. ________ *$*

Estimated start-up costs

Tanks ________ $

Blower ________ $

Pump ________ $

Heaters ________ $

Plumbing ________ $

Shell washer ________ $

Bagging Shell

of bags made ________ *bags*

# of men used ________ *men*

# of man-hours ________ *hours*

Tank Loading

of bags loaded ________ *bags*

# of men used ________ *men*

# of man-hours ________ *hours*

Tank Unloading

of bags unloaded ________ *bags*

# of men used ________ *men*

# of man-hours ________ *hours*

Planting

of men used ________ *men*

hours spent driving/riding ________ *hours*

hours spent working ________ *hours*

own vessel use? ________ *y/n*

fuel used during planting ________ *gallons*

Notes or Concerns:

APPENDIX 2

Remote Culture Enterprise Budget User Guide

The Remote Culture Enterprise Budget (RCEB) was developed for the purpose of estimating site specific feasibility of remote setting based extensive oyster aquaculture given user defined parameters. After parameterization by the user, the budget estimates annualized costs and returns as well as forecasts cumulative net revenue into the future. Note that annual returns are not observed immediately because revenue lags according to grow-out duration. Therefore predicted annual return will be realized in the first year of harvest. The budget was constructed with an emphasis on flexibility to allow for the most accurate representation possible of a potential remote culture operation.

The budget is broken into five main components: Production, Facility Set-up, Setting, Harvest, and a Cost/Benefit summary.

Production: This section includes those parameters that dictate annual production and summarizes the pertinent production information.

Facility Set-Up: This section allows a user to estimate total and annual cost for the setting facility. The size of the facility is defined by the user.

Setting: This section includes parameters for each cost associated with the actual production of spat-on-shell (SOS). The subsections for plant site preparation, feeding, and shell bags also fall into this category.

Harvest: This section includes those parameters associated with harvest of market oysters as well as survival and summarizes the pertinent harvest information.

Cost/ Benefit: This section itemizes and estimates annual cost, annual revenue, and annual net revenue. This section also forecasts cumulative net revenue. The cost/benefit section also allows for partitioning of total production into two categories, the first being normal production where SOS is planted and harvested after the grow-out period, the other being SOS seed production where SOS is produced and sold immediately after production as seed.

The following component sections define each input parameter (in blue) and its location on the budget interface (Fig. 2.1) by cell number. Following the input parameter descriptions is a description of each component output parameter (in green) and its location.

PRODUCTION

Input

Desired Annual Production (**B1**): enter the number of bushels of SOS to be produced annually. A setting facility with tanks totaling at least 6,000 gallons has a capacity of 2400 bushels given 300 bushels per set, one set every two weeks, and a four month setting season.

Cultch Shells (**B2**): enter the number of shells (or other cultch) found in one bushel. It is important to estimate this parameter as accurately as possible as it is used to determine the total number of oysters produced.

Larvae Cost (**B3**): enter the cost of 1 million eyed oyster larvae

Larval Density (**B4**): enter the number of larvae added to the tank for every one shell (or cultch piece) in the tank.

Setting Rate (**B5**): the percentage of seed produced in a tank relative to the number of larvae added to the tank during setting

Planting Density (**B6**): enter the density at which SOS will be planted in terms of bushels per acre.

Output

Larvae Required (**G1**): displays the number of eyed larvae required to meet the desired amount if annual production.

Seed produced (**G2**): displays the number of SOS seed produced annually

Seed bushels produced (**G3**): displays the number of bushels of seed produced

Seed per Bushel (**G4**): displays the number of SOS contained within one bushel

Spat per Shell (**G5**): displays the resulting average number of spat on a single shell given the defined production inputs.

Acres of Ground Required (**G6**): displays the number of acres of bottom required for planting SOS at the specified density.

FACILITY SET-UP

Tank Size (**B7**): enter the size of tank to be used in the setting facility. Also, enter the number of tanks to be used in G7. When choosing tank size and quantity, a good rule of thumb is 2000 gallons of tank volume for every 100 bushels of shell to be put in the tank.

Blower Size (**B8**): enter the size of the blower to be used measured as cubic feet of air per second at 40 inches of water depth. Given the power of the blower, and the size and number of setting tanks, the number of blowers required is displayed in G8.

Pump Size (**B9**): enter the size of the water pump measured as gallons of water pumped per minute. Given the size of the pump and the number and size of the setting tanks, the number of pumps required is displayed in G9.

Heater Size (**B10**): enter the size of the heaters to be used (if any) measured in wattage. Given the size of the heaters and the number and size of the setting tanks, the number of heaters required is displayed in G10. When selecting a heater a good rule of thumb is that 1 gallon of water requires roughly 5 watts to increase and maintain its temperature by 5°C.

Pump and Blower Specs (**B12 & B13**): enter the wattage of these two pieces of equipment. This value will help determine the electricity cost associated with running this equipment.

Cost Estimates (**H7-H12**): enter the itemized cost for each piece of equipment identified in F7-F12. Total cost for each equipment category is displayed in I7-I12.

Life (**J8-J13**): enter the life expectancy of each piece of equipment identified in F7-F12. This estimate helps to determine annualized equipment costs which are displayed in K7-K12.

Total facility cost and total annualized facility cost are displayed in I14 and K14 respectively.

SETTING

Input

Labor and Electric Rate (**B23 & B24**): enter the labor rate used in dollars per hour and the local electric rate in kilowatt hours.

Shell Bags (**B26, G23-G25**): enter the costs associated with cultch and cultch container material where B26 is the cost of one bushel of shell, G23 is the cost of the shell container per foot, G24 is the length of that container, and G25 is the number of bags that make up one bushel.

Setting Labor (**B28-B31**): enter the number of man hours required to produce and plant one bushel of SOS on bottom. This includes the labor associated with cultch cleaning and containerization (B28), tank loading (B29), tank unloading (B30), and deployment (B31).

Vessel Use (**B32 & B33**): if applicable, enter the cost of vessel use in B32 and any fuel costs incurred in B33.

Electricity Usage (**B34-36**): enter the number of days each piece of equipment is in use, including the air blower(s) (B34), the water pump(s) (B35), and the water heater(s) (B36). The model will predict electricity cost per set based on these inputs as well as previously entered equipment wattage and quantity in cells E34-E36. As heaters are not necessary during the entire setting season, enter the number of sets for which the heaters will be used in cell B37.

Output

Total Cost per Set (**D39 & D40**): displays the total cost of each individual set based on the entered values above. This total is calculated two different ways, one with heater electricity included (D39), and one without heater electricity (D40).

Capacity per Set (**G28**): displays the rough capacity of the setting facility derived from the size and quantity of tanks given that roughly 20 gallons of tank volume are required for every bushel to be set.

Sets this Season (**G29**): displays the number of sets necessary to complete the desired annual production (B1), given the capacity of the facility.

Larvae per Set (**G30**): displays the number of larvae required to complete each set based on the number of shells per bushel (B2), the desired larval setting density (B4), and the number of bushels to be set.

Annual Setting Cost (**G32**): displays the total cost of all sets completed to reach the production goal.

Cost per Seed Bu. (**G34**): displays the setting costs associated with the production and planting of one bushel of SOS.

Cost per Un-Set Shell Bag (**G35**): displays the material and production cost of one shell bag.

Labor Cost per Bu. (**G36**): displays the cost of labor associated with producing and planting one bushel of SOS.

Labor per Planted Set (**G37**): displays the total number of labor hours required to complete one set.

Larvae Cost per Bu. (**G39**): displays the cost of larvae for each bushel set based on larvae price (B3) and larvae setting density (B4).

Other Setting

Plant Site Preparation (**B15-B18**): by entering the inches of base shell (B15) desired on the planting area, D21 will estimate the number of bushels of shells required to reach that base depth. Vessel use, fuel, and other costs associated with plant site preparation may also be entered in B16-B18. Specific costs are displayed in E15-E18 with the total displayed in E19.

Feeding (**G15-G18**): if larvae are to be fed with algae paste during feeding, cells G15-G18 should be used. By entering the cost per bottle (G15), the size and density of each the bottle (G16 & G17), and the desired feeding density (G18), the model will display the volume of paste to be put in the tank (G19), the cost of each feeding (G20), and the number of bottles required and the total annual cost based on two feedings per day, and the number of days feeding occurs based on the value entered in (B38). Feeding is only necessary before flow-through is established.

HARVEST

Input

Harvest Cost (**B41**): enter the approximate cost incurred to harvest one bushel of oysters

Harvest Year (**B42**): enter the year in which oysters planted will be harvested. For example a value of 3 means oysters will be harvested in the third year after planting.

Post-Deployment Survival (**B44**): enter an estimated percent survival for SOS one to two weeks after planting. If you have no good estimate, consult the suggested parameter estimate table at the end of this document.

Market Survival (**B45**): enter an estimated percent survival for the interval after the post-deployment mortality interval until the time of harvest. To apply a single survival estimate, adjust B44 and B45 such that cumulative survival (B46) is equal to the single estimate.

Harvest Efficiency (**B47**): enter an estimate of the proportion of oysters that will be captured relative to the number surviving on the bottom prior to harvest.

Bushel Count (**B48**): enter an estimate for the number of oysters per bushel at the time of harvest.

Bushel Value (**B49**): enter an estimate for the value of a harvested bushel given the estimated count (B48).

Output

Seed Planted (**G41**): displays the total number of seed planted

Post-deployment Seed (**G42**): displays the total number of seed alive one to two weeks after planting.

Post-Deployment Spat per Shell (**G43**): displays the mean number of spat remaining per shell one to two weeks after planting.

Market Oysters (**G45**): displays the number of oysters alive at the time of harvest

Market Oyster per Shell (**G46**): displays the mean number of oysters remaining per shell at the time of harvest.

Market Oysters Harvested (**G47**): displays the total number of oysters harvested. This is not equal to the number of oysters alive at the time of harvest because of the limitation of the harvest efficiency (B47).

Market Bushels Harvested (**G48**): displays the number of bushels harvested given the bushel count (B48) and the total number of oysters harvested (G47).

Yield (**H49**): displays the number of bushels of market oysters harvested for every one bushel of SOS seed planted.

COST/ BENIFIT

Input

Percent Private Production (**B50**): Enter the percent of total production to be planted and grown internally. The remaining production is that sold as SOS seed and is displayed in (C50).

SOS Seed Price (**C60**): Enter the price at which SOS seed will be sold.

Output

Total Annual Cost (**BCD51-56**): Total annual cost for each remote culture component is displayed in cells D51-55: annualized facility cost (D51), site preparation cost (D52), eyed larvae cost (D53), setting cost (D54), and harvest cost (D55). Combined total cost is displayed in cell D56. Internal production annual costs are displayed in cells B51-B56 and annual costs for SOS seed sales in cells C51-C56 (C52 and C56 are excluded as they are not applicable to seed sales). If no SOS seed is sold externally, column B and D (51-56) will be identical, seed is 100% of total production then column C and D (51-56 will be identical.

Per Bushel Costs (**B57-B58 & C57**): For internal production, per bushel costs are displayed for the cost per seed bushel (B57) and the cost per harvested bushel (B58). The cost per harvested bushel is lower proportional to the estimated yield (G49). The cost per seed bushel for seed production (C57) is lower than that for internal production as it does not include harvest costs as the internal production value does.

Total Annual Revenue (**BCD59**): Total annual revenue is displayed in cell D59. Internal production annual revenue is displayed in cell B59 and annual revenue from SOS seed sales is displayed in cell C59. If there is no seed sold, B59 and D59 will be identical, if seed sales comprise 100% of the total, then C59 and D59 will be identical.

Per Bushel Revenue (**B60 & B61**): For internal production, revenue per seed bushel produced is displayed in cell B60. Revenue per harvested bushel is displayed in cell B61. As is the case with per bushel costs, revenue per harvested bushel is lower proportional to the yield.

Total Net Revenue (**BCD62**): Total annual net revenue is displayed in cell D62. Annual net revenue associated with internal production is displayed in cell B62. Annual net revenue associated with SOS seed sales is displayed in cell C62.

Per Bushel Net Revenue (**B63-B64 & C63**): For internal production, net revenue per seed bushel is displayed in cell B63. Net revenue per harvested bushel is displayed in B64 and is lower proportional to the yield. For external SOS seed sales, net revenue per seed bushel is displayed in cell C63.

Cumulative Net Revenue: The cumulative net revenue figure displays cumulative net revenue over a 10 year period. Assuming parameterization is constant over a 10 year period, this figure displays the maximum loss that must be incurred during remote culture startup, the year at which cumulative net revenue becomes positive, and the total net revenue accumulated over the 10 year period.

APPENDIX 3

Spat-on-Shell Seed Planting Enterprise Budget User Guide

The Spat-on-Shell Seed Planting Enterprise Budget (SPEB) was developed for the purpose of estimating feasibility of extensive oyster aquaculture where spat-on-shell is purchased direct from a setting facility by a grower for subsequent. This budget therefore does not include any of the setting details as does the RCEB. After parameterization by the user, the budget estimates annualized costs and returns as well as forecasts cumulative net revenue into the future. Note that annual returns are not observed immediately because revenue lags according to grow-out duration. Therefore predicted annual return will be realized in the first year of harvest.

This budget is broken into five main components: Production, Facility Set-up, Setting, Harvest, and a Cost/Benefit summary.

Production: This section includes those parameters that dictate annual production.

Planting: This section includes parameters for each cost associated with the actual production of spat-on-shell (SOS). The subsection for plant site preparation also falls into this category.

Harvest: This section includes those parameters associated with harvest of market oysters as well as survival and summarizes the pertinent harvest information.

Cost/ Benefit: This section itemizes and estimates annual cost, annual revenue, and annual net revenue. This section also forecasts cumulative net revenue.

The following component sections define each input parameter (in blue) and its location on the budget interface (Fig. 2.2) by cell number. Following the input parameter descriptions is a description of each component output parameter (in green) and its location.

PRODUCTION

Input

Desired Annual Production (**B1**): enter the number of bushels of SOS to be purchased and planted annually.

Bushel Count (**B2**): enter the number of spat per bushel of spat-on-shell. This will allow you to determine the total number of oysters planted. This information should be given to you be the setting facility.

Purchase Price of Spat (**B3**): enter the price you paid per bushel for the spat-on-shell

Planting Density (**B6**): enter the density at which SOS will be planted in terms of bushels per acre.

Output

.

Acres of Ground Required (**B5**): displays the number of acres of bottom required for planting SOS at the specified density.

PLANTING

Input

Labor Rate (**G6**): enter the labor rate used in dollars per hour

Vessel Planting Capacity (**G7**): enter in bushels the quantity of SOS that can be safely carried on the planting vessel.

Planting Labor (**G9 & G10**): enter the number of man hours required pick-up and plant one bushel of SOS on bottom. This includes the labor associated tank unloading (B30), and deployment (B31).

Vessel Use (**G11 & G12**): if applicable, enter the cost of vessel use in G11 and any fuel costs incurred in G12.

Output

Planting Costs (**J9-J12**): displays the per load costs of shell loading (J9) and deployment (J10) according to the specified labor rate. Costs for vessel use (J11) and fuel (J12) are displayed as specified in cells G11 and G12 respectively.

Loads Required (**J13**): displays the total number of planting trips required to achieve the desired annual production according to the vessel capacity.

Annual Planting Total (**J14**): displays the total annual cost of planting activities.

Plant Site Preparation (**B15-B18**): by entering the inches of base shell (B15) desired on the planting area, D21 will estimate the number of bushels of shells required to reach that base depth. Vessel use, fuel, and other costs associated with plant site preparation may also be entered in B16-B18. Specific costs are displayed in E15-E18 with the total displayed in E19.

HARVEST

Input

Harvest Cost (**B15**): enter the approximate cost incurred to harvest one bushel of oysters

Harvest Year (**B16**): enter the year in which oysters planted will be harvested. For example a value of 3 means oysters will be harvested in the third year after planting.

Post-Deployment Survival (**B17**): enter an estimated percent survival for SOS one to two weeks after planting. If you have no good estimate, consult the suggested parameter estimate table at the end of this document.

Market Survival (**B18**): enter an estimated percent survival for the interval after the post-deployment mortality interval until the time of harvest. To apply a single survival estimate, simply adjust B17 and B18 such that cumulative survival (B19) is equal to the single estimate.

Harvest Efficiency (**B21**): enter an estimate of the proportion of oysters that will be captured relative to the number surviving on the bottom prior to harvest.

Bushel Count (**B22**): enter an estimate for the number of oysters per bushel at the time of harvest.

Bushel Value (**B23**): enter an estimate for the value of a harvested bushel given the estimated count (B22).

Output

Seed Oysters Planted (**G15**): displays the total number of seed planted

Post-deployment Seed (**G16**): displays the total number of seed alive one to two weeks after planting.

Market Oysters (**G17**): displays the number of oysters alive at the time of harvest

Market Oysters Harvested (**G19**): displays the total number of oysters harvested. This is not equal to the number of oysters alive at the time of harvest because of the limitation of the harvest efficiency (B21).

Market Bushels Harvested (**G20**): displays the number of bushels harvested given the bushel count (B22) and the total number of oysters harvested (G19).

Yield (**G21**): displays the number of bushels of market oysters harvested for every one bushel of SOS seed planted.

COST/ BENIFIT

Output

Total Annual Cost (**B24-B28**): Total annual cost for each seed planting component is displayed in cells B24-27: site preparation cost (B24), seed cost (B25), planting cost (B26), and harvest cost (B27). Combined total cost is displayed in cell B28.

Per Bushel Costs (**B29-B30**): Per bushel costs are displayed for the cost per seed bushel (B29) and the cost per harvested bushel (B30). The cost per harvested bushel is lower proportional to the estimated yield (G21).

Total Annual Revenue (**B31**): displays gross earnings based on budget set-up

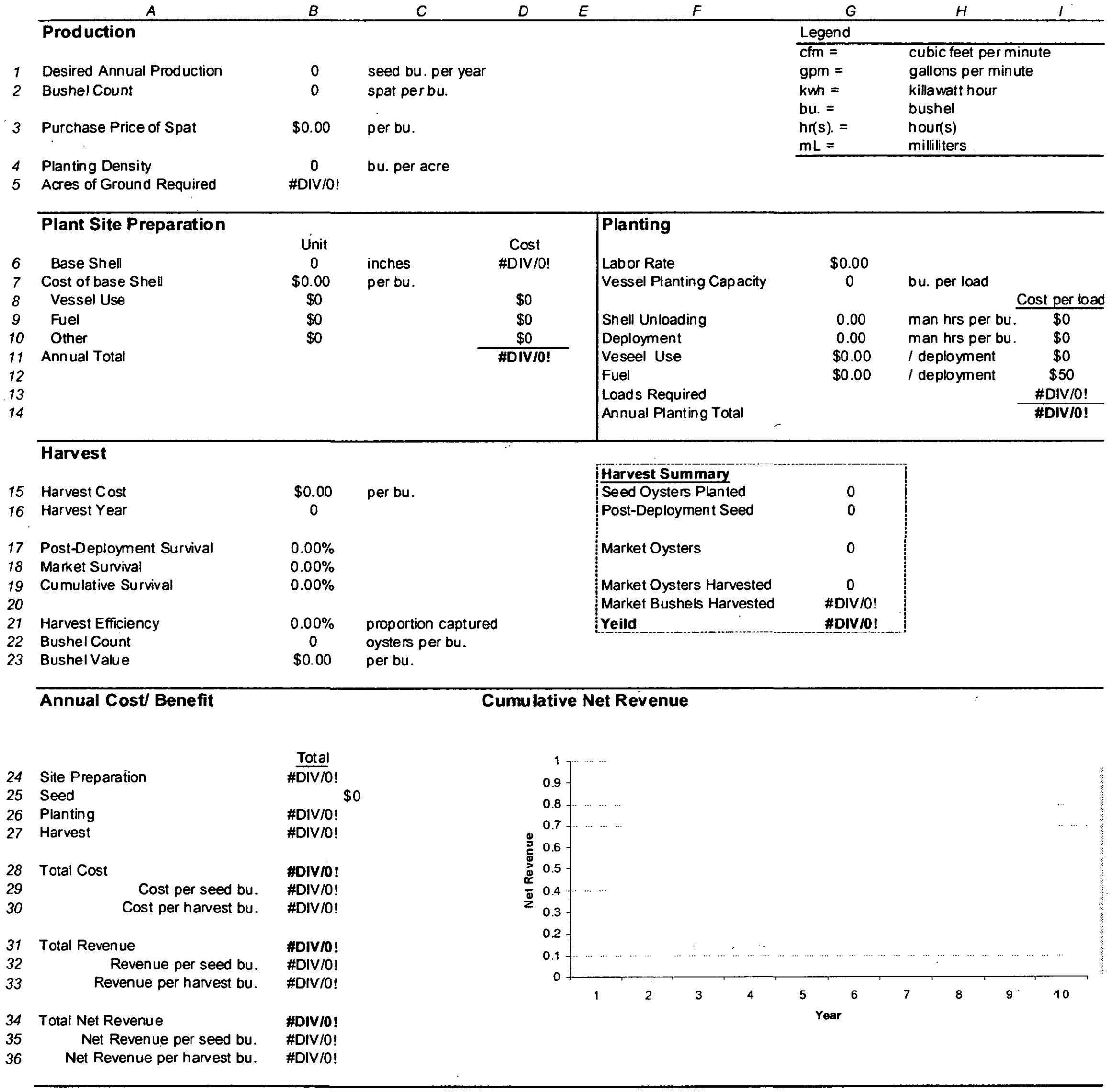
Per Bushel Revenue (**B32 & B33**): Revenue per seed bushel produced is displayed in cell B32. Revenue per harvested bushel is displayed in cell B33. As is the case with per bushel costs, revenue per harvested bushel is lower proportional to the yield.

Total Net Revenue (**B34**): Total annual net revenue, or profit, is displayed in cell B34.

Per Bushel Net Revenue (**B35-B36**): Net revenue per seed bushel is displayed in cell B35. Net revenue per harvested bushel is displayed in B36 and is lower proportional to the yield.

Cumulative Net Revenue: The cumulative net revenue figure displays cumulative net revenue over a 10 year period. Assuming parameterization is constant over a 10 year period, this figure displays the maximum investment that must be made during startup prior to any return, the year at which cumulative net revenue becomes positive, and the total net revenue accumulated over the 10 year period.

User Interface



A B C D E F G H I

Production

1	Desired Annual Production	0	seed bu. per year
2	Bushel Count	0	spat per bu.
3	Purchase Price of Spat	$0.00	per bu.
4	Planting Density	0	bu. per acre
5	Acres of Ground Required	#DIV/0!	

Legend
cfm = cubic feet per minute
gpm = gallons per minute
kwh = killawatt hour
bu. = bushel
hr(s). = hour(s)
mL = milliliters

	Plant Site Preparation	Unit		Cost	**Planting**			
6	Base Shell	0	inches	#DIV/0!	Labor Rate	$0.00		
7	Cost of base Shell	$0.00	per bu.		Vessel Planting Capacity	0	bu. per load	
8	Vessel Use	$0		$0				Cost per load
9	Fuel	$0		$0	Shell Unloading	0.00	man hrs per bu.	$0
10	Other	$0		$0	Deployment	0.00	man hrs per bu.	$0
11	Annual Total			**#DIV/0!**	Veseel Use	$0.00	/ deployment	$0
12					Fuel	$0.00	/ deployment	$50
13					Loads Required			#DIV/0!
14					Annual Planting Total			**#DIV/0!**

	Harvest			**Harvest Summary**	
15	Harvest Cost	$0.00	per bu.	Seed Oysters Planted	0
16	Harvest Year	0		Post-Deployment Seed	0
17	Post-Deployment Survival	0.00%		Market Oysters	0
18	Market Survival	0.00%			
19	Cumulative Survival	0.00%		Market Oysters Harvested	0
20				Market Bushels Harvested	#DIV/0!
21	Harvest Efficiency	0.00%	proportion captured	**Yeild**	**#DIV/0!**
22	Bushel Count	0	oysters per bu.		
23	Bushel Value	$0.00	per bu.		

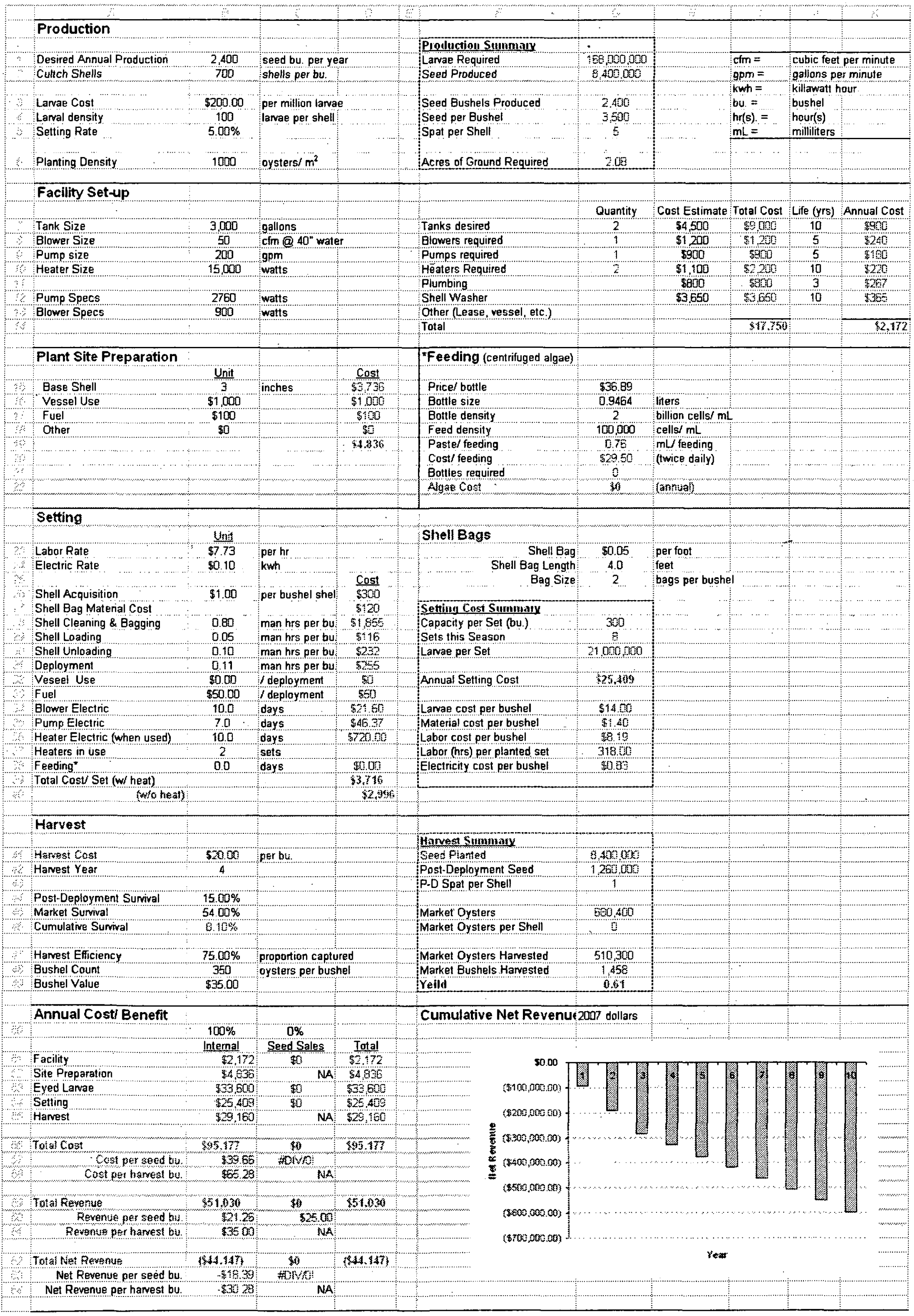
Annual Cost/ Benefit

		Total	
24	Site Preparation	#DIV/0!	
25	Seed		$0
26	Planting	#DIV/0!	
27	Harvest	#DIV/0!	
28	Total Cost	**#DIV/0!**	
29	Cost per seed bu.	#DIV/0!	
30	Cost per harvest bu.	#DIV/0!	
31	Total Revenue	**#DIV/0!**	
32	Revenue per seed bu.	#DIV/0!	
33	Revenue per harvest bu.	#DIV/0!	
34	Total Net Revenue	**#DIV/0!**	
35	Net Revenue per seed bu.	#DIV/0!	
36	Net Revenue per harvest bu.	#DIV/0!	

Cumulative Net Revenue

APPENDIX 4

Worst Case



Production

Desired Annual Production	2,400	seed bu. per year
Cultch Shells	700	*shells per bu.*
Larvae Cost	$200.00	per million larvae
Larval density	100	larvae per shell
Setting Rate	5.00%	
Planting Density	1000	oysters/ m²

Production Summary

Larvae Required	168,000,000
Seed Produced	8,400,000
Seed Bushels Produced	2,400
Seed per Bushel	3,500
Spat per Shell	5
Acres of Ground Required	2.08

cfm = cubic feet per minute
gpm = gallons per minute
kwh = killawatt hour
bu. = bushel
hr(s). = hour(s)
mL = milliliters

Facility Set-up

Tank Size	3,000	gallons
Blower Size	50	cfm @ 40" water
Pump size	200	gpm
Heater Size	15,000	watts
Pump Specs	2760	watts
Blower Specs	900	watts

	Quantity	Cost Estimate	Total Cost	Life (yrs)	Annual Cost
Tanks desired	2	$4,500	$9,000	10	$900
Blowers required	1	$1,200	$1,200	5	$240
Pumps required	1	$900	$900	5	$180
Heaters Required	2	$1,100	$2,200	10	$220
Plumbing		$800	$800	3	$267
Shell Washer		$3,650	$3,650	10	$365
Other (Lease, vessel, etc.)					
Total			$17,750		$2,172

Plant Site Preparation

	Unit		Cost
Base Shell	3	inches	$3,736
Vessel Use	$1,000		$1,000
Fuel	$100		$100
Other	$0		$0
			$4,836

*Feeding (centrifuged algae)

Price/ bottle	$36.89	
Bottle size	0.9464	liters
Bottle density	2	billion cells/ mL
Feed density	100,000	cells/ mL
Paste/ feeding	0.76	mL/ feeding
Cost/ feeding	$29.50	(twice daily)
Bottles required	0	
Algae Cost	$0	(annual)

Setting

	Unit		Cost
Labor Rate	$7.73	per hr	
Electric Rate	$0.10	kwh	
Shell Acquisition	$1.00	per bushel shel	$300
Shell Bag Material Cost			$120
Shell Cleaning & Bagging	0.80	man hrs per bu	$1,855
Shell Loading	0.05	man hrs per bu	$116
Shell Unloading	0.10	man hrs per bu	$232
Deployment	0.11	man hrs per bu	$255
Veseel Use	$0.00	/ deployment	$0
Fuel	$50.00	/ deployment	$50
Blower Electric	10.0	days	$21.60
Pump Electric	7.0	days	$46.37
Heater Electric (when used)	10.0	days	$720.00
Heaters in use	2	sets	
Feeding*	0.0	days	$0.00
Total Cost/ Set (w/ heat)			$3,716
(w/o heat)			$2,996

Shell Bags

Shell Bag	$0.05	per foot
Shell Bag Length	4.0	feet
Bag Size	2	bags per bushel

Setting Cost Summary

Capacity per Set (bu.)	300
Sets this Season	8
Larvae per Set	21,000,000
Annual Setting Cost	$25,409
Larvae cost per bushel	$14.00
Material cost per bushel	$1.40
Labor cost per bushel	$8.19
Labor (hrs) per planted set	318.00
Electricity cost per bushel	$0.83

Harvest

Harvest Cost	$20.00	per bu.
Harvest Year	4	
Post-Deployment Survival	15.00%	
Market Survival	54.00%	
Cumulative Survival	8.10%	
Harvest Efficiency	75.00%	proportion captured
Bushel Count	350	oysters per bushel
Bushel Value	$35.00	

Harvest Summary

Seed Planted	8,400,000
Post-Deployment Seed	1,260,000
P-D Spat per Shell	1
Market Oysters	680,400
Market Oysters per Shell	0
Market Oysters Harvested	510,300
Market Bushels Harvested	1,458
Yeild	**0.61**

Annual Cost/ Benefit

	100%	0%	
	Internal	Seed Sales	Total
Facility	$2,172	$0	$2,172
Site Preparation	$4,836	NA	$4,836
Eyed Larvae	$33,600	$0	$33,600
Setting	$25,409	$0	$25,409
Harvest	$29,160	NA	$29,160
Total Cost	$95,177	$0	$95,177
Cost per seed bu.	$39.66	#DIV/0!	
Cost per harvest bu.	$65.28	NA	
Total Revenue	$51,030	$0	$51,030
Revenue per seed bu.	$21.26	$25.00	
Revenue per harvest bu.	$35.00	NA	
Total Net Revenue	($44,147)	$0	($44,147)
Net Revenue per seed bu.	-$18.39	#DIV/0!	
Net Revenue per harvest bu.	-$30.28	NA	

Cumulative Net Revenue 2007 dollars

Best Case

Production

Desired Annual Production	2,400	seed bu. per year
Cultch Shells	700	shells per bu.
Larvae Cost	$200.00	per million larvae
Larval density	100	larvae per shell
Setting Rate	15.00%	
Planting Density	1000	oysters/ m²

Production Summary

Larvae Required	168,000,000
Seed Produced	25,200,000
Seed Bushels Produced	2,400
Seed per Bushel	10,500
Spat per Shell	15
Acres of Ground Required	6.23

cfm = cubic feet per minute
gpm = gallons per minute
kwh = killawatt hour
bu. = bushel
hr(s). = hour(s)
mL = milliliters

Facility Set-up

Tank Size	3,000	gallons
Blower Size	50	cfm @ 40" water
Pump size	200	gpm
Heater Size	15,000	watts
Pump Specs	2760	watts
Blower Specs	900	watts

	Quantity	Cost Estimate	Total Cost	Life (yrs)	Annual Cost
Tanks desired	2	$2,400	$4,800	10	$480
Blowers required	1	$900	$900	5	$180
Pumps required	1	$500	$500	5	$100
Heaters Required	2	$0	$0	10	$0
Plumbing		$300	$300	3	$100
Shell Washer		$1,800	$1,800	10	$180
Other (Lease, vessel, etc.)					
Total			$8,300		$1,040

Plant Site Preparation

	Unit		Cost
Base Shell	3	inches	$11,208
Vessel Use	$1,000		$1,000
Fuel	$100		$100
Other	$0		$0
			$12,308

*Feeding (centrifuged algae)

Price/ bottle	$36.89	
Bottle size	0.9464	liters
Bottle density	2	billion cells/ mL
Feed density	100,000	cells/ mL
Paste/ feeding	0.76	mL/ feeding
Cost/ feeding	$29.50	(twice daily)
Bottles required	0	
Algae Cost	$0	(annual)

Setting

	Unit		Cost
Labor Rate	$7.73	per hr	
Electric Rate	$0.10	kwh	
Shell Acquisition	$1.00	per bushel shel	$300
Shell Bag Material Cost			$120
Shell Cleaning & Bagging	0.14	man hrs per bu.	$325
Shell Loading	0.01	man hrs per bu.	$23
Shell Unloading	0.02	man hrs per bu.	$46
Deployment	0.01	man hrs per bu.	$23
Veseel Use	$0.00	/ deployment	$0
Fuel	$50.00	/ deployment	$50
Blower Electric	10.0	days	$21.60
Pump Electric	7.0	days	$46.37
Heater Electric (when used)	10.0	days	$720.00
Heaters in use	2	sets	
Feeding*	0.0	days	$0.00
Total Cost/ Set (w/ heat)			$1,675
(w/o heat)			$955

Shell Bags

Shell Bag	$0.05	per foot
Shell Bag Length	4.0	feet
Bag Size	2	bags per bushel

Setting Cost Summary

Capacity per Set (bu.)	300
Sets this Season	8
Larvae per Set	21,000,000
Annual Setting Cost	$9,083
Larvae cost per bushel	$14.00
Material cost per bushel	$1.40
Labor cost per bushel	$1.39
Labor (hrs) per planted set	54.00
Electricity cost per bushel	$0.83

Harvest

Harvest Cost	$2.50	per bu.
Harvest Year	2	
Post-Deployment Survival	85.00%	
Market Survival	39.00%	
Cumulative Survival	33.15%	
Harvest Efficiency	75.00%	proportion captured
Bushel Count	350	oysters per bushel
Bushel Value	$35.00	

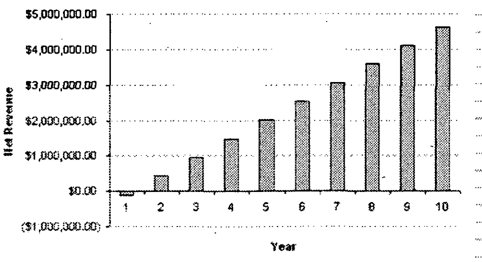
Harvest Summary

Seed Planted	25,200,000
Post-Deployment Seed	21,420,000
P-D Spat per Shell	13
Market Oysters	8,353,800
Market Oysters per Shell	5
Market Oysters Harvested	6,265,350
Market Bushels Harvested	17,901
Yeild	7.46

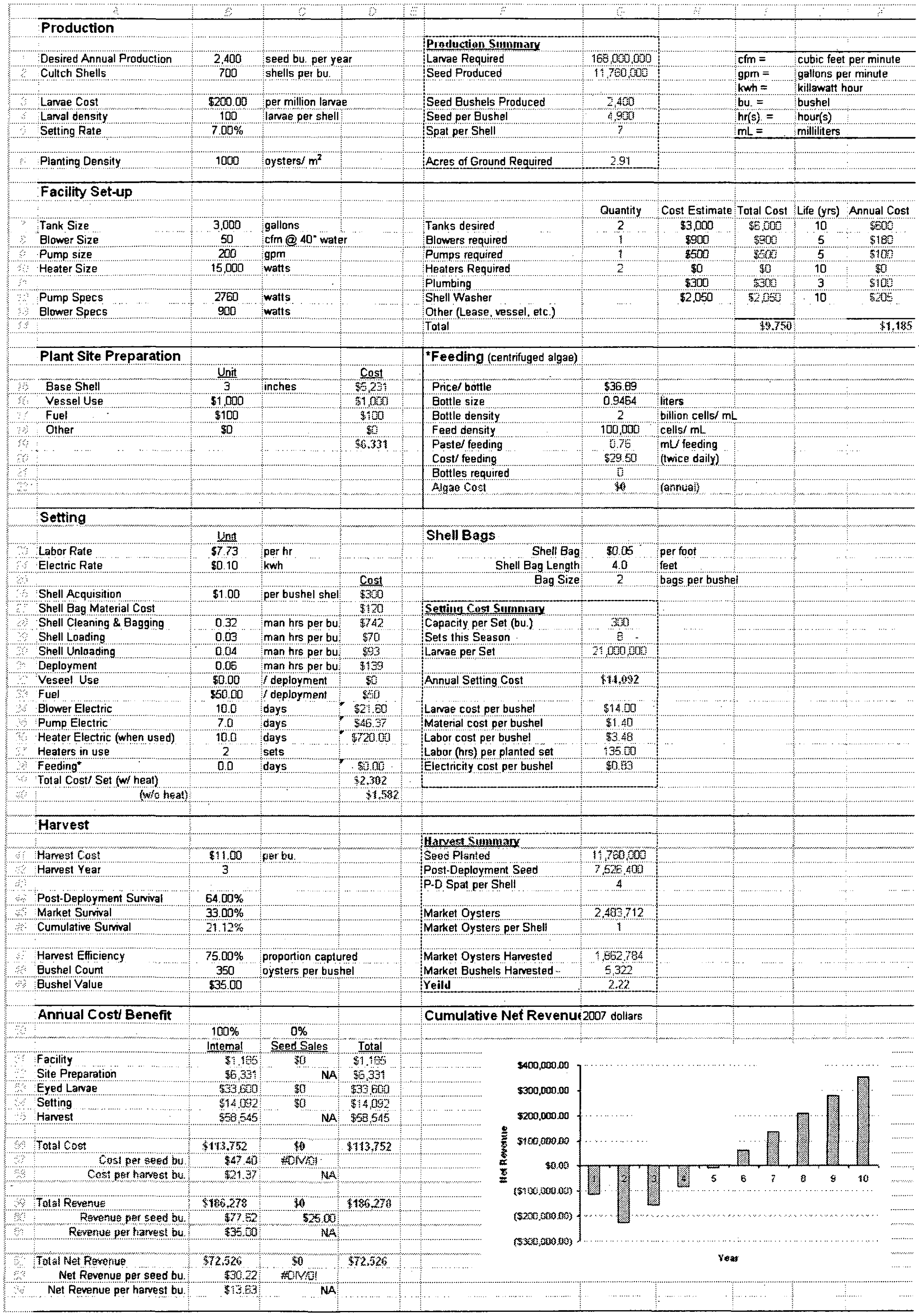
Annual Cost/ Benefit

	100%	0%	
	Internal	Seed Sales	Total
Facility	$1,040	$0	$1,040
Site Preparation	$12,308	NA	$12,308
Eyed Larvae	$33,600	$0	$33,600
Setting	$9,083	$0	$9,083
Harvest	$44,753	NA	$44,753
Total Cost	$100,784	$0	$100,784
Cost per seed bu.	$41.99	#DIV/0!	
Cost per harvest bu.	$5.63	NA	
Total Revenue	$626,535	$0	$626,535
Revenue per seed bu.	$261.06	$25.00	
Revenue per harvest bu.	$35.00	NA	
Total Net Revenue	$525,751	$0	$525,751
Net Revenue per seed bu.	$219.06	#DIV/0!	
Net Revenue per harvest bu.	$29.37	NA	

Cumulative Net Revenu 2007 dollars



Plausible



Production

Desired Annual Production	2,400	seed bu. per year
Cultch Shells	700	shells per bu.
Larvae Cost	$200.00	per million larvae
Larval density	100	larvae per shell
Setting Rate	7.00%	
Planting Density	1000	oysters/ m^2

Production Summary

Larvae Required	168,000,000
Seed Produced	11,760,000
Seed Bushels Produced	2,400
Seed per Bushel	4,900
Spat per Shell	7
Acres of Ground Required	2.91

cfm = cubic feet per minute
gpm = gallons per minute
kwh = killawatt hour
bu. = bushel
hr(s). = hour(s)
mL = milliliters

Facility Set-up

Tank Size	3,000	gallons
Blower Size	50	cfm @ 40" water
Pump size	200	gpm
Heater Size	15,000	watts
Pump Specs	2760	watts
Blower Specs	900	watts

	Quantity	Cost Estimate	Total Cost	Life (yrs)	Annual Cost
Tanks desired	2	$3,000	$6,000	10	$600
Blowers required	1	$900	$900	5	$180
Pumps required	1	$500	$500	5	$100
Heaters Required	2	$0	$0	10	$0
Plumbing		$300	$300	3	$100
Shell Washer		$2,050	$2,050	10	$205
Other (Lease, vessel, etc.)					
Total			$9,750		$1,185

Plant Site Preparation

	Unit		Cost
Base Shell	3	inches	$5,231
Vessel Use	$1,000		$1,000
Fuel	$100		$100
Other	$0		$0
			$6,331

*Feeding (centrifuged algae)

Price/ bottle	$36.89	
Bottle size	0.9464	liters
Bottle density	2	billion cells/ mL
Feed density	100,000	cells/ mL
Paste/ feeding	0.76	mL/ feeding
Cost/ feeding	$29.50	(twice daily)
Bottles required	0	
Algae Cost	$0	(annual)

Setting

	Unit		Cost
Labor Rate	$7.73	per hr	
Electric Rate	$0.10	kwh	
Shell Acquisition	$1.00	per bushel shel	$300
Shell Bag Material Cost			$120
Shell Cleaning & Bagging	0.32	man hrs per bu	$742
Shell Loading	0.03	man hrs per bu	$70
Shell Unloading	0.04	man hrs per bu	$93
Deployment	0.06	man hrs per bu	$139
Veseel Use	$0.00	/ deployment	$0
Fuel	$50.00	/ deployment	$50
Blower Electric	10.0	days	$21.60
Pump Electric	7.0	days	$46.37
Heater Electric (when used)	10.0	days	$720.00
Heaters in use	2	sets	
Feeding*	0.0	days	$0.00
Total Cost/ Set (w/ heat)			$2,302
(w/o heat)			$1,582

Shell Bags

Shell Bag	$0.05	per foot
Shell Bag Length	4.0	feet
Bag Size	2	bags per bushel

Setting Cost Summary

Capacity per Set (bu.)	300
Sets this Season	8
Larvae per Set	21,000,000
Annual Setting Cost	$14,092
Larvae cost per bushel	$14.00
Material cost per bushel	$1.40
Labor cost per bushel	$3.48
Labor (hrs) per planted set	135.00
Electricity cost per bushel	$0.83

Harvest

Harvest Cost	$11.00	per bu.
Harvest Year	3	
Post-Deployment Survival	64.00%	
Market Survival	33.00%	
Cumulative Survival	21.12%	
Harvest Efficiency	75.00%	proportion captured
Bushel Count	350	oysters per bushel
Bushel Value	$35.00	

Harvest Summary

Seed Planted	11,760,000
Post-Deployment Seed	7,526,400
P-D Spat per Shell	4
Market Oysters	2,483,712
Market Oysters per Shell	1
Market Oysters Harvested	1,862,784
Market Bushels Harvested	5,322
Yeild	2.22

Annual Cost/ Benefit

	100%	0%	
	Internal	Seed Sales	Total
Facility	$1,185	$0	$1,185
Site Preparation	$6,331	NA	$6,331
Eyed Larvae	$33,600	$0	$33,600
Setting	$14,092	$0	$14,092
Harvest	$58,545	NA	$58,545
Total Cost	$113,752	$0	$113,752
Cost per seed bu.	$47.40	#DIV/0!	
Cost per harvest bu.	$21.37	NA	
Total Revenue	$186,278	$0	$186,278
Revenue per seed bu.	$77.52	$25.00	
Revenue per harvest bu.	$35.00	NA	
Total Net Revenue	$72,526	$0	$72,526
Net Revenue per seed bu.	$30.22	#DIV/0!	
Net Revenue per harvest bu.	$13.83	NA	

Cumulative Net Revenu 2007 dollars

LITERATURE CITED

Abbe, GR. 1986. A review of some factors that limit oyster recruitment in Chesapeake Bay. American Malacology Bulletin, Special Edition, 1986.

Alford, JJ. 1975. The Chesapeake Oyster Fishery. Annals of the Association of American Geographers, Vol. 65, No. 2, p. 229-239.

Allen, SK Jr. Director – Aquaculture Breeding and Technology Center, Virginia Institute of Marine Science. Unpublished data.

Anderson, JL. 2002. Aquaculture and the fulture: Why fisheries economists should care. Marine Resource Economics: Vol. 17, p. 133-151.

Andersonbay.com – accessed 2008.

Andrews, JD. 1973. Effects of Tropical Storm Agnes on Epifaunal Invertebrates in Virginia Estuaries. Chesapeake Science, Vol. 14, No. 4, p. 223-234.

Baker, P 1994. Competency to settle in oyster larvae, *Crassostrea virginica*: wild versus hatchery-reared larvae. Aquaculture, Volume 122, Issues 2-3, p. 161-169.

Baylor, JB. 1870. Survey of oyster grounds in Virginia: report of J.B. Baylor to the governor of Virginia

Bisker, R and M Castagna, Predation on single spat oysters *Crassostrea virginica* (Gmelin) by blue crabs *Callinectes sapidus* Rathbun and mud crabs *Panopeus herbstii* Milne-Edwards. J. Shellfish Res. Vol. 6 p. 37–40.

Bonar, D. 1991. Cultchless oyster production and enhanced setting with Epinephrine and L-dopa. Remote setting and nursery culture for shellfish growers, p.14-21.

Bonar, DB, SL Coon, M Walch, RM Weiner, W Fitt. 1990. Control of oyster settlement and metamorphosis by endogenous and exogenous chemical cues. Bulletin of Marine Science 46: 484-489.

Bosch, DJ and LA Shabman. 1990. Reversing the decline of private oyster planting in the Chesapeake Bay: An evaluation of policy strategies.

Budge, WW. 1973. Method and package for storing and shipping oyster larvae. U.S. Patent 3,735,737.

Burke, RD. 1983. The induction of marine invertebrate larvae: stimulus and response. Canadian Journal of Zoology 61: 1701-1719.

Calvo, LMR, GW Calvo, EM Burreson. 2003. Dual Disease resistance in a selectively bred eastern oyster, *Crassostrea virginica* (Gmelin), strain tested in Chesapeake Bay. Aquaculture 220: 69-87

Cardenas, B and A Aranda. 2007. Differences in the exploited oyster (*Crassostrea virginica* (Gmelin, 1791)) populations from different coastal lagoons of the Gulf of Mexico. Transitional Waters Bulletin 2(2007), 21-35.

Carriker, MR. 1961. Interrelation of functional morphology, behavior, and autecology in early stages of the bivalve *Mercenaria mercenaria*. Journal of the Elisha Mitchell Scientific Society 77:168-241.

Castagna, M, MG Gibbons, K Kurkowski. 1996. Culture: Application. Ch.19 from The Eastern Oyster: *Crassostrea virginica*. A Maryland Sea Grant Book.

Coakley, JM. 2004. Growth of Easter Oyster, *Crassostrea Virginia*, in Chesapeake Bay. Master of Science 2004. University of Maryland, College Park.

Coon, SL, DB Bonar, RM Weiner. 1985. Induction of settlement and metamorphosis of the Pacific oyster *Crassostrea gigas* (Thunberg) by L-dopa and catecholamines. Journal of Experimental Marine Biology and Ecology.

Coon, SL and DB Bonar. 1986. Chemical production of cultchless oyster spat using epinephrine and norepinephrine. Aquaculture 58: 255-262.

Cranfeild, HJ. 1973. Observations on the function of the glands of the foot of the pediveliger of *Ostrea edulis* during settlement. Marine Biology. Vol 22:3.

Crisp, DJ. 1967. Chemical factors inducing settlement in *Crassostrea virginica* (Gmelin). Journal of Animal Ecology. 36:329-335.

Crowley, B. 1996. Taking Ownership; Property Rights and Fishery Management on the Atlantic Coast. Halifax: Atlantic Institute for Market Studies, 1996.

Dame, RF, E Koepfler, L Gregory. 2002. Benthic-Pelagic Coupling in Marsh-Estuarine Ecosystems. Concepts and Controversies in Tidal Marsh Ecology: 10.1007/0-306-47534-0.

Dugas, RJ. 1977. Oyster distribution and density on the productive portion of the state seed grounds in southeastern Louisiana. LDWF, Technical Bulletin . No. 23, 27p.

Dungan, CF, RM Hamilton, KL Hudson, CB McCollough, and KS Reece. 2002. Two epizootic diseases in Chesapeake Bay commercial clams, *Mya arenaria* and *Tagelus plebeius.* Diseases of Aquatic Organisms, Vol. 50: 67-78.

Engle, CR and N Stone. 1996. Baitfish production enterprise budget. Southern Regional Aquaculture Center. SRAC Pub. No. 122.

Fisher, Robert. Fisheries/ Seafood Technology Specialist, Virginia Sea Grant Program. Personal communication.

Frank-Lawale, A. Breeding Research Manager – Aquaculture Breeding and Technology Center, Virginia Institute of Marine Science. Unpublished data.

Gallager, SM and R Mann. 1986. Growth and survival of larvae of *Mercenaria mercenaria* (L.) and *Crassostrea virginica* (Gmelin) relative to broodstock conditioning and lipid content of eggs. Aquaculture 56:2, pp. 105-121.

Galtsoff, PS. 1964. The American oyster, *Crassostrea virginica* (Gmelin). Fishery Bulletin. US Fish and Wildlife Service. U. S. 64:1480.

Greene, J and R Grizzle. 2005. Oyster (*Crassostrea virginica* Gmelin) restoration studies in the Great Bay estuary, New Hampshire. Final Report for NOAA award number: NA03NOS4200060.

Guo, X, GA DeBrosse, SK Allen. 1996. All-triploid Pacific oysters (*Crassostrea gigas* Thunberg) produced by mating tetraploids and diploids. Aquaculture 142: 3-4, p 149-161.

Hargis, WJ Jr. and DS Haven. 1995. Chesapeake oyster reefs, their importance, destruction, and guidelines for restoring them. Oyster reef habitat restoration: a synopsis and synthesis of approaches: CH.23, p. 329-358

Hargis, WJ Jr. and DS Haven. 1988. The Imperiled Oyster Industry of Virginia. Special Report No. 290, Virginia Institute of Marine Science.

Henderson, B. 1983. Handling and remote setting techniques for Pacific oyster larvae *Crassostrea gigas* (Thunberg). Master's Thesis, O.S.U., Eugene OR, 33p.

Hidu, H. 1969. Gregarious settling in the American oyster *Crassostrea virginica* (Gmelin). Chesapeake Science 10:85-92.

Hidu, H and HH Haskin. 1971. Setting of the American oyster related to environmental factors and larval behavior. Proceedings from the National Shellfisheries Association 61:35-50.

Hidu, H. WG Valleau, and FP Veitch. 1978. Gregarious setting in European and American oysters: response to surface chemistry versus waterborne pheromones. Proceedings National Academy of Sciences 68: 11-16

Jones, C. 1978. Improved yield of domestic and imported oyster seed. Washington Department of Fish and Wildlife. Completion Report 19p.

Jones, G and B Jones. 1988. Advances in the remote setting of oyster larvae. British Columbia Ministry of Environment, Marine Resources Branch, Info. Report # ISSN 0-7718-8627-6, 88p.

Keck, R, D Maurer, JC Kauer, WA Sheppard. 1971. Chemical stimulants affecting larval settlement in the American Oyster. Proc. NSA. Vol 61 p.24-28.

Kemp, PS, N Bullock, J Militano, T Osborne, D Schmidt. 2006. Oyster hatchery manual: protocols for North Carolina oyster hatchery operations. Carter Community College Aquaculture technology Program. Written for the North Carolina Legislative oyster hatchery program. Dec. 2006.

Kennedy, VS. 1980. Comparison of recent and past patterns of oyster settlement and seasonal fouling in Broad Creek and Tred Avon River, Maryland. Proceedings from the National Shellfisheries Association. 70:36-46.

Kirby, MX and OF Linares. 2004. Fishing down the coast: Historical expansion and collapse of oyster fisheries along continental margins. Proc. National Shellfisheries Association, Vol. 101, No. 35, p. 13096-13099

Kirby, MX and HM Miller. 2004. Response of a benthic suspension feeder (*Crassostrea virginica* Gmelin) to three centuries of anthropogenic eutrophication in Chesapeake Bay. Estuarine, Coastal, and Shelf Science 62 (2005) 679-689.

Krantz, GE and JV Chamberlin. 1978. Blue crab predation on cultchles oyster spat. Proc. National Shellfisheries Association, 68:38-41.

Degremeont, L. Former Breeding Research Manager – Aquaculture Breeding and Technology Center, Virginia Institute of Marine Science. Unpublished data.

Lund, DS. 1972. Laboratory studies on the setting of the Pacific oyster (*Crassostrea gigas* Thunberg*)*. Master's Thesis, Oregon State University, Corvallis, OR., 85*p.*

Lutz, RA, H Hidu, and KG Drobeck. 1970. Acute temperature increase as a stimulus for setting in the American Oyster, Crassostrea virginica (Gmelin). Proceedings from the National Shellfisheries Association. 60:68-71.

Mackin, JG and SH Hopkins. 1961. Studies on oyster mortality in relation to natural environmental and oil fields in Louisiana. Publication of the Institute of Marine Science University, Texas, 7:3-131.

Melancon, EJ. 1990. Environmental and economic influences on the oyster fishery of lower Barataria Bay Louisiana. Ph. D. Dissertation, Lousianna State University, Baton Rouge, LA, 155p.

Melancon, E and R Condrey. 1992. Economics of a Lousianna oyster seed bedding fishery and influences of lease yield on expenses to operate. Journal of Shellfish research. 11(3): 143-147

Merriner, JV and JW Smith. 1979. A report to the oyster industry of Virginia on the biology and management of the cownose ray (*Rhinoptera bonasus* Mitchill) in lower Chesapeake Bay. VIMS Sea Grant program: Special report in applied marine science and ocean engineering No. 216.

Merrit, DW. 2008. Hatchery Program Director – Horn Point Laboratory, University of Maryland Center for Environmental Science.

Meyers, RA, JK Baum, TD Shepherd, SP Powers, CH Peterson. 2007. Cascading effects of the loss of apex predatory sharks from a coastal ocean. Science 315: 1846-1850.

Murray, TJ and MJ Oesterling. 2008. Virginia shellfish aquaculture situation and outlook report: Results of 2007 Virginia shellfish aquaculture crop reporting survey. Virginia Sea Grant Marine Extension Program. VSG-08-02

National Marine Fisheries Service. Landings data accessed 2007.

National Research Council (NRC) Committee on Nonnative oysters in the Chesapeake Bay. 2004. Nonnative oysters in the Chesapeake Bay. The National Academies Press

Nelson, TC. 1953. Some observations on the migrations and setting of oyster larvae. Proceedings from the National Shellfisheries Association, 43:99-104.

Newell, RIE. 1998. Ecological changes in Chesapeake Bay: Are they the result of overharvesting the American oyster, *Crasoostrea virginica*? Understanding the Estuary: Advances in Chesapeake Bay research. Conference proceedings. March 1988.

Newell, RIE, JC Cornwell, and MS Owens. 2002. Influence of simulated bivalve biodeposition and microphytobenthos on sediment nitrogen dynamics: A laboratory study. Limnology and Oceanography., 47(5), 2002, 1367–1379.

Newell, RIE, GS Alspach, Jr., VS Kennedy, D Jacobs. 2000. Mortality of newly metamorphosed eastern oysters (*Crassostrea virginica* Gmelin) in mesohaline Chesapeake Bay. Marine Bio 136: p. 665-676.

Newell, RIE and CJ Langdon 1996. Mechanisms and physiology of larval and adult feeding. *In:* V.S. Kennedy, R.I.E. Newell and A.F. Eble, (eds). The Eastern Oyster *Crassostrea virginica.* Maryland Sea Grant College, University of Maryland, College Park, Maryland. pp. 185-229.

Nosho, TY and KK Chew. 1991 Remote setting and nursery culture for shellfish growers. Washington Sea Grant Workshop Record. 68p.

Oesterling, Michael. Fisheries/ Aquaculture Specialist, Virginia Sea Grant Program. Personal communication.

Officer, CB. TJ Smayda, and R Mann. 1982. Benthic filter feeding: A natural eutrophication control. Marine Ecology Progress Series, Vol. 9: 203-210.

Penn State Cooperative Extension. 1994. Agricultural alternatives: Enterprise budget analysis. The Pennsylvania State University.

Perret WS and MF Chatry. 1998. The Louisiana oyster fishery: industry and management confront a changing environment. Journal of shellfish research 7(2): 303-308.

Porch, CE, CA Wilson, and DL Nieland. 2002. A new growth model for red drum (Sciaenops ocellatus) that accommodates seasonal and ontogenic changes in growth rates. Fishery Bulletin 100(1) p149-152.

Porter, ET, JC Cornwell, LP Sanford. 2004. Effect of oysters *Crassostrea virginica* and bottom shear velocity on benthic-pelagic coupling and estuarine water quality. Marine Ecology 2004, vol. 271, pp. 61-75.

Riepe, JR, L Swann, PB Brown. 1993. Analyzing the profitability of striped bass cage culture. Aquaculture extension, Illinois-Indiana Sea Grant. Pub No. IL-IN-SG-FS-92-IS.

Ritchie, TP and RW Menzel. 1969. Influence of light on larval settlement of American oysters. Proceedings from the National Shellfisheries Association. 59:116-120.

Roegner, GC 1991. Temporal analysis of the relationship between settlement and early recruitment in the oyster Crassostrea virginica (Gmelin). Journal of Experimental Marine Biology and Ecology, 151:57-69.

Roegner, GC, R Mann. 1995. Early recruitment and growth of the American oyster, Crassostrea virginica (Bivalvia: Ostreidae) with respect to tidal zonation and season. Marine Ecology Progress Series, 117:91-101.

Rothschild, BJ, JS Ault, P Goulletquer, M Heral. 1994. Decline of the Chesapeake Bay oyster population: a century of habitat destruction and overfishing. Marine Ecology Progress Series 111: 29-39

Shpigel, M, BJ Barber, and R. Mann. 1992. Effects of elevated temperature on growth, gametogenesis, physiology, and biochemical composition in diploid and triploid Pacific oysters, *Crassostrea gigas* Thunberg. Journal of Exp. Mar. Bio. and Eco. 161: 15-25.

Southworth, M, AT Legget, AJ Erskine, R Mann. IN PREP. Evaluation of triploid *Crassostrea virginica* for on bottom culture in Chesapeake Bay. Virginia Institute of Marine Science.

Supan, JE, CA Wilson, KJ Roberts. 1999. Economics of augmentation of natural production using remote setting techniques. In Luckenbach, MW, R Mann, and JA Wesson (Eds.). Oyster reef habitat restoration: a synopsis and synthesis of approaches. Virginia Institute of Marine Science Press, Gloucester Point, VA: CH.24, p. 359-356.

Swartz, FJ and DG Cargo. 1960. Recent Records of the Xanthid Crab, *Panopeus herbsti*, from Maryland and Virginia Waters. Chesapeake Science, Vol. 1, No. 3/4, p. 201-203.

Tobash-Alexander, S. Oyster Hatchery Manager – Horn Point Laboratory, University of Maryland Center for Environmental Science. Unpublished data.

Virginia Marine Resources Commission. Landings Bulletin 1973 – 2007.

Virginia Marine Resources Commision. Application for transfer of oyster planting ground.

Vrginia Cooperative Extension Farm Management Staff. 2001. Swine budget: Farrow to finish, weekly farrowing. Virginia Cooperative Extension.

Von Bertalanffy, L. 1938. A quantitative theory of organic growth (Inquires on growth laws. II). Human Biology a record of research. Vol.10, No.2 p.181-213.

Wallace, RK, FS Rikard, and JC Howe. 1999. Optimum Size for planting hatchery produced seed. Final Technical Report. Grant No. NA86RG0073. Auburn University Marine Extension and Research Center.

Wang, H, W Huang, MA Harwell, L Edmiston, E Johnson, P Hsieh, K Milla, J Christensen, J Stewart, X Liu. 2008. Modeling oyster growth rate by coupling oyster population and hydrodynamic models for Apalachicola Bay, Florida, USA. Ecological Modeling, Vol. 211:1-2. p.77-89.

Weibull, W. 1951. A statistical distribution function of wide applicability. J. Appl. Mech-Trans. ASME. 18(3). P. 293-297.

Weiland, R. 2006. Operating Costs in the Chesapeake Bay Oyster Fishery. Main Street Economics publication.

Weiner, RM, AM Segall, and RR Colwell. 1985. Characterization of marine bacterium associated with Crassostrea virginica. Applied Environmental Microbiology. 49:83-90.

Wells, WF. 1920. Growing oysters artificially, Conservationist. 3: 151.

Wesson, J. 2008. Head of oyster conservation and replenishment. Virginia Marine Resources Commission. Personal communication.

Wheatley, JJ. 1959. The economic implications of the York River oyster industry. Charlottesville, Bureau of Population and Economic Research, University of Virginia. 119p.

VITA

Michael Spohn Congrove

Born in Salisbury, Maryland, March 12, 1982. Graduated from Kecoughtan High School, Hampton, Virginia in 2000. Earned a B.S. in Biology from Old Dominion University, Norfolk, Virginia, in 2004. Worked as the oyster restoration assistant for Chesapeake Bay Foundation, Annapolis, Maryland in 2004 and 2005. Worked as manager of the *Crassostrea ariakensis* aquaculture field trials for the Virginia Seafood Council, Gloucester Point, Virginia in 2005 and 2006. Entered the Master of Science program at the Virginia Institute of Marine Science, College of William and Mary, in 2006. Accepted a position as hatchery manager of Oyster Seed Holdings, LLC, Gwynn's Island, Virginia in 2008.