Chapter 1

General Introduction

The domestication of our current farm animal species, and thus direct or indirect selection for desired characteristics, started 10 000 to 12 000 years ago (Simm 2000). From the 1930s/1940s, genetic improvement of modern breeds increased markedly. Robert Bakewell pioneered breeding programs in the mid-1700s using systematic selection utilising production records from performance recording, and progeny testing. Since the start of genetic improvement in the 1930s/1940s, the productivity of farm animals has increased by approximately 200% (pigs) and 300% (chickens) in volume (Gjedrem 2005).

Although aquaculture also has a long history, genetic improvement in aquaculture species is in its infancy when compared to livestock breeding programs. In addition, basic genetic and phenotypic parameters for economically important traits have been lacking (Gjedrem 2005). However, these issues are now being addressed and progress has been made (For example, see studies by Sheridan 1997; Benzie 1998; Ward et al. 2000; Gjedrem 2005; Ward et al. 2005; Appleyard and Ward 2006; Appleyard et al. 2006?). The reproductive biology of aquaculture species allows rapid genetic improvement. Breeding programs have recently been initiated internationally for several fish species. The first large scale artificial selection program was for Norwegian (Atlantic) salmon and commenced in the mid-1970s. This breeding program has been very successful; increasing productivity by around 175% (Gjedrem 2005).

Sydney rock oysters are an important commodity in Australia. However, these have historically been produced from wild-harvested spat. In 2005-06, the gross value of Australian aquaculture was $748 million. Oysters (predominately SROs) made up 82% of the total NSW aquaculture production in tonnes, with their value being 76% of the total value of NSW aquaculture production ($45 million ABARE 2007).

Breeding programs are necessary to maintain and/or increase this level and value of SRO production. Gjedrem (2005) ranked the most important traits for aquaculture farming to be included in a breeding goal as growth rate, disease resistance and quality traits. Outbreaks of disease and the aim of better productivity have led to breeding programs being implemented for SROs. The NSW DPI breeding program for Sydney rock oysters (SROs) commenced in 1990, initially selecting oysters exclusively for weight gain (fast growth) at Port Stephens, NSW. After the diseases of winter mortality (*Bonamia roughleyi*) and QX disease (*Marteilia sydneyi*) caused mortalities in the Georges River, this breeding program was expanded to incorporate selection for fast growth with improved disease resistance in 1997 (Nell and Perkins 2006). The most important issues have been the slow growth of SROs when competing with the faster growth of Pacific oysters, and the disease threats of Winter mortality and QX disease. Other traits considered important to this industry were shell shape and colour, and meat condition. However, the relative importance of all these traits has not been quantified.

The aims of this thesis were:

- To summarise literature related to SROs as well as to examine oyster breeding programs, with particular reference to the SRO breeding program.
- To characterise the current SRO industry of Eastern Australia and obtain production and economic data.
- To formally derive breeding objectives for a SRO breeding program by estimating economic values for SRO traits, and thus the importance of selected lines, to the SRO industry.
- To compare some breeding program alternatives and predict genetic gain and inbreeding for, using simulation.

To provide the necessary background information, a comprehensive review of the literature regarding both Australian and overseas studies of aquaculture species, particularly oysters, were provided in Chapter 2. The biology of the SRO was examined with reference to its implications for the development of a breeding program. Challenges which affect both SROs and other oyster species were discussed. Genetic improvement in regards to these challenges through selection requires knowledge of genetic parameters, in addition to economic weights for the most commercially important traits as determined by industry. Although rapid genetic improvement is possible in oysters, this must be balanced with inbreeding, to avoid any deleterious effects of inbreeding depression. Finally, the progress of current Australian and international oyster breeding programs were reviewed.

In the absence of solid economic data and trait economic values, a survey was conducted to characterise the current SRO industry and obtain production and economic data (Chapter 3). The survey identified the production systems practiced and the level of production for each respondent. Sale age and weight, proportion of grade classes sold and oyster condition and mortality levels constituted the production figures. Economic data consisted of returns and costs associated with each enterprise. Returns included sale destination and prices received for each grade class which enabled the development of price differentials. Costs associated with the SRO production systems included spat collection, grading, depuration and sale costs. The above values were then used to develop economic models for calculating trait economic values. Additional comments gained from respondents from the survey included the importance of several SRO traits and the importance of, and demand for, the SRO selected lines.

The basis for calculating economic weights is presented in Chapter 4. The main traits of interest were growth rate and mortality (and so disease resistance). Additional traits examined were shell shape and strength along with meat condition and colour. The relative importance of each trait and their estimated economic values were discussed. In addition, the definition and measurement alternatives, and so implementation issues, of these additional traits were considered. Lastly, the constraints to the calculation of these economic values were discussed.

In Chapter 5, simulation was used to further investigate how the population size and structure, sex ratio and trait heritability affect breeding program outcomes. The rate of response to selection for a single trait under mass selection in a closed population, along with the accompanying rate of inbreeding, formed the basis for comparisons. This selection method reflects the current SRO program. The scenarios tested examined different breeding structures which could plausibly be employed within the SRO breeding program. Factors that were varied included the number of separate lines maintained in the population; population size; trait heritabilities; and the proportion of males to females used as parents.

Chapter 2

Literature Review

2.1 Introduction

Aquaculture is one of Australia's fastest growing industries, worth an estimated $732 million in 2003-04 and employing over 4 000 people and of these, 926 were employed in New South Wales (ABARE 2004; ABARE 2005). This is an increase over the last decade of $238 million (an average annual growth rate of 4%). In New South Wales (NSW), the value of aquaculture production increased from $48.6 million in 2002-03 to $49.6 million in 2003-04. This rise was mainly the result of a $3.2 million boost from 2001-02 in wild (excluding hatchery production) edible oyster production value, worth $37.9 million in NSW in 2003-04. Edible oyster production makes up the majority of the value of the $49.6 million NSW aquaculture production (ABARE 2005).

The most important edible oyster in Australia has historically been the Sydney rock oyster (SRO: *Saccostrea glomerata,* formerly *Saccostrea commercialis*) (Toro et al. 1996; Brown et al. 1997) and is mainly (98%) (Brown et al. 1997; Dadswell 2002) consumed on the domestic market as an appetiser in the half-shell, either raw (50%) or cooked (Nell 2001b). Grades are primarily determined by oyster size, although meat quality is also considered important (Witney et al.

2001). Grades for SROs, assuming meat condition is acceptable, vary from Bottle (35g, shell height 66mm) to Bistro (45g, shell height 73mm) to Plate (50g, shell height 77mm) (Nell 2001b) for the fresh (half shell) and frozen and processed markets. Similarly, Tasmanian Pacific oysters are graded into categories based on upper shell height. Specifically Bistro (50-60mm), Buffet (60-70mm), Standard (70-85mm), Large (85-100mm), Jumbo (100-120mm) and Super Jumbo (120-150mm) (Ruello 2006, http://www.tasea.com.au/pacific_oysters.htm accessed 12 February 2007). TASEA Enterprises further classes POs by three quality categories: export, premium and thrifty (Ruello 2006).

Sydney rock oysters have been commercially farmed since around 1870 (Anon 1997). The SRO industry enjoyed consistent growth from the 1950's to the 1970's. Production increased rapidly from approximately 6 000t whole weight/year to around 8 400t whole weight annually (Nell 1993). During the 1980's, production declined due to the introduction of Pacific oysters into traditional SRO growing areas (e.g. Port Stephens), pollution, disease and toxic algal blooms (Brown et al. 1997) and the introduction of depuration (R. Tynan 2007, pers. comm., 12 February). From 1991-92, the industry slowly declined to produce 4 844t in 1995-96 (Brown et al. 1997), mainly due to increasing quality assurance program costs, the SROs slow growth rate (Nell 2006a) as well as losses through disease (Witney et al. 2001), before increasing again to 9 855t in 2002-03. Australian SRO production now (2004-05) sits at 4 583t (>$34 million) (O'Sullivan et al. 2007).

During the 1990's, Pacific oyster (*Crassostrea gigas)* production in NSW, Tasmania (TAS), South Australia (SA) and Victoria (VIC) increased from $11 million (2 300t) to $24 million (5 000t). In 2002/2003, the Pacific oyster overtook SROs in terms of quantity produced (Pacific oyster 6 687t; SRO 4 902t), although the SRO still had the overall highest value (Pacific oyster $30.3 million; SRO $33.3 million). The production of other edible oysters (e.g. native or flat oysters: *Ostrea angasi*; milky oyster: *Saccostrea cucullata* previously *S. amasa,* and the black lipped oyster: *S. echinata*; (Witney et al. 2001)) in QLD, TAS and Western Australia (WA) varied from $153 000 (48t) in 1990-91 to $95 000 (26t) in 1994-95 and $108 000 (35t) in 1995-96 (Brown et al. 1997).

Constraints to management practices for SROs include the variable, uncontrolled environment in which SROs are farmed. For example, medication is impractical to control disease or parasites and artificial feeding is not routinely practised. The seasonal nature of production limits marketing of all oyster species, including SROs, due to a decrease in body condition after spawning. The main biological threats to farmed SRO production are the Pacific oyster, disease and pests, pollution such as acid sulfate leachate (Dove and Ogburn 2003), toxic algal blooms and heat kill (Witney et al. 2001). Introduced marine species such as starfish, seaweed, fan worms and crabs also pose a threat (Brown et al. 1997). Production threats include quality assurance (consumer safety), marketing that fails to differentiate between oyster species, limited lease space and poor efficiency of production (Brown et al. 1997), along with increasing permit fees and lease charges (Nell 2005). In addition, further SRO growth is hindered by derelict leases, undercapitalisation of farms and competition for suitable lease sites (Brown et al. 1997).

2.1.1 Aim

The overall aim of this review was to summarise current knowledge of, and results from, aquaculture breeding programs, predominantly oyster breeding programs. A breeding program is already in place for the Sydney rock oyster, with the focus currently on fast growth and resistance to Winter mortality and QX diseases. Other aspects of genetic improvement, including breeding objectives, candidate evaluation and selection, genetic parameters, economic weights, and response to selection and implications for inbreeding were reviewed.

2.2 The Sydney rock oyster

Oysters are filter feeding bivalve molluscs which feed mainly on algae, bacteria and nutrients from the surrounding water (Anon 2005a). Their sedentary nature as adults means that their survival and growth is very dependant on settling, or being farmed, at the appropriate location. The native SROs naturally range from the temperate conditions near the Victorian/NSW border (37°S) through to the subtropical waters in northern NSW and southern Queensland, and the tropical waters of Townsville (19°S) (Nell 2001a). A relatively small proportion of Shark Bay (WA) SROs are also grown at Albany, WA (35°S), where there is a small hatchery (Nell 2005). Sydney rock oysters are farmed in estuarine areas and rivers. Brown et al. (1997) reported that most SRO farming occurred on leases located at Wallis Lake, Port Stephens and the Hawkesbury River. However, due to recent outbreaks of QX in 2004 and 2005, the SRO population in the Hawkesbury river has been severely reduced (Anon 2004; Hopwood 2005; Nell 2006a).

Nell (2001b) reported that no genetic differences have been observed across SRO populations, although SROs from WA have not been directly compared with those from NSW and QLD. New Zealand rock oysters are also the same species as SROs (Anderson and Adlard, 1994, cited in Nell 2001b). This is because New Zealand oyster stocks were imported into Australia to replenish depleted native oyster stocks in NSW around 1888 (Roughley 1922, cited in Nell 2001b). These different populations (Australian and New Zealand) have probably interbred which may be the reason for the lack of genetic differences in Australian SROs between locations.

When SROs are sexually mature and at their prime eating quality, the majority of the body tissue consists of the gonad, a large plump white area (Figure 2.1).

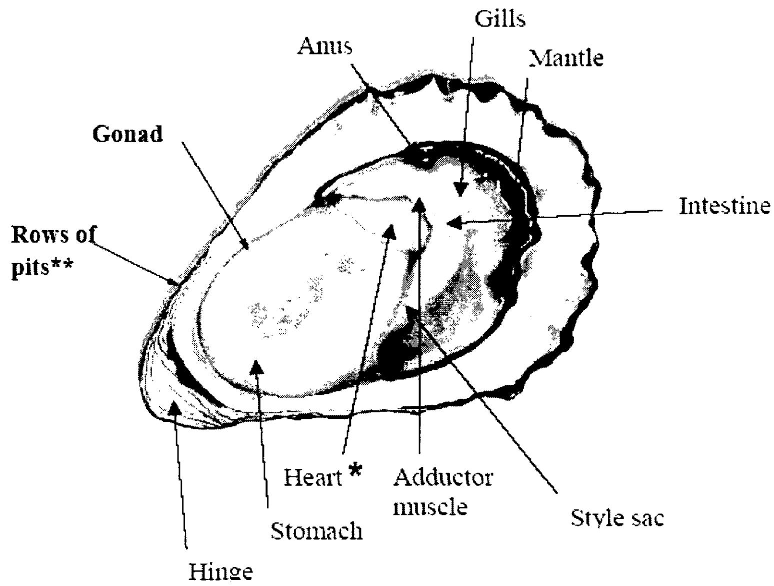

Figure 2.1 Photo of a SRO with annotated body parts
*: the heart (not visible) is located under the "slow" portion of the adductor muscle
**: the rows of pits on the lower shell associated with the hinge are exclusive to SROs
Source: adapted from Witney et al. (2001)

Sydney rock oysters frequently spawn in summer when water temperatures are between 21-23°C (Witney et al. 2001), around the same time as the November to January spawning season of Pacific oysters at Port Stephens (W. O'Connor 2007, pers. comm., 12 March). Spawning of SROs occurs within the first year of age, commonly as a male, with subsequent spawnings for some oysters as a female (Anon 2005a). Thus, similar to the Pacific oyster (Guo et al. 1998), the proportion of female oysters in the population is expected to gradually increase with age.

Although the SRO is able to change sex (termed protandric dioecy), the sexes are separate and fertilisation is external (Heasman and Lyall 2000). Functional hermaphrodites (1.1–1.8%) and oysters with no gametes before the spawning season (0.6%) were present in low numbers in a study of Pacific oysters (Guo et al. 1998)

Similar to the studies by Hayley in the late 1970's Guo et al. (1998) concluded from their study of Pacific oysters that the uneven sex ratio as the oysters age differed between families. Their study, using two of the four test families with adequate data, found that the phenotypic sex ratio between females and males on average changed from $37\%_f$:$63\%_m$ at one year of age to $55\%_f$:$45\%_m$ and $75\%_f$:$25\%_m$ in the second and third years, respectively. However, they also found that the sex ratio was influenced strongly by paternal effects (i.e. there were low female ratio and high female ratio sires), while maternal effects were very low. Similarly, Ward et al. (2005) reported a significant difference in sex ratios for the Pacific oyster. These authors found that of the 11 families in F3 lines, one family had female bias (93.9%) while the other 10 had male bias (mean: 92.8%) at between 23-27 months of age (April 2003). The latter may be the result of a delayed protandric transition from male to female, although Ward et al. (2005) hypothesised that this was primarily due to environmental factors as the oysters may not have reached their second spawning season in April. Although there is a lack of scientific publications for the SRO, anecdotal evidence suggests that there is a similarity in sex ratio changes between the species.

The change in sex ratio with age has implications for breeding programs, as the proportion of male SROs will decrease with age, resulting in an excess of female oysters when breeding occurs at a later age. In contrast, Guo at al. (1998) found some PO sire families had an increased proportion of females to males (50.8 – 60.4%) which was unusual at one year of age. This may allow for manipulation of sex ratios in broodstock populations as males can either have the hypothesised genotype MF (males that remain as males) or FF (males that change to females) whereas permanent females can only be of the FF genotype (Guo et al. 1998).

The increased performance, in terms of growth rate, of female oysters may also lead to altered sex ratios under selection (Baghurst and Mitchell 2002, cited in Ward et al. 2005). The improved performance of the females over the males is not thought to be solely related to the development of the gametes. Honkoop (2003) reported that the difference between sexes in the physiological costs of maintaining or growing soma and gonads or oxygen consumption was not significant in the period of data collection (March 2000 to January 2002).

As oysters do not have secondary sexual characteristics (Guo et al. 1998), sex determination was generally conducted on live animals by retrieving gametes and examining them microscopically. Until recently, this procedure could not be implemented on live SRO since opening generally caused destruction (Nell 2006a). However, protocols now exist for anaesthesia, so sex can be determined in SROs without significant losses (W. O'Connor 2007, pers. comm., 9 March). The study by Ward et al. (2005) further manipulated the breeding program through the spawning of males for the cryogenic storage of their semen to later produce progeny from 'selfed' crosses. This strategy was used to develop inbred lines.

An adult female can produce 20 million eggs per spawning, with males producing many times more spermatozoa (Heasman 2003). Both sexes are serial spawners and as such may spawn several times in a season, although the level of success at each spawning has not been reported. This characteristic could be used when developing a SRO breeding program: for example, to develop structured mating groups. Fertilisation occurs externally and development continues for 3-4 weeks as young planktonic larvae or "trochophore" (Figure 2.2 \Witney, 2001; Anon, 2005a) before the veliger larvae of the oyster become sessile after settling as spat, mainly on shell, rocks and mangrove roots in intertidal estuarine habitats. The surviving oysters, with commonly less than 0.1% survival rate in the wild (Anon 2005a), then grow to maturity where they have settled. In the hatchery, epinephrine is used to facilitate spat settlement as individual "cultchless" oysters (W. O'Connor 2007, pers. comm., 9 March; Heasman, 2000). Unselected (i.e. sourced from wild spatfall) farmed SROs have previously taken an average of 3½ years to reach Plate size (40-60g whole weight). This has now been reduced to an average 2½ years through selection for growth rate (Nell 2005) and rearing of single seed oysters settled in this way.

2.2.1 The influence of biological characteristics on breeding program development and practical management

Limitations of the life and reproduction cycles should be identified when developing breeding programs. Currently, the biggest limitation to producing structured matings or commercial quantities of spat is the lack of knowledge on the reproductive biology and physiology of the

SRO. For example, there has been no literature found on the extent to which reproductive success may vary with age or over spawnings within season. The reproductive lifespan has not been confirmed, since most oysters are sold when they reach commercial market size. However, 10 year old 'pet' SROs are known of (W. O'Connor 2007, pers. comm., 9 March) and 'pet' Pacific oysters had been grown for "several years" (Ward et al. 2005). Mass mortality occurs in young oysters and has been quantified generally. However, the pattern of mortality with age and the average age of death has not been reported.

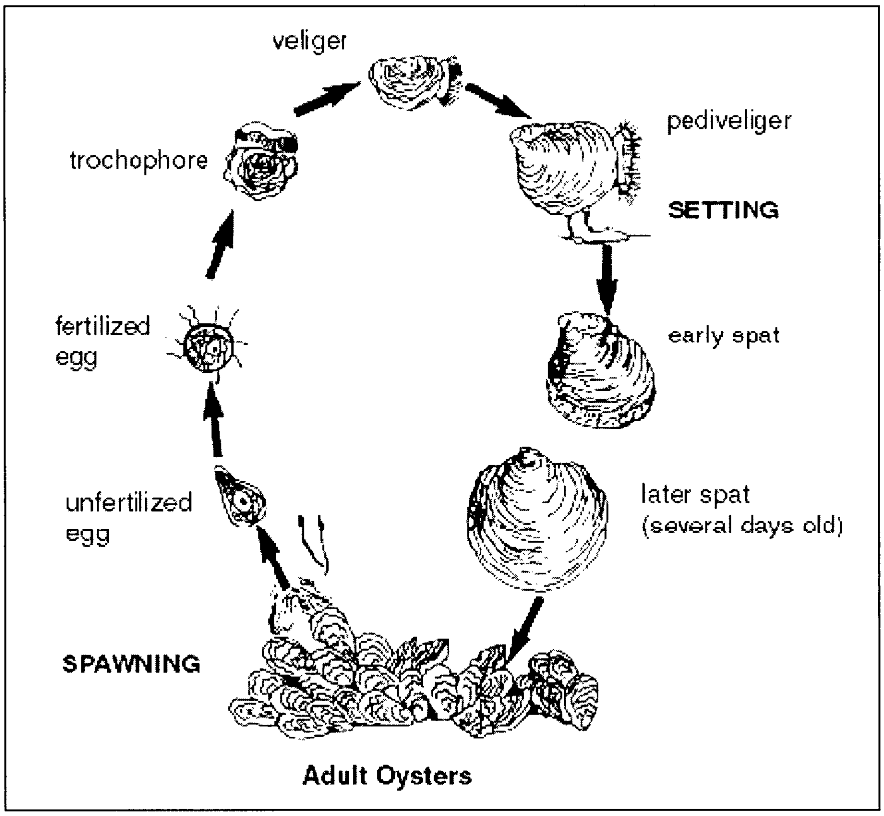

Figure 2.2 Life cycle of the Eastern oyster Crassostrea virginica
Source: Wallace (2001)

The ability of the SRO to survive lengthy periods out of the water provides advantages over the Pacific oyster for management (i.e. raising the oysters above the water for mudworm control), as well as for transport and shelf life. Sydney rock oysters survive 2-3 weeks out of water compared to 7-10 days for Pacific oysters (PIRSA 2000; Nell 2001b). These differences in the ability to remain out of water are due to the stronger adductor muscle of the SRO, and may be an adaptation to the region and tides where the oyster species evolved.

2.3 Threats and challenges facing the SRO: diseases and pests

2.3.1 Oyster diseases and pests

Unlike the relatively controlled nature of most intensive livestock production systems, oyster production systems (not including hatchery production) are subject to variable environmental conditions. Therefore, management practices commonly used in livestock industries are difficult to implement in oysters. For example, control of disease with antibiotics is impractical for oyster stocks. In addition, the identification of both major SRO diseases can only occur while the oysters are still alive (i.e. when oysters succumb to disease and die the shell soon becomes empty) using expensive laboratory testing. Therefore, cause of deaths can be difficult to establish and assumptions are usually made as to cause of death when it has been shown that the disease is present in a particular location. The following sections expand on the current and potential diseases and pests affecting oysters.

2.3.1.1 Winter mortality

Winter mortality (WM) caused by *Bonamia roughleyi*, previously thought to be *Mikrocytos roughleyi* (Nell 2003), was first detected in the Georges River, NSW, in the early 1920s (Roughley, 1926, cited in Nell 2001b). Disease outbreaks by this haplosporidian parasite occur annually, but are patchy with varying degrees of severity within the range from Port Stephens and south to the Victorian border. The number of oysters dying from WM greatly varies between years, estuaries and between and within leases. Survival of oysters when affected by WM can be as low as 20% (Smith et al. 2000). The disease mostly affects older oysters in their 3rd winter, just before reaching market size, although severe outbreaks can also kill spat (Nell 2001b). Winter mortality infection occurs in winter but the resulting mortality may not occur until summer, when temperatures increase. Nell (2001b) stated that even when oysters do not have one of these diseases, a mortality rate of 10% occurs. Natural selection pressure against WM is thought to be variable due to the patchy nature of WM (Heasman 2004).

The aetiology of *Bonamia roughleyi* is not fully known, although it is thought that direct transmission between oysters is possible (Benzie et al. 2002). Winter mortality can be managed and ameliorated by farming methods. These include raising oyster growing height and/or moving oysters upstream from autumn to spring. Alternatively, oyster farmers can reduce the impact of

WM on their business (but not control the disease) by selling larger oysters in their 3rd winter before disease onset.

2.3.1.2 QX disease

QX disease ('Queensland unknown': *Marteilia sydneyi*) was first reported in the 1970's in QLD (Brotohusodo 2005). The disease occurs in the warmer, northern parts of the SRO range, occurring in southern Queensland and a number of estuaries in NSW to the Clarence River and the Georges River (Nell 2001a). The lifecycle of this parasite (also a haplosporidian) is thought to include an intermediate host. The latest research suggests that the intermediate host may be a species of marine 'bristle' worms (polychaetes) (Fisheries 2007).

QX infection usually occurs in summer and while deaths occur year round, they are typically concentrated in autumn. Outbreaks of QX disease caused a large number of oysters to perish and were a major cause of the large production decline in the 1970s (Nell 1993; Nell 2001b). QX disease has caused a production drop of 56% in the Tweed, Richmond and Clarence Rivers in northern NSW over the last 26 years (Nell 2001b). In addition, Nell (2001b) reported that QX disease killed up to 90% of SROs per annum in the Georges River and has generally made oyster farming unviable in this area.

Microscopic examination of live animals is necessary to confirm diagnosis for QX and there is no cure for the disease (Witney et al. 2001). However, it has been suggested that, as Phenoloxidase is associated with disease suppression, the inhibition of Phenoloxidase activity may be a precursor for lethal infection of oysters by the QX disease pathogen (Peters and Raftos 2003; Bezemer 2004).

2.3.1.3 MSX disease

A disease similar to QX (MSX: Multinucleated Sphere Unknown) associated with infection by *Haplosporidian nelsoni* affects Eastern oysters (*Crassostrea virginica)* on the American east coast between May and July (Ewart and Ford 1993). In 1957 the disease was responsible for causing 90-95% mortality in lower Delaware Bay (Ewart and Ford 1993). The method of transmission is not known (Ewart and Ford 1993). Wild oysters were found to be naturally resistant to the disease, through restriction of infection and tolerance of the parasites (Ewart and Ford 1993). This ability to acquire resistance through natural selection has been subsequently exploited through artificial selective breeding programs, initially by Haskin and Ford (1979, cited in Nell 1993).

2.3.1.4 Dermo disease

Dermo disease (caused by *Perkinsus marinus* formerly thought to be *Dermocystidium marinum*) affects Eastern oysters in American waters and has not been reported for SRO or PO in Australia. Death from Dermo results from extensive lysis (rupture and destruction of a cell through damage to the outer membrane) of the tissues and blockage of major blood vessels within a couple of months of exposure. Oysters are infected with Dermo from May to October (Spring through to Autumn) with deaths occurring from July to October (Ewart and Ford 1993). The disease was originally thought to be caused by the fungus *Dermocystidium marinum*, hence its common name Dermo (Ewart and Ford 1993). The lifecycle of this fungus is known. Thus, artificial transmission and therefore infection has been possible in the laboratory and the field (Ewart and Ford 1993). This has allowed the implementation of controlled selection programs, for example by Calvo et al (2003), for dual disease resistance to MSX and Dermo. Selected Delaware Bay oysters showed a 34-61% reduction in mortality and a lower incidence and intensity of Dermo compared to the control line (Calvo et al. 2003).

2.3.1.5 Mudworm

Several species of mudworm (including *Polydora websteri*) affect most estuaries across the SRO range annually (W. O'Connor 2007, pers. comm., 9 March). Large numbers of oysters were killed by mudworms in 1895, which was the single largest cause of production decline at this time (Smith 1981/82, cited in Nell 2001b).

The mudworm invades the inside of most commercially grown mollusc species and forms a mud blister, mainly on the inside of the shell (Nell 2001b). Healthy, rapidly growing oysters can cover the worm and its mud patch with shell and so eliminate the worm, but weaker oysters may die. The energy, which would otherwise be used for growth, is diverted into fighting the parasite (Wargo and Ford 1993). "Oyster losses are often high and remaining infested oysters are unsaleable due to their poor condition and unsightly and foul smelling blisters, which rupture easily when the oysters are opened" (Nell 2001b). Wargo and Ford (1993) reported that in Delaware Bay the prevalence of mudworm blisters in one-year-old and two-year-old Eastern oysters were 56% and 94% respectively, and mean blister coverage was 4.1% and 14.7% of shell area respectively when assessed by image analysis. Blister coverage was defined as the total area of blisters on the inside of the right (flat) on the total area of the valve. Thus, in some locations, mudworm can cause significant problems for oyster sales.

Mudworm "is mainly controlled by management practices, mostly those which increase drying out at low tide" (Nell 2001a). However, reducing the time spent submerged also reduces the oysters feeding time, and therefore potentially growth rates, so care must be taken with these farming techniques. It has not been reported whether the selectively bred fast growth SROs also have reduced levels of mudworm infestation.

2.3.1.6 Pacific oysters

The Pacific oyster (*Crassostrea gigas*) is a native of Japan and is now the most widely farmed shellfish in the world. These extremely fertile oysters were intentionally introduced into TAS, VIC, WA and SA (Anon 2005b) in the 1940s as they were hardy, had fast growth and were highly fecund, allowing easy harvesting of spat (Anon 2005c).

Pacific oysters were later found in Port Stephens in 1984 (Holliday and Nell 1985, cited in Nell 2001b) and have been commercially farmed at Port Stephens since 1991. Their introduction was possibly through illegal deliberate planting or through contaminated SRO stock movement (Anon 2005b). However, they have now been declared a noxious pest in all other areas of NSW waters (Anon 2005a), because of their fecundity and its associated detrimental effects on farming costs. In NSW the spread of the Pacific oyster via transfers of stock from Port Stephens has become a major problem for stick culture SROs, and possibly other oyster species (Brown et al. 1997).

High fecundity combined with fast growth of Pacific oysters creates significant overcatch problems, similar to that which occurs with mussels and barnacles (Nell 1993), for farmed oysters and other shellfish. Pacific oysters are virtually impossible to contain in areas suitable for its growth and reproduction (Anon 2005c). Pacific oysters are also resistant to the two main diseases that affect SROs: Winter mortality and QX disease (Nell 2001b), as well as being resistant to MSX disease and Dermo disease, which affect the Eastern oyster (Crassostrea virginica Baker 1996) in the USA. However, Pacific oysters do succumb to mudworm infestation (O'Sullivan and Savage 2004).

The majority of the Australian Pacific oyster industry is single-seed (Heasman et al. 2000) hatchery-based, which allows for the ready implementation of genetic improvement programs (Ward et al. 2000). The ease of implementation of hatchery based breeding programs is likely to be a reflection of their fecundity in the wild. Selective breeding of Pacific oysters began in 1994/1995 (Nell 2001b), taking advantage of the genetic variation that exists in Tasmania's farmed and wild Pacific oyster stocks. Superior lines of oysters that are higher-yielding, faster growing and more uniform have since been developed (Bennett 2002). The breeding program will enable the superior lines of Pacific oysters to be made commercially available through Australian Seafood Industries Pty Ltd (ASI). Mass selection and family selection (between or within: based in the production of pedigreed lines) programs have been established for this breeding program (Ward et al. 2000).

The main threats from Pacific oysters to SROs are the reduced time taken for Pacific oysters to reach market size: 2.5 vs. 3.5 years, the ease of hatchery production of Pacific oysters and the problem of Pacific oyster overcatch (a problem for all oyster farmers). The fast growth and disease resistance of Pacific oysters makes for ease of production, thereby reducing costs for potentially larger profits. However, overcatch can increase production costs and SROs are perceived to be a superior oyster species for eating fresh.

2.4 Genetic improvement

Genetic improvement is the practice of altering traits through the use of selective breeding to further develop the quantity and/or quality of commercially important products in the most production-efficient manner. In contrast to most primary production (livestock) programs, aquaculture breeding programs have been slow to be developed and implemented (Gjedrem 1998). Genetic improvement programs are currently in place for salmon, trout and other fish species, as well as prawns (Benzie 1998) but in shellfish breeding programs are limited mainly to Pacific and Eastern oysters and abalone, with SRO breeding programs in their early stages.

2.4.1 The development of breeding programs

Breeding programs are used to achieve the breeding objective, which may incorporate changing one or several economically important traits. The response gained (expressed either per year or per generation) from selection in a population depends on the selection intensity, accuracy of selection and the generation interval. Genetic changes are permanent and cumulative (Smith 1984), and are especially desirable where management interventions cannot achieve necessary changes in a cost effective manner.

The success of any breeding program partially depends on the reproductive attributes of the species, understanding of operational limitations to selection, as well as market knowledge and estimation of economic values. Like many aquaculture species, SROs have high fecundity and the capacity for short generation intervals, since they start spawning at 1 year of age. Compared to traditional livestock species, these reproductive characteristics of oysters potentially allow for fast genetic progress. However, lack of individual identification and its associated limitations, along with the excess of females compared to males in the SRO population may limit progress. In addition, the current difficulties associated with strip spawning for controlled pair mating in SROs may also limit the degree to which breeding structures can be manipulated. Gjerde (1986) had previously suggested that the limited use of artificial reproduction techniques and controlled mating have constrained aquaculture development. These restrictions have largely been overcome for many aquaculture species but remain a constraint to SRO breeding.

Generally, there are nine steps to be implemented when developing a breeding program, as defined by Harris et al. (1984). These include:

1. Description of the biology and production system (discussed in Section 2.2.1)
2. Formulation of breeding objectives (Section 2.4.2)
3. Choice of breeding system and species (species already defined)
4. Estimation of genetic parameters and economic weights
5. Design of animal evaluation system (partially discussed in Section 2.2.1)
6. Development of selection criteria (traits)
7. Mating design for selected animals
8. Design system for expansion (to facilitate economically viable and effective dissemination)
9. Comparison of alternative breeding programs (run through steps 1-8 with different scenarios). The main costs for breeding programs lie in obtaining phenotypic measurements and possibly animal or family identification.

These steps are addressed in the current review, where possible.

2.4.2 Breeding objectives

Breeding objectives are developed to maximise long-term profit at the commercial level of production. Therefore the traits currently selected for in the SRO breeding programs, such as growth rate and disease resistance, are those which are economically important to commercial farmers. Breeding objectives are usually formulated to maximise the economic return per animal unit or per area unit, or can also be to minimise the cost per unit of product (Simm 2000). A general formulation of the profit function for SROs is:

$$\text{Profit} = \text{SRO}(n) \times (\text{meat grade} \times \$/\text{grade} - \$\text{cost per oyster})$$

Objectives are intended to improve the average phenotype through improving average genetic merit, thereby increasing productivity and/or and product quality, or reducing costs, for increased profit.

The selection index provides a score of the overall genetic merit whereby the importance of each trait is weighted by its relevant economic value. The selection index provides an efficient way of ranking animals when multiple traits are included in the breeding objective. Ranking animals on their index will identify the most genetically superior animal with regards to the complete breeding objective, rather than an animal that is just superior for one or two traits (for example).

2.4.3 Selection

Selection is based on specific selection criteria (measurements) that provide information towards the breeding goal (Simm 2000). These measurements may be for traits included in the breeding goal or for correlated traits, providing direct and indirect information respectively. Selective breeding exploits the genetic variation of the population and involves selecting specific superior individuals to be used as parents of the subsequent generation. The chosen individuals should possess the desirable phenotype (or predicted breeding value) for one or many traits. Allen et al. (1993) reports that most selection efforts in shellfish have been conducted through mass selection. This simply relies on the animals own phenotype instead of more accurate assessment of the underlying genotypes typically established through use of additional information from relatives and correlated traits.

Selection criteria can be either direct or indirect. A direct selection criterion is based on selecting an animal using measurements on the specific trait(s) of interest (i.e. breeding objective trait). Indirect selection occurs when genetic change is obtained for one trait when a different but genetically correlated trait is the basis for selection. Typical characteristics of effective indirect selection criteria include 1) an ability to be measured earlier in life and/or without sacrifice; 2) they may be easier or cheaper to measure; or 3) the response to selection may be higher than under direct selection which would make its use more efficient (especially when the indirect trait has a higher heritability). However, although there is a desire for early predictors of harvest size, there was little information on the correlations between growth traits at different ages in aquaculture in the mid-1980s (Shultz 1986, cited in Lymbery 1999). More recent research has addressed this deficit to some extent.

2.4.4 Methods of selection

There are a number of different selection methods that can be used in a breeding program and each is suited to particular species and/or traits. The selection program ultimately implemented depends on cost, operational constraints, complexity, trait heritabilities, genetic variation, selection intensity, population size and the ability to identify individuals.

2.4.4.1 Mass (individual or phenotypic) selection

Mass selection involves selecting individuals for breeding based solely on their own performance (individual phenotype). In aquaculture breeding programs, particularly for oysters, selection programs have been largely restricted to mass selection programs (Gjerde et al. 1996 and Villanueva et al. 1996, cited in Gjerde 2002 and Guo 1994). Mass selection was generally practised because of lack of control during 'mating'/spawning, corresponding lack of pedigree records, and difficulty in identifying individuals or indeed families (Bentsen and Gjerde 1994). As better control over mating and the verification of parentage become available, other selection methods also become available.

Selection can accelerate the build-up of inbreeding and resulting inbreeding depression and a loss of genetic variation (and thus a reduced response to selection) when few parents have been used in each generation. However, a non-selected population could also experience inbreeding. Inbreeding is difficult to manage, particularly when pedigree is not known (Gjedrem 1998).

Strategies must be planned to reduce inbreeding or minimise loss of heterozygosity (Ward et al. 2000). A method to reduce the likelihood of inbreeding in mass selection breeding programs is to use many pairs of parents, compare them through a limited number of progeny (Gjedrem 1998) and control parental representation in selected offspring. Inbreeding is dependent on effective population size (see Section 2.4.8).

Mass selection becomes more efficient than combined selection (see Section 2.4.4.3) as heritability increases (Gjedrem 1998). In this scenario, mass selection often leads to fast genetic gain, usually due to the high selection intensity. Mass selection is also relatively cheap and simple when compared to family-based or pedigree selection programs (Heasman 2004). However, the risk of inbreeding increases under mass selection with increasing heritability. Further, this selection method can only be used for traits measured without sacrifice on the live animal (Heasman 2004), such as growth rate. Mass selection is therefore limited in applicability and can not include traits with low heritability, traits which require destructive (sacrificial) measurements, or traits requiring long-term data collection. In addition, to be accurate candidates must be able to be measured at the same time.

2.4.4.2 Family selection

Family selection involves selection of individuals using family phenotypes (Simm 2000). Between family selection involves selecting broodstock based on family means. Within family selection is based on the performance within a family; whereby individuals are selected according to their superiority over their within family mean. Between family selection to improve traits such as shell shape has been used in the genetic improvement of the Pacific oyster (Ward et al. 2000). When trait heritability and genetic variation of the trait are low, or when the trait requires measurement on other animals (e.g. meat weight or survival), this method is more effective than mass selection. However, family selection requires increased investment, and incurs higher operational costs and data recording when compared to mass selection. As it is difficult to tag individual oysters, family selection may be more useful where families can be reared in separate tanks until they reach a suitable size to implement individual identification (mainly for fish species), or strategies such as DNA testing for parentage verification. However, the challenge here is to distinguish between the effects of family and environmental effects, such as those of tank effects.

2.4.4.3 Combined selection designs

A selection program (e.g. for growth rate) can be implemented using combined selection which incorporates both within and between family selection. The need to select only a restricted number of individuals from each family is of more importance in a combined selection program compared to mass selection (Bentsen and Gjerde 1994). Gjedrem (1998) stated that mass selection is recommended if only one trait is to be selected for. However, if the breeding goal contains several traits that cannot all be measured on the candidates for selection, it was necessary to use a combined selection.

2.4.4.4 Best Linear Unbiased Prediction (BLUP)

Selection programs utilising BLUP methodology to estimate genetic merit for individuals are widely used in livestock species, but have historically been rarely used in aquaculture due to the difficulty in obtaining individual identification. Selection programs using BLUP estimated breeding values (EBVs) are more expensive than alternatives but allow higher selection accuracy and faster genetic gains, especially for traits of low heritability (Elliot et al. 1999). In addition, information from relatives and correlated traits can contribute to EBVs (and allow selection) which is useful for traits measured on the dead animal/carcase traits (e.g. meat quantity and quality traits, or disease resistance). Selection is also possible across generations or environments. Selection based on BLUP EBVs can give more focused, consistent results and progress/response to selection can be more rapid than mass selection programs (Heasman 2004). This method of evaluation becomes increasingly important with decreasing trait heritabilities, or where measurement is limited. Gall and Baker (2002) state that any expense associated with maintaining a pedigree should be recovered through net gain from improved accuracy of selection.

Pedigree information is needed to estimate genetic parameters such as heritabilities and genetic correlations. In addition, pedigree information provides genetic links between tanks or sites, allowing for determination of, and if necessary adjustment for, environmental effects. Knowing the pedigree of individual oysters can also allow better monitoring of inbreeding. Maintaining individual identification and accompanying performance data and pedigree enables the selection and use of the most genetically superior individuals for breeding. Gall and Baker (2002) reported that genetic gain for 98-day body weight in tilapia over three generations was approximately 40% higher per generation than the control when selection was based on BLUP EBVs. This response was much larger than previous studies using mass selection techniques in tilapia (Hulata et al. 1986, Hershberger et al. 1990, cited in Gall and Bakar 2002) and twice as much as previous studies using family selection in salmonoids (Kincaid et al. 1977 and Hershberger et al. 1990, cited in Gall, 2002). Haggar ((1991, cited in Gall and Bakar 2002) suggested that selection based on mixed model EBV was superior to phenotypic selection by approximately 25% when heritability was low.

However, to accurately select superior individual animals we must be able to identify individual animals or families and accurately measure the traits of interest without major expense. Individual tags have been used in previous oyster experiments (for examples, see Jarayabhand and Thavornyutikarn 1995; Toro et al. 1996; Honkoop 2003). Individual identification allows the management of family structures, which is important to reduce the chance of inbreeding (Gjedrem 1998). However, it is highly unlikely that individual tagging will be implemented in SRO breeding programs due to the cost, impracticality and lack of technology.

Pedigrees can also be determined by the analysis of DNA, which facilitates the extra benefits of allowing the mixing of oysters from different families (to minimise tank effects), thereby increasing accuracy of genetic evaluation and therefore selection. These benefits should lead to higher genetic gains. However, for DNA analysis to be useful for parentage evaluation, suitable markers must be developed. Genetic markers for parentage verification have been used in fish breeding programs (Gall and Bakar 2002). However, individual oysters must still be identified through the use of tags, otherwise desired parents could not be selected.

2.4.5 Estimates of genetic parameters

Reliable estimates of genetic and phenotypic parameters are necessary to be able to plan breeding programs, predict response to selection and estimate breeding values (Gjerde 1986). In addition, estimates of genetic parameters, such as heritability (Table 2.1), genetic correlations and genetic variance, can be used to optimise breeding programs through tailoring program designs. However, few parameter estimates have been reported until recently for shellfish species, especially oysters. This is largely due to the inability to identify individuals and therefore provide pedigree data for parameter estimation. Further, the use of mass selection programs means that accurate parameters were not generally required.

Table 2.1 Heritability estimates for traits in other aquaculture species

(fs: full sib design; hs: half sib design; O/mP; Offspring-midparent regression)

Species	Trait	Heritability	Design	Source
Prawn (*P. japonicus*)	Weight at 185 days	0.21-0.41	34fs	K
(*P. monodon*)	6 week length	0.08-0.56	hs	L
(*P. vannamei*)	Survival to Taura Syndrome Virus (disease resistance)	0.2-0.3	hs, fs	M
Chilean blue mussel (*Mytilus chilensis*)	Larval growth to day 10 Larval growth to day 25 Spat growth to day 40	0.51±0.20 0.38±0.33 0.84±0.45	hs	J
Sea urchin (Strongylocentrotus intermedius)	Whole weight at 8 months Whole weight at 10 months Whole weight at 12 months Diameter at 8 months Diameter at 10 months Diameter at 12 months Height at 8 months Height at 10 months Height at 12 months	0.53±0.07 0.33±0.05 0.36±0.05 0.37±0.05 0.42±0.06 0.40±0.06 0.40±0.06 0.32±0.05 0.32±0.05	hs + fs	N
Pacific oyster (*Crassostrea gigas*)	Larval survival whole weight (18 months) shell weight (18 months) wet meat weight (18 months) wet meat: whole weight	0.31±0.06 0.33±0.19 0.32±0.30 0.37±0.20 0.46±0.22	fs fs fs fs fs	A
	Wet meat weight at commercial harvest size	0.20	hs	B
American oyster (*Crassostrea virginica*)	Larval growth rate: to 6 days Larval growth rate: to 16 days	0 – 0.46 0.08 – 0.25	fs, hs	C
	Larval growth rate: to 6 days Larval growth rate: to 16 days	0.09 – 0.51 0.50 – 0.60	fs, hs	D
	Larval growth rate: to 14 days	0.24		I
European oyster (*Ostrea edulis*)	Whole weight: 6 months Whole weight: 18 months Shell height: 6 months Shell height: 18 months	0.14±0.12 0.24±0.20 0.11±0.04 0.19±0.07	O/mP O/mP	E
	Whole weight (after 1 generation) Whole weight (after 2 generations)	0.39 - 0.72 0.16 - 0.22	Realised heritabilities	F
Chilean native oyster (*Ostrea chilensis*)	Whole weight (Up lines) Whole weight (Down lines)	0.43±0.18 – 0.69±0.11 0.24±0.06 – 0.35±0.08	Realised heritabilities from divergent selection lines	G
Common Rock oyster (*Saccostrea cucullata*)	Growth rate	0.28±0.006	Parent/offspring regression	H

Sources: K. (Hetzel et al. 1997 cited in Benzie 1998), L. (Benzie et al. 1997 cited in Benzie 1998), M. (Fjalestadt et al. 1997 cited in Benzie 1998), N. (Liu et al. 2005), A. (Lannan 1972 cited in Sheridan 1997), B. (Hedgecock et al. 1991 cited in Sheridan 1997), C. (Haley 1975 cited in Sheridan 1997), D. Newkirk et al. 1977, E. (Toro and Newkirk 1990 cited in Sheridan 1997), F. (Newkirk and Haley 1982 cited in Sheridan 1997), G. (Toro 1995), H. (Jarayabhand and Thavornyutikarn 1995), I. (Longwell & Stiles 1973 cited in Toro et al. 2004), J. (Toro et al. 2004).

In aquaculture species, heritability estimates for growth and reproductive traits are comparable to domestic livestock populations, although genetic variability appears to be wider (Kinghorn 1983;

Gjerde 1986; Bentsen and Gjerde 1994). Fitness traits (e.g. survival and fecundity) generally have low heritability estimates whereas production traits (e.g. growth rate) tend to be moderately heritable. A summary of parameter estimates for oysters as well as other aquaculture species are shown in Table 2.1

Numerous traits measured for fish, oysters, mussels and prawns display genetic variation (see review by Gjerde 1986). Variation indicates that the trait can be exploited through selection if it is also heritable. Further, due to the high fecundity of many aquaculture species, it is possible to practice very high selection intensity. Therefore, even at low heritabilities the potential for genetic improvement of traits through selection is possible (Kinghorn and Gjedrem 1982).

Previous oyster breeding programs have shown growth rate to be a heritable trait (Toro and Newkirk 1990 and Jarayabhand and Thavoryutikarn 1995, cited in Sheridan, 1997). However, the estimates of heritabilities for oyster production traits were extremely variable (Sheridan 1997), mainly due to sampling effects.

2.4.6 Economic weights

When selecting for more than one trait simultaneously a weighting is applied to each trait depending on its economic importance or value at the commercial level. An economic value of the trait reflects the change in profit that results from changing that trait by one unit (Simm 2000).

Economic analyses modelled as part of a NSW Fisheries/ORAC initiative have shown that if farmers can grow hatchery produced single seed oysters selected for a combination of increased growth rate and superior disease resistance, profitability will be improved by approximately 10% of the industry value (Heasman 2004). Traits identified as being economically important currently include growth rate and disease resistance. Disease resistance is important as the two major diseases (particularly QX) have the ability to devastate SRO operations (Heasman 2004). However, the relative economic values for each trait complex (e.g. growth versus disease) have not been quantified. The estimation of economic weights for a range of traits in oysters is the subject of current research and is presented in a separate chapter.

2.4.7 Measuring genetic progress: predicting response to selection

Annual response to mass selection can be predicted using the equation:

$$R_{yr} = \frac{i_m + i_f}{L_m + L_f} \times h^2 \times \sigma_p$$

where: R_{yr} = Response per year (in trait units); i ($_m$ or $_f$) = standardised selection intensity (males and females); L ($_m$ or $_f$) = generation interval (males and females); h^2 = heritability of the trait; and σ_p = phenotypic standard deviation.

From this equation it is clear that annual additive genetic progress will depend on a number of factors. These include (Bentsen and Gjerde 1994):

- selection intensity, or the average superiority of selected individuals. This is usually high with highly fecund species. However, it may not be easily measured in aquaculture species where continuous culling occurs to manage the sheer bulk of selection candidates.
- selection accuracy: the correlation between true and estimated breeding values, which depends not only on trait heritability (as above) but can also include information contributed from correlated traits and/or relatives
- variability in the population: the genetic variability is determined both by the phenotypic standard deviation and trait heritabilities
- the generation interval: how old animals are on average when they become parents. For SRO, this could be as low as 1 year, or 2-3 years if programs are designed to ensure all candidates receive disease exposure. A larger i/L ratio results in a larger R_{yr} for a given accuracy of selection.

However, the observed response to selection is often lower than that predicted due to limitations of the prediction model for long-term response. Some examples of observed responses to selection for aquaculture species are shown in Table 2.2.

Table 2.2 Observed response to selection, expressed as a percentage change relative to the population mean, per year and per generation for a range of aquaculture species

Species	Trait	R_{gen} (%)	R_{yr} (%)	Source
European oysters	Growth rate		11.5	A
(*Ostrea edulis*)	Growth rate		1.7 – 11.5	B
Oysters (unknown species)	Growth rate	10-20		C
Pacific oysters (*Crassostrea gigas*)	Meat yield	0.4-25.6		D
Chilean native oysters (*Ostrea chilensis*)	Live weight at 14 months Live weight at 27 months	25.4-36.5 9.2-12.5		E
	Shell length at 14mo Shell length at 27mo	6.01-29.2 10.2-12.9		
Chilean blue mussel (*Mytilus chilensis*)	Larval growth to day 10 Larval growth to day 25 Spat growth to day 40	20.1 33.7 18.3		
Fish	Various	10-20		F
Prawn (*P. vannamei*)	Growth	4.4		G
Prawn (*P. vannamei*)	Disease resistance[a]	12		

A. (Newkirk & Hayley 1982 cited in Gjerde 1986), B. (Newkirk & Hayley 1983 cited in Gjerde 1986), C. (Newkirk 1980 cited in Gjedrem 1998), D. (Langdon et al. 2003), E. (Toro et al. 1996), F. (e.g. Bondari 1983, Gjerde 1986, Dunham 1987 and Hershberger et al. 1990 cited in Bentsen and Gjerde 1994); G. (Fjalestadt et al. 1997 cited in Benzie 1998)
[a]Taura Syndrome Virus

Gjerde (1986) noted that the responses to selection for growth rate in fish and shellfish (2.7% - 11.5%) were typically 1-3% higher than of the mean that is generally reported for domestic livestock (Smith 1984). However, they reported results from single trait selection programs conducted over a few generations only, which are expected to achieve higher response rates than for multiple trait selection over numerous generations. Long term selection experiments in livestock have reported annual rates of genetic change between 0-4.1% of the mean, whereas commercial breeding programs have reported between 0.3-6.5% of the mean (Smith 1984). In both cases, the highest annual response occurred in broiler weight gain or weight (fecund species with high selection intensities). The response in an individual trait when for selecting numerous traits is generally less than when selecting for a single trait alone. However, the response is maximised with respect to the breeding objective, which maximises profit. In addition, response after the first generation of selection is generally higher than subsequent generations (Smith 1984) due to the Bulmer effect, which is the loss of variation through selection (Bulmer 1971). A reduction in genetic response due to the Bulmer effect can be up to 20%. An unselected control line should be maintained to allow the direct measurement of genetic change (Smith 1984) unless BLUP is used. In the latter case, genetic trends can be estimated from EBVs by year of birth.

2.4.8 Inbreeding

Inbreeding can be defined as the "mating of related animals" (Simm 2000) and can be used intentionally (line breeding) or can occur inescapably in a closed population of limited size under long-term selection. Inbreeding is approximated through the inbreeding coefficient (F) at generation t: $F_t = 1 - [1 - 1/2N_e]^t$, where N_e is the effective population size. In the case of no selection, N_e can be approximated by $4N_mN_f/N_m + N_f$ (and N_m or N_f is the actual number of males and females per generation). The effective population size would effectively be reduced under selection. Inbreeding is the "probability that two alleles at any locus are 'identical by descent'" (Simm 2000). Rather than the absolute value, it is the rate of inbreeding, the relative increase in inbreeding in each generation, which is more important: $\Delta F = 1/2\ N_e$.

Inbreeding can lead to both loss of genetic variation and inbreeding depression. Inbreeding depression means that the animals performance for some traits (particularly those associated with fitness: i.e. reproductive rate and disease resistance) is reduced (Simm 2000). Inbreeding depression has been well documented in selective breeding programs for fish species (Bentsen and Gjerde 1994) and is generally considered to be a problem in commercial fish farming (Eknath & Doyle, 1990 cited in Bentsen and Gjerde 1994). Inbreeding (measured as decreased genetic diversity) has been reported in 3rd generation hatchery-produced Pacific oysters in the USA (Hedgecock and Sly 1990) and the UK (Gosling 1982, cited in English et al. 2001). However, English et al (2001) stated that Pacific oysters bred in Tasmania have not had a reduction in genetic variation after three generations of selection. In addition, Sydney rock oysters in NSW showed a high degree of genetic variability when compared to control oysters sourced from the four estuaries that supplied the original broodstock population (English et al. 2001).

Evans et al. (2004) stated that performance traits of Pacific oysters in the USA were affected by relatively low levels on inbreeding. The traits of yield and growth rate were reported to experience inbreeding depression when the inbreeding coefficient (F) was 0.0625 (first-cousin crosses) and F=0.203 (sibling crosses). Survival was also adversely affected when F=0.203. The authors reported that there was a linear decline in phenotype with increasing F, and that an increase in F by 10% resulted in a decline in body weight (8.80%), survival (4.26%) and yield (12.2%). These results corresponded to results from similar studies in European oysters for body weight (10.7%: Naciri-Graven et al. 2000, cited in Evans et al. 2004) and fish species (5.12%-13.8%).

Inbreeding can be minimised by the selection of individuals, and the mating of pairs of animals, maintaining sufficiently large effective population size and maintaining adequate genetic variation of broodstock selection traits (Gjedrem 1998). However, due to the unequal parental contributions in marine bivalves, particularly (Pacific) oysters (in both wild and hatchery-produced stock), effective population size was reduced, resulting in small Ne/N ratios (Boudry et al. 2002). Thus, maintaining a large number of parents may not be effective unless their contributions to the next generation can be better controlled. In this situation, maintaining pedigree records and the use of DNA for parentage testing for selection and mating decisions can be used to prevent inbreeding (Evans et al. 2004).

Bentsen and Olesen (2002) used simulation to determine the effects of breeding structure on inbreeding under mass selection. They generally found that 50 broodstock pairs (the most influential variable), and selection from not less than 30-50 progeny raised per pair, was necessary to keep inbreeding rates low ($\Delta F \leq 1\%$) while maintaining response rates of between 5-13%. By reducing the number of broodstock pairs or selection of progeny raised per pair, selection response would be reduced by over one third due to both loss of genetic variation and inbreeding depression (Bentsen and Olesen 2002), assuming the breeding program was long term in a closed population. A generally accepted rate of inbreeding in livestock is approximately $\leq 2\%$ per generation. Parentage verification techniques (DNA fingerprinting) can also be used in controlling rates of inbreeding (Macbeth 2005).

2.4.9 Traits of interest

Gjedrem (1986) stated that economically important traits should be recorded close to the time of marketing, as this is when the results of genetic improvement can be assessed financially. However, measurements on correlated traits can potentially allow earlier selection, and can improve response to selection through a decrease in the generation interval.

Growth rate and disease resistance are currently the most economically important traits in the oyster industry worldwide, although other traits such as product quality should also be incorporated into any breeding program. Hand et al. (2004) report that the following traits are all factors that influence the marketability of SROs:

- oyster size (whole weight)
- meat condition (measured as dry meat weight g × 1000/cavity volume g)
- aspects of meat yield, measured as:
  - proportion of shell to weight (shell weight g /whole weight g) × 100
  - shell cavity size (cavity volume/whole oyster volume) × 100
  - ratio of whole oyster weight to shell height (cupping)

This is in agreement with the report by Ruello (2002), stating that product quality attributes are oyster appearance and meat size, particularly for Plate grade oysters.

Industry participants, managers and researchers alike, indicated that size at harvest was the most economically important trait in edible molluscs, with meat yield at market also a high priority (Lymbery 1999). Traits of lower priority included uniformity of size, feed efficiency and "survival to harvest", as well as temperature tolerance and shell shape. Disease resistance was considered to be very important for SROs but not other edible molluscs. Traits with no priority were "survival to (live) market", reproductive output, taste and flesh colour (Lymbery 1999). The traits of interest are discussed in further detail in the following sections.

2.4.9.1 Growth rate

Body weight at market age, and therefore growth rate, is an economically important trait in all commercial animals, including all aquaculture species, and is relatively inexpensive and easy to measure (Gjedrem 1998). Heavier weights usually lead to an increased sale price. Increased growth rates can also increase the rate of production turnover through earlier sales. Growth rate in oysters can be measured as weight, length or size (through grading). However, as with domesticated livestock species, growth rate should be measured to a fixed age, adjusted for initial age differences if necessary (Gjerde et al. 2002). Furthermore, although selection for increased growth rate can also result in increased mature weight, which creates an increase in the cost of maintaining broodstock, this factor is generally unimportant in aquaculture species due to their high reproductive rate (Gjerde 1986). The estimated percentage of total feed eaten by female broodstock are 72% for meat sheep, 52% for beef cattle, 33% for pigs and 10% for poultry (Large 1976, cited in Gjerde 1986). In contrast, Kinghorn (1983, cited in Gjerde 1986) has estimated these figures to range from <1% - 5% in fish and shellfish.

2.4.9.2 Survival (disease resistance)

Disease is difficult to control by management in a relatively uncontrolled environment (such as that for oysters) and causes large losses and financial hardship. Survival rate is an economically important trait but, from estimates in fish species, generally has a relatively low heritability (Kanis et al. 1976, cited in Gjedrem 1986). Disease resistance has been reported as the next great challenge facing animal geneticists (Bishop et al. 2002). Disease resistance in bivalves is usually determined by lower mortality and higher growth, which implies a 'tolerance' rather than complete resistance (Ford 1986, cited in Culloty et al. 2004). Strictly defined, resistance is the "ability of a host to reduce the number of parasites that establish, reproduce or survive" whereas tolerance is the "ability of a host to thrive in the presence of parasites" (Gray 1995). However, Naciri-Gravin et al. (1998) stated that delayed mortality of selected oysters may be associated with improved resistance. The level of disease resistance can be difficult to determine because disease exposure can be patchy, thus the exact level of exposure may not be known. In addition, it is the cumulative mortality that is of importance as increased costs are associated when mortality occurs at later stages. Controlled challenge tests are one opportunity of selecting 'disease resistant' oysters, or those that survived a known level of challenge. However, these survivors could quite possibly be carriers of the disease (Gjedrem 1998). In addition, challenge tests require the aetiology of the disease to be known (not known for QX disease) to enable the development of an effective artificial infection process, and for quarantine of the disease and infected oysters to be feasible.

2.4.9.3 Meat quality

Meat quality can be difficult to measure objectively, and definitions may vary. Aspects of oyster meat quality consist of appearance and colour, fat/glycogen content and condition index.

Consumer acceptance of oyster attributes can be estimated through sensory evaluation. Sensory evaluations have previously been conducted on SROs, Pacific oysters and Suminoe oysters (*Crassostrea ariakensis*). In a comparison between the acceptability of SROs and Pacific oysters, raw and cooked oysters were evaluated by 32 (raw test) and 30 (cooked test) subjects (McBride et al. 1988). Acceptability was defined through appearance, flavour, texture and an overall score for general acceptability. The raw SROs were significantly ($P<0.05$) more acceptable than the Pacific oysters in terms of flavour, texture and general acceptability, but not for appearance (McBride et al. 1988). There was no significant difference between the species in the cooked test for any of the above attributes.

A later study (Korac et al. 1996) included sensory evaluation over three sessions, as well as measurements of whole weight, wet and dry meat weight and condition index, of raw diploid and triploid SROs. Sensory evaluations included appearance, texture/mouth feel, flavour and overall acceptability (potential trait score range of 0-100). Overall, acceptability increased with increasing meat condition (and age) over the three sessions. When the oysters were at marketable condition (40g: the older oysters of S3) the acceptability of diploid and triploid oysters was not significantly different (P>0.05) in terms of their sensory attributes (Table 2.3).

Table 2.3 Overall acceptability: mean sensory score (%) over three sessions (S)

	S1	S2	S3
Diploid	62.2	54.5	64.8
Triploid	51.1	57.6	61.9

Source: (Korac et al. 1996)

Another consumer acceptance test was conducted between cooked Suminoe (*Crassostrea ariakensis*) and Pacific oysters (Langdon and Robinson 1996). Flavour, taste and appearance in the half shell of the oysters were rated (0-9) by 42 subjects (Table 2.4). More subjects preferred the appearance of the Suminoe oyster (97%) to the Pacific oyster (90%).

Table 2.4 Results of consumer acceptability tests for cooked oysters (SD)

Method	**Stewed**		**Broiled**	
Species	Suminoe	Pacific	Suminoe	Pacific
Flavour	6.83 (1.40)^{a}	6.36 (1.64)^{b}	7.07 (1.52)	6.93 (1.63)
Texture	6.44 (2.04)^{a}	6.00 (2.17)	6.78 (1.86)	6.83 (1.61)

Values with different superscripts are significantly different (P<0.05).
Source: (Langdon and Robinson 1996)

2.4.9.4 Fecundity

Fecundity is very high in most aquaculture species and therefore does not need to be genetically improved. However, mortality of gametes/larvae/spat is generally high, which may be linked to egg characteristics. Further, the relationship between fecundity and growth traits has not been established. In addition, the actual fecundity of the species may be limited in hatchery situations where the reproductive cycle is artificially manipulated. Parental contribution may be unequal (thereby limiting N_e) due to gamete quality, non-random mating and zygotic competition and differential variability between families (Boudry et al. 2002).

2.4.10 Correlations between traits

It is important to be aware of correlations between traits in any breeding program, as adverse genetic correlations between traits may result in undesired changes under selection. In reality, there are usually unknowns for the set of correlations between all important traits. For example, some commercially important traits may be more difficult to measure or may require 'sacrifice'. However, in oyster breeding, and indeed for much of the aquaculture industry, the value of each animal is low and so samples of animals from different genetic groups or families can be sacrificed to enable these sort of measurements (Gjedrem 1998).

Estimates of correlations from literature are presented in Table 2.5. It can clearly be seen that correlations between weight and dimensional traits are positive and very high in oysters, indicating that a change in one dimension will result in a change in the other dimensions and weight. In comparison, the correlations between dimensions and weight for the sea urchin study appear to be relatively small. This has implications for selection as, for example, dimensions would be useful as an indirect selection criterion for weight. Of note, nomenclature for dimensions in oysters needs to be standardised (see Figure 2.3).

Whole weight may in turn be an indirect selection criterion (as it already is) in the more difficult to measure trait (sacrifice is required) of meat weight. However, of importance, meat condition and therefore weight is seasonal whereas shell weight is not. The study by Honkoop and Bayne (2002), found that there was a low correlation between shell mass and soft tissue mass (measured as ash-free dry mass: AFDM) in both Pacific and Sydney rock oysters. However, the trait of AFDM may not be an accurate predictor of meat weight in oysters since a high percentage of oyster meat is water. A similar result was also previously reported by Hilbish (1986) and Cote et al. (1993, cited in Honkoop and Bayne 2002), who found that total mass was a poor predictor for soft tissue mass. In contrast, Nielsen (1985, cited in Toro et al. 2004) found that growth rate, as determined by shell length, was highly correlated with an increase in meat weight in Common mussel (*Mytilus edulis*) juveniles. In addition, Langdon et al. (2003) reported that, when sampling the top 15 PO families (in terms of performance at each site), whole weight was highly correlated with meat weight (r=0.71-0.93).

Table 2.5 Estimates of genetic (r_g) and phenotypic (r_p) or Pearson (r) correlations between dimensional traits and weight for aquaculture species

Species	Traits	Correlation	Source
Pacific oyster	WT & L WT & W WT & D L & W L & D W & D	$r_g = 0.82\pm0.09$: $r_p = 0.95$ $r_g = 0.90\pm0.06$: $r_p = 0.92$ $r_g = 0.82\pm0.09$: $r_p = 0.93$ $r_g = 0.78\pm0.11$: $r_p = 0.98$ $r_g = 0.60\pm0.17$: $r_p = 0.98$ $r_g = 0.66\pm0.17$: $r_p = 0.98$	Ward et al.(2005)
European oyster	WT & L	$r_g = 0.99$	Toro and Newkirk (1990, cited in Ward et al. 2005)
Chilean native oyster	WT & L	$r_p = 0.94$	Toro (1995)
Pacific oyster	WT & MEAT WT	r = 0.71 – 0.93	Langdon et al. (2003)
Sea urchin (*Strongylocentrotus intermedius*)	WT & d BW & HT d & H	$r_g = 0.35\text{-}0.65$ $r_g = 0.39\text{-}0.40$ $r_g = 0.35\text{-}0.60$	Liu et al. (2005)

WT = whole weight, L = length, W = width, D = depth, H = height, MEAT WT = meat weight, d = sea urchin test diameter, BW = body weight

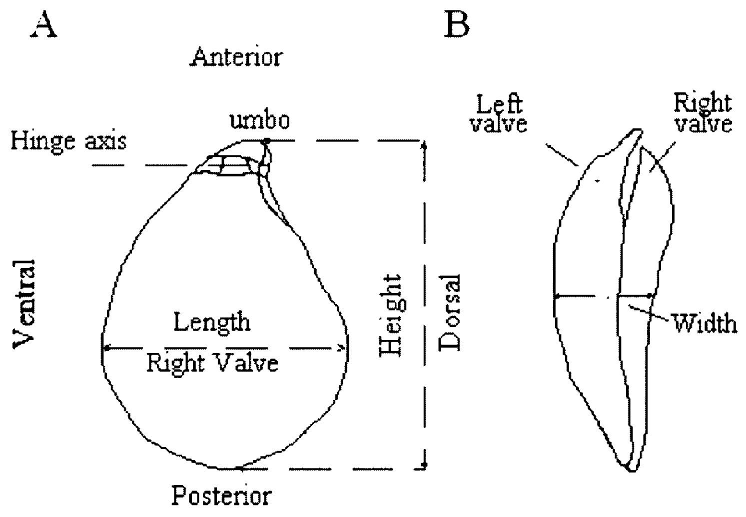

Diagram showing method of measuring the height, length, and width of oyster valves. A. interior view of right valve; B. side view of valves. Diagram, after Galtsoff, 1964 and reproduced by Carriker, 1996.

Figure 2.3 Cited in Nell 2006b

There is also evidence to suggest that larval or spat size is correlated to adult size. Hand et al. (1999) found that when SROs were graded into two size classes as spat (small or large), this had a significant influence on both initial (P<0.01: 16mm and 27mm) and final (P<0.05: 69mm and 71mm) mean shell height in addition to both initial (P=0.01: 0.4 and 2g) and final (P<0.05: 42 and 50g) weight for both diploid and triploid oysters. Nell (2003) reported that initial weight of SROs had a significant (P<0.05) influence on final weight. An experiment using Pacific oysters found that, for all cohorts, initial set-out weight was significantly (P<0.01) correlated with harvest yield (Langdon et al. 2003). In addition, Collet et al. (1999) found that there was a significant correlation between PO larval growth rate (sieving group rank) and spat growth rate (P=0.0001) as well as with final live weight at 11 months of age (P<0.0001). However, none of these studies establish whether variation in initial spat size was genetic or environmental in origin. Thus, the cause (genetic and/or environmental) of the observed correlations is not established.

The Molluscan Breeding Program (MBP) conducted a study on the genetic control of pigmentation in Pacific oysters (Brake et al. 2004). They found that pigmentation of mantle edge and shell had a positive correlation (r: 0.58, P<0.0001). Family effects were significant (P<0.001) for all cohorts. Both family mantle edge pigmentation and family shell pigmentation were, generally, not correlated with the family performance traits of weight, survival or yield (P>0.09).

This may have implications for a breeding program as the pigmentation and performance traits were independent of each other and therefore selection for one would not lead to a correlated response in the other. However, there was a significant ($P<0.05$) correlation in two cases. These correlations were between mantle pigmentation with survival (r: 0.53) and shell pigmentation with tissue weight (r: 0.54).

2.4.11 Dissemination of genetics

Genetic improvement made at the nucleus level must be disseminated to commercial producers, either directly or through a multiplier level, for genetic improvement to be realised by commercial producers (Figure 2.4). Issues involved with dissemination are that there is often a lag of one generation between levels and there is sometimes a decreased correlated response in the lower levels due to the possibility of genetic by environment (g×e) interaction (Harris et al. 1984). However, for example, no genotype by environment interaction was found in Pacific oysters (Ward et al. 2005). In addition, the only genetic by environment interaction found in Pacific oysters in the study by Swan et al. (2007) were scale affects, which would not result in re-ranking of families.

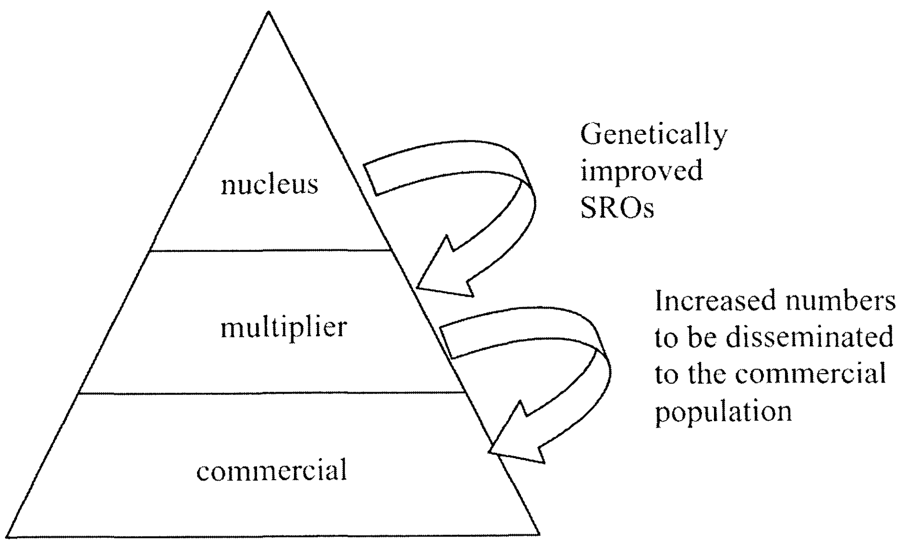

Figure 2.4 Diagram of the flow of genetics through the different levels from the nucleus

2.4.11.1 Dissemination through triploidy

Triploid oysters have three sets of chromosomes, two from the female and one from the male (Baker 1996). A very high percentage of triploid oysters are sterile and therefore don't spawn, remaining edible for a longer season (Baker 1996). Triploid oysters use energy for growth instead of developing gametes, thereby improving growth rate, size and the capacity to maintain body condition.

Baker (1996) reported that triploidy in Eastern oysters is the product of tetraploids crossed with diploids, which results in 100% triploidy. Guo and Standish (1994) had previously stated that sterility in triploids was variable and not always complete. However, Guo and Standish (1994) did not use tetraploid oysters for the crosses. Cox et al. (1996) found that although the triploid SROs were functionally sterile and did not spawn, there was evidence of limited gonadogenesis in the triploid oysters during the spawning season. The technique for generating triploidy in SRO is through chemical retardation (Hand et al. 1999), resulting in 85% (Cox et al. 1996) to 88% (Hand and Nell 1999) triploidy. However, the chemicals used in this process are now banned (Nell 2006b). Tetraploidy has not been reported for SROs. Caution should be used when introducing an exotic triploid species to an area to ensure that no gametes are present and therefore the species cannot breed in that location.

Triploid SRO are potentially desirable as they reach market size (50g whole weight) an average of six months earlier than the 3.5 years of contemporary diploids (Nell 2001b). Further, Hand et al. (2004) found that selective breeding for growth rate and triploidy were additive, with triploids being 74% heavier than the diploid controls on average, reducing time to reach market size by more than 10 months (Nell 2006b). In addition to faster growth, triploids survived better than diploids, even during periods of winter mortality (Hand et al. 1998, cited in Nell 2001b), and hold their meat condition better than diploids in winter and spring (Nell et al. 1994, Hand et al. 1998 and Nell and Maguire 1998, cited in Nell 2001b). However, Troup et al. (2005) reported that although triploids did grow markedly faster than diploids, in an area where the only disease that occurred was mudworms, there was no significant difference between triploid and diploid SROs in terms of mortality. A disadvantage of SRO triploids is that a proportion may suffer meat discolouration. Maguire et al. (1994, cited in Nell 2001b) reported that 6% of triploid SRO were affected by discolouration in summer and autumn.

Triploids may have some production and marketing (e.g. size and extended period of high condition index) advantages over diploids. However, there is no genetic progress made by solely breeding triploids. Triploidy could be used to produce a complimentary tool as an 'off season' (winter crop) SRO, and is also a tool for secure dissemination of genetic improvement (Nell 2006b).

2.4.11.2 Hatchery reared spat for commercial use

Since 1996, NSW DPI (Fisheries) at Port Stephens Fisheries Centre, has been trying to breed and supply commercial quantities of genetically improved spat to the oyster growers (Heasman et al. 2000). However, until recently, hatchery produced SRO have suffered from highly variable and unpredictable production, with common failures (Heasman 2004). This was a major hindrance to the commercialisation of the 10 year breeding plan developed by NSW Fisheries (Heasman 2004).

By 2007, the high mortality rate of larvae and spat had been overcome and success rates were currently much better than PO hatcheries. By March 2007, over 60 million genetically improved seed had been distributed to the SRO industry (W. O'Connor 2007, pers. comm., 9 March). The goal for the SRO industry is $100 million/yr gross value of production. This will largely be possible through continuous genetic improvement, technological advances (and so improved reliability of hatchery spat production) and rapidly increasing demand (W. O'Connor 2007, pers. comm., 9 March).

2.5 Review of current oyster breeding programs

2.5.1 Introduction

Genetic improvement of the Eastern oyster, Pacific oyster and Sydney rock oyster have largely focused on developing strains that are faster growing and more disease resistant (Allen et al. 1993; Ward et al. 2005; Nell 2006a). A positive response to selection for these traits was found in early selection experiments in several fish species, as well as oysters. For examples, see Embody & Hyford (1925), Schaperclaus (1962), Kirpichnikov et al. (1993), and for growth rate see Lewis (1944), Donaldsen & Olson (1955), Hayley et al. (1975), Kincaid et al. (1977), and Newkirk (1980), all cited in Gjedrem (1998) and McBride et al. (1988). Selection for disease resistance to the QX-like disease (MSX) in Eastern oysters in the USA and *Bonamia* in flat oysters in France has been very successful.

Oyster breeding programs are currently being conducted internationally, mostly using mass and family selection techniques or a combination of both. Aside from the Pacific oyster and SRO breeding programs in Australia, two large breeding programs include the Molluscan Breeding Program (MBP: Pacific oyster), operated through Oregon State University and the University of Guelph, as well as a program operated through the French Research Institute for Exploitation of the Sea (IFREMER) for the European flat oyster. Results from different breeding programs are summarised in the following sections.

2.5.1.1 Sydney rock oysters (Saccostrea glomerata)

Mass selection breeding programs to select SROs for fast growth was founded in 1990 (Nell 2001b) in Port Stephens and the Georges River (Nell 2005). Throughout the program (see Figure 2.5) oysters were constantly graded on size to remove slower growing oysters. Grading was conducted using sieves, which would indirectly select for both shell shape/dimensions and growth rate. As this repeated grading on size occurred, selection pressure for growth rate was applied to all four Port Stephens and four Georges River fast growth selection lines. The breeding program and the evaluation of selection lines were conducted separately. Port Stephens comparisons for fast growth lines were run between 1993-1995 (G2), 1995-1997 (G3), 1999-2002 (G4: including the ploidy comparison) and 2001-2004 (G4). Georges River disease resistance lines were compared between 2000-2002 (G1), 2002-2005 (G2) and another (G3) is operating from 2005-2008 (Nell, 2006). The results from available line comparisons are shown in Table 2.6 to Table 2.10.

<table>
<tr><td colspan="2">January Year 1; Generation 0 (G0) spawned (222 females and 51 males)
4 mass fertilisations for each line (2 “Loose” + 2 “Slat” + 2 Control lines)
July Year 1: selection on spat size/weight into 4 grades (Gr)</td></tr>
<tr><td>Gr 1: largest spat (≥ 12mm)</td><td>Gr 2 ***</td></tr>
<tr><td>24 heaviest oysters/tray × 3 trays × 3 sites = 216 SROs/line (× 4 lines = 864 SROs)</td><td>Experimental stock</td></tr>
<tr><td>864 SROs selected as broodstock to produce next generation. Approx. 7% surviving Loose oysters and 10% surviving Slat oysters selected from remaining oysters (Nell et al. 1999)</td><td>At initial and final 20-50 SROs/rep were weighed</td></tr>
<tr><td>“Loose” >1000 spat/tray × 3 trays × 3 sites (9000). 50% tray coverage maintained after sieving and discarding smallest oysters (quarterly)
“Slat” 2 reps/tray × 140 = 280 spat/tray × 3 trays × 3 sites (2520)
Therefore, initially there were 9 000 + 2 520 + Controls (11 520 + C)</td><td>August Year 1. Initial: 4 reps × 140 SROs × 6 lines × 3 sites = 10 080 SROs</td></tr>
<tr><td>February Year 3: G2 spawned (4 mass spawnings/line). Gametes from each spawning group pooled (eggs and sperm separately) before fertilisation</td><td>January Year 3. Final: 55 half trays × 50 SROs/half tray = 2750 SROs</td></tr>
</table>

Figure 2.5 Schematic representation of the SRO breeding and line comparison programs

A study using SROs found that time to market size (50g whole weight) in diploids was reduced by 7 months from the 38 months (3.2 years) taken for the diploid control (Nell 2001b). This indicates that selection for growth rate has been successful. However, there was considerable variation in growth rate response between the different selection lines. The selection lines consisted of 4 lines differing in growing method and with populations maintained separately: 2 “Loose” and 2 “Slat”. The study by Smith et al. (1995) found that spat grown on slats grew significantly ($P<0.05$) faster (3.47±0.12g) than spat grown on loose trays (2.43±0.18g). In addition, the slat oysters had significantly less variation (CV: 5.77±0.26g) than the loose spat (CV: 8.87±0.53g) for whole weight. Growing method may have had an influence on response to selection.

The reports by Heasman (2004) and Nell et al (1999) stated that after one generation of selection an increase in whole weight of 0–8.5% over the averaged control lines was achieved in the Port Stephens experiment 1 (PSExp1) of selection for growth (see Table 2.6). This response increased to 14.2–22.7% after two generations of selection in the PSExp2 (Table 2.7). Nell et al. (2000) reported that an average response of 18% would reduce time taken to reach 50g for SROs by three months (resulting in market size at 3.2yrs). In addition, there was no significant line by site interaction.

Table 2.8 (PSExp3) showed that after three generations of selection the four selected populations were 33-52% heavier than the control, and these differences were significant ($P<0.05$). However, the initial controls (PSExp1) were taken from the four estuaries that supplied the original broodstock population, whereas the controls for the PSExp2 and PSExp3 were taken from three of the four same estuaries. Thus, controls varied between the line comparison trials. Nevertheless, there is evidence that the selected oysters grew more quickly but also more efficiently, which has positive implications for their commercial adoption (Heasman 2004). The efficiency of selected faster-growing oysters from the "Loose 2" selection line were tested (Bayne et al. 1999). These oysters were found to have a higher feeding rate, invested more energy in growth per joule ingested and had a higher net growth efficiency than oysters showing slow growth rates. Nell and Perkins (2005) reported that after four generations of selection the selected line oysters had reductions of 11-15 months (mean: 12.5 months) in the time taken to reach Plate size (50g). This reduced the total number of months taken for the selected line oysters to reach market size to an average of 28.5 months, compared to the 41 months taken for the control.

Table 2.6 Comparison of growth rates in (means±se) Port Stephens second generation SRO selection lines (August 1993 – January 1995)

Selection line or control	Start whole weight (mg)	End whole weight (g)	Percentage Δ from control average
Loose 1	42.3 ± 0.7^{bc}	35.3 ± 0.23^{bc}	2.9%
Loose 2	40.7 ± 0.7^{c}	37.2 ± 0.24^{a}	$8.5\%^{a}$
Slat 1	43.1 ± 0.7^{abc}	34.3 ± 0.21^{c}	0
Slat 2	45.1 ± 0.8^{ab}	36.0 ± 0.25^{b}	$5\%^{a}$
Control 1*	45.9 ± 0.8^{a}	34.0 ± 0.22^{c}	Control mean= 34.3^{b}
Control 2*	46.1 ± 0.7^{a}	34.6 ± 0.22^{c}	

Means with different superscripts differ significantly ($P<0.05$)
*controls originated from Wallis Lake, Port Stephens, Hawkesbury and Georges Rivers
Source: (Nell et al. 1999)

Table 2.7 Comparison of growth rates in (means±se) Port Stephens third generation SRO selection lines (November 1995 – May 1997)

Selection line or control	Start whole weight (mg)	End whole weight (g)	Percentage Δ from control average	Mortality (%)
Loose 1	0.20±0.003^{a}	43.2±0.40^{a}	18%^{a}	1.1±1.0^{ab}
Loose 2	0.18±0.003^{b}	44.9±0.39^{a}	23%^{a}	1.0±1.3^{ab}
Slat 1	0.17±0.002^{c}	41.8±0.32^{a}	14%^{a}	8±1.1^{b}
Slat 2	0.18±0.003^{b}	42.6±0.35^{a}	16%^{a}	11±1.9^{ab}
Control 1*	0.25±0.005^{a}	37.0±0.33^{b}	Control mean= 36.6^{b}	16±2.2^{a}
Control 2*	0.19±0.002^{ab}	36.1±0.34^{b}		13±1.0^{ab}

Means with different superscripts differ significantly (P<0.05)
*controls were taken from Wallis Lake, Port Stephens and Hawkesbury River
Source: (Nell et al. 1996)

Table 2.8 Comparison of growth rates in (means±se) the progeny of Port Stephens fourth generation SRO selection lines (February 2001 – July 2004)

Selection line or control	July 2001 whole weight (mg)	April 2003 whole weight (g)	July 2004 whole weight (g)	Percentage Δ from control average
Line 1	77.5±0.8^{b}	47.9±0.6^{b}	67.8±1.0^{b}	33%
Line 2	72.9±0.8^{b}	52.8±0.6^{a}	77.4±1.3^{a}	52%
Line 3	74.4±0.8^{b}	49.4±0.5^{b}	70.3±1.3^{b}	38%
Line 4	75.6±0.9^{b}	47.3±0.8^{b}	70.6±1.8^{b}	38%
Control*	85.8±1.2^{a}	35.7±0.7^{c}	51.0±0.9^{c}	

Means with different superscripts differ significantly (P<0.05)
*controls were taken from the non-selected control populations
Source: (Nell and Perkins 2005)

After the 1995 Georges River QX disease mortalities, the SRO breeding program was altered to include survivors of QX as parents in a selection line for QX resistance. A similar program was implemented to select for resistance to Winter mortality (Heasman 2004). The Georges River section of the selective breeding program was expanded to include breeding for WM and QX disease resistance, as well as a dual resistance to both diseases, in 1997. Selection candidates were exposed naturally to these diseases through choice of location.

After one generation of selection for QX disease resistance (GRExp1) the selected line oysters were significantly heavier than the control and mortality levels were significantly less than the control (Table 2.9). Lines 1 and 2 performed best in terms of final weight. However, Line 3 had a significantly lower initial weight but growth rate was actually significantly higher than the other lines. The three selection lines had significantly lower mortality than the control. The difference in mortality levels between the control and selection lines varied from 6.2% to 26% improved survival. The QX disease resistance breeding lines showed a lower mortality (64% vs. 86%) compared to the controls. However, this QX disease resistant oyster still hosts the parasite that causes winter mortality (Nell 2001b).

Table 2.9 Comparison of weight and mortality in (means±se) the progeny of Georges River second generation SRO disease resistant selection lines (July 2000 – February 2002)

Selection line or control	Initial weight (g)	Final weight (g) (difference from control %)	Instantaneous growth rate	Percentage Δ from control average
QX (1)	0.23 ± 0.007^{a}	43.8 ± 2.2^{a} (21)	0.0126^{b}	63.5 ± 1.2^{d} (26)
WQ (2)	0.24 ± 0.011^{a}	42.3 ± 2.2^{a} (17)	0.0125^{b}	72.7 ± 1.1^{c} (15)
WM (3)	0.15 ± 0.003^{b}	38.3 ± 1.7^{b} (6.5)	0.0134^{a}	80.4 ± 2.4^{b} (6.2)
Control*	0.24 ± 0.005^{a}	36.3 ± 1.8^{c}	0.0121^{c}	85.7 ± 1.5^{a}

Means with different superscripts differ significantly ($P<0.05$)
*controls were taken from Wallis Lake, Port Stephens and Hawkesbury River
Source: (Nell and Hand 2003)

Compared to controls, whole weight was significantly higher (17%) only in Line 2. Table 2.10 shows that Line 2 also had a significantly higher weight in 2004. Line 1 and 3 actually had significantly lower final weights than the controls, even though the control had a significantly lower weight in 2004. Cumulative mortality over two years was significantly higher for controls compared to selection lines (Table 2.10).

Table 2.10 Comparison of weight and mortality in (means±se) the progeny of Georges River third generation SRO disease resistant selection lines (February 2002 – February 2005)

	Feb 2004			Feb 2005		
Selection line or control	**Whole weight (g)**	**Shell height (mm)**	**Mortality (%)**	**Whole weight (g) (Δ from control %)**	**Shell height (mm)**	**Mortality (%) (Δ from control %)**
QX (1)	48.1 ± 3.3^{b}	75.4 ± 1.9^{b}	21.2 ± 1.6^{b}	67.1 ± 3.2^{ab} (1.5)	81.5 ± 1.2^{a}	52.6 ± 3.0^{b} (33)
WQ (2)	51.4 ± 3.3^{a}	77.0 ± 1.8^{a}	20.6 ± 2.1^{b}	68.5 ± 2.3^{a} (0.6)	82.1 ± 0.9^{a}	50.3 ± 5.4^{c} (36)
WM (3)	47.5 ± 2.5^{b}	72.7 ± 1.3^{b}	23.5 ± 5.1^{b}	64.2 ± 1.9^{b} (5.7)	78.2 ± 0.5^{b}	56.5 ± 8.2^{b} (28)
Control*	33.1 ± 2.3^{c}	62.8 ± 1.6^{c}	41.3 ± 8.3^{a}	68.1 ± 0.8^{c}	68.1 ± 0.8^{c}	78.4 ± 7.0^{a}

Means with different superscripts differ significantly ($P<0.05$)
*controls unreported
Source: (Nell and Perkins 2005)

The level of inbreeding in selection lines is currently unknown (Heasman 2004). However, English et al. (2001) reported that selective breeding for increased weight in the SRO had not led to a loss of genetic diversity, specifically allozyme variation, in the second or third generations. An initial report found that the SRO breeding program had not caused any significant levels of inbreeding (W. O'Connor 2007, pers. comm., 9 February).

Heasman (2004) noted that the results from the line comparison for disease resistance in SROs should be interpreted with caution as environmental variables influence the outcome, controls differ in different years, and the effective level of exposure to the disease is unknown. However, the most recent results are reasonably compelling (Figure 2.6) and will be published shortly.

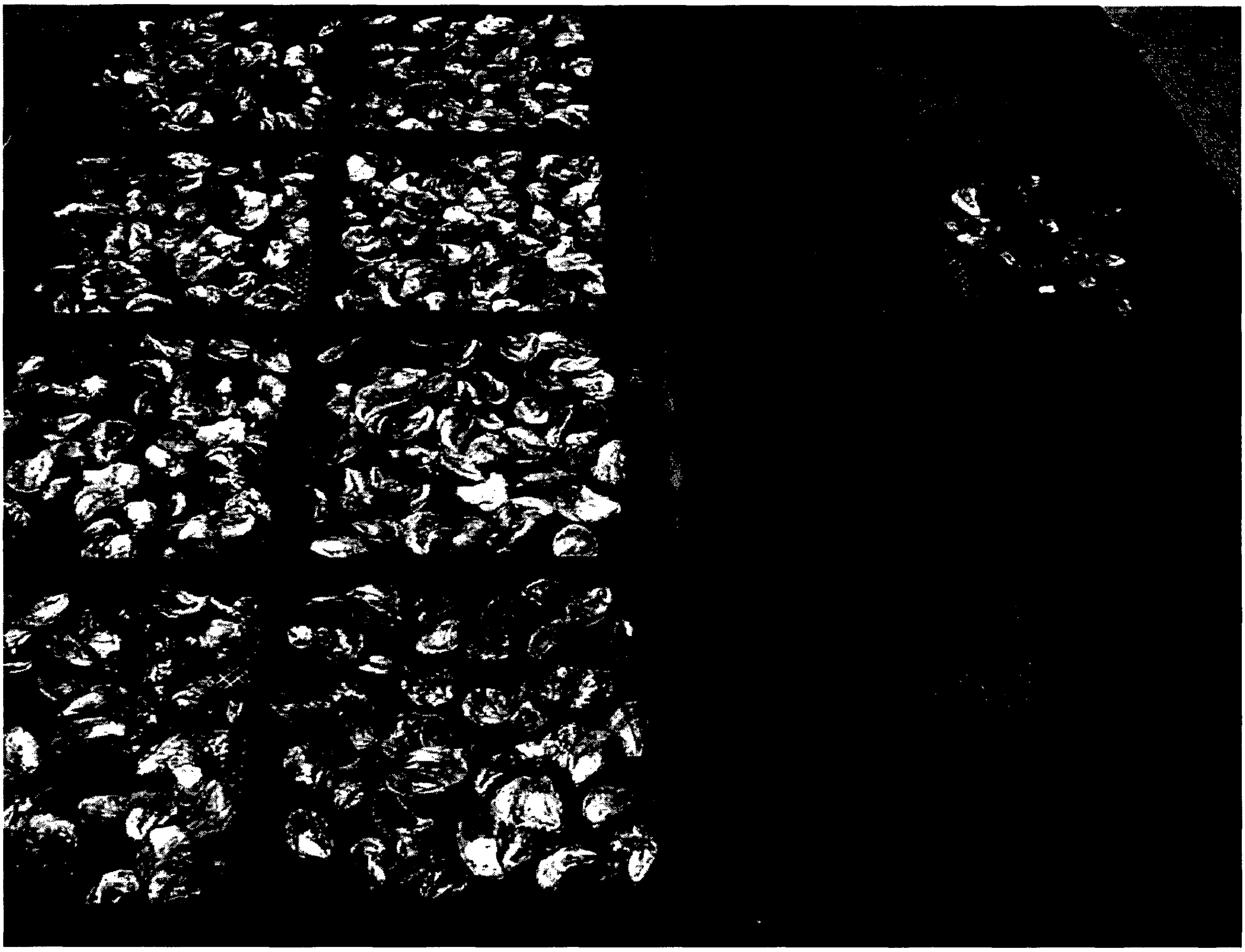

Figure 2.6 Photograph showing QX disease resistance line (left) and the control (right) which had been farmed in the Hawkesbury River (Photo: Anna Hansson, 2006)

2.5.1.2 Eastern or American oysters (Crassostrea virginica)

Selection of Eastern oysters for faster growth was started in the 1970's by crossing fast growing oysters of the new "Wilde strain" generation with their surviving fast growing parents (Allen et al. 1993). This founding parent/offspring cross had implications for increasing the rate of inbreeding in the population. After the introduction of a new selection line in 1992, there was a 10% improvement in growth rate after the first generation of selection (Allen et al. 1993). The breeding program only selects on growth rate, so although there was no selection for resistance to either

MSX or Dermo diseases, high growth rate provides an indirect and practical approach for avoiding Dermo, since this disease is usually more severe in older individuals.

Using the American oyster, Hayley and Newkirk (1982, cited in Sheridan 1997) found that the offspring of three lines selected for increased live weight were significantly heavier than the control at 27 months of age. Paynter and Dimichele (1990, cited in Sheridan 1997) also found that native American oysters selected for improved growth rate (mm/month) for 18 generations had a significantly ($P<0.05$) faster growth rate than native unselected oysters in both the first (+28%) and second (+24%) growing seasons. This is a relatively low response rate for the generations of selection. However, the selection had been conducted by a local farmer and both test oyster groups (N: $100 \times 2 = 200$) originated from only two male and three female broodstock.

Selection for disease resistance in Eastern oysters to MSX disease was implemented after an enormous outbreak of MSX in Delaware Bay, USA, which caused devastating mortalities (90-95%) in 1957 (Allen et al. 1993). Following the initial outbreak, the mortality level tended to decline, which led researchers to believe that natural selection was occurring and that disease resistance to MSX was heritable. A breeding program designed to select Eastern oysters for both of the major USA diseases, MSX and Dermo, was then established in the 1990's (Calvo et al. 2003).

Foundation stock were collected from wild populations (Calvo et al. 2003). Selection was based on survival for the two diseases after two to five years of exposure. Second, third and fourth generation (GEN 2, 3 and 4 respectively) oysters were produced in the 1990's. Broodstock ranged from 11 – 41 oysters per spawning. The strains were defined by their original location, and comparisons were between Delaware Bay (DEBY) strains with four 'comparison' strains from different locations (James River: JR; Louisiana: LA; Tangier Sound: TS and Mobjack Bay: MB) acting as the 'control' (Calvo et al. 2003). Different controls were used to test each generation. Performance was measured in terms of survival: dead oysters/(original number of oysters – disease test oysters), growth (defined as shell height) and disease susceptibility (measured by histological examination of 25 oysters/month from May to October each year) (Calvo et al. 2003).

From 1993 to 1995 the performance of the DEBY strain GEN 3 oysters was compared with GEN 3 JR oysters and GEN 1 LA (N: 500/strain) in York River (Calvo et al. 2003). Final cumulative mortality was significantly ($P<0.008$) lower for selected DEBY oysters (53%) compared to unselected strains (JR: 83% and LA: 75%, which did not differ significantly from each other). The DEBY overall mean growth rate (24mm/year) was significantly ($P<0.047$) higher than the other two strains (19.2mm/year; which did not differ significantly from each other) (Calvo et al. 2003). Approximately three months before the end of the experiment (Sept vs. Oct), oysters were sampled for the presence of disease. Dermo was present in DEBY (92%), LA (68%) and JR (96%) oysters, although disease presence varied over the experiment (Calvo et al. 2003). The presence of MSX was also variable and was present in DEBY (0–10%), JR (8–16%) and LA (4-12%) oysters.

From 1997 to 1999 the performance of DEBY GEN 4 oysters were compared with MB GEN 1 and TS GEN 1 oysters (N: 500/strain) (Calvo et al. 2003). Final cumulative mortalities for DEBY were 21.0%, 52.4% and 35.5% at the three different sites. The mortality was above 86% for both MB and TS strains at all sites. Growth between July 1997 and December 1999 in DEBY ranged from 56-84mm and in the other two strains ranged from 40-72mm. Thus there was a significant ($P<0.005$) difference in mortality and average growth rate between the DEBY oysters with the MB and TS strains.

Disease resistant lines have resurrected the Eastern oyster industry, especially in affected areas such as Delaware Bay (Allen et al. 1993). However, many of the MSX affected areas where oysters were tested may have been sheltered from the other disease that can severely affect Eastern oysters, Dermo disease. There is evidence that Dermo disease resistance in Eastern oysters is also heritable and so can be improved through selective breeding programs. This research has only been conducted on oyster strains already deemed resistant to MSX (Allen et al. 1993). The association between resistance and/or tolerance to the two diseases has not been reported in the literature reviewed.

2.5.1.3 Pacific oysters (Crassostrea gigas)

Australia

A breeding program has been implemented (1996/97) in TAS and SA to improve growth rate of Pacific oysters, thereby reducing the time taken to reach market size from the average of 2.5 years observed in unselected populations. Other commercially important traits, determined through an industry survey (Ward et al. 2000), have also been used for selection decisions. The FRDC/CRCA programs were based on a combination of mass selection and family (between and within) selection every year (Ward et al. 2000). The ability to strip spawn Pacific oysters creates an advantage over SROs (where strip spawning is not yet feasible) in terms of producing controlled matings for a selective breeding program. Since 2002/03, the Australian Seafood Industries Pty Ltd (ASI) has taken over the breeding program and also provides extension to farmers. Another goal of ASI is to increase the proportion of Pacific oyster farmers using selectively bred Pacific oyster lines above the 20% in 2005 (Ward et al. 2005).

The breeding program has been successful in terms of increasing Pacific oyster growth rate despite the large environmental variation in the trait (Ward et al. 2005). There was little evidence of an interaction between genetics and environment (g×e). Thus, generally, the rank of different families was maintained across farms in both TAS and SA. The selected oysters ("fast line") resulting from the first spawning (~70 broodstock/selection line and 57 broodstock/control line) performed approximately 9-10% better than the controls (commercial lines) and 20-25% better than the "slow lines" in terms of weight gain (Ward et al. 2005; Swan et al. 2007).

In a random sample of 10 oysters/replicate, the relationship between average oyster weight and condition index in the mass selection lines was negative and therefore unfavourable. This negative correlation was confirmed by generation two, where the overall correlation coefficient was -0.39 ($P<0.05$). This relationship occurred at each site (r: -0.10 to -0.56) although it was significant for only two of the four sites (Ward et al. 2005). The negative correlation was still evident at generation four, where a negative correlation (r:-0.63, $P<0.01$) between mean weight and condition index was evident across data from 19 family and control lines. "Further research is required to investigate this unfavourable relationship" (Ward et al. 2005).

Generation five (spawned in 2002/03) consisted of three mass selection lines (~200 broodstock/line) family lines and a commercial line control (Ward et al. 2005). At this time, EBVs for oyster growth rate were estimated using BLUP. After adjusting for the effect of density (overall correlation between progeny number with average weight = -0.60: $P<0.01$), the top seven families performed almost six times better than the control in terms of average weight. At an early stage of life, EBVs of the non-inbred lines for oyster growth rate were not significantly correlated with juvenile growth rate (r = -0.06) (Ward et al. 2005).

United States of America

A research team based in the USA used three genetically different wild Pacific oyster populations for the foundation population (Langdon et al. 2003). Broodstock were sampled to gain individual genetic identities. Only larvae of the desired pedigrees were kept with 60 full-sib families being raised. Full-sib selection was conducted on total meat yield per plot, thereby indirectly selecting for survival, as total meat weight would depend on the number of surviving animals. A random sample of 15 oysters from each of the 15 families were used to measure meat weight (Langdon et al. 2003). The largest oysters within each of the selected families were used as broodstock. These broodstock were used to create the first generation of meat yield selection. Three lines were created based on the origin of separate founder populations (Dabob Bay, Willapa Bay and Pipestem Inlet). Wild stock controls as well as industry controls were used in the experiment.

The Pacific oysters selected for live weight and meat yield at market age had a 0.4% to 25.6% (mean: 9.5%) increase in average progeny whole weight when compared to the non-selected controls (Langdon et al. 2003). This difference was significant ($P<0.001$) for four out of the seven evaluation sites. This confirms the correlation between the traits of live weight and meat yield shown in Table 2.5.

2.5.1.4 European flat oysters (Ostrea edulis)

United Kingdom

The 'Rossmore' strain of oysters, selectively bred for *Bonamia ostreae* resistance in Ireland for more than 10 years, has reduced infection and mortality rates, both in laboratory and field conditions, compared to other naïve Irish oyster strains when exposed to the parasite *Bonamia ostreae* (Culloty et al. 2001, cited in Culloty et al. 2004). From June 1999 to January 2000 the Rossmore (IER) strain had the lowest prevalence of *Bonamia ostreae* infection when compared to naïve lines from Ireland, Scotland and Holland (Culloty et al. 2004). In January 2000, the prevalence of infection in the IER strain over two of the four sites was 50% and 26%. Oysters of all strains were dead at the other two sites. The level of *Bonamia ostreae* infection in three of the naïve strains was high to very high at 100%, 88.9%, 50% at one of the sites (all oysters of the fourth strain were dead). The three naïve strains at the other site had infection levels of 73.3% and 90% (all oysters of the third strain were dead). This difference (measurements occurring approximately every three months) reached significance ($P<0.001$) in June 1999 and October

1999. The naïve strains all had a similar prevalence of infection during this time. Infection intensity, as measured by cumulative mortalities, for IER were lower than naïve strains at all four sites (Culloty et al. 2004).

The native NLG strain from Lake Grevelingen in Holland where *Bonamia* had been present for 10 years would have undergone natural selection. This was confirmed as the NLG strain had a significantly ($P<0.001$) greater whole wet weight increase (2.5%) during the first trial (Culloty et al. 2004). In the second trial the IER strain had the greatest performance in whole weight (6.1%), however this was not significantly different from the other strains. These results demonstrate that there are differences between European populations of *O. edulis* with regards to *B. ostreae* infection. The Rossmore strain (IER) was reported to have the lowest prevalence and intensity of infection of the disease when compared to other populations, and generally had the lowest cumulative mortality. The change in the ranking of strains over the different sites in terms of performance may indicate a genotype by environment (g×e) interaction.

Rossmore oyster breeding program currently involves large scale random mating using a population of older oysters which have survived four years field exposure to naturally occurring populations of *Bonamia.* However, they conclude that variation in disease pressure in each generation of selection, as well as other environmental variables, can have an effect on the observed level of disease resistance (Culloty et al. 2004). As was reported for MSX disease resistant oysters (Myrge & Haskin 1970 and Ford 1986, cited in Culloty et al. 2004) and *Bonamia* resistant oysters (Elston et al. 1987, cited in Culloty et al. 2004), it has been suggested that the selectively bred oysters are able to contain and sometimes eliminate the disease.

France

In France, a mass selection breeding program was implemented to select the European flat oyster, *Ostrea edulis*, for resistance to *Bonamia ostreae* in 1985 (S85) and 1989 (S89) (Naciri-Gravin et al. 1998). Disease resistance was solely characterised as improved survival, and implies nothing about the mechanism of host-parasite interactions. The third generation of S85 was 4 times more resistant to *Bonamia* in terms of percent survival compared to controls (46% parasite prevalence compared to the controls). However, the results were disappointing for the second generation of S89, possibly due to low experimental power (i.e. small numbers limiting ability to detect significant differences) or inbreeding. The percentage survival (74% parasite prevalence compared to the controls) of the cross between S85 and S89 was more than two times that of the controls (Naciri-Gravin et al. 1998), suggesting that resistance to *Bonamia* is additive. That is, the effect of one gene adds to the effect of another gene and the resulting phenotype is the sum of genetic effects. The selected strains were also found to have increased weights and weight variation in comparison to the control strain.

Since 1993 this breeding program was changed, whereby each selection cycle used pair matings constructed within and between strains (in contrast to mass spawning of the earlier program). Tests were then conducted in controlled conditions (Naciri-Graven et al. 1999). Control oysters were collected from the wild in Quiberon ('wild Quiberon') until 1990 when they began producing hatchery bred controls ('Quiberon control') from wild parents. The second year of the experiment (Naciri-Graven et al. 1999) found similar results in that the mortality of the selected lines was less than that of the controls. However, there was a contrast as the S89G1/wild oyster cross had a significantly lower mortality than the S89G1/S85G2 cross.

2.5.1.5 Chilean native oysters (Ostrea chilensis)

Chilean oysters take around five years to reach market size (50mm) in the wild and 30 months on oyster farms (Toro et al. 1996). Toro (1995), found that divergent mass selection for live weight at 40 months in Chilean native oysters (*Ostrea chilensis*) lead to a significant response for both live weight and shell length (r_p: 0.94; N: 5030). As expected, they also found that there was a large environmental effect on these traits at 14 and 27 months. Year to year variation is also common for many livestock species and is not considered a concern. However, the ranking of each group in each environment remained the same, indicating little g×e effect. In addition, for live weight, the g×e interaction was not evident when the oysters reached 40 months of age.

2.5.1.6 Tropical oysters (Saccostrea cucullata)

In 1990, a selection program using the three economically important species of tropical oysters (*Saccostrea cucullata, Crassostrea belcheri* and *Crassostrea lugubris*) was established in Thailand (Jarayabhand and Thavornyutikarn 1995). The founder population (*Saccostrea cucullata*: N: 203) was randomly collected from commercial oyster farms and mass spawned. In 1992 the oysters were divided into three broodstock groups based on their individually recorded (oysters were individually tagged) whole weights representing fast, medium and slow growth rates. These oysters were mass spawned to produce the F2 generation which were used to estimate the heritability of growth rate (Jarayabhand and Thavornyutikarn 1995). The individual whole weights of the F2 oysters were recorded every three months over the grow-out period until the oysters were 15 months of age. The three groups had significantly different ($P<0.05$) growth rates of 2.81±0.04, 2.63±0.05 and 2.46±0.04 for the fast, medium and slow groups respectively. The survival rate of the fast line oysters (74.0±3.46%) was significantly different ($P<0.05$) from the medium line (55.3±5.03%) but not the slow line (60.7±10.1%) oysters. The realised heritability estimate for growth rate in this study was 0.28±0.01 after one generation of selection (Jarayabhand and Thavornyutikarn 1995).

2.6 Summary and Conclusions

Genetic improvement is achieved through the implementation of breeding programs, aimed to reach the breeding objective through selection of genetically superior animals. Aquaculture breeding programs indicate that response to selection is achievable for growth rate, meat yield and disease resistance. So far, most programs are based on simple mass selection procedures and, for disease control, rely on natural infection strategies. More sophisticated strategies are possible with individual identification and family structures, but are currently not applied in SRO due to difficulties with achieving reliable results from structured matings.

A review of Australian and international Eastern, Pacific and Sydney rock oyster breeding programs indicated that the main traits of growth rate and disease resistance were heritable and responded to selection. High levels of selection intensity characteristic of aquaculture species facilitate a high response to selection. The results of the SRO selection program show that genetic improvement in both growth rate and resistance to WM and QX has been successful. Genetic improvement is necessary for both growth rate and disease resistance to allow the SRO industry to remain economically viable, as management options are few.

The latest results from the SRO breeding program of Port Stephens fourth generation selection lines are positive. Selected line oysters had a whole weight 33% to 52% greater than the control. The progeny of Georges River third generation lines selected for disease resistance had a decreased mortality when compared to the control: the mortality was reduced by 33%, 36% and 28% in the QX, dual and WM selection lines respectively.

Expansion of oyster breeding programs to include other traits will require the ability to achieve planned matings in SROs, the development of breeding goals and strategies for measurement and selection.

Chapter 3

Survey of the current status of the Sydney rock oyster industry: production and economic data

3.1 Introduction

Historically, the Sydney rock oyster (SRO) is the most important edible oyster in Australia (Brown et al. 1997). However, the commercial production of SROs is potentially under threat from Pacific oysters (POs). Pacific oysters grow faster than SROs and are not affected by the two main diseases that affect SROs: QX disease (QX) and Winter Mortality (WM). These constraints for SROs can be at least partially negated using genetic improvement through breeding programs. Further constraints to oyster production generally include environmental and management threats, such as the variable, uncontrolled farming environment, pollution (Dove and Ogburn 2003), other pests or predators and poor efficiency of production (Brown et al. 1997).

Breeding programs can be designed to influence those traits that are under some degree of genetic control. Genetic improvement is widely achieved in terrestrial livestock through selective breeding. That is, animals which are genetically superior to their contemporaries for important traits are selected as parents for the next generation. International breeding programs for oysters and other marine species have so far also achieved a high response to selection. For example, a

37% response per generation was achieved over the short term in Chilean native oysters selected for increased growth rate (Toro et al. 1996) and up to 12% per generation improvement for disease resistance has been reported in fish species (Kinghorn 1985). Breeding programs are implemented to achieve the breeding objective, which typically involves changing one or more commercially important traits. Commercially relevant traits for SROs are increased growth rate to increase economic efficiency of production, and increased resistance to the two major SRO diseases: QX and WM. Also potentially of economic importance to SRO farmers are oyster meat condition, shell shape and shell strength, as well as meat colouration.

In 1990 a mass selection breeding program for SROs was founded by the NSW Department of Primary Industries and Fisheries (DPI&F) to improve growth rate. In 2000, this breeding program was expanded to include two disease resistance lines: one line for resistance to QX and the other for WM resistance (Nell 2006b). The numerous reports regarding the SRO breeding program showed that final whole weight increased in the lines selected for growth rate when compared to controls (Table 3.1 Nell, 2005; Nell, 1999; Nell, 1996). This equates to a response in growth rate per generation of 13% when using the largest difference between a selected line and the control.

Table 3.1 Improvements in whole weight of four lines selected for growth rate when compared to controls

Progeny of generation	Control mean (g)	Selection lines mean (g)	Difference from control (g)	Difference from control (%)
2nd	34.3	35.7	0 to 2.9	0 to 8.5
4th	51.0	71.5	16.8 to 26.4	33 to 52

Source: (Nell and Hand 2003; Nell and Perkins 2005)

In terms of disease resistance to QX and WM, the mortality of oysters in the Georges River (Table 3.2) was reduced under selection in the second and third generation when compared to unselected controls. Selection against QX and WM is continuing to further reduce losses from these diseases, particularly where two seasons of exposure occur, when compared to the control. The superscripts within columns indicate that all lines selected for disease resistance had a significant reduction in mortality when compared to the control.

Table 3.2 Improvements in cumulative mortality of lines selected for disease resistance after field exposure to QX, QX + WM (QXWM) or WM when compared to the control

Selected line or control	Mortality (% difference from control)		
	2nd generation progeny	3rd generation progeny*	
		Feb 2004	Feb 2005
1: QX	63.5 (-22)^{d}	21.2 (-20)^{b}	52.6 (-26)^{b}
2: QXWM	72.7 (-13)^{c}	20.6 (-21)^{b}	50.3 (-28)^{c}
3: WM	80.4 (-5.3)^{b}	23.5 (-17.8)^{b}	56.5 (-22)^{b}
Control	85.7^{a}	41.3^{a}	78.4^{a}

*mean data for each breeding line and control were pooled across three experimental sites, the experiment began in July 2002
Within columns, values with different superscripts were significantly different ($P<0.05$)
Source: (Nell et al. 1999; Nell 2003; Nell and Hand 2003; Nell and Perkins 2006)

Now that genetic improvement has been achieved for the traits already recorded in these SRO lines, it is important to consider what other traits should be included in the breeding goals. These traits include those for which changes are desired (e.g. growth rate, disease resistance, meat condition, meat colour, shell shape and shell strength) as they affect costs and/or returns to SRO farmers. In addition, selection may need to be exerted on traits that have responded to indirect selection. For example, it can be observed from the data of Dove (2006, unpublished) that unfavourable changes were evident in the meat condition of the select line (L2) oysters. Control oysters had a significantly higher condition index than the select line oysters averaged over several months of measurements (N: 9) and sites (N: 3). This was also reported in the Australian PO breeding program, where the unfavourable genetic correlation was high between weight at 25 months and condition index (-0.74±0.16) for oysters grown at the Pittwater site (Ward, 2005).

Breeding objectives aim to improve the overall phenotype by improving the average genetic merit. The economic weight or value is an estimate of the relative importance of different traits that will contribute to this breeding objective. From this, particular genotypes can be ranked against each other using a single aggregate value derived from breeding values and the economic weights for traits included in the aggregate genotype. Multiple-trait selection is important as individual traits should not be considered in isolation (as occurs with single-trait selection). This is because traits may be unfavourably correlated; an improvement in the selected trait (e.g. growth rate) may lead to a reduction in another trait (e.g. meat condition as stated above, or similarly shell shape or shell strength). However, currently no estimates of economic weights exist for traits common to oyster production.

The relative economic importance of a trait is established though its economic value. Economic values are derived from the (variable) costs and returns associated with each trait. They identify the relative importance of traits which influence the level of net returns or profit to a producer. Economic values are defined as the change in profit resulting from one small, sensible genetic change of that trait when all other traits remain constant. For example, how much is profit increased when growth rate is increased by 0.1 grams per month (g/mo)? This change would result in an average whole weight at 36 months of 54g (1.5g/mo) vs. 57.6g (1.6g/mo), enabling a higher proportion of oysters to be sold in a higher grade class. Similarly, if mortality is reduced by 1%, how much is profit increased?

The aim of this chapter was to obtain relevant production and economic data to enable the calculation of economic values for a range of SRO traits in Chapter 4. This means that the current SRO breeding program can be focused in the future on the most economically important traits as determined by the SRO industry.

3.2 Material and methods

3.2.1 Survey of the Sydney rock oyster industry

Production and economic data were collected in mid-2006 using a survey of 35 oyster farmers located from Moreton Bay in Southern QLD to Sydney ('North Coast', N: 18) and from Sydney to Bega in Southern NSW ('South Coast', N: 17). Farmers had to answer more than just basic questions about the level of production to be included in the dataset. This led to four farmers not being included in the data set used to develop economic values, leaving 31 farmers. In addition, five Sydney wholesalers/retailers were surveyed. Appendices A1 and A2 contain the questionnaires for both the SRO farmers and wholesalers/retailers respectively. The farmers were located in the following regions and estuaries:

- North Coast
    - Moreton Bay (N: 1)
    - Brunswick River (N: 1)
    - Bellinger River (N: 1)
    - Nambucca River (N: 1)
    - Macleay River (N: 2)

- Hastings River (N: 2)
- Camden Haven (N: 1)
- Manning River (N: 2)
- Wallis Lake (N: 2)
- Port Stephens (N: 2)
- Brisbane Waters (N: already included in the Manning and Port Stephens estuaries)
- Hawkesbury River (N: 3)

- South Coast
  - Georges River (N: 1)
  - Crookhaven River, Shoalhaven River (N: 4)
  - Clyde River (N: 2)
  - Tuross Lake/Wagonga Inlet (N: 5)
  - Wapengo Lagoon and Nelson Lagoon (N: 2)
  - Merimbula Lake and Pambula Lake (N: 3)

N.B. Many farmers produced oysters in more than one estuary. For simplicity, the number of respondents surveyed in each estuary (N: shown above) was determined by where the main operation was conducted.

Farmers surveyed were referred by industry representatives. The estuaries where their operations were conducted represented 22 (63%) of the approximately 35 NSW oyster producing areas and were considered to be representative of the current SRO industry. This supposition is based on the following 2004/2005 figures (Anon 2005a):

- Total 377 NSW licence holders
- Minus 108 with 'nil production' or 'reports not returned'
- Minus 130 producing less than 100 bags (~10 000doz).
- The remaining 139 permit holders produced from 100 to >1000 bags (~10 000 to more than 100 000doz).

Therefore, although the farmers not included in the survey (108+130=238) constituted approximately 48% of the total NSW permit holders, these farmers contributed only 9.3% to the total production (dozens). Approximately 22% of the remaining permit holders were represented in this survey. However, as the 24 respondents who gave production levels collectively produced

2 067 125 doz, and total SRO production for 2004/2005 was 7 186 420 doz (Anon 2005a), these farmers represented approximately 29% of the total SRO production.

The data collected from the farmer survey included production means, variable costs and returns. These values represented recent averages and/or minimum and maximum values. This raw data from the farmer survey was collated and entered into Excel. Costs were not given on the same basis (e.g. per dozen, per bag, per half bag) or were differentiated into different variables (e.g. time taken for each activity, number of workers required, cost per worker per unit of time, fuel, cost/stick×doz/stick, cost as % of total returns or overall value). Thus, costs were recalculated to the same basis (dollars per doz: $/doz) for each producer.

Data were then imported into SAS (© 2000, SAS Institute Inc.). Means (PROC MEANS), frequencies (PROC FREQ) and distributions (PROC UNIVARIATE) were used to characterise the data. In addition, associations between variable values and region or production system were investigated using frequency interactions (PROC FREQ), plots (PROC PLOT) and general linear models (PROC GLM) procedures.

The values ultimately used in models to estimate trait economic values were derived from the survey results, in addition to results from literature to ensure sensible outcomes. Production information, costs and returns were used to develop a series of models that would allow the estimation of economic weights for individual traits. Models were adapted for different scenarios. As an example, several outcomes for the growth rate model are shown in Appendix A3. To provide corroborative information, oyster farmers were also specifically questioned regarding the importance of alternative SRO breeding lines and/or traits to their production system or sales.

3.3 Results and discussion

3.3.1 Characterisation of data obtained from survey

3.3.1.1 Regions represented

Oyster farmers surveyed (N: 35) were almost equally represented between the North (N: 18) and South Coast (N: 17). However, data was not used from two North Coast and two South Coast farmers as they were unable to answer required questions for various reasons (e.g. had never been in commercial SRO production or were unable to differentiate costs and returns or production variables between the different oyster species farmed). Therefore, the *maximum* number of respondents possible was 31.

Farmers (N: 17) had been in the industry from as little as four years to their entire working lifetime. One respondent had been in the industry for less than 10yrs and four respondents had been in the industry for less than 20yrs. Nine of the 19 farmers had been in the industry from 20-40yrs. Four were reported to be 3rd or 4th generation farmers.

3.3.1.2 Respondents for each category of variables

Not all farmers were able to answer all questions in all categories. Therefore the total number of farmers surveyed for each production, return or cost variable was not indicative of the number of questions where information was supplied by a farmer. The maximum number of actual responses for each category of variables ("Production", "Returns" and "Costs") is shown in Table 3.3. This Table shows that although 31 farmers appeared in the data set, 27 was the maximum number of responses for any given question, and this was for the "Production" variable category. The maximum number of responses by region was approximately equal.

Farmers were least able to answer questions regarding (variable) "Costs" relating to their operation, with a maximum of only 13 responses. The minimum number of responses for the "Production" category was one for the percentage of Large Plate sales. However, this was because few respondents (N: 6) either estimated returns for this grade class or actually sold in this grade class. For the "Returns" category, only two farmers gave information regarding the price of opened Cocktail oysters, and this was also because few farmers sold these. The "Cost" category had a minimum response of two, as many farmers did not cost a process, did not conduct a process, or integrated their costs across processes.

Table 3.3 Maximum number of responses for each of the three categories

Category	**Maximum number of responses**		
	North	**South**	**Total**
Production	10	12	**22**
Returns	11	13	**24**
Costs	8	5	**13**

3.3.1.3 Production systems practised

Farmers were allocated into one of three main production systems, the maximum number of responses is shown in Table 3.4. Some farmers practised more than one production system, giving rise to the larger N than the total number of respondents. Of the 26 farmers who provided information on *both* initial and final cultivation methods, the majority (N: 15) purchased hatchery spat, six caught wild spat, while five both purchased spat and caught wild spat. Only one farmer sold both stick and single seed oysters while the other 25 respondents (96%) indicated that they sold single seed oysters only. However, it was unclear whether the farmers who sold 'single seed' oysters also met the definition : "A single seed oyster should be defined as one that has been removed from the growing surface when no larger than a 10 cent coin" (Ruello 2006). Numbers obtained by ABARE (2003) support the results for the final cultivation method. There was a higher volume of production in NSW from the "rack tray" method (87%) compared to the "rack stick" method (13%) of culturing oysters.

In accordance with the production systems defined in Table 3.4, most farmers (N: 19) were classified as having a single seed (SS) production system. Ten farmers were defined as having mixed (MXD) production systems, four of these were also included in the single seed respondents as they both purchased and caught spat. The one farmer who used the stick (STK) production system was also included in both the MXD and SS respondents. This was because the farmer both caught and purchased spat, and also sold both single seed and stick oysters. The North and South Coasts were approximately equally represented, although the one STK producer was from the North Coast.

Table 3.4 Number of farmers who answered this question who were grouped into one of the three classes of productions systems

Cultivation method			
Initial	**Final**	**Production system**	**Number of responses**
Single seed	Single seed	Single seed (SS)	19
Sticks/slats	Single seed	Mixed (MXD)	10
Sticks/slats	Sticks/slats	Stick (STK)	1

Farmers varied with respect to the size and/or age at which oysters were removed from sticks or slats for further cultivation as single seed. A report by Nell (2005) stated that wild caught SROs are knocked off sticks anywhere from 6-36 mo of age. One farmer, who stated that growth rate and a "cuppy" shape were the most important traits, actually retained oysters on sticks for a significant period. A personal observation of the primary author was that these oysters had large flat areas from being grown on sticks and had great variation in shape.

3.3.1.4 Production levels

The 24 respondents produced between 10 000 and 875 000 doz/yr. Approximately one third (N: 9/24 = 38%) produced 25 000 doz/yr or less, 13 (54%) produced 40 000 doz/yr or less, and 79% produced less than 80 000 doz/yr. This shows that few farmers produced a very large volume, with only five respondents (21%) producing over 80 000 doz/yr. For this reason the median (middle) value of 40 000 doz/yr was more indicative of production levels for these SRO farmers than the mean of 86 130 doz/yr.

3.3.1.5 Grading methods

Half (N: 14) of the 27 farmers who reported their method of grading, graded their oysters by hand, while nine used a machine only. Four farmers used both methods, usually grading by machine during the growth phases and then by hand for sale. In hindsight, this question should have been clarified to gain a more accurate response. This is because it is unclear what type of grading was used and at what point in the oysters lifecycle that particular grading occurred. Grading may imply two things: 1) that the oysters were simply brought in and restocked at a lower stocking density as they grew; or 2) the oysters were subjectively assessed and graded into classes for selling purposes. In addition, for wild caught oysters, the number and type of gradings needs to be known, consistent with the age and/or size oysters were knocked off the sticks or slats.

3.3.2 Production variables

The maximum number of farmers who were able to answer questions relating to production variables was 22. Please note, Table 3.5 to Table 3.9 show information on minimum values, maximum values, average values and calculated averages for age and weight variables, in addition to other production variables. For each of these variables, the number of respondents (N) and characteristics of variables *across* respondents (Mean, SD, Min, Max, CV and Median) are reported. Not all respondents could provide average values. Therefore, a calculated average value is presented for those respondents who provided information on both minimum and maximum ages and/or weights.

3.3.2.1 Sale age (months: mo)

All of the 22 respondents (Table 3.5) sold oysters at a minimum 24 to 42 mo (mean: 33.7 mo). Ten were able to start selling oysters at 24-30 mo while twelve of the 22 only started selling oysters at 36 mo or greater. Maximum sale age (N: 19) ranged from 36-48 mo, with a mean of 41.6 mo. Eight farmers sold all oysters when they reached 36 mo, but seven kept a batch of oysters until 48 mo (Table 3.5).

Table 3.5 Summary of age at sale

SD=standard deviation, Min=minimum, Max=maximum, CV=coefficient of variation

Age at sale (months)	N	Mean	SD	Min	Max	CV	Median
Minimum	22	33.7	5.64	24	42	16.8	34.6
Maximum	19	41.6	5.52	36	48	13.1	42.0
Average	6	36	6.57	24	42	18.3	36
Average*	16	37.3	4.68	30	45	12.5	36.7
Sale period	16	9.36	5.52	0	21	58.3	6.00

*Calculated average=(minimum age+maximum age)/2

Sixteen respondents provided information on *both* the minimum and maximum age at sale for a year batch. Therefore, 16 values were available for the calculation of average age at sale. These calculated average ages ranged between 30 to 45 mo (mean: 37 mo, rounded to whole years: 36 mo). Average age was provided by six respondents and had a large difference between the minimum (24 mo) and maximum (42 mo) values. Only one producer sold oysters at 24 mo. This farmer sold 30% Bistro oysters and 70% Bottle oysters at this age due to the risk of WM. Three respondents sold oysters at an average 36 mo and two at an average 42 mo. Average age estimates were slightly lower than calculated average values for the Mean, Min, Max and Median values. This was expected as farmers would try to sell their oysters at the minimum age possible. Due to the low number of observations, average age estimates had a larger SD and CV than calculated estimates.

The 16 minimum and maximum values were also used to calculate the sale period within a year batch (maximum age-minimum age). Sale period ranged from a single sale (N: 1, all oysters were sold when they reached 36 mo) to a maximum sale period of 21 mo (N: 1, oysters were sold between 27 and 48 mo of age). The median sale period was six months. Eight of the remaining 14 respondents sold oysters within six months of commencing sales. Four (25%) sold all oysters within 12 mo of commencing sales. The remaining two respondents (12.5%) had sale periods of 15 mo and 18 mo. There was a loose association between minimum age and the sale period. As the minimum age at sale was increased, the sale period tended to be shorter. This could be expected as oysters at an older age should have a higher average weight and so more can be sold in high value grades over a shorter time frame.

Variation in sale age shows that SRO farmers have varying selling strategies, both in the minimum and maximum age at sale and the age range and sale period over which they were sold.

3.3.2.2 Proportion of grade class sales

Grade classes were generally defined by the respondents as Large Plate, Plate, Bistro, Bottle and Cocktail grades. Twenty two farmers responded to proportion of sales for *at least one grade* class. One respondent estimated that they sold 50% Plate oysters but were unable to provide estimates for any other grade class. Table 3.6 shows that the majority of the 22 respondents sold oysters in the Plate (N: 19), Bistro (N: 21) and Bottle (N: 19) grade classes. Nineteen farmers sold oysters in all these three main grade classes. Relatively few respondents distinguished sales into further grade classes such as Large Plate (N: 1) or Cocktail (N: 4) grades. A higher percentage of oysters were sold in the Bistro (35.1%) grade class with a slightly smaller percentage sold as Plate (31.7%) and Bottle (30.4%) oysters. Sales of Cocktail (17.5%) and Large Plate (15%) oysters were much lower. This result is supported by reports by Nell (2005) and ABARE (2003), which state that sales of Plate oysters have gradually reduced from 50% to 25% over the last decade as sales of Bistro and Bottle oysters have increased.

Table 3.6 Summary of proportion of sales

SD=standard deviation, Min=minimum, Max=maximum, CV=coefficient of variation

Sales (%)	N	Mean	SD	Min	Max	CV	Median
Large Plate	1	15.0	0	15	15	0	15.0
Plate	19	38.2	20.6	15	85	53.0	31.7
Bistro	21	30.4	10.0	15	50	34.8	30.0
Bottle	19	35.1	17.0.	5	70	53.2	33.3
Cocktail	4	20.0	14.7	5	40	73.6	17.5

These data indicate that while the majority of farmers sell oysters in the three main middle grade classes, a small percentage of farmers (18%) were forced into selling a moderately large percentage of low value Cocktail oysters. These four respondents were from the South Coast, two exclusively caught on sticks and the other two both caught wild stock and purchased hatchery stock. Conversely, only one farmer (5%) sold a high value premium product such as Large Plate oysters, and achieved a significant amount of production in this grade class. This single seed respondent was located on the North Coast.

Nineteen producers completely differentiated their total sales into grade classes, meaning that their total sales equalled 100%. The proportions of each grade class sold across these farmers are shown in Table 3.7. Means are lower than Table 3.6 as sale proportions of zero (e.g. Large plate and Cocktail grade classes) were included. As above, approximately half of these producers (58%) sold oysters in three grades, predominately in Plate, Bistro and Bottle grades. Four farmers sold in four production classes, with three of these selling Cocktail rather than Large Plate oysters. Three farmers sold in only two grades, either Bistro and Bottle (N: 1) or Plate and Bistro (N: 2). All 19 respondents sold Bistro oysters, 14 sold Plate oysters and 14 sold Bottle, one sold Large Plate and three sold Cocktail oysters.

Table 3.7 Summary of proportion of sales for oyster farmers providing complete information (N: 19)

SD=standard deviation, Min=minimum, Max=maximum, CV=coefficient of variation

Sales (%)	Mean	SD	Min	Max	CV	Median
Large Plate	0.79	3.44	0	15	435	0
Plate	34.7	23.2	0	85	66.9	30
Bistro	30.9	10.3	15	50	33.3	30
Bottle	30.6	19.5	0	70	63.7	33.3
Cocktail	3.16	9.60	0	40	304	0

3.3.2.3 Grade class weights

Weight averages and minimum and maximum values for each grade class were provided by various farmers and are shown in Table 3.8. There is a discrepancy in the numbers between Tables as these numbers indicate the number of respondents for that question. For example, 22 farmers were able to provide information on the minimum age at sale (Table 3.5) but only five were able to estimate minimum weights of the Large Plate grade class (Table 3.8). Many producers could not provide average weights for grade classes, but could provide minimum and maximum values. This was similar to the average estimates provided for age at sale (Table 3.5). All oyster weights were whole weights.

Table 3.8 Summary of grade class weights from the Sydney rock oyster survey

SD=standard deviation, Min=minimum, Max=maximum, CV=coefficient of variation, NA=not applicable

Weight at sale (g)	N	Mean	SD	Min	Max	CV	Median
Minimum Large Plate	5	59.0	2.24	55.0	60.0	3.45	60.0
Minimum Plate	11	54.9	7.70	45.0	70.0	14.0	52.0
Maximum Plate	11	60.9	12	45.0	85.0	19.7	60.0
Average* Plate	11	57.9	9.24	47.5	75.0	16.0	55.0
Average Plate	6	53.0	5.66	45.0	60.0	10.7	52.5
Minimum Bistro	14	44.2	6.54	30.0	50.0	14.8	45.0
Maximum Bistro	14	51.5	6.32	40.0	65.0	12.3	50.0
Average* Bistro	14	47.9	5.51	40.0	57.5	11.5	47.5
Average Bistro	2	45.0	NA	45.0	45.0	0	45.0
Minimum Bottle	11	34.8	8.38	20.0	50.0	24.1	34.0
Maximum Bottle	11	42.7	5.18	35.0	50.0	12.1	45.0
Average* Bottle	11	38.8	4.56	30.0	45.0	11.8	37.5
Average Bottle	4	40.3	6.65	35.0	50.0	16.5	38.0
Maximum Cocktail	7	34.4	4.54	30.0	40.0	13.2	35.0

*Calculated average=(minimum age+maximum age)/2

Five respondents provided minimum weight estimates for the Large Plate grade, with these oysters weighing over 55g (N: 1) or 60g (N: 4). One farmer with a niche market, who was not included in the Table, sold Large Plate oysters from 90-100g. From the limited amount of data available, it appears that oysters have to exceed 60g to be sold as Large Plate oysters.

The mean of average weights for Plate oysters were provided by six respondents and was approximately 53g, ranging from 45-60g. Both minimum and maximum Plate grade weights were given by 11 producers. The minimum and maximum values were then averaged. Minimum weights were between 45 and 70g and maximum weights were between 45 and 85g. Average weights calculated from these values ranged from 47.5-75g.

Bistro average weights were estimated by only two respondents and were both 45g. Bistro weight minimums and maximums were given by 14 respondents and ranged from 30 to 50g and 40-65g respectively with a mean of 48g. The averages calculated from these values were between 40 and

57.5g. Taking the midpoint, we estimated a mean value of 46g with a range of 30-50g for Bistro weights.

Average weights for Bottle oysters were estimated by four respondents and ranged from 35-50g with a mean of 40g. Both minimum and maximum weights of Bottle oysters were estimated by 11 respondents ranging from 20-50g and 35-50g respectively. The averages calculated from these values were from 30-45g with a mean of 39g. Maximum Cocktail weights (N: 7) were less than 35g on average. Values tabulated here show that grades overlap, even when they were not in adjacent classes (e.g. Plate and Bottle weights overlap). That is, grade classes were not exclusive in terms of weight. Nevertheless, a positive trend in average weight with grade was evident and confirms the previously observed wide ranges of weights for a given grade (Ruello, 2006).

The averages calculated from minimum and maximum values were likely to be biased as farmers would generally try to sell heavier oysters. This was evident in the differences between the calculated averages and those provided by the respondents who estimated actual averages. The minimum average values were 5g less for the calculated averages than for averages supplied directly by the respondent for both Bistro and Bottle grade classes.

To obtain the average sale weight overall, Large Plate minimum weight, calculated average Plate weight, calculated average Bistro weight, calculated average Bottle weight and Cocktail maximum weight were averaged for each respondent who had a calculated average value for the three main production classes (N: 8). The mean of these values was 49.0±6.70g (median: 46.3g), with a range from 40.0g to 58.3g.

3.3.2.4 Oyster condition

Although minimum sale condition was a subjective measurement, farmers were confident in their own assessment. Table 3.9 shows information regarding the minimum condition at sale. It can be seen that average minimum condition assessed by farmers (N: 23) was 77% with a range from 60 to 85%.

Table 3.9 Summary of remaining production variables

SD=standard deviation, Min=minimum, Max=maximum, CV=coefficient of variation

Variable	N	Mean	SD	Min	Max	CV	Median
Minimum condition (%)	21	76.9	6.61	60	85	8.59	80
Mortality (%)	10	17.3	18.0	3	50	104	10

There did not appear to be an association between minimum condition in which the oysters were sold with either the number of years the farmer had been in the industry or production level (dozens). The majority (N: 14) of 21 respondents sold oysters with a subjectively assessed minimum oyster condition of over 80% and declared that they would not sell oysters below this. Two South Coast farmers sold at a minimum 75% condition, two North Coast respondents sold at a minimum 70% condition and two South Coast farmers sold at a minimum 60% condition. One North Coast respondent sold oysters at a minimum 85% condition. However, since this was a subjective measurement, it is possible that minimum sale condition was more similar than these values suggest, as farmers estimates are not standardised against each other.

There was no differentiation of oyster condition between grades and it was understood that it is generally the size, not condition, of the oyster that determines the grade. The exception was for premium (Large Plate) grades where good condition is important. However, it was also indicated that certain buyers wanted to purchase cheap oysters and did not worry about the condition the oyster was in. It can be observed that oysters in poor condition were for sale at various (large chain) outlets in most locations visited, which suggests that some SRO farmers do sell oysters in condition that is below optimal. A number of farmers commented that farmers only check the condition of their oysters before depuration and not after, so condition could be reduced through spawning events. This should be obviously evident without the need to open the oysters (W. O'Connor 2007, pers. comm., 29 January). However, loss of condition after depuration or on the shelf is essentially unknown. In addition, lower grade oysters with poor condition could be sold if bottled (T. Troup 2006, pers. comm., 21-22 November).

From the survey data, minimum condition for oysters started as single seed ranged from 60-85% and for oysters started on sticks/slats ranged from 70-80%. North Coast farmers sold oysters at a slightly higher condition of between 70-85% (mean: 78%) than South Coast farmers who sold from 60-80% condition (mean: 76%). However, differences in location or production system with sale condition were not significant, and thus the same value was used in all models (Chapter 4).

Nell (2006b) stated that SROs reach a maximum condition index (CI) of around 160 in mid-summer, prior to spawning. However, these results were not directly comparable with farmers data as the condition score and CI were calculated in different ways and on different scales. The condition score used by farmers was subjectively assessed as a percentage (e.g. 1-100%). In contrast, the condition index was calculated using the formula developed by Lawrence and Scott (1982, cited in Hand and Nell 1999):

$$\text{Condition Index (CI)} = \frac{\text{dry meat weight (g)} \times 1000}{\text{cavity volume (g)}}$$

Where the proxy for cavity volume = whole weight – shell weight. Condition index generally ranged from 50 to 150 with an average of approximately 120 (M. Dove 2006, pers. comm., 3 October). This range (100) could be compared to the farmers' subjective measurement of condition on a 1:1 basis.

3.3.2.5 Mortality

The majority of farmers could not objectively answer questions regarding mortality levels. In addition, many were unable to provide averages or only gave very rough estimates. This is because many farmers did not know how many spat they started with (especially for those who have harvested wild spat). Eighteen farmers provided information on mortality rates, while one respondent simply described mortality as being "variable". Most farmers only provided overall estimates. The information on average total mortality was estimated by ten farmers (Table 3.9) and ranged from 3% to 50% with a median of 10%. However, the time period/s that respondents provided estimates for varied. For example, some respondents were unclear over which stage of the life cycle the mortality occurred, others gave total mortality and one respondent's estimate was from "flick off" to final grow out.

Total mortality was estimated by two farmers to average 24%. Three farmers estimated total mortality to be less than 5%. One farmer who differentiated mortality into different production phases estimated 25%, 10%, 5% and 10% for spat, nursery, first grow out and final grow out growth phases respectively. Therefore, for this respondent, cumulative mortality totalled 62% (25% + 12% + 8% + 17%). Another farmer differentiated mortality into first grow out (10-20%) and final grow out (0%). The zero estimate was unfeasible and not included. This indicates that farmers who estimated mortality based on the phase of production estimated a higher total mortality than those who did not. The latter group perhaps only accurately know the mortality level during grow out. This was especially the case for MXD farmers. Nell (2006b) states that background SRO mortality for a 2-3 year growing period ranges from 10-20%. However, it is not clear whether this mortality occurs early or late in the growing cycle.

3.3.3 Returns

The maximum number of farmers who were able to answer questions regarding returns was 24. Returns included price per dozen for whole and opened oysters for each of the grade classes. The majority of farmers sold only whole oysters, which is reflected in the number of responses for the whole (N: 24) vs. opened (N: 7) returns. The highest number of respondents was evident for Bistro grade oysters, which was expected as the majority of respondents sold these. Characteristics of this data are shown in Table 3.10. Please note, as in the previous section, Table 3.10 and Table 3.11 provide information on minimum values, maximum values, average values and calculated averages for returns for whole and opened oysters per dozen. For each of these variables, the number of respondents (N) and characteristics of variables *across* respondents (Mean, SD, Min, Max, CV and Median) is reported. Figure 3.1 provides graphical information on price differentials.

3.3.3.1 Sale destination

Sale destinations were differentiated into wholesalers, restaurants and/or public/retail (selling oysters directly from the shed or shop front). Of the 18 respondents, the majority (N: 17) sold to wholesalers who provide a large volume market compared to quality driven restaurants or retailers. Several sold to restaurants (N: 9) and/or the public (N: 8) as well. Four respondents sold oysters to all destinations, eight sold to two destinations, and six to wholesalers only. Anecdotal evidence from farmers indicated that they preferred to sell through wholesalers as they were more reliable and faster in terms of payment than other sale avenues.

3.3.3.2 Whole oyster returns

Average prices for Large Plate oysters (N: 5) ranged between \$8.50-\$10.00/doz. One farmer sold 90-100g Large Plate oysters at \$48.00/doz to a very high quality catering business. This respondent sold Plate, Bistro and Bottle oysters for \$12.00/doz, \$8.00/doz and \$5.50/doz respectively. This producer had a niche market and location advantage, so the high prices this farmer received in each grade were not representative of the industry. Therefore, these values were excluded from Table 3.10.

There was an overlap of returns across grades. For example, most Plate oysters (N: 23) sold from $5.50-$9.00/doz (mean: $7.44/doz) whereas Bistro oysters (N: 24) sold from $4.20-$7.00/doz (mean: $5.45/doz) and Bottle oysters (N: 20) sold from $2.80-$5.00 (mean: $3.92/doz). Eight respondents sold Cocktail oysters from $1.65/doz to $3.50/doz (mean: $2.74/doz). Means were calculated from respondents who provided information on returns for the three main categories. These means were only slightly higher than those reported in Table 3.10, being $7.58/doz, $5.53/doz and $3.99/doz for Plate, Bistro and Bottle grade classes respectively. All these estimates were higher than those from the 2003-2005 report by Anon (2005a) who reported prices received of $6.68/doz, $4.97/doz and $3.48/doz for Plate, Bistro and Bottle/Cocktail grades respectively. The returns presented by Anon (2005a) were the same for all culture methods. However, it is well known that stick prices are generally lower than single seed prices, due to factors such as poor and variable shape, and this may have brought the average price down in the report by Anon (2005a). This is supported by the Anon (1997) report, which states that oysters grown in trays have superior shape and so are of improved quality compared to oysters grown on sticks.

Table 3.10 Summary of average returns for whole Sydney rock oysters

SD=standard deviation, Min=minimum, Max=maximum, CV=coefficient of variation

Whole oysters ($/doz)	N	Mean	SD	Min	Max	CV	Median
Large Plate	5	9.00	0.71	8.50	10.00	7.86	8.50
Plate	23	7.44	0.80	5.50	9.00	10.70	7.50
Bistro	24	5.45	0.63	4.20	7.00	11.50	5.50
Bottle	20	3.92	0.60	2.80	5.00	15.40	4.00
Cocktail	8	2.74	0.71	1.65	3.50	25.70	3.00

3.3.3.3 Opened oyster returns

As expected, opened oysters sold for a higher price than unopened oysters in order to recover the cost of processing (Table 3.11). The actual difference for one respondent between whole and processed Large Plate oysters was $2.00/doz. Price differences for Plate oysters from the farmers who sold both whole and opened oysters (N: 5) ranged from $1.00-$3.00/doz (mean: $2.40/doz).

Seven respondents sold both whole and opened Bistro grade oysters, with a difference ranging from $0.30-$4.50/doz (mean: $2.34/doz).

Those who reported both whole and opened prices for Bottle oysters (N: 5) had differences ranging from $0.40-$7.70/doz (mean: $3.28/doz, median: $2.50/doz). Given the very large range, it is possible that some respondents provided prices per jar of oysters (e.g. a difference of $7.70/doz is not feasible) and this needs to be clarified. As farmers usually put 2-2½ doz in a jar, the higher values were divided by this, and more sensible estimates were obtained. However, as it was not clarified as to whether the returns were per dozen or per jar of oysters, the farmers estimates as provided were used. There was no difference in price for one of the two observations for opened and unopened Cocktail oysters. The second respondent only sold opened Cocktail oysters. It was not clarified whether Cocktail oysters were sold in jars or as individual oysters. Lower grade opened oysters are not always sold in jars but in "all you can eat" seafood buffets and sometimes supermarkets (T. Troup 2006, pers. comm., 21-22 November).

Table 3.11 Summary of average returns for opened Sydney rock oysters

SD=standard deviation, Min=minimum, Max=maximum, CV=coefficient of variation

Opened oysters ($/doz)	N	Mean	SD	Min	Max	CV	Median
Large Plate	3	12.00	2.50	9.50	14.50	20.80	12.00
Plate	5	11.20	2.39	9.00	15.00	21.30	10.00
Bistro	7	8.83	1.47	7.30	11.50	16.60	8.00
Bottle	5	6.88	2.75	4.40	10.50	39.90	6.00
Cocktail	2	3.00	0.00	3.00	3.00	NA	NA

3.3.3.4 Price differentials

There did not appear to be a relationship between average weight and price received within a grade class, although there was a clear price differential on average between grade classes, even though the range of prices received overlapped between classes. The price differentials were compared using the means presented in Table 3.10 and Figure 3.1. Returns ($/doz) for whole oysters were used as well as the data from the 20 respondents who sold oysters in the three main grades. Eleven of these 20 respondents sold oysters in Large Plate and/or Cocktail grades. The price differentials were similar regardless of the way they were calculated. When rounded to the nearest $0.05/doz, price differentials between the grade classes were $1.55/doz between Large Plate and Plate, $2.00/doz between Plate and Bistro, $1.55/doz between Bistro and Bottle and

$1.20/doz between Bottle and Cocktail. The very high premium that some producers can command for Large Plate suggests that the price differential between Large Plate and Plate can be larger than that observed here, but not on average across producers.

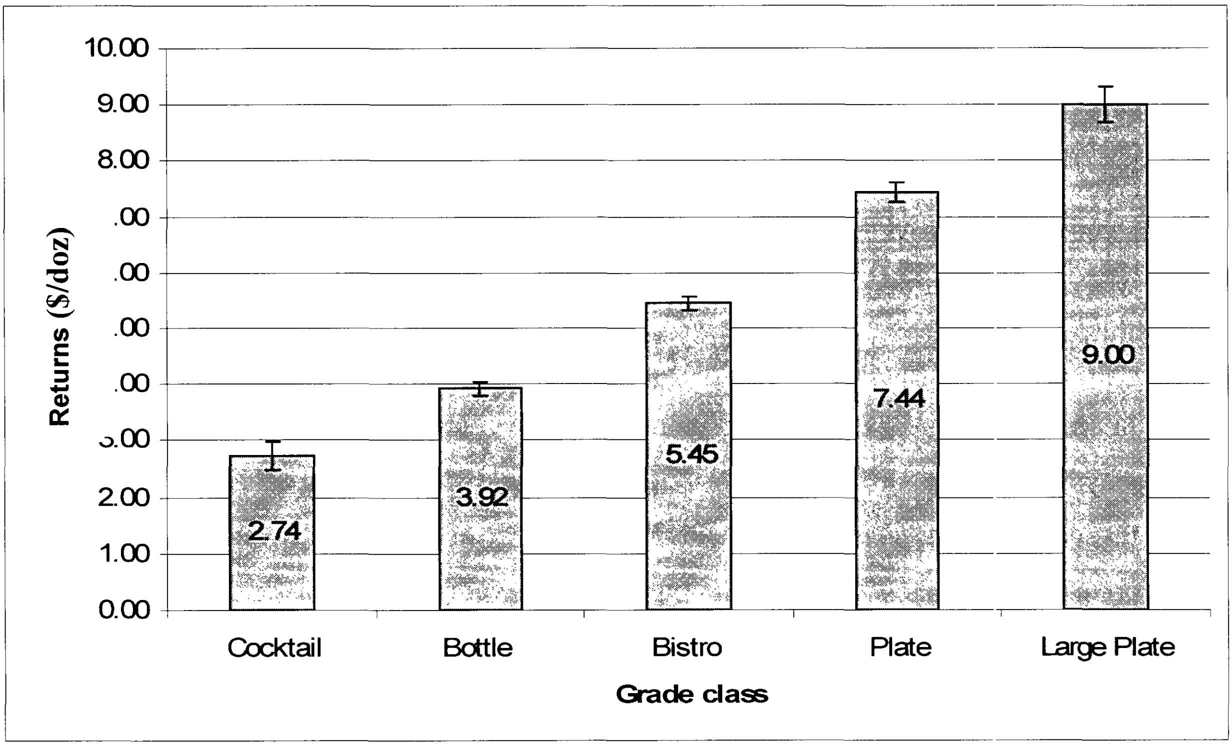

Figure 3.1. Returns ($/doz) for whole oysters

3.3.3.5 Proportion of sales for each grade class

From Table 3.10 and Table 3.11 it can be observed that the majority of farmers sold oysters in only three main grade classes, confirming observations regarding the number of respondents in the production data set. Observations for the extreme grade classes were low for whole oysters and very low for opened oysters. Therefore, average returns for these grades must be interpreted with caution.

3.3.4 Costs

For the purpose of this study, the costs considered important are variable costs. Variable costs vary with the level of output of the operation and include costs such as wild spat collection, grading, depuration, packaging and freight. Fixed costs remain constant regardless of the level of production (for which only small changes are envisaged). As described previously, Table 3.12 indicates the number of respondents (N) and characteristics of variables across respondents (Mean, SD, Min, Max, CV and Median) are reported for each variable.

Some farmers found it hard to differentiate between the fixed and variable costs of their operation. There was a maximum of 13 responses to the questions involved in this section of the survey. Of the 23 respondents who were able to cost any activity, eight respondents only provided one cost estimate, five provided two estimates and two provided five of the eight possible estimates. This was because farmers found it very difficult to quantify the costs incurred with each of their activities. This was a strong contrast to response rates for the returns farmers received.

In addition, farmers found it difficult to attribute costs to the labour involved in any activity. This may be the cause of considerable variation in the results for cost categories. This was particularly the case for costs associated with the catching of wild spat which had a significant labour component. Costs were often confounded. For example, the cost of drying oysters for control of overcatch and/or mudworm was included in grading costs. This was because, in most instances, oysters were left out of the water for a period of time after grading. In addition, farmers differed in the way they partitioned costs (e.g. freight, depuration or processing costs differentiated from selling costs), or were only able to cost part of an activity. Processing costs included both manual opening and opening with the use of a pneumatic drill.

Variable costs were broken down into the five main sections shown below. All costs were calculated on a $/doz basis even though most farmers presented costs on a different basis. For example, as most oysters were sold in bags, the selling cost provided was calculated as $/bag sold. This value was then divided by the average number of dozens per bag (or half bag) to convert to a $/doz basis. The general costs associated under the main categories were as follows:

- Wild spat collection:
    - Labour involved in making up groups of sticks/slats
    - Materials involved in making up groups of sticks/slats (e.g. wire)
    - Labour to put the sticks/slats out and to bring them in
    - Fuel involved to put sticks/slats out and bring them in
- Grading:

  - Labour to bring in, grade on size, tray up and put out
  - Fuel involved to bring oysters in and put out
  - Electricity to run grading machine
  - Also included under this heading was chipping costs as many farmers did not differentiate between the two (e.g. chipping involves extra labour to knock off overcatch and/or separate clumps of oysters off sticks into individuals)
  - OR grade by weight to sell so labour and fuel to bring in and grade SROs
- Depuration (differentiated from selling costs):
  - Labour to put oysters into depuration tank
  - Electricity to run pump and UV filter
- Selling:
  - Labour to bring oysters in and bag/box them up
  - Fuel involved in bringing them in
  - Cost of bags/boxes with printing/labels, cost of jars
  - Freight (e.g. labour and fuel to deliver oysters or payment of courier)
  - Commission
  - Extra labour (e.g. liaising with buyers, document production)
- Processing:
  - Labour to open the oysters for sale

Any cost that the farmer indicated to be zero was not included in the results as it is unfeasible that an activity had no cost, even if it involves only a small amount of labour.

3.3.4.1 Wild spat collection

Wild spat collection is also referred to as "spat collection", as differentiated from "spat purchase". Spat collection costs were estimated by 13 farmers and information on this is shown in Table 3.12. This Table shows that collection costs ranged from a very low \$0.00003/doz to \$0.38/doz, resulting in the very large CV (132). The mean (\$0.09/doz) and median (\$0.04/doz) were dissimilar so the median was the preferred estimate. Wild spat collection also incurs a small fixed cost collection permit fee of \$178 (Anon, 2006?a) which would not be incurred by those farmers who exclusively bought in spat.

Table 3.12 Summary of costs for the Sydney rock oysters

SD=standard deviation, Min=minimum, Max=maximum, CV=coefficient of variation

Cost variable*	N	Mean	SD	Min	Max	CV	Median
Wild spat collection	13	*0.09*	0.11	0.00003	0.38	132	0.04
Cost/grading	11	*0.21*	0.22	0.0042	0.68	102	0.18
Grading number	7	*8.77*	4.79	1.00	15.00	45.4	9.4
Total grading cost	6	*1.76*	2.46	0.04	2.81	140	0.63
Depuration	9	*0.22*	0.17	0.02	0.50	70.1	0.26
Processing	3	0.66	0.40	0.22	1.00	60.7	0.75
Selling	10	*0.71*	1.27	0.0054	3.90	178	0.16

*All costs are given in $/doz except grading number which is an actual number

3.3.4.2 Grading

Grading costs were estimated by 11 respondents (median: $0.18/doz) but only seven respondents provided information on the number of gradings over the oysters lifetime (median: 9.4). Therefore, total grading costs were calculated for six farmers only. Total grading costs ranged from $0.04/doz to $2.81/doz (median: $0.63/doz). The wide variation in total costs may reflect the very significant differences in costs for alternative grading techniques e.g. hand vs. machine or type of machine used. The higher grading costs may include the cost involved with knocking wild catch off sticks or slats.

3.3.4.3 Depuration

Depuration costs (N: 9) exhibited large variation between the minimum ($0.02/doz) and maximum ($0.50/doz) values. However, this did not create a large difference between the mean ($0.22/doz) and median ($0.26/doz) values. Depuration costs were only incurred by those farmers harvesting oysters from conditionally restricted (CR) leases. Depuration is mandatory for CR leases under the Safe Foods Quality Assurance Scheme (Anon, 2005?) and often the estimate appeared to correlate with the farmers opposition to the Scheme. For example, one farmer who was not legally required to depurate reported that they purged 50% of oysters at sale as it incurred a "negligible" cost. Most farmers were not in favour of mandatory depuration and stated that depuration cost was "too much" or "too expensive due to extra handling". The maximum cost for this was $0.50/doz, estimated by a farmer clearly opposed to depuration.

Farmers with CR and conditionally approved (CA) leases could potentially move oysters from CR to CA areas for a specified period of time. This would enable them to avoid depuration costs. However, an indirect cost would be incurred with this unless the move is also required to obtain or maintain condition. A cost involved in depuration is the reduction of the farmers ability to respond to the market (R. Tynan 2007, pers comm., 3 March). However, this cost is difficult to define.

3.3.4.4 Selling and freight

Two farmers differentiated between selling and freight costs (Table 3.12). One of these respondents estimates combined gave a total selling cost of $0.13/doz, which is very close to the median value for selling costs ($0.16/doz). However, the other respondent had a combined selling and freight cost of $3.90/doz which was the highest cost reported and far greater than the median. The two highest estimates of selling costs skewed the data towards high values and increased the mean and CV.

3.3.4.5 Concluding remarks regarding costs

Since no producer was able to provide complete information regarding variable costs of production, values used for economic models were a combination of literature and survey values (described in the following sections).

3.3.5 Development of the economic models

A series of economic models were developed in Chapter 4 with varying complexity. The basic model used the mean or median values from the survey regardless of the production system or region in which the farmer was based. Input values were then differentiated into the different production systems defined in Section 3.3.1.3 (Single seed: SS; Mixed: MXD and Stick: STK) and regions (North or South Coast). Two production systems were used (SS, MXD) for the characterisation of the data as there was only one farmer who reported selling oysters directly off sticks. Depending on the age of the oysters when they were knocked off sticks or slats, it is expected that cultivation methods would influence the shape of the oyster at harvest. Prices received for MXD oysters were lower than those prices for SS and this is thought to be indicative of the poor and more variable shape of wild caught (e.g. not single seed) oysters. The basic model carried assumptions on distribution of weight at sale, age at sale, grade class costs, processing, mortality and grading costs. However, the preliminary economic values calculated in Chapter 4 were not differentiated into region or production system.

3.3.5.1 Production variables

Age at sale

Overall average age at sale across grade classes was 37.3 mo. The sale of SS oysters began at 24 mo of age (mean: 35.8 mo), whereas the MXD oysters were generally harvested at a minimum 36 mo (mean: 41.4 mo). This difference was close to six months on average. Mean sale age for MXD oysters was very similar to the (Nell 2001b) estimate of 42 mo to reach 50g.

Sale weight and growth rate

Fifteen respondents provided information on weight at sale for the three main grade classes. The average population weight for these respondents was 47.7±5.84g, ranging from 40.0g to 58.3g. The average growth rate of the population was 48g/37 mo = 1.30 g/mo with corresponding average growth rates of: Plate: 1.52 g/mo; Bistro: 1.28 g/mo; Bottle: 1.06 g/mo.

There was a difference in the proportion of the different grade classes sold between locations (Table 3.13). The North Coast sold a higher proportion of the heavier grade classes, which is expected due to their faster growth rates compared to the South Coast. There was no significant difference between average weights for the three main grade classes between locations. Location approached significance (P<10%) for average age at sale between North Coast (mean: 34.7 mo) and South Coast (mean: 38.9 mo) farmers. However, this did not result in a significant difference in returns between the regions.

Table 3.13 Proportion of sales in different grade classes for the North (N: 10) and South Coast (N: 9) regions

	Mean proportion (%)	
Grade class	**North Coast**	**South Coast**
Large Plate	1.50	0
Plate	44.3	24.1
Bistro	28.6	33.5
Bottle	25.5	36.3
Cocktail	0.50	6.11

As expected, there was also a difference between production systems in proportion of the different grade classes sold, with SS systems being able to sell a higher proportion of the higher grade classes (Table 3.14).

Table 3.14 Proportion of grade class sales for SS (N: 9) and MXD (N: 8) production systems

	Mean proportion (%)	
Grade class	**SS**	**MXD**
Large Plate	1.67	0
Plate	40.0	29.6
Bistro	28.3	31.2
Bottle	28.3	34.2
Cocktail	1.67	5.62

Plate weight at sale (55g) did not vary with average age at sale, with oysters sold at this weight ranging between 30 mo to just over 36 mo of age. Data regarding sale age and weight were used to estimate average growth rates, with the assumption that the growth rate close to sale age was generally linear over time. This assumption was supported by the data from Dove (2006, unpublished) who measured SRO weight from 18-29 mo, demonstrating the growth trend was linear. There were a very limited number of respondents who estimated both grade class weight *and* age at sale.

3.3.5.2 Returns

Sale prices for grade classes

Single seed producers sold four comparable grade classes at an equal or higher price than MXD producers. However, there was no significant difference in returns for any grade class between the production systems. An anecdotal industry value was that prices for stick oysters were generally \$0.50/doz lower than single seed oysters due to the increased difficulty of opening, poorer shape and greater variability in shape. The survey data supports this supposition, with an average difference of \$0.32/doz across the bottom three grade classes (Table 3.15). This is further supported by a farmer who sold Plate single seed oysters for \$8.00/doz and stick oysters for \$7.50/doz. However, another farmer sold Plate oysters for \$7.50/doz and \$7.30-7.40/doz, Bistro oysters for \$5.50 and \$5.40/doz and Bottle oysters for \$4.50 and \$4.00/doz from single seed and stick production respectively. This would lead to an average difference of only \$0.23/doz. Two

South Coast farmers reported that they sold oysters caught on sticks at $0.50/doz less than those they purchased as spat.

Few farmers sold oysters from the two different production systems. Therefore, as the same farmers were not present in both production categories, and there is no correction for different customers or sale locations, these results should be interpreted with caution. A general conclusion would be that there was a *tendency* for a price difference. However, the limitations described above and the small sample size suggests that the accuracy of the estimate for the price differential is low.

Nevertheless, assuming that these values are representative of the industry, this indicates that even if oysters were knocked off the sticks or slats early, the prices received were still not as high as those received for oysters purchased as hatchery spat. As most farmers reported that they were 'price-takers', this suggests that wild caught oysters were of lower quality than single seed oysters, probably due to poor shape and variation in shape given the consistent weight, as previously mentioned.

Table 3.15 Returns ($/doz) for farmers who had a production system of SS or MXD

Grade class	N (SS, MXD)	Median		Difference
		SS	MXD	
Large Plate	4, 0	8.50	-	-
Plate	10, 10	7.50	7.50	0
Bistro	11, 10	5.50	5.35	+0.15
Bottle	8, 9	4.10	3.80	+0.30
Cocktail	4, 3	3.00	2.50	+0.50

N.B. The producer with the very highly priced niche market was not included in this Table

South Coast farmers generally sold Large Plate and Bottle oysters at a higher price than the North Coast (Table 3.16). This difference was only significant ($P<0.05$) for returns on Bottle oysters. There was no difference in returns for Plate and Bistro oysters. Therefore, the average difference between the locations for the main grade classes (Bottle, Bistro and Plate; mean: $0.23/doz) was driven by the large difference in returns for Bottle oysters. North Coast farmers sold Cocktail oysters at a slightly higher price than South Coast farmers. Limitations as described above would also apply to estimates of these differences. There was a tendency for South Coast farmers to sell oysters at a higher price but this was not statistically significant. This was possibly because North Coast farmers also sold slightly heavier oysters on average.

Table 3.16 Returns ($/doz) for North (Nth) and South (Sth) Coast farmers

Grade class	N (Nth, Sth)	Median		Difference
		North	South	
Large Plate	3, 2	8.50	9.25	-0.75
Plate	11, 12	7.50	7.50	0
Bistro	11, 13	5.50	5.50	0
Bottle	9, 11	3.50	4.20	-0.70
Cocktail	4, 4	3.00	2.75	+0.25

N.B. The producer with the very highly priced niche market was not included in this Table

Farmers' average returns per dozen ($/doz) were calculated using the following equation:

$$\text{Mean return per doz} = \frac{(\text{sale proportion} \times \text{doz sold}) \times \text{returns for each grade class}}{\text{doz sold}}$$

Large Plate was not included in this equation as complete information was unavailable. Overall average returns across locations were $5.62/doz.

Figure 3.2 illustrates that South Coast farmers (mean: $5.73/doz) have an average income per dozen slightly higher than North Coast farmers (mean: $5.50/doz). However, this difference was not significant. When returns per dozen were averaged over the three main grade classes, the South Coast again had a higher average return (mean: $5.84/doz) than the North Coast (mean: $5.40/doz), similar to the values obtained from Table 3.16.

Figure 3.2. Mean returns per farmer for North (N: 8) and South Coast (N: 7) regions

3.3.5.3 Costs

Wild spat collection costs

The range of wild spat collection costs were similar regardless of the location in which they were caught. The North Coast (N: 9) had a range from $0.00003-$0.38/doz and the South Coast (N: 5) $0.0006-$0.23/doz (Table 3.18). The means were also similar (North Coast: $0.095±0.125/doz; South Coast: $0.075±0.009/doz). The range of estimates was large because of the varying assumptions made by farmers in calculations to obtain the cost estimate. For example, some farmers did not attribute a cost to total labour whereas others detailed the number of hours of labour required and number of workers involved in all processes that they costed.

Table 3.17 Costs ($/doz) for farmers who farmed SS or MXD oysters

Cost	N (SS, MXD)	Mean		Difference
		SS	MXD	
Wild spat collection	8, 3	0.04*	0.20	-0.16
Grading cost/grading	6, 2	0.15	0.19	-0.04
Number of gradings	4, 1	10.4	1	+9.40
Total grading cost	3, 1	2.16	0.18	+1.98
Depuration	6, 1	0.26	0.30	-0.04
Selling	5, 4	0.14*	1.07	-0.90

*median

Table 3.18 Costs ($/doz) for North (Nth) and South (Sth) Coast farmers

Cost	N (Nth, Sth)	Mean		Difference
		North	South	
Wild spat collection	8, 5	0.06*	0.05*	+0.01
Grading cost/grading	8, 5	0.20	0.22	-0.02
Number of gradings	3, 4	7.00	11.40	-4.40
Total grading cost	2, 4	0.17	2.56	-2.39
Depuration	6, 2	0.24	0.26	-0.02
Selling	3, 7	0.48*	0.14*	+0.34

*median

Grading costs

There was little difference in costs for MXD oysters *per grading* and SS oysters (Table 3.17). Grading costs per dozen ranged from $0.004-$0.53/doz per grading for SS (mean: $0.15/doz) and $0.18-$0.20/doz for MXD oysters (mean: $0.19/doz). Therefore, the cost per grading was considered to be the same for MXD and SS oysters. However, the only observation (N: 1) for MXD oysters was a single grading before sale, whereas single seed oysters (N: 4) were graded from four to 20 times throughout their lifetime (mean: 10.4). If oysters were sold as single seed oysters, it is probable that they would have been graded three times per year. It was not clarified at what stage producers using wild caught spat started grading their batch of oysters. For single seed producers, this meant that oysters sold at the average 3yrs old were graded approximately every 3.5 months. This would lead to a difference in total grading costs for the different production systems.

Further information from the respondent who provided very detailed information indicated that in the final year before sale, single seed oysters were graded three times; twice to reduce stocking density and once for sale (and so this last grading cost also includes some selling costs). The oysters were graded in spring, summer and autumn, but not winter as the growth rates were expected to be low. There was also no major difference in average costs *per grading* between North and South Coast farmers. The difference between the regions was not known but these differences may be due to the differences between the costs of catching wild oysters on sticks vs. slats (R. Tynan 2007, pers. comm., 3 March).

Total grading costs were calculated using grading cost estimates and the number of gradings over the oysters' lifetime when the oysters were sold at an average 36 mo. There was no significant difference between regions in the total number of gradings. However, the number of respondents was very low.

Depuration costs

Table 3.17 and Table 3.18 show that, as expected, there was no major difference in average depuration costs between the North (N: 6, mean: $0.24/doz) and South Coast (N: 2, mean: $0.26/doz) farmers or SS (mean: $0.26/doz) or MXD (mean: $0.15/doz) production systems.

Packing, freight, and selling costs

Packing and freight costs estimates were generally too low in number to be useful (N: 2). However, several farmers included factors such as packing and freight costs in selling costs, so these cost categories were combined into a single selling cost value. Selling costs were much lower for SS oysters (mean: $0.17/doz) than MXD oysters (mean: $1.07/doz). This may be because they were easier to harvest than oysters harvested off sticks. This was accommodated in models comparing production systems. There was a difference in selling costs between locations, with South Coast farmers attributing an average $0.30/doz and North Coast farmers $1.50/doz. The PROC GLM procedure in SAS indicated that both region and initial method of cultivation had a significant ($P<0.05$) effect on selling cost. There was no apparent reason for this difference in cost.

Plots of variables (not presented) indicated that there was no obvious trend between either the number of years a farmer had spent in the industry or the size of the operation (dozens produced) with variable costs, returns, the percentage break-up of grade class sales, average weights of each grade class or average age at sale.

3.4 Additional comments from the survey

3.4.1 Importance of SRO traits

Twenty farmers provided information regarding the importance of various traits to their operation and the ranking of these (Table 3.19). Growth rate was the most important trait for 10 farmers and important to an overall 15 respondents. Shape was the trait of second priority for seven respondents (and important to 10 overall). The condition of oysters was important to 14 respondents and the highest priority trait for five respondents. Appearance and eating quality were important to only one respondent each. However, these should be viewed as sub-classes of larger categories (e.g. of shell shape and meat condition and colour). Winter mortality resistance was of importance to only three South Coast respondents. Two North Coast and two South Coast respondents rated QX resistance in their top three priorities in terms of traits. Growth rate was considered the most important trait overall, followed by meat condition and shell shape.

Table 3.19 Number of respondents who ranked traits according to the traits importance to the farmers operation*

Trait	GR	QXR	WMR	SH	AP	MORT	COND	EQ	COL
1	10	2	3	1	1^{p}	1^{p}	5	0	$1^{5\%p}$
2	3^{p}	0	0	7	0	2	6	1	1 (shell)
3	2	2	0	2	0	2	3	0	2 (meat)
Total	15	4	3	10	1	5	14	1	4
Wt'd total	38	8	9	19	3	9	30	2	7

GR: growth rate/size; QXR: QX resistance; WMR: WM resistance; SH: shape/variation in shape; AP: appearance (size and condition); MORT: decreased mortality; COND: condition; EQ: eating quality; COL: colour
*Traits were ranked from one (being the highest priority) to three
p: respondents would pay a premium for oysters with these characteristics
Wt'd: weighted

Four large wholesalers ranked traits of importance. All of these considered meat condition to be the number one priority (Table 3.20). Two respondents reported that SRO shape was important to their business, and one respondent found the variation in shape to be important. Meat colour was important to two respondents, with size and presentation being important to one respondent each.

Table 3.20 Number of respondents who ranked traits according to the trait's importance to the wholesaler's operation*

Trait	Size	Shape	Presentation	Condition	Meat colour
1				4	
2	1	2			1
3		1	1		1
Total	1	3	1	4	2
Wt'd total	2	5	3	12	3

*Traits were ranked from one (being the highest priority) to three

3.5 Conclusions

There were a number of constraints to obtaining specific, reliable estimates of variable costs and returns from the survey of individual SRO farmers. This particularly included a lack of detailed cost data. For example, many SRO farmers did not allocate a cost to catching wild stock even though the labour involved would be significant. There was "noise" in returns for the different grade classes, with overlapping grades and prices. For example, Plate grades ranged in weight from 45-85g, yet Bottle weights ranged from 20-50g. Plate returns ranged from \$5.50-\$12.00/dozen and Bottle oyster returns ranged from \$2.80-\$5.50.

There was limited data available to quantify the effect of various characteristics on costs and returns. For example, the level of the mortality rate sustained through machine grading was not known. Farmers did not appear to consistently receive premiums or penalties for traits such as meat condition, shell shape or meat colour. Of the farmers surveyed, none used the same cultivation technique (e.g. baskets, tumblers, trays) during the same growth period so comparisons should be conducted with caution.

Chapter 4

Derivation of economic weights

The derivation of costs, returns and production parameters for Chapter 4 was outlined in Chapter 3. From this information, economic weight were derived for the traits of growth rate, mortality, shell shape and strength and meat condition and colour. For the purpose of estimating economic values weights for each of the grade classes were considered discrete: Large Plate >60g; Plate 50-59g; Bistro 40-49g; Bottle 30-39g; and Cocktail <30g. Preliminary evaluation showed that this approach resulted in similar proportions produced per grade class as was indicated by the survey results. All economic values were reported on a dollars per dozen ($/doz) basis for a one unit change in the trait of interest.

4.1 Growth rate

From survey data, average population weights ranged from 40.0g to 58.3g. Therefore, normal distributions were used to model five populations with average weights ranging from 40g to 60g, at 5g increments.

Each population was generated assuming a normal distribution (NORMDIST). Standard deviations were based on a fixed CV of 18-20%. Therefore, standard deviations differed with the different means of each population. This CV was derived from the data of Dove (2006, unpublished) and is similar to estimates for growth in livestock (Figure 4.1). Characteristics of resulting populations are shown in Table 4.1. From these distributions, the proportions of the population that fell into each grade class could be estimated (from the discrete classes above). Grade classes were differentiated into either five or three grade classes. This enables differentiation of results for producers who have different selling strategies.

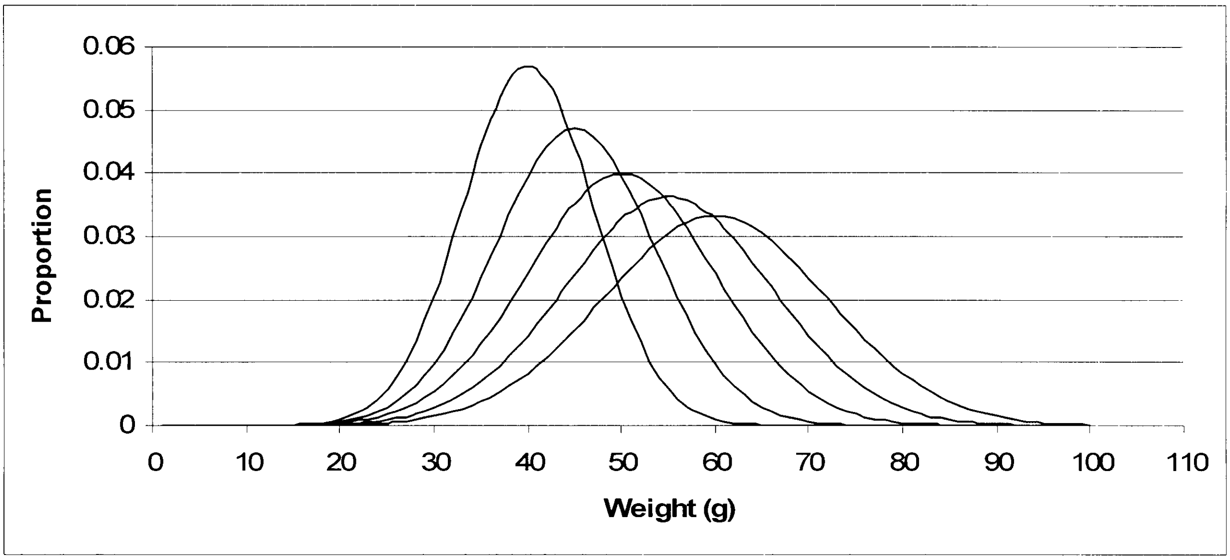

Figure 4.1. Normal distributions for five populations differing in average weight by 5g

Table 4.1 Increases in growth rate for five average weights at sale (age constant basis)

Average weight ± standard deviation (g)	Growth rate to 36 mo (g/mo)	Increase from previous average (%)
40±7.0	1.11	-
45±8.5	1.25	13
50±10	1.39	11
55±11	1.53	10
60±12	1.67	9

The proportion of the population in each grade class (Table 4.2) was calculated from normal distribution theory, assuming threshold values for each grade class. This was then multiplied by the returns per dozen, relevant to each grade class. From this, the average returns for each population distribution were calculated. The difference between the average return for each scenario indicates the economic values of 5g incremental changes in average population weight.

Table 4.2 Proportion (%) of oysters sold in each of the five and three grade classes when the average weight of the population changes from 40g to 60g at 5g intervals

Weight (g)	40	45	50	55	60
Five grade classes					
Large Plate	0.26	4.39	14.5	34.1	**51.6**
Plate	8.45	25.4	**37.7**	**35.0**	29.3
Bistro	**44.1**	**44.3**	35.6	22.9	14.7
Bottle	40.5	22.5	11.0	6.91	3.82
Cocktail	6.66	3.40	1.13	1.02	0.55
Three grade classes					
Plate	8.72	29.8	**52.2**	**69.2**	**80.9**
Bistro	44.1	**44.3**	35.6	22.9	14.7
Bottle	**47.2**	25.9	12.2	7.93	4.37

* bold indicates highest proportion.

The assumptions for the economic model for growth rate include:

- Constant average age at sale (36 mo) and a relatively short and constant selling period. This leads to the growth rate differences shown in Table 4.1 between the five average weights. Each 5g increase in average sale weight would lead to an average increase in growth rate of 0.14g/mo.
- Growth rate of oyster meat is not linear, but seasonal, restricting the potential for earlier or later sales (Dove, 2006, unpublished). This seasonality of condition indicates that oysters cannot be sold outside of the sale period even if they have reached the desired weight. Instead, increased growth rate implies that farmers would be able to sell a larger proportion of oysters in the larger grade classes during the fixed sale period. Other restrictions may also apply, as farmers sell oysters to avoid mortality (e.g. from WM) or for logistical reasons (e.g. need equipment for subsequent year batch).

- Existing grading rates were sufficient to accommodate small incremental changes towards faster growth rates. Therefore, grading costs did not vary, leaving the total cost the same (which can then be ignored).

As expected, as the average weight at sale increases, a greater proportion of oysters were sold in the higher value grade classes (Table 4.2). When producers differentiated between five grade classes at an average sale weight of 40g, less than 1% of oysters could be sold as Large Plate oysters. The majority of oysters were sold in the Bistro (44%) and Bottle (41%) grade classes. As the average weight increased to 45g, just over 4% were sold as Large Plate oysters and the majority were sold as Bistro oysters. With a population average weight of 50g, the percentage of oysters sold as Large Plate increased to 15%. The greatest proportions were sold in the Bistro (36%) and Plate (38%) grades. When the average weight was again increased by 5g to 55g, approximately equal proportions were sold as Plate (35%) and Large Plate (34%) oysters. When the average population weight reached 60g, less than 1% of oysters were classed as Cocktail grade, and 52% of oysters could potentially be sold as Large Plate oysters. Please note that all other factors (e.g. mortality or meat condition) were assumed unchanged by changes in growth rate.

When grades were differentiated into only three classes, the majority of the population were sold in the higher value grade classes when the average population weight was 50g and above. Only 4% of oysters were sold in the Bottle grade when the average population weight reached 60g. When the population average weight fell to 45g, the greatest proportion of the population (44%) were sold in the Bistro grade, with approximately equal proportions sold in the Plate (30%) and Bottle (26%) grade classes. A further 5g decrease in the population's average weight to 40g meant that a higher proportion of the population were sold in the Bottle grade (47%), with a slightly lower proportion of the population sold in the Bistro grade (44%).

Figure 4.2 illustrates the differing returns on a per dozen basis when the average population weight of oysters at sale was increased (e.g. how the returns per dozen increased with an increase in the average weight of the population). The linear and quadratic trend lines have been projected by 10g in either direction. The quadratic trend line explained 99.96% of the variation in the data compared to the linear trend line (R^2: 99.32) when oysters were differentiated into five grade classes. Oysters from a population with the lowest average sale weight of 40g, sold a higher proportion of oysters in the lower sale grades and so received an average return of $4.82/doz. In contrast, oysters sold from a population with an average weight of 60g received an average return of $7.79/doz, as an increased proportion of oysters could be sold in the heavier grade classes.

When oysters were only differentiated into the three main grade classes (e.g. Plate, Bistro and Bottle grade classes), it became more apparent that the change in returns with change in growth rate was not linear. As expected, the linear trend line explained less of the variation in the data (R^2: 96.48%) than when oysters were differentiated into five grade classes.

The selection index assumes a linear relationship, and as such a constant economic value. The linear regression indicated that for each 1g increase in average population weight, the increase in returns per dozen will change by $0.15/doz (0.1499). In Figure 4.3, a 1g change in average population weight resulted in a smaller change in returns ($0.11/doz) when grade classes were differentiated into three grades only. Non-linear trends in returns with linear changes in average population weight were the result of proportions sold in each grade class and the non-linear change in returns with approximately linear changes in weight.

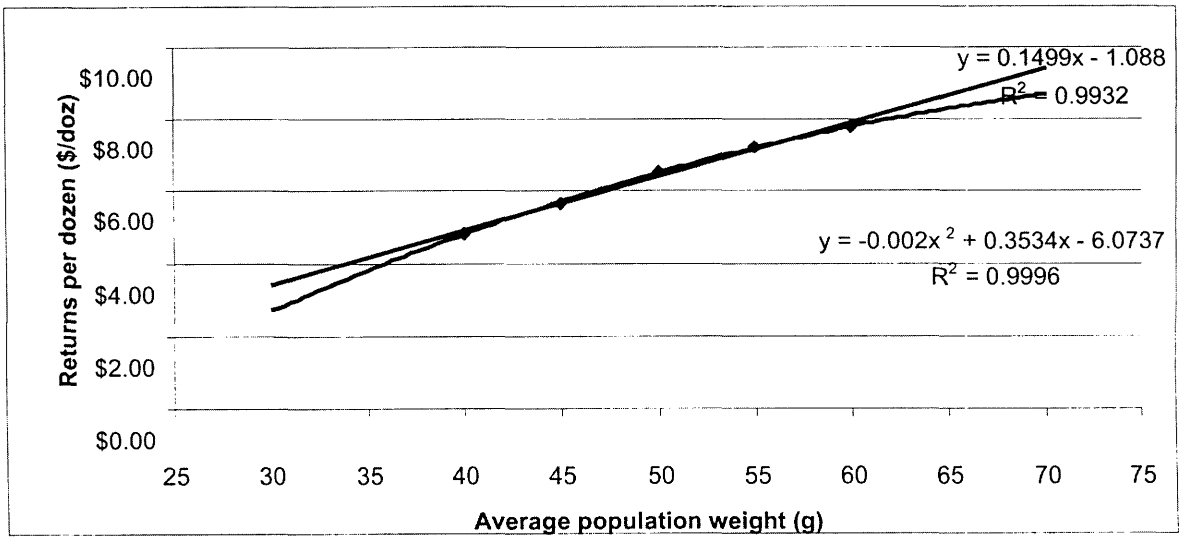

Figure 4.2. The relationship between average weight of oysters and the returns received when differentiated into five grade classes

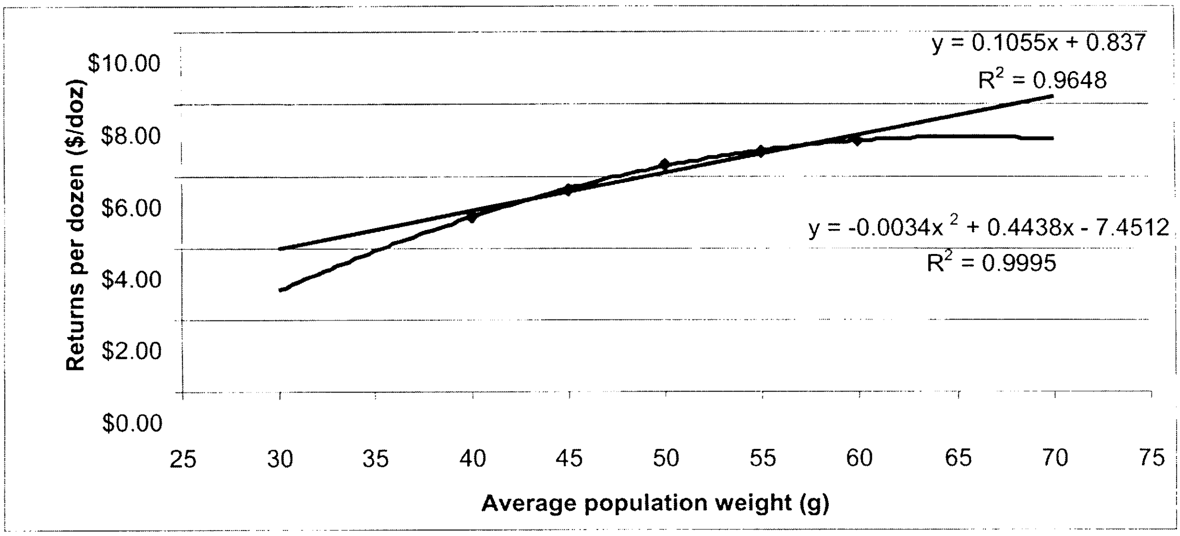

Figure 4.3. The relationship between average weight of oysters and the returns received when only differentiated into the three main grade classes (Plate, Bistro and Bottle)

Economic values were higher for 5g increases when the average population sale weight was lower (Table 4.3). This was because as the average weight increased, a relatively greater proportion of oysters were allocated into the heavier grade classes which had higher returns per dozen. The decline in the economic value for growth rate with increasing population weight is also illustrated in Table 4.4. These values assume that there are no changes in costs associated with the small changes in growth rate. The value of a 5g increase in average population sale weight is generally consistent with the values that would be derived from the linear regression of returns on weight (Figure 4.3). These results show that, as the economic value changes under different mean population weight, the economic value is specific to that mean.

Table 4.3 Economic values with a 5g change in average sale weight for the base scenario, when differentiated into either five or three grades (assuming no changes to costs)

Average weight (g)	Average return ($/doz)		Economic values per 5g change	
	Five grades	Three grades	Five grades	Three grades
40	4.82	4.89	-	-
45	5.67	5.65	0.85	0.76
50	6.52	6.31	0.85	0.66
55	7.23	6.71	0.71	0.40
60	7.79	7.00	0.56	0.29

N.B. Nil cost change

As these economic values are calculated for a change in weight of 5g, the preliminary values for a one unit (1g) change in weight are shown in Table 4.4.

Table 4.4 Preliminary economic values ($/doz) for a 1g change in sale weight

Preliminary economic values per 1g change			
Five grades		**Three grades**	
0.85/5 = 0.170		0.76/5 = 0.152	
0.85/5 = 0.170		0.66/5 = 0.132	
0.71/5 = 0.142		0.40/5 = 0.080	
0.56/5 = 0.112		0.29/5 = 0.058	
Average	0.1485	**Average**	0.1055

4.2 Mortality

Mortality influences profitability through both increased costs and decreased returns. Costs incurred include hatchery spat purchase or wild spat collection costs along with grading costs, while returns were lowered proportionally to the level of mortality. For example, increased mortality means that fewer oysters could be sold (assuming no more are purchased). Therefore, assuming oysters were sold at a constant return, the farmer would receive a relatively lower return than had the mortality been less. A 10% increase in mortality leads to a 10% reduction in returns. The timing of mortality predominantly affects the accumulation of costs, in particular the cost of grading.

The following spat costs and average returns were used:

- The cost of wild spat collection was $0.04/doz ($3.33/1000 spat)
- The purchase price of hatchery/nursery spat were:
  - Retained on 0.5 mm mesh: $7.00/1000 spat = $0.08/doz
  - Retained on 1 mm mesh: $10.00/1000 spat = $0.12/doz
  - Retained on 3 mm mesh: $22.00/1000 spat = $0.26/doz
  - Retained on 8 mm mesh: $40.00/1000 spat = $0.48/doz
  - Retained on 12.5 mm mesh: $80.00/1000 spat = $0.96/doz (these were able to be on-grown with standard single seed husbandry methods so incurred only initial and final grow out costs, not nursery costs)

- An average return of \$6.52/doz was used (Table 4.3).

Mortality would increase the final cost of spat per oyster sold proportional to the mortality level (Table 4.5):

- If 90% (0.9) of oysters survive, 1/0.9 × \$0.96/doz = \$1.07/doz
- If 80% (0.8) of oysters survive, 1/0.8 × \$0.96/doz = \$1.20/doz

This means that a 10% increase in mortality from 10% to 20% increases the final cost of spat to the farmer by \$0.13/doz. This would increase proportionally with an increase in mortality.

Table 4.5 Final spat cost (\$/doz) after accounting for overall mortality

Initial spat cost (\$/doz)	Mortality (%)								
	10	**20**	**30**	**40**	**50**	**60**	**70**	**80**	**90**
0.04	0.04	0.05	0.06	0.07	0.08	0.10	0.13	0.20	0.40
0.08	0.09	0.10	0.11	0.13	0.16	0.20	0.27	0.40	0.80
0.96	1.07	1.20	1.37	1.60	1.92	2.40	3.20	4.80	9.60

The grading cost depends on the growth phase when mortality occurred. The older an oyster is before it dies, the more costs would have been incurred. The first model used the median grading cost of \$0.18/doz during each growth phase. For comparison, the growth phases were also partitioned into three phases for hatchery and wild caught spat (Table 4.6).

Table 4.6 Growth phase differentiation of age and cost (\$/doz) for hatchery (H) and wild caught (W) stock

	Age (months)		Grading cost (\$/doz)		Number of gradings		Total cost (\$/doz)	
	H	**W**	**H**	**W**	**H**	**W**	**H**	**W**
Spat	-	6-12	-	0.002	-	1		0.002
Nursery	0-12	-	0.00014	-	52*	-	0.007	-
Initial grow out	12-24	12-24	0.29	0.29	3	3	0.87	0.87
Final grow out	24-36	24-36	0.26	0.26	3	3	0.78	0.78
						Total	**1.66**	**1.65**

N.B. Hatchery spat purchased at a later age (and higher cost) incur no nursery grading cost.
* nursery operator graded oysters in upwellers every week of the year

Wild caught spat would have incurred a one-off cost to knock them off the sticks or slats and grade them. For the purpose of this report, this will be referred to as "grading". Total grading costs did not differ between production systems in the grow out phases as it was assumed that all oysters were grown individually from 12 months of age. Grading cost for the nursery growth phase was based on data obtained from a nursery operator on the South Coast. The one-off grading cost for wild catch was based on a North Coast respondent's data. The cost for the grow out phases were based on one South Coast respondent's data for machine grading. The total grading costs obtained remain in the range of \$2.16/doz for single seed production systems and \$0.18 for mixed stock and single seed systems.

In addition, total grading costs are similar to the following calculation: Median cost per grading (\$0.18/doz) × median number of gradings (9) = \$1.65/doz. The difference in costs between the nursery growth phase (\$0.07/doz) and initial grow out phase (\$0.87/doz) also tally with the difference in hatchery spat purchase cost after the nursery phase. The difference in cost between nursery oysters retained on a 0.5 mm mesh (\$0.08/doz) and oysters retained on a 12.5 mm mesh (\$0.96/doz) was \$0.88/doz.

The fact that the total costs were similar reflects the small difference in cost per grading between (\$0.15/doz) and (\$0.19/doz) production systems. The overall number of gradings (9), regardless of production system, was used due to the very low number of observations (N: 4; N: 1) from survey respondents.

Total cost was therefore spat cost + grading cost. Net returns were defined as returns minus variable costs. Economic values were calculated as the differences in profit for mortality levels from 0 – 90% (Table 4.7). As expected, when mortality occurred in the later growth phases, the economic values for mortality increased due to an increase in the impact of grading costs.

For illustrative purposes, the following five scenarios were modelled:

a) Overall grading costs (\$0.18/doz) and hatchery stock purchased at a cost of \$0.96/doz (OVERALL_0.96)
b) Overall grading costs (\$0.18/doz) and wild stock caught at a cost of \$0.04/doz (OVERALL_0.04)
c) Differentiated SS grading costs (Table 4.7) and hatchery stock purchased at a cost of \$0.08/doz (HATCH_0.08)

d) Differentiated SS grading costs (Table 4.7) and hatchery stock purchased at a cost of $0.96/doz (HATCH_0.96)

e) Differentiated MXD grading costs (Table 4.7) and wild stock caught at a cost of $0.04/doz (WILD_0.04)

Figure 4.4 illustrates the net returns (returns – variable costs) for each scenario as the level of mortality increases. Please note that only *final grow out* values have been graphed to provide a visual example for *only one growth period.* A linear trend is evident until very high levels of mortality are reached (approximately 70%). This indicates that with current levels of mortality economic values are relatively constant. At very high levels of mortality, which are not expected to occur routinely in an average SRO operation, the trend becomes non-linear. The HATCH_0.96 and OVERALL_0.96 have an obvious exponential reduction in net returns as mortality increases. This development is due to a combination of high spat purchase cost and accumulated grading costs.

Net returns for final grow out became negative after 50% mortality (specifically 56% mortality) for OVERALL_0.96. This was a similar level of mortality (51%) when net returns became negative for HATCH_0.96, but these were of a higher magnitude for the latter. Net returns did not fall below zero for OVERALL_0.04 or WILD_0.04 until the mortality level exceeded 80%. Net returns fell below zero at a mortality greater than 70% for HATCH_0.08.

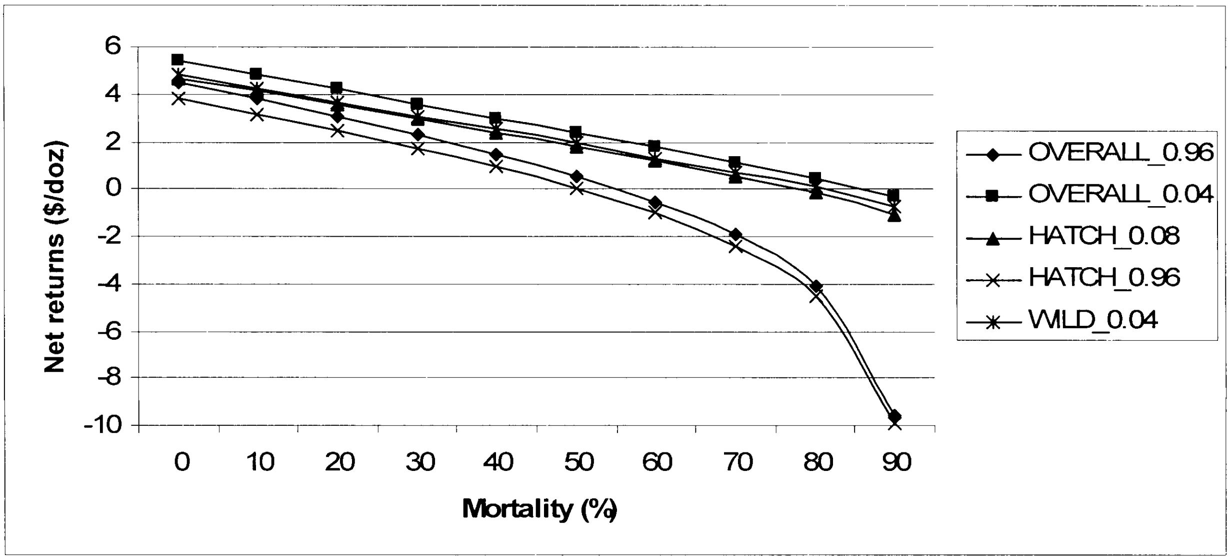

Figure 4.4. Net returns ($/doz) for the *final grow out* growth phase only for the five scenarios

As the net returns shown in Figure 4.4 were not strictly linear, especially as the mortality rate increased above 70%, the economic values (Table 4.7) were also not linear with linear changes in mortality. Economic values for mortality increased with increasing mortality and with an increasing initial cost of spat. The smallest economic value was -$0.48/doz for a change of 10% nursery or initial grow out mortality under the HATCH_0.08 scenario. As expected, the maximum economic value was -$5.37/doz for a 10% change from 80% to 90% final grow out mortality under the HATCH_0.96 scenario. Average economic values ranged from -$0.53/doz (WILD_0.04; spat and initial grow out) to -$1.56/doz (OVERALL_0.96; final grow out).

The appropriate economic weight to place on changes in mortality levels depends on both the level of mortality and the growth phase/s when the mortality occurs. For example, economic weights increased with increasing level of mortality, increasing initial spat cost, and with a later growth phase in which mortality occurs. Economic values for mortality were slightly lower when mixed production systems were employed (OVERALL_0.04 vs. WILD_0.04). This decrease was due to the lower grading costs associated with the mixed production system compared to single seed or overall values. There was little difference between wild caught lines (WILD_0.04) and hatchery spat retained on 0.5mm mesh (HATCH_0.08) at low mortality rates. There is a large difference between both these scenarios and that where large hatchery spat are purchased (HATCH_0.96).

As current mortality in select line SROs are towards the lower end of the scale where the difference between economic values becomes smaller in magnitude, it is not expected that these economic values would change dramatically over time. Economic values for generic oyster mortality, as well as those values differentiated for the two major SRO diseases, Winter Mortality and QX disease were investigated in a paper submitted to the Proceedings of the 17th Conference for the Association for the Advancement of Animal Breeding and Genetics (Appendix A4). However, it must be taken into account that currently the two traits of mortality from WM and mortality from QX disease cannot be measured. Therefore, these differentiated economic values are currently not directly applicable to the current breeding program.

Table 4.7 Economic values with a 10% change in mortality for the different growth phases under the five scenarios

Scenario	Growth phase	0-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90	Average
OVERALL_0.96	Initial grow out	-0.65	-0.68	-0.71	-0.78	-0.86	-1.02	-1.35	-2.14	-5.35	-1.50
	Final grow out	-0.70	-0.74	-0.77	-0.82	-0.92	-1.08	-1.40	-2.19	-5.40	-1.56
OVERALL_0.04	Spat	-0.55	-0.55	-0.55	-0.55	-0.56	-0.57	-0.57	-0.61	-0.75	-0.58
	Initial grow out	-0.55	-0.55	-0.55	-0.55	-0.56	-0.57	-0.57	-0.61	-0.75	-0.58
	Final grow out	-0.60	-0.61	-0.60	-0.61	-0.61	-0.62	-0.63	-0.67	-0.79	-0.64
HATCH_0.08	Nursery	-0.48	-0.49	-0.49	-0.50	-0.50	-0.52	-0.54	-0.62	-0.87	-0.56
	Initial grow out	-0.48	-0.49	-0.50	-0.49	-0.51	-0.52	-0.54	-0.66	-0.83	-0.56
	Final grow out	-0.57	-0.58	-0.58	-0.58	-0.59	-0.61	-0.68	-0.65	-0.96	-0.64
HATCH_0.96	Initial grow out	-0.58	-0.62	-0.65	-0.70	-0.80	-0.96	-1.28	-2.07	-5.28	-1.43
	Final grow out	-0.67	-0.70	-0.74	-0.79	-0.88	-1.05	-1.37	-2.16	-5.37	-1.53
WILD_0.04	Spat	-0.49	-0.50	-0.49	-0.50	-0.50	-0.50	-0.52	-0.56	-0.68	-0.53
	Initial grow out	-0.49	-0.50	-0.49	-0.50	-0.50	-0.50	-0.52	-0.56	-0.69	-0.53
	Final grow out	-0.58	-0.58	-0.58	-0.58	-0.59	-0.60	-0.60	-0.64	-0.78	-0.61

4.3 Additional quality traits

Both SRO farmers and wholesalers reported that the traits of shell shape and strength, along with oyster condition and meat colour were important to their business and the SRO industry. Therefore, in addition to the two main traits considered previously (growth rate and mortality), the calculation of economic weights for oyster quality traits was also estimated. However, it should be noted at the outset that the implications of quality traits on costs and returns were difficult to quantify. This was due to several reasons, the main being that several traits combined were considered to represent oyster quality, and costs and returns were often based on oyster quality in general rather than specific traits contributing to quality. For example, returns may be increased or decreased by oysters characterised as “milky, white with venation”, which could be considered to represent aspects of both oyster condition and meat colour.

Oyster quality also includes aspects of ‘presentation’ or ‘appearance’. Consumers further consider flavour and freshness to be important, although wholesalers would consider freshness to be important in terms of shelf life. For example, the survey conducted for this study found that stick oysters received discounts for several reasons including poor shape, large variation in shape, excessive shell strength and ‘bad’ visual presentation. Ruello (2006) reported an attractive appearance to be a clean, bright, moist, plump oyster. A wholesaler interviewed during this survey defined an appealing appearance as a “white, fat oyster”. Ruello (2006) reported that businesses such as restaurants would pay an unspecified premium for oysters that were above average in quality in terms of condition and colour. Quality was especially important for restaurateurs whose consumers pay high prices, and as such demand high quality oysters.

4.3.1 Shell shape

Importance

Survey results showed that shell shape was considered important by 10 farmers and three wholesalers, as this affects the overall visual presentation of SROs. This is probably of more importance for the sale of opened oysters, which are sold in boxes (wholesale) or on trays (retail), than whole oysters sold in bags. However, the shape of the unopened oyster is likely to indicate what the shape of the opened oyster will be. Consumers may also use the shell shape of whole oysters as a possible cue for meat content.

The study by Nell and Mason (1991, cited in Nell 2006) measured the ratio of weight to height (g/mm) as well as shell density and weight, and percentage cavity volume. However, the weight and/or age of the oysters when measurements were made was not reported. Their study found that there was a highly significant ($P<0.01$) difference between hatchery reared single seed oysters and those grown using stick culture for all measured traits. Single seed oysters had a larger cavity volume than stick oysters (40±5% vs. 36±4% of whole oyster volume) which may indicate a relatively more "cuppy" oyster shape, containing more meat.

One wholesaler surveyed stated that they only purchased single seed SROs as stick oysters presented badly and had a misshapen shell. Another wholesaler preferred single seed SROs to stick oysters as they "look better". In addition, the report by Ruello (2006) found, using a random sample of SROs (N. Ruello 2007, pers. comm., 15 February), that single seed oysters were generally not as long as stick oysters, which may indicate that they also had a more cuppy shape. In addition, (ABARE 2003) reports that oysters grown on trays had a better shape, and so were of better quality, than those grown solely on sticks.

Neither wholesalers surveyed, nor the Ruello (2006) study, specifically reported a lack of consumer acceptance to shell shape. However, the Ruello (2006) report stated that approximately 3% of consumers suggested that sales may be boosted if oysters on trays had a better presentation. It is assumed that the presentation of oysters, and therefore at least partially shape, would give purchasers their initial impression of quality.

Economic value

Farmers who produced *both* single seed and stick oysters reported a reduction of \$0.50/doz for stick oysters compared to returns received for single seed oysters. This was higher than the calculated estimate of \$0.23/doz across farmers (Section 3.3.5.2), possibly because this value reflects the overall average of single seed plus stick prices from individual farmers. Therefore, the value of \$0.50/doz was used as a preliminary economic weight for shell shape at a constant sale weight for farmers.

In this scenario, the average difference in the cavity volume of single seed and stick oysters (11±16%) could also be used as an indicator of shell shape (Nell 2006b). Therefore, a \$0.50/doz change in economic value for a 11% change in cavity volume is equivalent to \$0.0455/doz for each percentage unit change in cavity volume. However, while a price differential exists that is related to shape, it is difficult to establish an economic value related to a unit change in shell shape. A similar procedure could be applied to alternative shell shape traits, such as individual dimensions of shape indices (Appleyard et al. 2006?).

A different level of price differentials was indicated by wholesalers. Two wholesalers reported that single seed oysters received a $0.70/doz or $1.00/doz increase in returns when compared to stick oysters.

The Ruello (2006) report states that any oysters not considered acceptable in shape, or deviating excessively from the average shape, were often downgraded and bottled. This provides an alternative price differential to that used above. However, this price differential might be more applicable to shell strength issues, so it is not applied here.

Implementation issues

The methods used to measure "shape", or what constitutes a desirable shape, have not been clearly defined. Many people involved in the SRO industry use the term "cuppy" to describe a desirable oyster shape. This is in contrast to PO breeders for whom a desirable shape is one that is "flat and wide" for "sitting flat on the plate" (Ward et al., 2005). While there is no formal definition of what constitutes a "cuppy" oyster, many oyster farmers use the generally accepted ratio of 3:2:1 between height (h), length (l) and width (w) respectively to describe a desirable shape (Figure 4.5). However, the data of Dove (2006, unpublished) shows that the ratio of dimensions and the correlation between height, length and width with whole weight changes with increasing age and thus weight. For example, when oysters were 18 months old (average weight: 23.8g), shell height was the largest predictor of whole weight and the ratio of H:L:W was 6:3:1. This ratio continued to reduce with increasing age and weight until the sale end point (age: 29mo; weight: 47.5g; ratio: 1.6:1.3:1). Thus, while shape is age and weight dependent, the desired shape ratio of 3:2:1 reflects a common market end point with respect to weight. A different target ratio would be required if shape based selection was implemented for oysters measured at a different age and weight.

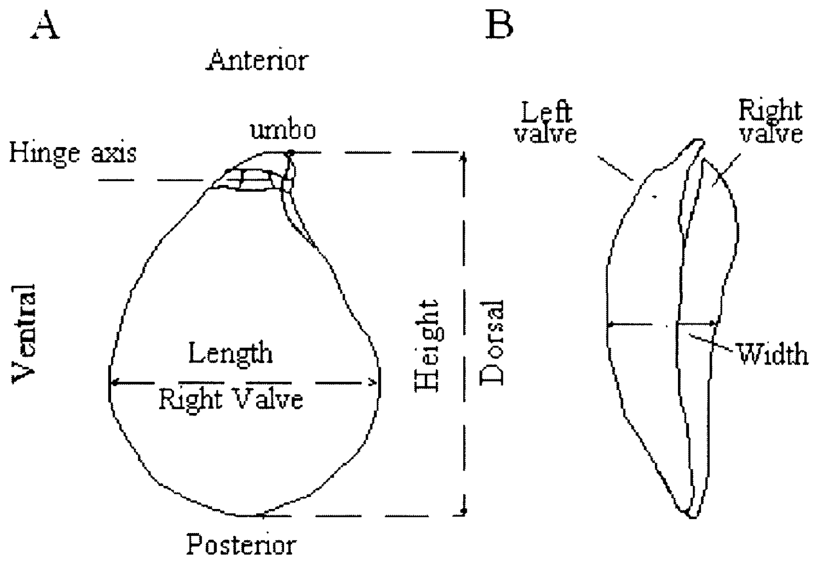

Diagram showing method of measuring the height, length, and width of oyster valves. A. interior view of right valve; B. side view of valves. Diagram, after Galtsoff, 1964 and reproduced by Carriker, 1996.

Figure 4.5. Cited in Nell, 2006

The presentation by Appleyard et al. (2006?) reported a moderate to high coefficient of variation (CV) in two year old POs for the shape traits (Figure 4.5) of height (CV: 21%), length (CV: 14%) and width (CV: 17%). This is similar to the range of CVs for production traits in domestic livestock (CV: 15-20%). In addition, Appleyard et al. (2006?) defined a width index (W/L) and depth index (D/L) to describe shell shape. Heritabilities (h^2) for the three shape traits ranged from moderate (depth: 0.26±0.14) to high (height 0.58±0.15 and width: 0.43±0.15). The width index and depth index had CVs of 81% and 114% respectively. However, the heritabilities of these traits were not reported.

Since traits with higher heritabilities and larger levels of variation respond better to selection, the trait of length is expected to have the largest response to selection and the trait of width the least, when recorded at two years of age. However, dimensional traits were positively correlated with each other, with genetic correlations of between 0.57–0.77, and phenotypic correlations of between 0.94–0.96. These large phenotypic correlations potentially illustrate the difficulty of identifying individuals with the desired characteristics away from the normal ratio, using variation in three dimensions. The width index and depth index were lowly to very highly negatively correlated with all traits measured (r_g: -0.07 to -0.70).

Variability in shell shape

The report by Nell (2006b) noted that single seed oysters had less variation in shape when compared to stick oysters. Many farmers and wholesalers surveyed specifically mentioned that a small variation in shell shape was important to the marketing of their oysters but had no data to support this. Two wholesalers interviewed stated that a larger variation in shape was acceptable as long as the oysters could be presented well. Selection for a reduction in variation of shape is generally difficult, can most likely be dealt with through grading and as such will not be further considered here.

4.3.2 Shell strength

Importance

There are three aspects of shell strength that are relevant to SROs:

1) Oysters with thin shells can suffer increased mortality levels through damage during handling (e.g. grading). Mortality may occur over a period of time after the actual grading process when the oysters were back on the lease. In addition, the cause of mortality was not always clear. This is most relevant to Single seed oysters, which are regularly graded.
2) Oyster shells can break during processing. This results in damage to oyster meat, and therefore downgrading of the meat. This is most applicable to Single seed oysters as they are more likely to have a thin shell.
3) Thick, hard oyster shells make them difficult, slower and more costly to open. This is most pertinent to stick oysters, but may become relevant for older oysters from either production system.

These points indicate that an optimum shell strength may exist, although this has not been quantified.

Economic value

One wholesaler reported that losses were minimal but thin lids made opening the oysters fiddly and took a little extra time. Another wholesaler stated that approximately 2% of their SROs were downgraded for bottling due to meat being damaged during processing when the "lids" (Figure

4.5: right valve) of thin oysters break. However, one wholesaler indicated that, by bottling damaged and unattractive meat, they "get their money back". These statements indicate that low shell strength will likely have a relatively low economic value unless it has a significant impact on mortality during grow out.

To calculate economic values for shell strength, the average scenario is based as previously on an average SRO population weight of 50g and oysters sold in all five grade classes (returning $6.52/doz). The assumption is that 1% of oysters are downgraded due to damage. Table 4.8 shows that downgrading oysters by reducing those sold in the higher grade classes and increasing the percentage sold in lower grade classes (in bottles), the average weighted return is changed by only -$0.015/doz to -$0.062/doz per 1% change in the proportions sold in the grade classes. For a more extreme example, when 5% of Large Plate oysters are downgraded to the Cocktail grade, average returns reduced to $6.21/doz (-$0.31/doz) but on the basis of a 1% change this is still only -$0.06/doz. As a point of reference, this is a still a higher average return than that received if the average population weight was reduced to 45g ($5.67/doz).

Table 4.8 Differences in weighted average returns after changing the percentage sold in each grade class

	Change in percentage sold (%)				
Large Plate	0	0	0	-1	-1
Plate	0	-0.5	-1	0	0
Bistro	-1	-0.5	0	0	0
Bottle	+1	+0.5	+1	+1	0
Cocktail	0	+0.5	0	0	+1
Average weighted return ($/doz)	6.503	6.487	6.483	6.467	6.456
Difference ($/doz) from average scenario	-0.015	-0.031	-0.035	-0.051	-0.062

Stick oysters have a thicker shell than single seed oysters, due to the method of cultivation. Very dense shells can make processing slower and harder, and therefore more costly. Many large wholesalers commented that stick oysters were slower to process than single seed oysters, but the difference in time or cost could not be quantified. One large wholesaler only purchased single seed oysters because stick oysters were "hard to open, amongst other things". This respondent stated that stick oysters took 50% longer to open than single seed oysters. This would therefore increase the cost by the same magnitude. The overall median processing cost was $0.75/doz so this would double to \$1.50/doz which is higher than expected. However, the median value was based on only three estimates.

Further research resulted in an average processing cost of \$0.50±0.28/doz (range: \$0.23/doz to \$1.00/doz) or \$0.50 to \$0.75/doz (R. Tynan 2007, pers. comm., 21 March). The latter value was the same as the calculated median. One wholesaler reported that there was an increased time of five to ten minutes per box for stick oysters when compared to single seed oysters. Under the assumptions that labour costs \$15/hour (\$0.25/minute) and a box holds 30 dozen oysters, this equates to an increased cost of \$1.25/30doz or +\$0.042/doz (+5mins) and \$2.50/30doz or +\$0.083/doz (+10mins). These estimates show wide variation in the increased cost associated with the hard shells of stick oysters and are not yet related to a specific measure of shell strength. The lower estimate of +\$0.042/doz is of a similar magnitude to economic values associated with the impact of weak shells on net returns (e.g. -\$0.015/doz to -\$0.062/doz), so are more consistent with expectations. Economic values for shell strength may revolve around an optimum value for shell strength.

Implementation issues

The method of measurement of shell strength could be conducted through measuring shell density (g/ml), which indicates shell thickness relative to cavity volume. However, the relationship between shell density and integrity, or strength, is not known. The study by Nell and Mason (1991, cited in Nell 2006b) found that hatchery reared single seed oysters had a lower shell density (mean±sd: 1.7±0.1g/ml) than stick oysters (1.8±0.2g/ml). Many farmers reported that stick oysters had a relatively strong shell due to their growing method. Anecdotal evidence suggests that certain methods of cultivation would thicken the shells of single seed oysters. These methods included production in tumblers and baskets where the oysters knock against each other and the plastic sides of the tumbler or basket. This will knock the "lip" off at the posterior end of the oyster (Figure 4.5) and cause the shell to thicken. Many farmers suggested that grading single seed SROs through a tumbler would also achieve this. Farmers also suggested that these management methods also gave the oysters the desired cuppy shape.

Extensive research has been conducted on methods of measuring egg shell strength and shell quality that may be applicable to oyster shells.

- Measurements of strength include:
    - Egg specific gravity, an index of shell thickness

  - Breaking strength – the actual force required to fracture the shell
  - Shell deformation under a fixed load (usually 0.5 or 1.0kg)
- Measurements of egg shell quality include:
  - Shell weight
  - % shell
  - Weight of shell/unit of surface area
  - Shell thickness
  - Beta-particle backscatter
  - Ultrasound wave reflection

Source: Hunton (2005)

Such measurements shown above could potentially be adapted to objectively measure shell strength for oyster breeding programs.

4.3.3 Meat condition

Importance

The level of meat condition was considered important to four wholesalers/retailers who responded (Table 3.20) and 14 of the 20 farmers (Table 3.19) who provided their ranking of the three most important traits to their business. Meat condition refers to, or is closely associated with (amongst other things), the level of glycogen contained in the gonad (Mason and Nell 1995). Meat condition was subjectively assessed and as such the assessment may differ between individuals (whether they be farmers or wholesalers).

There are two aspects to SRO meat condition which are important to the SRO industry: both the level of condition (e.g. 60% vs. 90%) and the timing and maintenance of this condition. The level of meat condition is important for sales, with oysters having to meet market criteria. However, the seasonality of meat condition and the length of time oysters are in a saleable condition determines the period over which SROs can be sold. It is desirable to have oysters in a high level of condition at sale. Thus, care must be taken that they are sold before they spawn, which dramatically drops meat condition for a period of time.

The survey found that oysters on the North Coast start to spawn around February and sales generally do not occur during winter. South Coast oysters will start spawning around Easter but can recover condition, with further sales occurring through winter. This seasonal characteristic of the timing of meat condition and maintenance of condition cannot be viably altered in a commercial operation unless selection against spawning is practised. However, these oysters would potentially have reduced reproductive performance and as such may not perform well as broodstock. This would disrupt the breeding program and make dissemination of genetic improvement more difficult. Triploid SROs are sterile and as such do not spawn at all, or to the same extent, as diploid SROs, thus maintaining condition (Hand et al. 1999).

Economic values

In the report by Ruello (2006), processors assessed minimum condition and would only accept SROs for sale at a condition above 60 or 70%. However, this report also found that "several" processors interviewed would only attribute premium quality to SROs with a condition of over 80%. A criterion for "premium" quality SROs was meat condition of 80% or better in 28/30 oysters (Ruello 2006). The "Regular" grade SROs had a minimum condition of 60% in 27/30 oysters.

The economic value for meat condition was assessed using three scenarios:

A Where a premium is received for oysters in an above acceptable condition (e.g. >80%).

B Where a discount is received for oysters in a below acceptable condition (e.g. <70%).

C Seasonality on age: holding oysters until they achieved condition, which then increases the sale age, and so grading costs, but also increases the sale weight and so returns.

Scenario A: Premiums received

Only one farmer could demonstrate that premiums were received for oysters with high meat condition. However, it must be taken into account that this farmer had a niche market and received premiums for several reasons. This farmer was selling premium Large Plate oysters for $48.00/dozen ($4.00/oyster), ($39/doz above the average) to a very high quality catering business (Table 4.9). However, these were an extreme grade which would rate above what is commonly termed Large Plate in the commercial SRO industry.

Table 4.9 Difference in returns for Premium SROs and Average SROs ($/doz)

Grade class	Premium (N: 1)		Average*		Difference	
Large Plate	48.00	Av^{X}	9.00 (N: 5)	Av^{X}	39.00	Av^{X}
Plate	12.00	8.50	7.45 (N: 23)	5.60	4.44	2.90
Bistro	8.00		5.45 (N: 24)		2.55	
Bottle	5.50		3.90 (N: 20)		1.60	

Av^{X} average of the three main grade classes (Plate, Bistro and Bottle)
* Values taken from the price differential values in Section 3.3.3.4

Premiums (above the average price differential values from Section 3.3.3.4) this farmer received were reduced with decreasing grade class: $4.44/doz, $2.55/doz and $1.60/doz for Plate, Bistro and Bottle oysters respectively. The premium is $1.98/doz higher than the average for a population weight of 50g ($8.50/doz - $6.52/doz) after accounting for the proportion sold in each grade. If this difference was received for a 10% change in condition, this would equate to a premium of $0.198/doz for a 1% change in condition. If the assumption is that premiums associated with condition are only received for SROs in the Plate and Large Plate grade classes, the estimate will be altered. Assuming that Plate and Large Plate oysters were sold for $12/doz and $20/doz respectively, this equates to an average difference of $7.72/doz. This was $1.20/doz more than the average $6.52/doz, or $0.120 per 1% change in condition (Table 4.10).

The Ruello report (2006) suggested that 40% of buyers interviewed would pay a minimum extra $1.00/dozen for "premium" grade oysters, or approximately 20% per dozen, for better quality SROs in terms of condition. In addition, restaurateurs were willing to pay extra for an above average quality SRO in terms of meat condition and colour. This is because restaurateurs were under pressure from their consumers to provide plump oysters, especially when consumers were paying a high price for these oysters (Ruello 2006). However, in industry it has not been well defined what comprises "above average" quality for SROs.

Although premiums were paid for oysters in good condition, many buyers and consumers would not accept 'over-condition' oysters where the meat showed "venation" or was "milky" or "creamy" (Ruello 2006). This indicates that there may be an optimum for oyster condition. The threshold above which oysters are considered 'over-condition' has not been established. However, a photograph and description in the Ruello (2006) report is of a SRO in 90%+ condition, with venation clearly visible. Not only is this relevant to condition, but buyers and consumers reactions to these oysters may also have implications for oyster colour.

Scenario B: Penalties

An alternative approach is to consider that oysters which are not in prime condition are downgraded and put into bottles (T. Troup 2006, pers. comm., 22 November) and so will receive a discounted return, particularly for lower grade oysters. For example, Bistro oysters ($5.45/doz) would be discounted to Bottle grade class returns ($3.90/doz), a discount of $1.55/doz (Table 4.10). This would equate to a $0.155/doz decrease for each 1% change when assuming the discount is based on a 10% decrease in condition (Table 4.10). This is of a similar magnitude to the premium received for SROs in above average condition providing some confidence in the robustness of the estimate. This leads to an average value of $0.138/doz per 1% change in condition.

Table 4.10 Premiums and penalties associated with changes in meat condition

Scenario	A: Premiums	B: Discounts*
Return for 1% condition Δ on a $/doz basis	0.120	-0.155
Assumptions	Plate and Large Plate classes have high meat condition	Bistro oysters have low meat condition and are downgraded to Bottle

*Based on three grade classes only

The interviews conducted by Ruello (2006) indicated that SRO buyers would prefer not to buy oysters in "poor condition" for opened raw consumption, even if this means going without SROs at some times of the year. This was supported by anecdotal evidence of restaurateurs taking SROs off the menu if they could not source SROs of high quality. Many restaurants would not substitute SROs with POs, making the availability of SROs for consumers seasonal. In addition, some wholesalers who would not sell SROs below a certain meat condition, no longer supplied SROs to customers if adequate SROs could not be sourced. However, as previously stated, only one wholesaler was reported to have sold SROs in low condition (<70%) due to market demand.

Scenario C: Increased sale age

If SRO farmers have to wait for oysters to reach specific levels of meat condition to enable sale this would mean that age at sale would be increased. According to Ruello (2006), farmers who can delay oyster sales to improve oyster quality (condition) incur an extra cost of approximately

10% but can then achieve a 10% increase in profit, implying that this exercise is considered to be cost effective.

The number of gradings prior to sale would be increased with this strategy. If age at sale was increased by three months, the extra grading required would cost an average of $0.18/doz. If age at sale was increased by six months then this would reach $0.36/doz. However, the oysters will also have increased in size over this period, providing there was enough feed for adequate growth. Therefore, there would be increased returns as a higher proportion of oysters would be sold in higher grade classes. An extra 3 months of growth will increase the population mean by approximately 5g to 55g (1.39g/mo × 3mo = +4.17g), increasing the average return from $6.52/doz to $7.23/doz. This results in a net return of $7.05/doz, an increase of $0.53/doz (8%) from $6.52/doz. A six month increase in growth would incur an extra cost of two gradings ($0.36/doz), but also an extra return of $7.79/doz for a population with an average weight of 60g. This equates to a net return of $7.43/doz, an increase of $0.91/doz (14%). Therefore, the extra grading cost is offset by the extra returns provided the average population weight increases. The 8% to 14% increases in net return are consistent with the 10% increase in profit predicted by Ruello (2006).

In summary, premiums are received when SROs are in "above average" condition. To quantify this, farmers received a premium of $1.20/doz for SROs with meat condition of 80% and over ($7.72/doz vs. $6.52/doz). A penalty of $1.55/doz for SROs is incurred when oysters that are not in adequate condition are downgraded from the Bistro grade to Bottle oysters. Holding on to the oysters until they reach adequate condition is expected to net a smaller premium of between $0.53/doz and $0.91/doz. If this change in meat condition for all scenarios is assumed to be 10%, each 1% increase in condition should result in an economic value varying somewhere between $0.053/doz and $0.155/doz.

4.3.4 Meat colour

From the survey, three farmers and two wholesalers ranked meat colour as one of the most important traits to their business. One farmer who purchased whole oysters for processing, ranked meat colour as the most important trait and as such was willing to pay a 5% premium for this. There are two aspects to meat colour: 1) a tinge of green or pink associated with the oysters' natural habitat, or 2) discoloured brown or black areas resulting from oysters which have suffered disease or pests (e.g. mudworm) or possibly incorrect handling and/or storage. Clearly however, discoloured meat due to disease is not sold to consumers.

Industry representatives have stated that the meat colour and flavour of SROs often depends on where the oysters are grown along the coast. For example, Martin's Seafoods has categorised characteristics of SROs from eight estuaries to try and inform consumers of natural meat colour differences. The reference guide shows that the meat of SROs grown in the Nambucca/Hastings River region naturally has a "slight yellow hue": http://www.martinsseafoods.com.au/oysterReference.html
A farmer in this region confirmed that in winter, fat oysters may have a tinge of green or pink depending on what the oysters are feeding on. What may be referred to by consumers, or other SRO industry participants, as "discolouration" may affect sales of opened oysters as consumers could be deterred by the colour differences without understanding that it is a naturally occurring phenomenon. However, there is no data to specifically support this assumption. Buyers and consumers reportedly preferred SRO meat to be "white or pale coloured" (Ruello 2006) and would not accept dark, khaki yellow or green coloured oyster meat. One farmer from the Nambucca/Hastings River region reported that meat colour was important because of their ability to develop a niche market. They described a quality oyster from their estuary to be a "creamy yellow butternut colour". In contrast, the wholesaler who sold oysters from the Nambucca/Hastings River region and described them as being a bit yellow, which was less appealing. However, they marketed on this natural appearance as there was "nothing they could do about it".

Implementation issues

The details above (excluding one farmer's comments) suggest that SROs receive only penalties, not premiums, for unusual meat colour. Therefore, it is assumed that SROs are either:

A Yellow/green: sold on their characteristic colour with no penalty or premium, marketed on these estuary characteristics.

B Dark brown/black: still sold due to demand or thrown out if discolouration covers a certain percentage of meat or the intensity of this discolouration. The proportion of oysters not sold due to discolouration (currently unknown) could be used to establish economic values for colour traits.

C Cream/white: no premium but this is the desirable colour.

It must be taken into account that there is currently no quantifiable evaluation for colour and as such, there is no payment based on this. Therefore, it is more sensible to assume economic values of zero. It is also important to note that there may be several colour traits of economic importance, and the significance of each must be quantified separately.

The definition and/or measurement of meat colour in SROs has not been developed. However, it can be assumed that meat colour would consist of both the percentage of the meat affected plus the intensity of this discolouration. In fish, measurements of colour are defined as (Bell et al. 2004):

> "Colour measurements include lightness, hue, chroma (saturation) and the Roche colour score. The Roche colour score is a subjective comparison of fillet colour against standard colour cards. The other measurements are made using a colour meter."

Discolouration has been noted in triploid SROs (Hand and Nell 1999) using the following scoring scale (Table 4.11).

Table 4.11 Graded scoring criteria for localised gonad discolouration of diploid and triploid Sydney rock oysters

Score	Criteria
1	Gonad 'normal' and consistent colouration or indistinct pale yellow patches covering less than 50% of gonad surface
2	Distinct, pale yellow to pale brown patches frequently covering less than 50% of gonad surface
3	Distinct fawn coloured patches
4	Distinct brown patches on gonad frequently covering 50% or more of the gonad surface
5	Distinct dark brown patches frequently covering 50% or more of the gonad surface

Source: (Hand and Nell 1999)

A common system for measuring colour in food science is the product of a function of the L*a*b* system as measured using a ultra-violet/visible spectrophotometer. These three parameters are:

- L*: lightness where 0= black and 100=white
- a*: the colours position between magenta and green where - = green and + = magenta
- b*: the colours position between yellow and blue where - = blue and + = yellow.

An index function could be implemented to determine optimal colour in SROs, or to allow grading of oysters into differentiated classes based on colour. For example, tomato ripeness is evaluated using the function: a*/b* + 0.3a*/L* which may result in the following grades

Grade C	Grade A	Grade B
-1.0	0.0	+1.0

4.4 Summary and Conclusions

The SRO breeding program has developed selection lines for increased growth rate and resistance to the two major diseases of QX and WM. These have resulted in permanent genetic improvements in all three traits, which is of great benefit to the SRO industry. In the future, the objectives of the SRO breeding program are likely to include other traits that have been identified as being of commercial importance to the SRO industry. The relative importance of these different traits can be determined through their economic value. Economic values are defined as the change in net returns (returns – variable costs) resulting from a small change in one trait, when all other traits remain constant. This study aimed to estimate economic weights for several commercially important traits as no estimates currently exist for these traits in SROs, or indeed any species of oyster. Economic weights were estimated for six traits: growth rate, mortality, shell shape, shell strength, meat condition, and meat colour and are summarised in Table 4.12.

Table 4.12 Economic values for commercially important SRO traits per unit increase

Trait	**Economic value ($/doz)**
Growth rate (g)	+0.1055
Mortality (%)*	Overall range: -0.049 to -0.146 WM: -0.061 QX: -0.146
Shell shape (volume, %)	+0.0455
Shell strength (kg)	Average$_{thin\ shells}$: +0.040 Average$_{thick\ shells}$: -0.063
Meat condition (%)	Average: +0.105
Meat colour (e.g. L*a*b index)	0

* see Appendix A4

Growth rate was modelled based on normal distributions of five populations with average weights ranging from 40g to 60g at 5g increments. Growth rate ranged from 1.11g/mo to 1.67g/mo under these scenarios. From the normal distributions it was calculated what proportion of the population fell into each discrete grade class. Grade classes were differentiated into sales of both three and five grade classes to reflect the farmers' different selling strategies. This proportion in each grade class was then multiplied by the average returns per dozen relevant to each grade class to obtain the weighted average return. The difference between populations for weighted average returns could be used to estimate preliminary economic values for weight on an age constant basis (e.g. growth rate). Estimates of economic values ranged from +$0.058/doz to +$0.170/doz per 1g increase in weight measured on an age constant basis. The linear coefficient when sales occurred in three grade classes is assumed to be an accurate estimate of the economic value (Figure 4.3).

Economic weights for mortality were affected by both increased costs and decreased returns. The total costs included spat and grading costs and returns were based on the previous calculations used for growth rate. Five different scenarios were modelled with differing spat and grading costs. From these five scenarios, the net returns were calculated for mortality levels ranging from 0-90%. The difference in net returns allowed the estimation of economic values for: a) each scenario; b) mortality level; and c) growth phase in which the mortality occurred. Economic weights for mortality increased with higher mortality levels. In addition, the higher the spat and grading costs and the later the mortality occurred in the oysters production cycle, the larger the economic values for mortality became. A 1% increase in mortality results in economic values ranging from -$0.049/doz to -$0.146/doz. Infection with the diseases of WM and QX can result in mortality levels of 40-50% and 90% respectively. These levels of mortality correspond to economic values of -$0.061/doz and -$0.146/doz for a 1% increase in mortality.

Additional quality traits were then analysed based on the survey data and a review of the literature. Shell shape was considered commercially important by both SRO farmers and wholesalers. The difference in returns between single seed and stick oysters of $0.50/doz was used as an initial indicator of the importance of shell shape. It was found that single seed oysters were 11% larger in cavity volume than stick oysters at the same age, indicating a more desirable shape. This resulted in an economic value of +$0.0455/doz for each percentage increase in cavity volume. It is assumed that the main economic influence of shape is on cavity volume, and therefore meat yield.

Shell strength affected SROs in two ways. When SROs shells were not strong enough (more typical of single seed SROs), the lids of the shell may break during processing, resulting in damage and thus downgrading of meat. A 1% increase in the percentage sold in the lower grade classes resulted in economic values of +\$0.02/doz to +\$0.06/doz (average: 0.040). Oysters with a very strong shell (more typical of stick oysters) were more difficult, and therefore more costly, to process. Based on information from a single wholesaler, the economic value ranged from +\$0.042/doz to +\$0.083/doz (average: 0.063) for an *increase* in shell strength. Thus, the range of economic values for shell strength is of the magnitude \$0.02/doz to \$0.083/doz, which needs to be related consistently to standard trait units for shell strength.

Premiums and penalties received for SROs were based on a high or low level of meat condition. A premium received for a 1% increase in condition resulted in an economic value of +\$0.120/doz. A 1% *decrease* in condition resulted in a penalty of -\$0.155/doz. By having to keep the oysters for a longer period of time in order to reach the desired meat condition, the economic values ranged from +\$0.053/doz to +\$0.091/doz. These four values were averaged to calculate the economic value (\$0.105/doz) per percent change in meat condition.

The two aspects of meat colour are discolouration due to the estuary in which the oyster is farmed, and discolouration due to disease or pests or incorrect handling. No consistent evidence for penalties or premiums was received in the first instance and so a neutral economic value can currently be assumed.

In Table 4.12, the economic values for the different traits are summarised. The differences between traits in the magnitude of economic values has implications for the relative importance of each trait in the SRO breeding program. However, as the traits are measured in different units, their direct comparison is not valid. The approximate importance of each trait to a breeding goal is better illustrated by standardising the expression of economic values to one genetic standard deviation (\$/GSD). After making assumptions regarding trait heritabilities (from literature) and variability, the relative importance of each trait is shown in Table 4.13. The traits were ranked in their economic importance to a breeding program in the following order:

1. Mortality due to QX disease
2. Mortality due to WM disease
3. Growth rate (weight)
4. Meat condition
5. Shell shape and strength

Mortality: The trait of mortality was considered a binary trait in that the oysters either live or die. The magnitude of economic values is largest for mortality overall ($0.91/doz/GSD to $2.72/doz/GSD). This indicates that, as expected, reducing levels of mortality is economically very important for SRO farmers. When these values were differentiated into mortality caused by WM (35% mortality: $1.13/doz/GSD) or QX (65% mortality: $2.70/doz/GSD) diseases, it can be shown that resistance to QX disease is more economically important than resistance to WM as there are no management practices that can reduce the disease and the levels of mortality are very high. In contrast, respondents from the survey did not consider mortality, or resistance from WM or QX, to be the most important traits. This is assumed to be because these specific farmers did not suffer significant mortality from either of these diseases.

Table 4.13 Economic values (EV) expressed on a common basis (e.g. per genetic standard unit: GSD) for commercially important SRO traits

Trait	D	h^2	SD	GSD	EV ($/doz): v	Absolute "relative" EV (v × GSD)
Weight (g)[a]	3 5	0.30	10	5.48	+0.106 +0.150	0.58 0.82
Mortality (%)[b]	O WM QX	0.15	48.0	18.6	-0.049 to -0.146 -0.061 -0.146	0.91 to 2.72 1.13 2.72
Shell shape (volume, %)[c]		0.45	0.53	0.356	+0.0455	0.016
Shell strength (kg)[d]	thin thick	0.30	0.625	0.34*	+0.040 -0.063	0.014 0.021
Meat condition (CI)[ef]		0.29	10	5.39	+0.105	0.56
Meat colour fg		0.25	3	0.75	0	0

D: differentiated into either grade classes or specific trait
a: heritability (h^2) estimate based on various literature estimates, the standard deviation (SD) based on the data from Dove (2006) and the linear coefficient determines the economic value based on grade classes differentiated into either 3 (3) or 5 (5) grade classes
b: estimate of heritability based on the report by Toro (2004) with the sd based on mortality estimates of $\sqrt{pq} = \sqrt{0.65 \times 0.35} = 0.48$ (rescaled by 100), O: overall mortality, WM: winter mortality (35%), QX: QX mortality (65%)
c: heritability estimates and SD based on the depth index of Ward (2005)
d: heritability estimate based on the specific gravity of hens eggs. SD based on the paper by Grefsrud and Strand (Grefsrud and Strand 2006), rescaled from Newtons to kg, (10N = 1kg) where the SD was based on a range of 50N/8sd = 0.625kg (population mean of 10kg)
e: heritability estimate based on the data regarding condition index from Ward et al (Ward et al. 2005) and the SD of condition index was based on the data from Dove (2006). It is assumed that condition was assessed in a non-spawning period
f: in the absence of any data regarding the relationship between with meat condition (%) with condition index, or subjective meat colour with a colour index, a 1:1 ratio between these traits is assumed
g: L*a*b index

Weight: Whole weight (or growth rate) was economically the second most important trait to the SRO breeding program ($0.58/doz/GSD to $0.82/doz/GSD), particularly when oysters were sold in all five grade classes. Growth rate, or weight, was considered an important trait for 30% of SRO respondents, and was ranked as the number one trait of importance by 30 respondents. The economic values for mortality and whole weight, in addition to respondent's comments, indicate that the current SRO breeding program is addressing the most important traits to the SRO industry.

Meat condition: Meat condition was considered the third highest economically important trait ($0.56/doz/GSD). This trait was also considered important to 14 farmers and four wholesalers during the survey. Therefore, this is the next trait that should be considered in the SRO breeding program. The condition index provides an objective measure of condition and is assumed to be highly correlated with meat condition assessed subjectively by farmers and wholesalers. Measurements should consist of both the level of condition and the maintenance of this condition.

Shell shape and strength: Shell shape was ranked as the fourth most economically important trait ($0.016/doz/GSD). This was also considered important to 15% of respondents and two wholesalers. Shell strength had an economic value of the fifth highest magnitude for either shells that were too thin ($0.014/doz/GSD) or too strong ($0.021/doz/GSD). This trait was not ranked by farmers or wholesalers as being important. The reason this was not included in the respondent's ranking may be that it was not considered to be in the top three traits of importance.

Meat colour: Meat colour was considered to be of importance to three farmers and two wholesalers. However, meat colour was considered to have a neutral economic value as the trait/s of colour are currently subjective measures with no premiums or penalties based on meat colour.

Chapter 5

Simulation of response to selection and inbreeding in a closed Sydney rock oyster breeding program

5.1 Introduction

Breeding programs consist of a breeding objective which specifies which traits to improve, breeding plans which specify mating structures and recording strategies and methods of selection to be implemented for relevant traits. It is important to consider how particular traits are able to be measured effectively. The breeding program is optimised according to the specific reproductive and biological characteristics of the species and the attributes of the trait/s selected as well as the resources available.

Biological limitations of SROs affecting the ability to develop controlled mating plans include sex reversal (changing the sex ratio of the population) and mass spawning (e.g. no controlled mating). These create an unknown and variable parental genetic contribution. The unknown gamete quality and gamete competition during the spawning period also leads to a high variance in family size (Brown 2003). The sex ratio changes with age as the majority of one year old males change to females after spawning (Guo et al. 1998). However, this sex ratio could also be affected by selection through the program as selection is across sexes. For example, female Pacific oysters were approximately 10% heavier than the males at the same age (see review by Sheridan 1997). Therefore, selection across unknown sexes on weight may favour a higher number of females, increasing the proportion of females to males used as broodstock. Advantages of the SROs biology include high fecundity, which allows the ability to impose high selection intensities. There is also the possibility of a short generation interval (1 year for growth traits or 2-3 years for disease resistance traits).

The current SRO breeding program was historically based on a single trait (growth rate) mass selection program, and has now been expanded to include disease resistance. Mass selection involves selecting SROs based on their own phenotypic performance for a specific trait or traits. This method of selection is common to aquaculture breeding programs (Gjerde et al. 2002) due to its simplicity and low cost (Heasman 2004) and the inability to feasibly identify and maintain individual SROs to produce pedigreed individuals, or families (Bentsen and Gjerde 1994). Rapid genetic gain can be made through mass selection providing the heritability of the trait/s selected for is high. It is a useful method for traits which can be measured directly, for example whole weight or shell shape, without the need for sacrifice. In addition, mass selection does not require long-term pedigree information or sophisticated genetic evaluation programs as only individual performance contributes to selection decisions.

A limitation of mass selection is that the potential problems of inbreeding cannot be controlled as accurately as with other selection methods. Individuals are not identified and the parental contributions (and effective population size: Ne) to the next generation are generally unknown. A reduced Ne can lead to inbreeding, and because of this it is advisable to use many parents of both sexes. A simulation study by Bentsen and Olesen (2002) found that a minimum of 50 pairs of broodstock producing 30-50 progeny or more per pair was necessary to maintain the rate of inbreeding under mass selection at an acceptable level of approximately 1% per generation. The response to selection in their study averaged 5-13% per generation across a range of trait heritabilities (h^2: 0.1, 0.25 or 0.4).

Inbreeding does not appear to be a major problem in the SRO breeding program, based on measures for allozyme variation in the third Port Stephens generation (English et al. 2001). However, inbreeding depression associated with inbreeding has been reported in other aquaculture species (e.g. Sheridan 1997), including the Pacific oyster (Evans et al. 2004). When comparisons were based on microsatellite loci studies, Australian Pacific oyster mass selection lines had lost some genetic variation when compared to wild stock (Appleyard and Ward 2006). Therefore, a sustainable breeding program for SROs should consider strategies to limit rates of inbreeding.

The objective of this study was to evaluate, using simulation, the response and inbreeding for alternative breeding structures that could be feasibly employed with the SRO breeding program.

The parameters able to be varied in the SRO breeding program, and tested in this study under the following scenarios, were:

1. **Number of selection lines within a constant population size.** The SRO breeding program currently maintains four separate lines. However, the selection response will be greater, and inbreeding lower, in one larger single line compared to four separate lines. In addition, there will be genetic variation between the sub-lines (for a constant population size: 1 line or 4 sub-lines).
2. **Population size (and selection intensity).** The current breeding program selects approximately 200 broodstock from 2000 SROs. The effect of changes in the population size from which these 200 broodstock were selected was examined. Increasing the population size, thereby increasing the selection intensity for a constant broodstock number, will increase the selection response as well as the rate of inbreeding.
3. **Trait heritability.** Trait heritably estimates are currently unknown in SROs; thus the effects of three different levels of heritability were investigated. Rates of response and inbreeding will increase with increasing trait heritability. The parameters estimated for other aquaculture species appear similar to those for livestock species; being low for fitness traits (e.g. disease resistance: 0.2) and moderate to high for production traits (e.g. growth rate: 0.3-0.4).
4. **Proportion of males to females selected to provide 200 (10%) broodstock.** The sex ratio of broodstock is essentially unknown until examination of the gametes at spawning. However, procedures are now available to anaesthetise SROs for sex determination (W. O'Connor 2007, pers. comm.). It was assumed in the first instance that the proportions of males and females remained equal (100_m:100_f). However, as previously stated above and in Chapter 2, there was an increased proportion of females to males in the unselected

population, in addition to the superior performance of females, which would result in a larger proportion of females to males being selected as SRO broodstock (66_m:134_f).

Phenotypically superior males and females were selected as broodstock. Therefore, when the number of selected males was lower than the number of females, the males (N: 66) were selected from a smaller proportion (i.e. higher selection intensity: i) of the population than the females (N: 134). Thus, it was assumed that these males would therefore also be genetically superior on average. The effect on response and inbreeding of the proportion of males and females selected depends on that which results in a higher *average* selection intensity ($(i_m + i_f)/2$). For example, when 10% of both males and females were selected, the average selection intensity was $(1.76_m + 1.76_f)/2 = 1.76$ and when the proportion of males (6.6%) and females (13.4%) was differentiated, the average selection intensity became $(1.94_m + 1.61_f)/2 = 1.78$. Higher average selection intensities will result in greater rates of response and inbreeding.

These scenarios cover a wide range of circumstances which are likely to be encountered in oyster (specifically the SRO) breeding programs, making their assessment relevant to these breeding programs.

5.2 Materials and methods

In any breeding program, the level and rate of response in genetic improvement and the level and rate of inbreeding are important (and must be balanced). Therefore, in this study, several scenarios were compared to examine response to selection and inbreeding in a closed population. Simulations are useful to rapidly test a number of alternative breeding program scenarios of varying complexity, without incurring real costs and long time frames. The scenarios tested, under a specific set of assumptions, can be compared to identify the most efficient and/or effective scenario. A stochastic simulation program was developed using Visual Basic for Applications (VBA) in Microsoft Office Excel for that purpose.

5.2.1 Basic assumptions

The simulation operated under the following assumptions/conditions:

a) The single trait under mass selection was continuously distributed, following a standard normal distribution. This implies that the trait was influenced by a large number of genes, each with a small effect, under the additive infinitesimal model (Bulmer 1971).

b) For each scenario, 200 parents were used as broodstock for the next generation in a closed population. Parents were mated within population. Individual records for the trait were available on all selection candidates. No family information was available

c) Discrete generations, whereby animals were mated within generations to produce progeny for selection in the next generation. Generations were therefore distinct and there was no overlapping reproduction between generations. The SRO breeding program uses selection and mating in discrete generations.

d) Uneven family size as the reproductive success of parents is variable (Table 5.1).

Table 5.1 Mean number and range of progeny for each population size

Population size	Number of lines	Number of Broodstock/line	Sires†/line	Mean progeny/sire†	Range of progeny*
200	1	200	100	2	0-5
	4	50	25	2	0-5
400	1	200	100	4	0-8
	4	50	25	4	0-8
2000	1	200	100	20	10-30
	4	50	25	20	10-30
3000	1	200	100	30	18-42
	4	50	25	30	18-42
4000	1	200	100	40	26-54
	4	50	25	40	26-54

*: Calculated using the Java Applet "Normal Approximation to the Binomial Distribution" and π: 0.5 (http://onlinestatbook.com/stat_sim/normal_approx/index.html)

†: N sires = N dams

e) Random mating; "any individual has an equal chance of mating with any other individual within that population" (Falconer 1989). Thus, selected broodstock could mate with any member of the opposite sex within the same population and generation.

f) The phenotype was not adjusted for any inbreeding depression (proportional to the level of inbreeding).

5.2.2 Parameters

Ten generations (NGENS = 10) of progeny were produced to reflect the SRO breeding program, which is currently evaluating the progeny of the 6th generation of the fast growth lines (and the 4th generation of the fast growth/disease resistance lines). Each population was replicated 50 times to account for sampling (NREPS = 50).

Population parameters were: total population size for each generation (POPSIZE); number of populations per generation (NPOPS); and proportions of selected males and females (PSM/PSF) to result in 200 broodstock.

As the SROs sex is not known at the time of selection, equal proportions of males and females were selected for most scenarios. However, in the sixth spawning of the current SRO breeding program for fast growth, the ratio of males to females was approximately 1_m:2.3_f (Nell 2006b). Guo (1998) also reported that the ratio of males to females in the SRO program at the time of their study was 1_m:2_f. This ratio of males to females was achieved by altering the PSM and PSF to result in 200 (10%) broodstock selected from a POPSIZE of 2000. Therefore, the selected parents consisted of 66 males and 134 females.

The phenotypic standard deviation (σ_p) was set to one for all scenarios. However, the heritability of the base population (h^2) was varied. Genetic standard deviations for each h^2 were calculated from $\sigma_a = \sqrt{h^2} \times \sigma_p$. The basic scenario consisted of 200 broodstock selected from 2000 animals per generation in one population, recorded for a trait with a heritability of 0.2 ($\sigma_p = 1$).

5.2.3 Simulation of the founder population

The founder population consisted of a number of population sizes (POPSIZE), of which 200 were selected as parents for the next generation. Each founder animal was allocated to a single population according to NPOPS. These animals were assumed to be unrelated, unselected (randomly sampled from a normal distribution) and non-inbred. The true breeding values (A_i~N(0, σ_a^2)) and residuals (E_i~N(0, σ_e^2)) were generated for each animal based on normal distributions, in order to create a phenotype ($P_i = A_i + E_i$ with $\sigma_p^2 = \sigma_a^2 + \sigma_e^2$). The phenotype of base animals followed a standard normal distribution of $P_i \sim N(0, \sigma_p^2)$. The values of σ^2 are the variance of the additive genetic (a) and environmental (e) components of the total phenotypic (p) variance.

Founder animals were then sorted based on their phenotype. A proportion of the top performing animals (to result in 200 broodstock: $100_m:100_f$ or $66_m:134_f$) were then selected based solely on truncation as parents for the next generation, as would be typical under idealised selection. For simplicity, selection was based on a single trait. Selected males and females were then randomly mated to generate offspring. The effect of sex on phenotype was not simulated. Random mating of sires to dams was conducted using VBA's Linear Congruential Pseudo-Random Number Generator algorithm (see http://www.noesis.net.au/resources/prngs/prng.html). The mean and range of progeny per sire/dam was previously shown in Table 5.1. Broodstock were confined within a single population when NPOPS was greater than one (i.e. there was no mating of parents across populations).

5.2.4 Simulation of subsequent generations

Progeny additive genetic values (BV) were generated according to the following algorithm (Foulley and Chevalet 1981):

$$A_i = (½A_s + ½A_d) + \varepsilon_i\,(0.5\sigma_a^2(1 - (F_s + F_d)/2))^{0.5}$$

Where A_s and A_d were the true breeding value of animal i with sire s and dam d, ε_i was a random number from N~(0,1) and σ^2_a was the additive genetic standard deviation in the base population, F_s and F_d were the inbreeding coefficients of sire s and dam d. With no inbreeding, Mendelian sampling is distributed as $0.5\sigma_a^2$. However, when parents are inbred, Mendelian sampling is reduced proportionally to the parental inbreeding. Inbreeding coefficients (F) for all individuals (assumed to be zero for base animals) were calculated using the method of Meuwissen (1992) and expressed as a percentage. Individual phenotypes were generated by adding environmental effects to genetic effects as described previously ($P_i = A_i + E_i$).

Each generation of progeny were again sorted on phenotype of the next round of selection, and random mating of selected broodstock were performed, according to that previously specified for the founder population.

5.2.5 Information per record

For each record simulated, the following information for *each animal* was stored: sequential identification number (ID), the generation in which the animal belonged (GEN), the population in which the animal belonged (when the population was divided into four lines: POP), true breeding value (additive genetic merit A_i: BV), phenotypic value (P_i: P), sire and dam ID (SIRE/DAM) and inbreeding coefficient (F_i: F). The sex of offspring was randomly attributed, with broodstock having an equal chance (0.5) of generating males or females after fertilisation.

5.2.6 Summary statistics

The average BV of records by GEN and POP were calculated, along with the average level of F. An average BV and F across populations was also calculated when NPOPS was greater than one. The rate of response or inbreeding was determined over the nine generations of selection, as the base population was not selected.

The results presented below concern the mean and standard deviation (SD), and thus standard error (SD/√NREPS) of the mean values from 50 replicates. After the simulation was run, the average BV at each GEN, rate of response simulated in the base scenario was compared to the predicted genetic response (R) per generation: $R_{gen} = i\, h^2\, \sigma_p$ where i is the selection intensity. The parameters of PSM and PSF from the simulation were used to calculate the intensity of selection (Falconer 1989).

A sensitivity index (Leitch Sensitivity Index: LSI = $\Delta F/\Delta BV$) relating rates of inbreeding to rates of response (determined over the nine generations of selection) was adapted from Leitch (1994). The LSI provided a single value for simple comparisons of strategies for their "ability to effect changes in rate of inbreeding relative to changes in rate of genetic response", with lower values being preferable. However, the LSI should not be considered independently of low response rates. These values provide a simple estimate of the effectiveness of different scenarios when compared. Scenarios which result in a decrease of the LSI were preferred as they will provide the best balance between the rate of inbreeding and genetic gain, providing genetic gain remains adequate.

A z-test (Walpole 1982) was used to determine whether significant differences occurred between average results at any of the 10 generations (GEN) from the four different scenarios regarding the breeding values (BV) and inbreeding (F) levels. Where the difference between the two means at any generation occurs the level of significance is stated, being at the 5% ($P<0.05$) or 1% ($P<0.01$) level.

5.2.7 Input parameters

Several scenarios were simulated by varying a combination (Table 5.2) of parameters relating to the population structure (e.g. number of selection lines), intensity of selection and population size, proportion of males to females, along with trait characteristics (e.g. heritability).

Table 5.2 Input parameter values*

Parameter	Values
NPOPS	1 or 4
POPSIZE	200, 400, 2000, 3000 or 4000
PSM to PSF†	0.5_m to 0.5_f or 0.3_m to 0.7_f
h^2	0.2, 0.3 or 0.4

*: 200 broodstock were selected in all scenarios
†: These resulted in ratios of 1_m:1_f or 1_m:2_f or 100_m to 100_f or 66_m to 134_f

5.2.7.1 Population structure

The population initially consisted of 2000 animals in one large line, with 200 broodstock selected from these animals. The PSM and PSF were equal (10% males and 10% females). The population was either maintained as one large line, or divided into four smaller lines. Subsequent scenarios varied the total POPSIZE from which broodstock were selected, and the selection intensity reflected the proportion of these populations that had to be selected to result in 200 broodstock. The proportions of males and females selected as broodstock were equal under most scenarios. These were later differentiated into an increased proportion of females selected compared to males, but still resulted in 200 broodstock from a POPSIZE of 2000.

5.3 Results and discussion

5.3.1 Results for base scenario

The base scenario was used to illustrate trends that could be expected in the current SRO breeding program under mass selection of a lowly to moderately (h^2: 0.2) heritable trait. This scenario involved the mass selection of 200 phenotypically superior broodstock from one large recorded population of 2000. This resulted in 10% (i=1.755) of the population being selected (100_m:100_f) within each GEN.

5.3.1.1 Response

Figure 5.1 shows that the mean BV and P averaged over 50 replications, along with the prediction of response (R), increased linearly over successive generations. The linear trend occurs as the results were averaged over REPS. However, in reality generation means fluctuate and, after several generations of selection, a regression line should be fitted to indicate the average response to selection (Falconer 1989). The mean phenotype at all generations was consistently similar to the mean breeding value as expected so the phenotypic values were not presented further. The annual genetic response to selection possible in livestock under natural reproduction (in phenotypic SD: PSD) has been estimated to be 0.09PSD (sheep) and 0.14PSD (beef cattle) for extensive livestock species and 0.38PSD (pigs) and 0.46PSD (poultry) for intensively farmed species (Smith 1984). The base scenario tested in this study had an average 0.10PSD rate of gain, which is similar to that of extensive species. It would be possible to increase the annual rate of gain per generation by breeding oysters at one year of age rather than three. Relatively high rates of response were expected in this study due to the relative high selection intensity. Aquaculture programs typically display a high rate of response due to large variation and the differences in reproductive characteristics between farm and aquaculture species; particularly high selection intensities possible, large populations, and short generation intervals possible in aquaculture species.

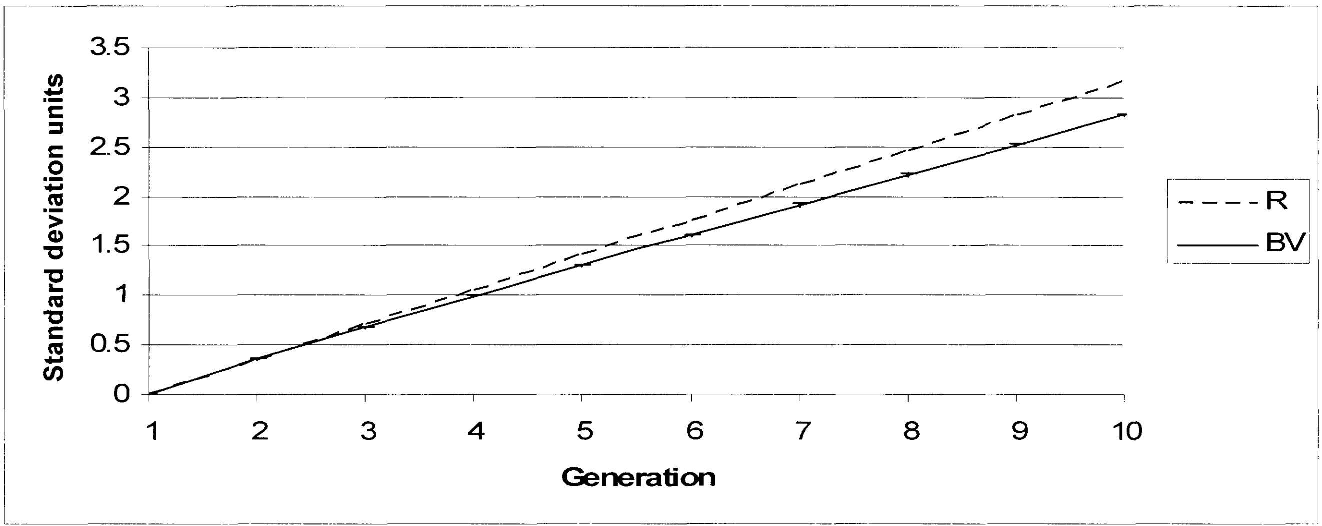

Figure 5.1. Means for simulated breeding value (BV±se) by generation averaged over 50 replications, along with the predicted response (R)

5.3.1.2 Predicted response

The predicted response (R) to selection for this scenario at GEN 10 was 3.16 units, which corresponds to a response of 0.35 units per generation, compared to the rate of response from simulation of 0.31 units per generation. The simulated response to selection was lower than the predicted response to selection (R) from GEN 3 onwards and became increasingly differentiated over subsequent generations. For example, The R and BV were slightly different (D) 0.68 and 0.70 (D = 3.5%) at GEN 3, 1.30 and 1.40 (D = 8.1%) at GEN 5 and 2.83 and 3.16 (D = 11.7%) at GEN 10. This was because the simple prediction equation has several flaws for predicting gain over more than one generation, as discussed in detail by (Falconer 1989). For example, the genetic variation will decrease over subsequent generations of selection due to the Bulmer effect and inbreeding, resulting in an over-prediction of response (R) at later generations if these factors are not accounted for. The Bulmer effect decreases genetic variation (V_A*) according to:

$$V_A^* = (1-h^2k)V_A$$

where k = $i(i-x)$ and V_A is the additive genetic variation (previously cited as σ_a^2) before selection, i is the selection intensity and x is the truncation point (Falconer 1989) in the first generation of selection, but the loss of variation becomes increasingly smaller over successive generations (Gjedrem 2005).

5.3.1.3 Inbreeding

Mean levels of inbreeding (%) in all scenarios were zero in generations 1 and 2, thus these were excluded from all Tables illustrating F. Inbreeding increased from 0.27±0.007% at GEN 3 to 2.63±0.004% at GEN 10. An increase in F was expected in a closed population (Simm 2000). However, the level at GEN 10 (2.63%) was below 10% and so is not likely to cause serious inbreeding depression (Simm 2000). This also led to a rate of inbreeding of 0.29% per GEN, which was lower than the rates regarded as sustainable of 1% per year (Simm 2000) or 1% per generation (Bentsen and Olesen 2002). The actual level or rate of inbreeding in the current SRO breeding program is essentially unknown, but was not expected to be significant (English 2001). However, inbreeding should be constrained or at least monitored (e.g. Appleyard and Ward 2006) to prevent inbreeding depression (Moss et al. 2007).

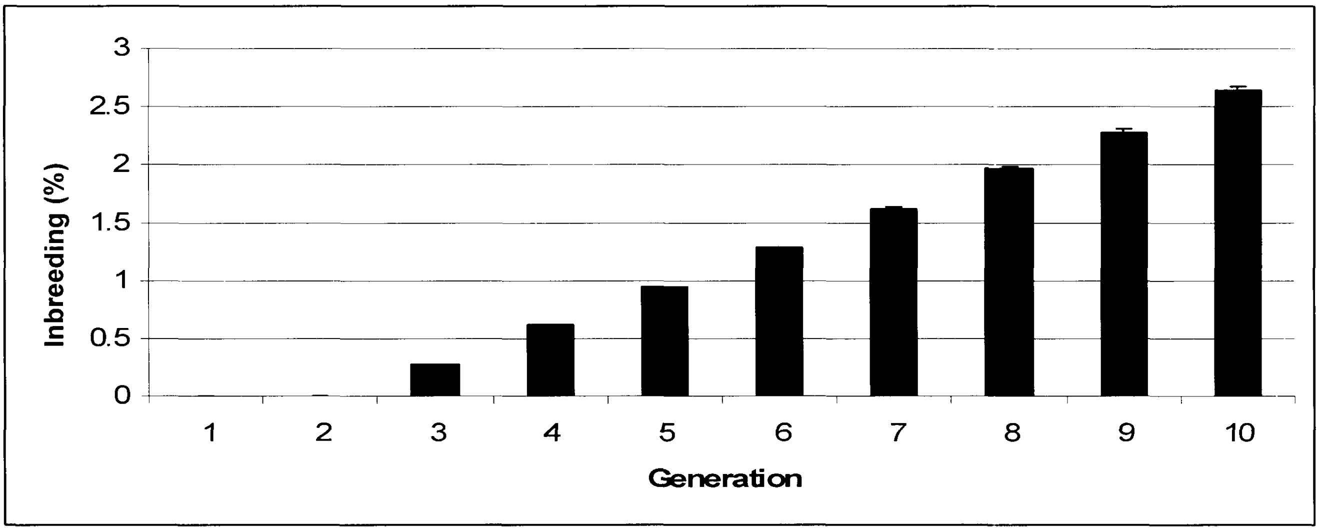

Figure 5.2. Means for inbreeding (%±se) by generation averaged over 50 replications

The Index of the ratio of rate of inbreeding to rate of gain (LSI: $\Delta F/\Delta R$) adapted from (Leitch et al. 1994) was 0.29/0.31 = 0.94 for this base scenario.

5.3.2 The effect of number of selection lines

These scenarios were simulated to compare the effects on response and inbreeding when the population remained as one relatively large single line or was differentiated into four smaller selection lines. This can occur in order to maintain lines at different sites. The proportion of broodstock selected remained constant (10%) for both these scenarios, resulting in either 200 broodstock (L1) or 50 broodstock (L4) selected per line; totalling 200 broodstock for both scenarios. These scenarios were conducted to evaluate the effectiveness of the current SRO breeding program, which currently maintains four separate lines of SROs, and breeds from a minimum of 216 SROs per line per generation (Nell 2006b) compared to the simplest base scenario. Within a constant population size, it should be more effective to maintain one (or very few) selection lines than a greater number of lines (e.g. four) due to the expected effects on genetic gain and inbreeding. The benefits of maintaining a number of lines could reduce the risk of inbreeding if these lines were not independent, and the crossing of lines may have the added benefit of heterosis. In addition, maintaining lines at different locations may also reduce risk through the loss of one line (e.g. through disease or theft).

5.3.2.1 Response

The level and rate of genetic gain for both scenarios is shown in Table 5.3. The positive linear trend of genetic gain was similar for both scenarios, with an average BV at GEN 10 of 2.83±0.02 for L1 and 2.71±0.01 for L4 across the four lines. Due to the sampling from smaller populations, L4 had a 4% lower level of genetic gain on average at GEN 10. The resulting responses were 0.31 for L1 and 0.30, averaged across the four lines for L4. The smaller lines exhibited variability between the lines, as illustrated in the means for each sub-line shown in Table 5.4.

There was a consistently significant difference between the mean BVs for scenario L1 and the average across the four lines (L4) at the 5% level by GEN 4 onwards, being 0.99±0.01 (L1) and 0.96±0.01 (L4).

Table 5.3 Individual and mean breeding values (BV±se) for single trait selection in one line (L1) or across four lines (L4)

GEN	L1 Mean	L4 (Lines 1 to 4) 1	2	3	4	Mean
2	0.35±0.005	0.35	0.34	0.34	0.33	0.34±0.004
5	1.30±0.011	1.26	1.29	1.25	1.25	1.27±0.009
10	2.83±0.016	2.73	2.73	2.70	2.70	2.71±0.014
Rate/GEN	*0.31*					*0.30*

5.3.2.2 Inbreeding

The trend in mean inbreeding coefficient from GEN 3 onwards was linear and positive (Figure 5.3). When the population was divided into several smaller lines (L4) maintained separately, the rate of inbreeding was significantly increased. The levels of F (%) for the four lines at GEN 10 were 9.99, 9.64, 9.75 and 9.85; the difference in these means illustrate the increased variation in the L4 scenario. Fewer parents contributing to subsequent generations within that line are expected to increase rates of inbreeding (Simm 2000). This leads to a higher mean percentage of inbreeding.

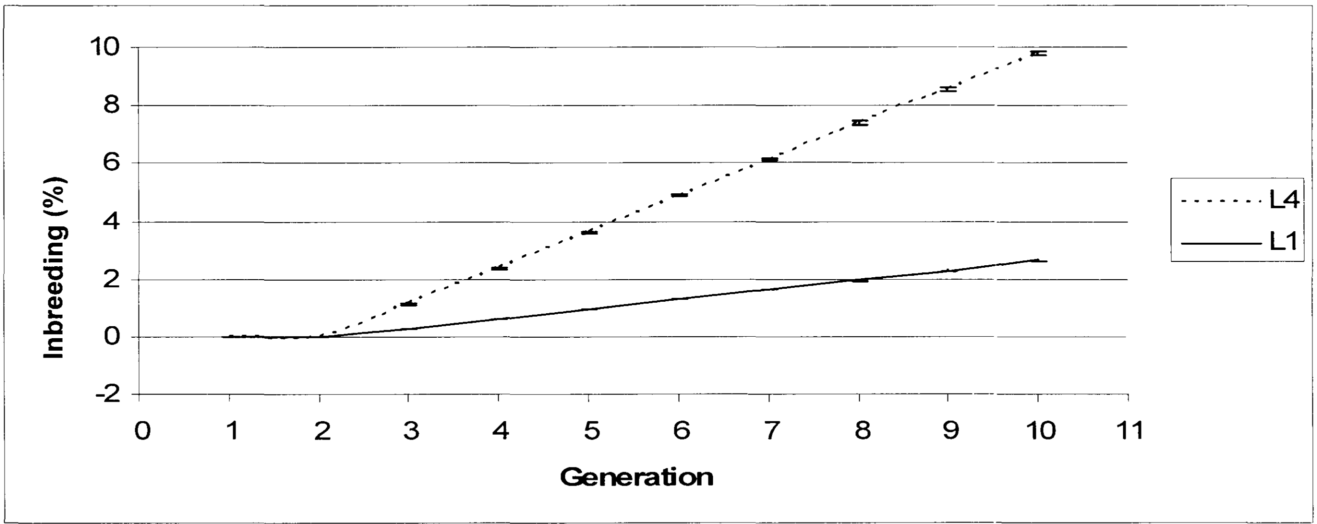

Figure 5.3. The mean inbreeding coefficient (%) per generation (F±se) when the population was in one line (L1) or divided into four lines (L4)

At GEN 10 the level of inbreeding was more than three times higher, and more variable as indicated by the larger standard errors for L4. This then resulted in a higher average rate of inbreeding nearly four times higher for L4 (1.1%/GEN) than for L1 (0.29%/GEN) even though the total number of broodstock selected was the same. This high rate of inbreeding has implications for the SRO breeding program in terms of the risk of associated loss of genetic variance and inbreeding depression.

From GEN 3 to 10, inbreeding increased from 0.27±0.01% (GEN 3) to 2.6±0.03% (GEN 10) for scenario L1 and 1.1±0.02% to 9.8±0.08% over the corresponding range for scenario L4. These differences were highly significant ($P<0.01$) from GEN 3 onwards.

As a result of the relatively high rate of F for scenario L4 when compared to L1, the resulting LSI (1.1/0.30 = 3.7) was far higher than that for L1 (0.94). These results illustrate increased risk of high inbreeding rates relative to response when one relatively large population is sub-divided into four smaller populations. Therefore, the L1 scenario was preferred and a reduction in line size for the current SRO breeding program does not appear to be an appropriate option. When the POPSIZE was increased to 4000 the LSI for L4 was 1.16/0.35 = 3.3. Therefore, even a reduction in population size from 2000 to 1000 will result in an even higher ΔF relative to ΔR. This increase in F mainly results from an increase in selection intensity.

5.3.3 The impact of trait heritability (H0.2; H0.3; H0.4)

Three scenarios were used to compare the response and inbreeding at low to moderate trait heritabilities. These reflect the range of heritability estimates for oyster weight currently reported in the literature (e.g.Gjedrem 2005). However, the actual heritability, and other genetic parameters, for growth rate and other traits in SROs are unknown. The resulting genetic standard deviations (when $\sigma_p = 1$) were 0.45 (H0.2), 0.55 (H0.3) and 0.63 (H0.4). The POPSIZE (2000), proportion of animals selected (10%; 200) and number of lines (one) remained unchanged from the base scenario.

5.3.3.1 Response

Table 5.4 illustrates that, as expected, the mean level of response (BV) at GEN 10 increased as heritability increased: 2.83±0.016 (H0.2), 4.08±0.017 (H0.3) and 5.31±0.018 (H0.4) units. The predicted response to selection (R) also increased with heritability. Corresponding genetic gains for each heritability per GEN were 0.31 (H0.2), 0.45 (H0.3) and 0.59 (H0.40) units. The relative response rates indicated that response was increased by a substantial 45% when heritability was increased by 50% from the base scenario (H0.2). A heritability estimate of 0.4 (an increase of 100% from 0.2) again increased response by 90% relative to the base scenario. The relative difference in response between the two higher heritability estimates was 31%. The increase in BV with heritability was expected as the additive genetic variance comprises a higher proportion of the phenotypic variance at higher heritabilities (i.e. more genetic variation as well as more accurate selection Falconer 1989)

Table 5.4 Mean breeding value (BV±se) for single trait selection at three different trait heritabilities

	Heritability		
GEN	**0.2**	**0.3**	**0.4**
2	0.35±0.005	0.53±0.006	0.70±0.007
5	1.30±0.011	1.89±0.013	2.48±0.015
10	2.83±0.016	4.08±0.017	5.31±0.018
Rate/GEN	*0.31*	*0.45*	*0.59*
Relative response (%)	*100*	*145*	*190*

There was no significant difference ($P<0.05$) in genetic gain (not shown) between any scenario at GEN 1 due to the relatively large standard errors associated with these estimates. However, the differences in genetic gain between the three heritability combinations was significant ($P<0.01$) from GEN 2 to GEN 10.

5.3.3.2 Inbreeding

The mean levels of inbreeding increased over generations with higher values occurring at higher levels of heritability (Table 5.5). The mean inbreeding estimates at GEN 10 were 2.63±0.033% (H0.2), 2.78±0.022% (H0.3) and 2.95±0.034% (H0.4). This trend was expected under phenotypic selection (Falconer 1989). The estimates of inbreeding were consistently and significantly ($P<0.01$) different between H0.2 and H0.3 from GEN 5 onwards. The differences between H0.3 and H0.4 were significant ($P<0.01$) from GEN 4 onwards. These averaged out to rates per GEN of 0.29, 0.31 and 0.33 respectively. The rate of inbreeding increased by 7% for each 10% rise in heritability.

Table 5.5 Percent (%) inbreeding (F±se) for traits differing in heritability

	Heritability		
GEN	0.2	0.3	**0.4**
3	0.27±0.007	0.30±0.006	0.31±0.008
5	0.95±0.009	0.10±0.012	0.68±0.011
10	2.63±0.033	2.78±0.022	2.95±0.034
Rate/GEN	*0.29*	*0.31*	*0.33*
Relative inbreeding (%)	*100*	*107*	*114*

The response and inbreeding per generation were proportional to the level of heritability. These resulted in LSI of (0.29/0.31) 0.94, (0.31/0.45) 0.67 and (0.33/0.59) 0.48. This indicated that, although inbreeding was greatest at the highest level of heritability, the level of genetic gain was proportionally higher resulting in a lower, and preferable, LSI. Therefore, a trait with a higher level of heritability would result in a greater increase in BV relative to F.

5.3.4 The impact of population size (P200, P400, P2000, P3000, P4000)

It was previously noted that each scenario involved the selection of 200 broodstock. This number of parents was unchanged regardless of the initial population size. This was because, in oyster breeding programs, the number of spat retained for selection is relatively high (POPSIZE) when compared to the number of broodstock feasibly able to be retained for spawning (proportion selected). Five population sizes were compared. When the population size consisted of only 200 animals (P200), all animals were selected as broodstock replacements, giving a selection intensity of zero (Table 5.5). As the POPSIZE increased, the proportion of the population selected as broodstock was reduced, thereby increasing the selection intensity (Table 5.6).

Table 5.6 Selection intensities relative to population size and proportion of the population selected

Population size	Proportion selected (%)	Selection intensity (i)
200	100	0
400	50	0.80
2000	10	1.76
3000	6.67	1.94
4000	5	2.06

5.3.4.1 Response

Table 5.7 shows that, as expected from the selection intensities shown in Table 5.6, response to selection (BV) increased with increasing POPSIZE. The difference between all adjacent POPSIZE reached significance ($P<0.01$) by GEN 2. The mean BV at GEN 10 increased from 0.010±0.015 (no response for P200) to 1.31±0.013 (P400). This then more than doubled in value for P2000 (2.83±0.016), and increased 9% further for P3000 (3.08±0.013) and 7% for P4000 (3.30±0.016). Therefore, there were decreasing increments in response with the corresponding increase in selection intensity, provided the selection intensity was greater than zero (e.g. not P200).

The rate of genetic gain for P200 was negligible (0.001). This was expected as there was no selection applied to this population (i = 0). When considering the base population scenario as the benchmark (100%), P400 had 48% rates of genetic gain. A relative increase in POPSIZE of 50% to 3000 or 100% to 4000 resulted in increased rates of gain from the basic scenario of 10% and 19% respectively. Therefore, a POPSIZE of 2000 should provide adequate rates of genetic gain, with only small increases in response at greater population sizes.

Table 5.7 Response (BV±se) under five different population sizes (and selection intensities)

	Population size				
GEN	**200**	**400**	**2000**	**3000**	**4000**
2	0.005±0.005	0.16±0.0.005	0.35±0.005	0.39±0.004	0.41±0.004
5	0.002±0.099	0.61±0.009	1.30±0.011	1.42±0.008	1.53±0.009
10	0.010±0.015	1.31±0.013	2.83±0.016	3.08±0.013	3.30±0.016
Rate	*0.001*	*0.15*	*0.31*	*0.34*	*0.37*
Relative response (%)	*0*	*48*	*100*	*110*	*119*

5.3.4.2 Inbreeding

Inbreeding increased with POPSIZE due to an increase in selection intensity. In the larger populations more progeny would result from fewer parents (larger family sizes) as was shown in Table 5.1, thus there would be an increased chance of selecting related animals. The difference between P200 and P400 did not reach significance until GEN 7 ($P<0.01$). The difference between P2000 and P3000 was consistently significant at GEN 5 onwards ($P<0.05$). The difference between P3000 and P4000 was significant from GEN 4 onwards ($P<0.05$). Levels of inbreeding were well below the absolute value of 10% and the average rate of 1% per generation as suggested as suitable to control the deleterious effects of inbreeding by (Simm 2000).

The difference between mean F for the largest and smallest POPSIZE at NGEN 10 was only about 1%, but this constituted a 50% increase. There was a 39% increase in the rate of F over 9 generations from the smallest POPSIZE to the largest. Although P200 showed a negligible rate of genetic gain due to lack of selection, this POPSIZE still showed a fundamental rate of inbreeding (0.23%). This rate was consistent with P400. The rate of inbreeding increased only marginally over increases in POPSIZE for the larger populations. This illustrates that a relatively large increase in selection intensity does not markedly increase inbreeding for a fixed number of parents selected.

Table 5.8 Inbreeding (%±se) under five different population sizes (and selection intensities)

	Population size				
GEN	**200**	**400**	**2000**	**3000**	**4000**
3	0.26±0.020	0.24±0.014	0.27±0.007	0.29±0.006	0.30±0.005
5	0.74±0.02	0.77±0.02	0.95±0.01	0.98±0.01	1.03±0.01
10	2.03±0.02	2.10±0.02	2.63±0.03	2.78±0.03	2.90±0.03
Rate/GEN	*0.23*	*0.23*	*0.29*	*0.31*	*0.32*
Relative inbreeding (%)	*79*	*79*	*100*	*107*	*110*

Genetic gain was lowest for the smallest population and greatest for the largest population. The level of inbreeding also followed this trend although the difference between the POPSIZE extremes was relatively much smaller. Although the POPSIZE differed, the number of broodstock selected was fixed, thereby changing the selection intensity. The effect of these factors was an increase in both BV and F, but by relatively different amounts.

Overall, the P400 had a relatively high LSI (0.23/0.15 = 1.53) when compared to the larger POPSIZE, mainly due to the difference in response. The three largest POPSIZE had similar LSI values of 0.94 (0.29/0.31), 0.91 (0.31/0.34) and 0.86 (0.32/0.37) respectively. The similarity of these results indicate that a POPSIZE of 2000 should be adequate to obtain a genetic response with low rates of inbreeding. The benefits of increasing the population size to improve genetic response by 10-20%, with only small increases in F (7-10%), needs to be weighed against the cost of increasing the population size.

The smallest POPSIZE had the highest LSI (230) as the genetic response was negligible but inbreeding still occurred. As no artificial selection occurred, this scenario was not actually considered to be a breeding program as there was no strategy for improvement.

5.3.5 The impact of the proportion of males and females selected

The ratio of females to males selected is usually high for livestock breeding programs. However, in oyster breeding programs the majority of SROs at selection are female. This was because there is expected to be an increasing proportion of females in oyster populations at increasing age (Guo et al. 1998; Ward et al. 2005), in addition to female oysters being larger (Baghurst and Mitchell 2002, cited in Ward et al. 2005) potentially inadvertently resulting in more females selected as broodstock. In this study, females constitute the higher proportion of selected broodstock purely to reflect the SRO breeding program. The following scenarios compared the differences in genetic gain and inbreeding when the sex of the parental ratio is either equal (EQ) or differentiated (DF). These scenarios compare 200 (10%) broodstock selected in equal numbers (100_m:100_f thus average i = 1.76) or unequal proportions (66_m:134_f thus $i = (1.94_m+1.61_f)/2 = 1.78$) from an initial population size of 2000. The difference between these average selection intensities was 1%. The differences in BV and F between these scenarios were driven by the mean selection intensities for each scenario. If the selection intensity remained constant but fewer males than females were selected as broodstock, there would be no change in genetic gain (under constant h^2 and σ_p) but inbreeding would increase due to the lower proportion of males selected.

5.3.5.1 Response

The differences between BVs in the two scenarios were not significantly different at any GEN as was also illustrated by the means and standard errors. The level of response at GEN 10 for the under the EQ scenario was only 1% higher (2.86 units) than for the DF scenario (2.83 units). This result was largely due to the higher selection intensity of males in the latter scenario, and was the same as the difference between selection intensities.

Table 5.9 Response (BV±se) under selection under equal or unequal ratios of males to females

	Male:female ratio	
GEN	**100m:100f (EQ)**	**66m:134f (DF)**
2	0.35±0.01	0.36±0.01
5	1.30±0.01	1.31±0.01
10	2.83±0.02	2.86±0.02
Rate/GEN	*0.31*	*0.32*

5.3.5.2 Inbreeding

In contrast to the rate of genetic gain, inbreeding was significantly higher in the DF scenario than the EQ scenario. This difference was significant at the 1% level from GEN 3 onwards. The rate of inbreeding under the DF scenario (0.33%) was 14% higher than for the EQ scenario (0.29%). The level of F is largely dependent on the low number of parents in one sex.

Table 5.10 Inbreeding (%±se) under selection under equal or unequal ratio of males to females

	Male:female ratio	
GEN	**100m:100f (EQ)**	**66m:134f (DF)**
3	0.27±0.01	0.32±0.01
5	0.95±0.01	1.04±0.04
10	2.63±0.03	3.01±0.08
Rate/GEN	*0.29*	*0.33*

LSI values were lower for EQ (0.29/0.31 = 0.94) than for DF (0.33/0.32 = 1.03). Therefore, mating an even number of males and females would be the preferred option. However, it is very likely that there will be an increased proportion of females to males in the SRO population, thus this may not be possible without the capacity to sex SROs. Another option would be to breed SROs at one year of age when the proportions of the sexes are more similar than occurs in older broodstock.

5.4 Comparisons with previous simulation studies

Simulation studies examining aspects of aquaculture breeding programs are generally limited. Bentsen and Olesen (2002) examined the effects of broodstock and progeny numbers (N: 5-50/pair), along with trait heritability, on response to selection and inbreeding over 15 generations of selection. Analogous to the current study, they considered mass selection for a single trait in the absence of inbreeding depression. Breeding structures were based on paired matings only.

Bentsen and Olesen (2002) found that rates of response of 5-13% from the base population mean were possible whilst maintaining inbreeding rates at ~1% per generation for three different trait heritabilities (0.1, 0.2 and 0.4). Similarly to this study, reducing the numbers of broodstock selected reduced the response to selection and had a marked increase in inbreeding. Therefore the differences in breeding structure between the simulation conducted in this thesis and that by Bentsen and Olesen (2002) did not appear to influence this result. They found that inbreeding was mainly the result of the number of broodstock pairs selected. By selecting 50 pairs of broodstock or more, the rate of inbreeding was ~1% per generation for all heritability levels. The number of progeny per pair (on average a minimum 30-50 progeny to be later used as broodstock per pair) had little effect on the rate of inbreeding but increasing the number of progeny evaluated per pair increased response to selection (through increased selection intensity). In agreement with this study and to expectations, response and inbreeding were greater, and more predictable due to reduced variation, at higher heritabilities. However, in contrast to this study, Bentsen and Olesen (2002) compared response and inbreeding under the same selection intensity and using pair mating.

A later simulation (Dupont-Nivet et al. 2006) studied the effect of balanced and unbalanced mating designs, with a constant family size before selection, on response and inbreeding. Effective population size (20-100) was calculated from total population size, either 1 000 or 5 000 animals. These authors found that mating design had the greatest influence on response and only a small effect on inbreeding given similar selection intensities. For example, when 100 sires were mated to 100 dams (Ne = 200, resulting in a total 1000 offspring) under a partial factorial mating design, cumulated genetic response (in genetic standard deviations units: GSD) and level of inbreeding were 11.9GSD and 7.5% and 23.3GSD and 9.6% respectively when H2 was 0.1 or 0.5. These levels of inbreeding were the lowest simulated in any mating design by Dupont-Nivet et al. (2006) and were considered acceptable after 30 generations of selection. In contrast to Bentsen and Olesen (2002), a single pair design using 50 males and 50 females had response and inbreeding levels of 7.32GSD and 8.7% at a low heritability of 0.1 and 14.4GSD and 14.1% (h^2 = 0.5) (Dupont-Nivet et al. 2006).

5.5 Model limitations

The simulation should provide adequate medium-term trends under the assumptions made. However, the simple model assumed only one polygenic, additive trait. Inbreeding depression, batch mating and mortality were not considered. However, such effects can be accounted for retrospectively given results on inbreeding. As with any simulation study, the assumptions for, and limitations of, simulations should be taken into account for the comparison with any results in practice. Implications of the simulation results will be discussed in reference to the current SRO breeding program.

5.6 Discussion and Conclusions

There is a great potential for improving response to selection for several traits in aquaculture species (e.g. high selection intensities possible and large genetic variation for many traits). The focus of this chapter was SROs which have had a breeding program in place since 1990. However, the reproductive characteristics of SRO which allow this high response to selection can also have implications for increasing inbreeding which must be taken into account. In addition, the unknown genetic parameters and proportion of males and females selected as broodstock may be a restriction.

This chapter studies rates of response and inbreeding when mass selection was practiced for a single trait. In reality, several economically important traits should be included in the breeding program, their importance weighted by relative economic values. Further, different methods of selection will be required for traits that cannot be measured on selection candidates. Finally, the measurement of genetic and phenotypic parameters should be considered for this species to establish whether unfavourable genetic correlations exist. This would facilitate prediction of response under different breeding structures and allow the possibility of selection methods having higher accuracy.

Breeding programs should be designed to maximise rates of genetic response while keeping rates of inbreeding under levels which have been deemed as sustainable (Δ0.5-1% per generation: for example see Bentsen and Olesen 2002 and Simm 2000). Assuming an infinitesimal additive genetic model with random mating of 200 phenotypically superior broodstock over 10 generations, the base scenario was simulated to reflect a single line in the current SRO breeding program. Parameters were then varied to investigate the effects on rates of response and inbreeding.

The rates of response when the population was maintained as one relatively large line or divided into four smaller lines were generally similar given the large numbers of oysters involved.

However, overall genetic gain was reduced in the subdivided population relative to a single population of the same size, and rates of inbreeding were higher (1.1% per generation) than what is considered sustainable (0.5-1.0% per generation). The implication of these results is that, assuming a fixed resource base, it is more advantageous to select broodstock from fewer but larger lines. However, the actual number of selection lines required to service the industry and reduce possible risk was a separate issue and is not considered here. However, the population could be maintained as one line, with lines held at different sites, to reduce risk of loss

Several scenarios with differing population size were subsequently compared. Rates of inbreeding remained under 0.33% per generation for all scenarios except when the population was divided into four lines (1.1% per generation); thus inbreeding under the majority of the simulated structures was not considered to be an issue. However, the rate of gain when the population consisted of either 200 or 400 broodstock was negligible to very low so these scenarios were effectively unviable. The rates of gain for the three larger populations were similar. The response increased by 10-19% when the population size was increased from 2000 to 3000 and 4000 respectively. Therefore, on an economic level (through a reduction in costs), the P2000 scenario would probably be the desired option for implementation. However, the relative costs and benefits associated with population size would have to be assessed.

The heritability is associated with the trait/s under selection and this is currently unknown for SROs. Therefore, three trait heritability estimates were simulated representing what might be expected for oyster traits. The effect of increasing the level of heritability had only small effects on the rate of inbreeding (differences of 7-14%). However, there was a great effect on the rate of response; increasing by 45% and 90% at heritabilities of 0.3 and 0.4 when compared to a trait heritability of 0.2. Trait heritabilities and genetic variation have real implications on the progress for the SRO breeding program and therefore trait parameters should be accurately estimated. The trait heritabilities have little effect on the optimal strategy so accurate estimation is more important for a indicator of potential progress. The estimation of the correlations between traits is of more importance than specific trait heritabilities.

The ratio of males to females, either equal of differentiated, was examined as this is essentially unknown at selection in the SRO population. Higher rates of inbreeding occurred when there were fewer males relative to females, but this remained below 1% per generation (0.33% per generation). Rates of gain were higher when the population the selection intensity of males was higher than that for females, although this was only of a small degree. This indicates that the proportion of sexes in the population has implications for SRO breeding.

In a multi-trait breeding program, the rate of gain for any individual trait would be reduced as selection is practiced over several traits. However, it is also expected that the rate of inbreeding would also decrease under the inference that animals did not rank in the same order for the different traits under selection. Selection for disease resistance could increase the rate of inbreeding under the assumption that the population reached a genetic bottleneck. This would be proportional to the level of mortality and therefore the number of males and females available for breeding. This study did not consider selection for disease resistance as there are too many assumptions to consider regarding the genetic control of disease resistance.

In conclusion, inbreeding rates were almost always well below levels that would be associated with risk of inbreeding depression in the simulated population. The exception was when the population was subdivided into four lines (ΔF = 1.1% per generation). The scenario with the greatest rate of genetic gain, at the lowest cost (e.g. a population size of 2000), would be the ideal to provide the greatest genetic response in the long term. The number of populations had the biggest impact of the rate of inbreeding, and the level of heritability had the largest influence on genetic response.

Chapter 6

General Discussion and Conclusions

The NSW Department of Primary Industries and Fisheries (DPI&F) have conducted a breeding program for SROs since 1990. Initially the breeding program selected oysters for growth rate only (defined as weight at a constant age) but then selection criteria were expanded in 2000 to include disease resistance. The SRO breeding program has thus far been successful in achieving increased growth rate in addition to resistance to the two major SRO diseases; QX disease and Winter mortality (Nell 2006). The initiation of this breeding program was designed to benefit the entire SRO industry, and as such is currently being commercialised by the Select Oyster Company (SOCo).

This thesis evolved around the progression of current breeding programs to consider other traits and breeding structures. The thesis was structured to consist of a general introduction (Chapter 1), a comprehensive review of available literature (Chapter 2), a survey of the SRO industry to determine its current status (Chapter 3), which then enabled the estimation of economic weights for commercially important SRO traits (Chapter 4). The final experimental chapter (Chapter 5) investigated genetic gain and inbreeding using simulation. The purpose of this chapter is to discuss the main findings from this thesis, and the limitations established. The findings indicate that further research into a number of issues is warranted.

6.1 Survey results

The development of economic values requires detailed production and economic data, which was largely unavailable in the SRO industry. Consequently, a survey of SRO farmers and wholesalers/retailers was conducted to investigate the current status of the SRO industry in terms of individual production levels, returns and costs.

The survey included 35 farmers from Southern QLD to Southern NSW, of which 31 provided useful information. In addition, five Sydney wholesalers/retailers were surveyed. The proportion of farmers interviewed on the North and South Coast of Eastern Australia were approximately equal (N: 18 and N: 17 respectively). These farmers represented 22% of permit holders producing 100 to >1 000 bags of SROs (median 40 000doz/yr) sourced from both hatchery stock and wild catch, and as such were considered representative of the industry. Respondents were able to provide anecdotal information regarding generic SRO operations. However, few were able to provide quantifiable data, and none were able to provide answers to every section of the survey. Clarification of the results and further information was obtained from literature and industry representatives.

Production data. The varying age of oysters at sale and different lengths of sale periods indicated that farmers had differing selling strategies. However, SRO farmers sold the majority of oysters in the three main grade classes; namely Bistro (35.1%), Plate (31.7%) and Bottle (30.4%). These results were similar to those reported by Nell (2005) and ABARE (2003). The weights of oysters sold overlapped across the different grade classes. However, there was a positive trend of increased average weight for consecutive grade classes, comparable to that found by Ruello (2006).

The meat condition of the oysters at sale (a major sale criterion) was subjectively assessed by the farmers as a percentage, which differs to the condition index used by many scientists (e.g.Mason and Nell 1995; Hand et al. 1999). Meat condition is seasonal thus the sale period depends on the level and maintenance of condition. In addition, farmers responded with the minimum condition in which they would sell SROs.

Mortality was unknown or only approximately assessed by farmers (N: 10) resulting in a median value of 10% and a mean of 17.3%. This was assumed to be a base mortality level under low level encounters with normal environmental fluctuations or minor pests and predators. Although the results for mortality were variable (ranging from 3 to 50%) , the mean and median were within the range reported by Nell (2006b) of 10-20% base mortality over a 2-3 year growing period. However, the pattern of mortality with age was not well defined. One farmer was able to differentiate mortality into spat (25%), nursery (10%), first grow out (5%) and final grow out (10%) phases. Another farmer differentiated mortality into first grow out (10-20%) and final grow out (0%) phases. These estimates of mortality were relatively consistent. However, it is cumulative mortality that is considered important.

Returns and costs. Analogous to weight at sale, returns ($/doz) overlapped across grade classes. Therefore, whole SRO returns were differentiated for grade classes based on mean values, rounded to the nearest $0.05/doz: $2.75/doz (Cocktail); $3.90/doz (Bottle); $5.45/doz (Bistro); and $7.45/doz (Plate); and $9.00/doz (Large Plate). Mean returns to producers then depended on the proportions of SROs sold in each grade class. Respondents were able to provide the most accurate information on the returns to their operation.

Many farmers were not able to differentiate fixed and variable costs and/or were unable to differentiate production costs (e.g. selling costs) or did not cost some activities (e.g. labour). In addition, respondents expressed returns and costs on a different basis. For example, returns and costs per dozen, or average dozens per bag or per half bag where the dozens per bag were not constant. Therefore, costs were generated from the survey, in addition to consultation with industry representatives (e.g. cost of hatchery spat).

Importance of SRO traits. Respondents were queried on the importance of specific traits to their business. Growth rate was considered the most important trait by the majority of respondents (weighted total = 38), which was a positive outcome as this is already included in the DPI&F breeding objectives. However, this was followed by meat condition (weighted total = 30) and shell shape (weighted total = 19) and so the possibility of including these traits in the breeding program should be investigated. Resistance to WM (South Coast) and QX (North Coast) were judged to be important by three and four respondents respectively. The importance of disease resistance traits was generally associated with where the farmer was located as these diseases generally occur in separate regions. However, one South Coast farmer found resistance to QX was important in the longer term as the disease has spread (e.g. to the Georges and Hawkesbury Rivers) from where it has historically been a problem.

The top three SRO traits of importance to farmers operations were obtained, and then weighted depending on their level of importance to each producer. The weighted totals (shown to compare relative importance) resulted in the following ranking:

1. Growth rate (38)
2. Meat condition (30)
3. Shell shape (19)
4. General mortality (9); WM resistance (9); and QX resistance (8)
5. Meat colour (7)
6. Appearance (3) and eating quality (2)

The same weightings were applied to the wholesalers/retailers data (N: 4), giving rise to the following ranking:

1. Meat condition (12)
2. Shell shape (5)
3. Meat colour (3); presentation (3); and size (2)

The results of both farmers and wholesalers included some similar traits. However, only producers are affected by mortality from disease, and slow growth rates, which explains why these traits were not considered important by wholesalers.

These results, and the results of the ranking of traits based on economic values, have implications for the current breeding program, and the entire SRO industry.

Implications. These results indicate that although information regarding the SRO industry was perceived to be lacking, there was a high consistency between what was obtained from the survey and industry information obtained by other authors (e.g. Ruello 2002; ABARE 2003; Nell 2005). This was a very positive outcome, and confidence can be placed on the survey data. However, farmers and scientists/researchers do not always evaluate traits on the same basis. An approximate correlation between the measurements of these traits from farmers and scientists, or a single objective measurement, would be useful to ensure that the scientists are assessing the same trait in the breeding program as is required by the farmers. For example, the range of meat condition measurements is the same for farmers (measured as a percentage: 0-100) and scientists (measured as dry meat weight g × 1000/cavity volume g: 50-150), and it is only the means that differ. However, the correlation between the two measures is currently unknown.

Further investigation could clarify results and provide more accurate data. For this, farmers need to be more aware of details associated with their SRO operations. This is particularly true regarding the economic aspects of their operation, especially costs. It is likely that increased financial information would allow respondents to define the strengths and weaknesses of their business, in particular economic information, and consequently increase profit. However, the low number of farmers to providing detailed economic information is probably characteristic of wild harvest aquaculture industries that have remained relatively unchanged and unsophisticated throughout their long history.

For the reasons stated above, economic values presented in this thesis should only be considered as preliminary values. The estimation of economic values could be improved by better knowledge of the commercial industry through data collection. However, this will only occur where farmers recognise the need to record the relevant data.

6.2 Estimation of economic values

Economic values define the relative importance of specific traits to the breeding objective, but for SRO these had not been established to date. The importance of economic values are only now being realised as the aquaculture industry expands and options for improving aquaculture breeding programs are investigated. Production and economic data derived from Chapter 3, considered in context with available literature values, were used for the estimation of economic values for the specific SRO traits deemed by oyster farmers as most important (Chapter 4). These traits included growth rate and mortality (disease resistance) in addition to shell shape and strength, and meat condition or colour. Economic values were calculated on a $/doz basis for each one unit change (e.g. g or %) in the trait.

From survey results presented in Chapter 3, the importance of SRO traits were ranked by oyster farmers and wholesalers. Standardised economic values (shown in $/GSD) estimated in Chapter 4 ranked the traits in the following order of importance:

1. Mortality due to QX disease (%) ($2.72/GSD)

2. Mortality due to WM disease (%) ($1.13/GSD)
3. Weight (g) ($0.58-$0.82/GSD)
4. Meat condition (CI) ($0.56/GSD)
5. Shell shape (volume, %) ($0.016/GSD)
6. Shell strength (kg) ($0.014-$0.021/GSD)

There was a lack of consensus in ranking between farmers (Chapter 3) and the standardised economic values calculated in Chapter 4. This may be because of the low number of farmers who responded to these questions and/or the lack of information available to calculate these preliminary economic values.

The progress of the current SRO breeding program indicates that the traits under selection are heritable. However, heritabilities are unknown as there are no genetic parameters available from recorded structured populations or estimates from realised response.

Implementing additional traits in the current mass selection breeding programs is difficult due to non-standardised or subjective trait measurements, and the absence of correlated non-sacrificial trait measurements. Measurements were unquantified (e.g. shell strength) or subjectively assessed (e.g. meat condition). In addition, trait parameters in SROs are essentially unknown. Thus, several assumptions regarding trait heritabilities and variation were made in order to derive standardised economic values. Consequently, changes to assumed genetic standard deviations may change the relativities of trait importance. The absence of genetic parameters for the traits of interest means that the relative genetic progress of any trait under selection, under different breeding structures, can not be accurately predicted.

Mortality (disease resistance). The relationship between costs and returns was influenced by the level of mortality and the growth phase in which this occurs. Several scenarios were modelled with varying spat and grading costs over a range of starting mortalities (10-90%). The average net return for all models was based on an average sale weight of 50g (sold at $6.52/doz) less the variable costs accumulated prior to the mortality event.

Economic values increased with increased spat cost, increased level of mortality and when mortality occurred in later growth phases after significant costs had accumulated. Economic values based on calculations per dozen ranged from -$0.049/% (0 to 1% mortality) to -$0.146/%

(90 to 91% mortality). It should be noted that, above a certain level of mortality, the economic viability of sorting through oysters to select the live from dead oysters would be unfeasible.

The impact of disease (QX and WM) increases the magnitude of economic values due to high mortality levels. Winter mortality commonly caused around 46% mortality when no management practices were implemented. The resulting economic value was -\$0.061/doz per percent increase in mortality. When oysters were sold prior to their third winter, decreasing their sale weight (and returns) whilst also decreasing associated costs, the economic values per dozen for FGO mortality were approximately -\$0.047/% for initial mortality levels between 10% to 30%. When the growing height of SROs was changed, cumulative mortality was reduced, resulting in economic values per dozen of -\$0.049/%, -\$0.050/% and -\$0.052/% at initial mortality levels of 10%, 20% and 30% respectively.

Oysters affected by QX generally suffer mortality in the later stages of growth, and the mortality level from infection with this disease can be very high. A 1% increase in mortality from 80% or 90% would lead to economic values of -\$0.078/% and -\$0.146/% per dozen respectively. Although these values provide a range of preliminary results, mortality resulting from either WM or QX cannot be measured or distinguished at the same time. Therefore, the direct application of these values to the SRO breeding program under mass, or possible future index selection, would not currently be feasible.

The higher ranking of mortality estimated from economic values than for farmers responses may be due to the low number of respondents (N: 10) who estimated mortality levels and/or the largely unknown costs associated with disease. In addition, not all estuaries are routinely affected by these diseases and competition with Pacific oysters due to growth rate differences may be deemed more important currently. The importance of disease resistance will rapidly increase if QX disease spreads to previously unaffected estuaries, as has been illustrated by the recent incident of QX disease causing effectively 100% mortality in 2004 and 2005 in the Hawkesbury River (Nell 2006b).

Growth rate (weight at sale). The economic values per dozen for a 5g increase in sale weight of 40g to 60g ranged from \$0.112/g to \$0.170/g when SROs were sold in all five grade classes. As a higher proportion of oysters were sold in the higher grade classes, with increasing mean weight, greater average returns were obtained. When oysters were sold in the three main grade classes, economic values were lower than above, ranging from \$0.058/g to \$0.152/g. This was because the difference in price differential between grades was larger when the population was sold in five grade classes. Preliminary economic values for a 1g increase in weight at sale were an average \$0.15/doz and \$0.11/doz when sales were divided into either five or three grade classes.

Meat condition. Meat condition was considered important to all wholesalers and 70% of farmers responding to the survey. Meat condition is a seasonal trait and SROs are generally not able to be sold below a certain, arbitrarily defined, level of condition. Measurement by farmers is currently subjective and may differ between farmers and between farmers and research staff. A standardised measure of meat condition would be useful in standardising grade class specifications (Ruello 2006). Delays in obtaining adequate meat condition for sale may increase the sale age. Price premiums or penalties also occur depending on the meat condition.

Premiums were estimated for a 10% increase in meat condition. Returns were assumed to increase to \$7.72/doz on average, an increase of \$1.20/doz more than the average weighted return of \$6.52/doz. This produced an economic value of +\$0.120 per 1% change in condition. In contrast, many buyers would not purchase 'over-condition' SROs Ruello (2006), therefore there may be an optimum level of condition but it is likely to be at the higher end of the scale (e.g. 90%+).

An alternative was to approach the economic value from the perspective of penalties for poor condition. Penalties existed if oysters were sold in a lower level of condition, resulting in them being downgraded and bottled, reducing overall returns. For example, the downgrading of Bistro SROs (\$5.45/doz) to Bottles (\$3.90/doz) when condition was reduced by 10% led to a reduction of \$1.55/doz. The resulting economic value was therefore -\$0.155/doz per 1% decrease; of similar magnitude to the above.

Holding SROs until they reached desired meat condition would incur greater grading costs (plus 3mo = \$0.18/doz; 6mo = \$0.36/doz) but also increased returns as a higher proportion could be sold in the larger grade classes (plus 3mo = \$7.23/doz; plus 6mo = \$7.79/doz). This scenario thus received net returns of \$7.05/doz and \$7.43/doz respectively. When net returns were compared to the overall weighted average return (\$6.52/doz), economic values were +\$0.053/doz and +\$0.091/doz under an assumption of a 10% increase in meat condition over this time period.

The magnitude of the estimate and the economic value per dozen, averaged over the three scenarios, and was \$0.105 per 1% change in condition. The economic values for premiums and penalties were of a similar magnitude. However, holding SROs for an increased period until desired meat condition was achieved resulted in an economic value per dozen of a lesser magnitude (\$0.072/%). Therefore, the level and maintenance of meat condition over the desired sale period at the desired sale weight has implications as to what economic value would be applied in the breeding program. Anecdotal evidence from the survey indicated that some farmers believe that some lines of fast growing oysters do not hold their meat condition as well as slower growing wild stock do. In addition, the study by Ward et al. (2005) found an antagonistic genetic correlation (rg: -0.74) between whole weight and condition index. However, this estimate was calculated from data from only one a and based on POs held at only one site.

Shell shape. The economic value for shell shape was based on cavity volume and estimated to be \$0.0455/doz for each 1% increase in cavity volume (expressed as a percentage of whole oyster volume). An increase in cavity volume is assumed to be associated with increased meat yield. However, measurement of meat yield requires sacrifice and therefore is not recorded for use in mass selection breeding programs. In contrast, shell shape can be measured on live oysters and is thus suitable for inclusion in a breeding program under mass selection. The best measurement of shell shape for SROs has not been clearly defined and several possible measurements exist. For example, the trait has been defined by shape indices (width or depth index) and the ratios between height, length and width (e.g. \(Ward et al. 2005; Appleyard and Ward 2006; Nell 2006b). In addition, the survey found that a reduction of shell shape variation was also considered important by the farmers and wholesalers/retailers. This may not have relevance to the SRO breeding program as management practices (e.g. grading) can reduce shell shape variation in a batch of oysters sold. Suitable measures for shell shape of SROs must be defined before the implementation of this criteria in the SRO breeding objectives is possible. Further, how shell shape attribute contribute to breeding goal outcomes (e.g. through yield or presentation characteristics) needs to be clarified.

The survey outcomes revealed that an optimum level of shell strength may exist (e.g. not too thin or too thick) but this has not been well characterised. The estimation of economic values for shell strength were based on differences between the 'average' scenario (\$6.52/doz) and the average weighted returns when the proportions sold in specific grade classes were varied by 1% as SRO meat was either downgraded due to shell breakage during processing, or through increased processing costs associated with thick shells. Economic values for thin shells due to shell breakage and therefore downgrading of the proportion sold in the different grade classes by 1% ranged from -\$0.015/doz to -\$0.062/doz, with an average value of -\$0.039/doz. The economic value for thick shells due to increased processing costs was -\$0.042/doz. Therefore, the magnitude of economic values was consistent when SROs were sold below and above optimum shell strength.

Shell strength. Objective measurements of shell strength have also not been developed. Nell and Mason (1991 cited in Nell 2006b) measured shell density which could be adequate to describe strength but required sacrifice. In addition, this measurement has not been associated with downgrading due to damaged meat or increased processing costs. Alternatively, much research has been conducted on egg shell strength and quality (e.g.Hunton 2005). It may be possible to adapt one of these objective measures to SROs if this it was informative, cost effective and able to be measured on live SROs. Processors do not directly pay a penalty or premium for shell strength. However, some processors would simply not accept stick SROs as these were reputed to have thick shells so the decrease in sales to certain processors for these oysters also lead to a hidden cost. In addition, anecdotal evidence from the survey revealed that shell strength can be altered by the production system employed and therefore short-term control could be used in place of long-term selection in a breeding program.

Meat colour. Meat colour was considered relatively unimportant by oyster farmers and wholesalers/retailers as was discussed in Chapter 3. The colour of the meat could be the result of

a) the estuary where the SROs were grown: (http://www.martinsseafoods.com.au/oysterReference.html)
b) the level of condition of the oysters (Ruello 2006)
c) and/or the effect of pests or disease (Nell 2006a).

Further, there is currently no quantifiable information regarding premiums or discounts based on meat colour. Therefore, although hidden costs (e.g. consumer rejection) or premiums (e.g. marketing SROs on their colour) were associated with the meat colour of the oyster, the economic value was assumed to be essentially zero.

6.3 Evaluation of breeding programs using simulation

Response to selection and inbreeding under single-trait mass selection was investigated for different breeding structures and trait heritabilities using simulation in Chapter 5. The scenarios investigated were developed with particular reference to the current SRO breeding program. The objective was to investigate the outcomes of breeding programs under several scenarios by varying the population size and structure, parental sex ratio and trait heritability. Only one parameter was changed in each scenario for simple comparative purposes. Many assumptions and simplifications are necessary in simulation studies, and so practical outcomes may differ from those results simulated.

The base scenario was simulated using the selection of 200 broodstock from a population size of 2000 oysters with individual records available, similar to the size of an individual line of SROs for mass selection. Parents (equal number of each sex) were selected on phenotype by truncation and mated at random, with varying numbers of offspring per parent. The predicted and possible response to selection was obtained for the base scenario. This scenario had a predicted (R) and simulated response to selection (BV) of 0.35 and 0.31 units per generation of selection respectively. This rate of response per generation is comparable to what has been achieved in both livestock and aquaculture species. The rate of inbreeding in the base scenario was 0.29% per generation, which would be regarded as sustainable over the long term (Bentsen and Olesen 2002). The results of all successive scenarios were compared to this base scenario.

The impact of increasing the size of the population recorded, for a fixed number of selected broodstock, was evaluated by increasing population size. The 200 broodstock were selected from five increasing population sizes, resulting in increasing selection intensities. When 100% of the population was selected, (P200) the rate of genetic gain was negligible, as expected when no selection pressure is applied. Response increased with increasing population size, from P400 to P4000. However, the differences between rates of gain became less at increasingly larger population sizes (e.g. P2000, P3000 and P4000). Rates of inbreeding increased with increasing selection intensity but remained under the rate of 0.5-1% per generation deemed as risky (Simm 2000). As the change in both genetic response and inbreeding was relatively small for the larger population sizes, but there would be an increase in cost when maintaining and recording much larger populations, the population size of 2000 was regarded as efficient and as such was used under subsequent scenarios.

The base scenario of selection under a single relatively large population was then compared with a selection line being maintained as four separate populations (L4), as is the current status of the SRO breeding program. All other parameters remained constant. The response to selection was reduced by 4% per generation in the L4 scenario. In addition, the relatively large standard errors of the mean response to selection under the L4 scenario indicate the response to selection will be more variable when selection is practices in smaller lines, as would be expected from theory (Hill 2000). Thus, an increase in the number of selection lines under a set population size would increase the risk to the breeding program. In addition, the differences in the level of inbreeding became highly significant ($P<0.01$) from generations 3 to 10 and the very large rate of inbreeding over generation (1.1% per generation) was above rates considered feasible to avoid the risk of inbreeding depression in the long term. The current SRO breeding program will be reducing the number of independent selection lines for a given population size.

The heritabilities of SRO traits are currently unknown. Therefore, scenarios were performed under three levels of heritability likely to span that expected for growth traits. As expected, genetic response increased with increasing levels of heritability. Rates of gain over the nine generations of selection were 45% greater than for the base scenario (0.31 units per generation) when heritability increased to 0.3 (0.45 units per generation). Rates of gain then increased by a lesser 31% when the heritability was again increased by the same amount (h^2: 0.4 with a gain of 0.59 units per generation). The relative rate of inbreeding increased by only a relatively small amount (7% per generation for each increase in heritability) and the rate of inbreeding remained below that which was considered risky (Simm 2000).

The ratio of males to females selected was equal for all previous scenarios, as this strategy is commonly targeted in aquaculture breeding programs to increase effective population sizes. This was altered to reflect deviations from this ratio which were likely to occur in SROs. It should be noted that sex is unknown at selection, and typically there are fewer males than females. When a higher proportion to females to males was selected to supply the 200 broodstock in total per generation, rates of response were only 3% greater than for the base scenario. However, the rate of inbreeding increased by 14% to 0.33% per generation, which was reaching the rate (0.5-1% per generation) regarded as risky (Simm 2000). Procedures that assist with the determination of sex prior to selection and the use of an adequate proportion of males to females, in addition to monitoring inbreeding, should be implemented. There are also more sophisticated strategies that could be employed if planned mating structures could be developed. However, the reproductive biology of SROs, and lack of feasible individual identification, is currently limiting this area (Nell 2006b).

Overall response to selection will be greater when selecting on a single trait than when multiple traits are included in the breeding objective. Rates of response in any individual trait will be reduces as more traits are included in the breeding program. However, when the relative economic importance of specific traits (economic values) are taken into account, overall profit should be increased through a breeding program that incorporates all economically important traits. Suggested further work would to develop multi-trait simulations where index selection is used, and an approximation of profit estimated. This would require estimates of genetic parameters for SRO traits in addition to further investigation into the economic values for specific traits. For example, the effect of disease resistance on the genetic response or inbreeding could not be simulated as there is no information available on any genetic parameters, including the manner of resistance, for this trait. These simulation results provide a simple comparison in genetic gain and inbreeding when altering population and trait parameters. The results can assist in the development of breeding program structures, especially those in their infancy.

6.4 Conclusions and Recommendations

Sustainable breeding programs aim to improve the profitability of specific species through the genetic improvement of economically important traits as defined by the breeding objective. This thesis illustrated that aquaculture breeding programs are currently in their infancy in comparison to those implemented for terrestrial species and there is little information on trait genetic parameters, especially for traits other than growth. However, there is much potential for genetic gain for aquaculture species due to the large genetic variation, high fecundity, high selection intensities and short generation intervals possible. Selection of younger oysters as broodstock could reduce the generation interval of SROs to only one year of age, greatly increasing response. However, the importance of monitoring inbreeding should not be underestimated, and some traits may not be accurately evaluated on very young oysters.

There is much anecdotal information of the SRO industry but little quantifiable data available. A survey of the industry found that the majority of SRO farmers could provide limited information on the commercial aspect of their business, especially in relation to economic data. The survey found that, when queried about returns and costs, farmers were most able to measure returns to their business and least able to quantify costs related to their operation. In addition, traits were often measured subjectively and not always on the same basis (e.g. meat condition), both between farmers and between farmers and scientists. Standardised objective measures should be implemented throughout industry.

The estimation of preliminary economic values for several SRO traits illustrated that the importance of SRO traits ranked differently to that obtained from the survey results. However, these inconsistencies were easily explained depending on where farmers are located and if they have had experienced previous mortality caused by QX or WM. The actual traits estimated to be important were similar. Traits considered important by respondents and quantified through economic values included disease resistance, growth rate, meat condition and shell shape and strength.

The information obtained from the literature and the simulation results indicated that there is a great potential for rapid genetic gain in oysters when compared to terrestrial species. Recommendations include maintaining the SRO breeding lines in large, instead of subdivided populations. However, defining the number of lines required for the industry was outside the scope of this thesis. A population size of 2000 was sufficient to increase genetic response under a sustainable rate of inbreeding, whilst reducing costs associated with maintaining and recording SROs.

The differences in response and inbreeding under different levels of trait heritability illustrate the importance of estimating genetic parameters for commercially important SRO traits. In addition, the ratio of males to females as broodstock is generally not known until spawning. A higher proportion of females to males, as may happen in a SRO breeding program, influences inbreeding more than genetic response. The level/rate of inbreeding should be monitored as it is a potentially major problem in aquaculture species. The benefit:cost ratio of these different breeding strategies should be implemented to determine the scenario with the greatest economic efficiency.

Further investigation should be conducted for SROs. For example, genetic parameters for economically important SRO traits should be estimated. The response to disease causing pathogens should be further investigated. In addition, more investigation into the aetiology of the two main SRO diseases could assist in developing strategies for artificial exposure in laboratories or ensuring infection in the field. For example, QX disease has been located in some estuaries but no deaths due to disease have thus far occurred.

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Appendix A1

INDUSTRY MANAGEMENT AND COMMERCIALISATION PLAN FOR THE SYDNEY ROCK OYSTER BREEDING PROGRAM

Farmer economic survey

CONFIDENTIALITY

Your responses to this survey will remain confidential, and will be stored at AGBU. Data relating to specific individuals will not be identified in the final report.

Section A. Business details

A1. Business details (or attach business card)

Business name____
Address____
____
Postal address (if different to above)________________________________
____
Phone____________________Mobile_____________________________
Fax______________________Email address____________________

Total number of employees
Full time_______________________
Part time_______________________
Casual_________________________
Cost of employees (average cost/employee/year)________________

Time in oyster industry________________________
Time on current lease/s________________________
Number of farmers in estuary (if known)_____________________

A4. Oyster Profit

Do you own (and use) the economic evaluation software "OysterProfit"?______________
If so, could you please enter the relevant details and email or post a copy to me.

A5. Species farmed

Do you farm other species (of oysters or other aquaculture species, please specify)?
____
Why or why not?
____
What proportion of your business is made up of species other than SROs?
____

THE FOLLOWING QUESTIONS RELATE ONLY TO YOUR SYDNEY ROCK OYSTER (SRO) BUSINESS

THE DATA SHOULD REFLECT THE (LONG-TERM) USUAL OR AVERAGE SITUATION. PLEASE INDICATE IF THE SITUATION IS LIKELY TO CHANGE DRAMATICALLY IN THE FUTURE.

Section B. Farm operations

B1. Size of current operation

Please note that not all production phases will occur for all operations. Spat collection is if spat are wild caught on sticks etc. (not bought from hatchery). Nursery only applies if it is not considered the first stage grow out. It would be good if you specified which production phases you have and the timing of operations (e.g. final stage grow out is from July to December or from when the oysters are 30g).

If you provide me with your lease numbers I can obtain sizes etc.

Table 1. Annual size and production achieved from each lease area

Production phase	Annual production (#)	Lease number/s	Size of lease area (ha)*	Annual lease cost ($)	Stocking density (#/ha)
Spat collection					
Nursery					
Initial grow out					
Final grow out					
Fallow	NA				NA
Other (please specify)					
TOTAL **					

* = total size of lease area for production phase
** = please specify what proportion of total lease area is fully developed and usable
NA = not applicable

Is production limited to the size of your current usable lease area (i.e. no fallow area to allow more trays etc.)?

____

____

____

Are there any other limitations to production (e.g. production quota, based on what?)?

____

____

____

What are your production method/s (i.e. spat caught on sticks, final grow out on trays)? Please fill in Table 2.

Table 2. Production method for each production phase (i.e. tarred sticks for spat collection, bought from hatchery, single seed)

Production phase	**Production method/s**
Spat collection	
Nursery	
Initial grow out	
Final grow out	
Other (please specify)	

B2. Timing of operations

Please specify typical months or time frames (e.g. Feb-Apr or 12 months)

Spat collection
Bought from hatchery______________________________
Wild spatfall harvested______________________________
Nursery______________________________
First stage grow out______________________________
Final stage grow out______________________________
Other(please specify)______________________________

Can the timing of operations be altered (e.g. bring whole production phase forward by buying hatchery spat out-of-season or only catching wild spat that settle in the first month)? Please explain.

____

What are the constraints to the timing of operations?

____

How many "batches" of oysters (oysters managed together as a group) are started in one year?______________________________

What is the typical "batch" size?

____

If you do mix batches, in what phase of production is this conducted (i.e. between nursery and first grow out phase)?

____

Does this lead to multiple ages in the batch (e.g. oysters mixed according to size but not age) and what is the maximum gap in age that you would have in the one batch?

____

Table 3. Timing of oyster sales

Production class	Average age (months)	Timing of sales (i.e. what month/s sold)	Sales every year?	% of each production class?
Plate				
Bistro				
Bottle				
All ins (bags, bulk)				
Other (please specify)				

Is the timing of sales primarily related to oyster meat condition (i.e. plumpness)?

___

Is the timing of sales related to the threat of disease (i.e. sell oysters before disease onset or before winter)?

___

What other factors motivate sales at particular times?

___

___

What percentage of sales are forced (e.g. to make space available or selling before a disease threat)?

___

___

Do forced sales mean you have to accept whatever the current price is (and is it always reduced and why for. oysters in poor condition or market glut etc.)?

___

Do you have any niche markets (i.e. selling under brand or estuary names)? Does this attract a premium (of how much; % or $/doz increase). What proportion of total oysters sales is this?

___

B3. Characteristics of phases

Table 4a. Size, weight and age of each production phase based on an average batch

	Size		Weight		Age	
	Average	**Range**	**Average**	**Range**	**Average**	**Range**
Spat						
Nursery						
First stage grow out						
Final stage grow out						
Other (please specify)						

Please note that the production classes (the grades into which you sell your oysters) and the size of oysters that fit into each production class may vary between oyster businesses. Please identify the production classes you use.

Table 4b. Size, weight and age of each production class based on an average batch

	Size		Weight		Age		Condition	
Production class	**Av***	**Range**	**Av**	**Range**	**Av**	**Range**	**Av**	**Range**
Plate								
Bistro								
Bottle								
All ins (bags, bulk)								
Other (please specify)								

* Average

Can you usually sell your oysters in 'finished' condition?________________________
What percentage are sold in 'finished' condition?____________________________
Is condition only assessed at sale time?__________________________________
During what months are your oysters in suitable condition for selling to quality driven markets (e.g. restaurant plate oysters)?

____
____
____

B4. Average losses (%)

Table 5. Average losses for each production phase for **handling and grading** (not including mortality)

	Handling	Grading*	Number of grading's	Timing of grading's**
Spat				
Nursery				
First stage grow out				
Final stage grow out				
Other (please specify)				
TOTAL				

* = please enter not done or unknown in any column when appropriate; grading is defined as the use of machine or hand graders to sort oysters based on size and/or shape.
** = i.e. monthly, at sale time?

Table 6. Average **mortality** (%) for each production phase

	TOTAL (%)	Due to QX disease	Due to Winter mortality	Due to other (please specify)
Spat				
Nursery				
First stage grow out				
Final stage grow out				
Other (please specify)				
TOTAL				

Does the figure for TOTAL mortality include heat kill, predators (e.g. mudworm, fish species, crabs), accident (i.e. dropping the tray or large waves) or theft?

If disease or pests are a problem (please specify), when did they first occur and what was your average natural mortality before that?

Did this mortality fluctuate widely between years (before the onset of disease or pest) and does it now that the disease or pest is present?

What risk preventative measures do/could you implement (i.e. growing oysters at a higher level to reduce Winter mortality)?

If oyster mortality declines, what will you do with the extra oysters (e.g. would you use more of your lease area or would you purchase less spat)?

____

____

____

Grading

Is grading conducted manually or by machine (can you attribute a cost to this per dozen oysters)?

____

What is grading based on (i.e. time, size, age, stocking density)?

____

Does the number or timing of grading's depend on growth rate (please specify e.g. have to grade more often (but the same total number of times) and/or more total number of times to maintain stocking density?

____

Would you then increase the number of trays or sell off the small ones or the larger ones (or increase stocking density)?

____

Do you sell off oysters every time you grade in final stage grow out (opportunistic sales)?

____

If so, what % of total sales is this?______________________________________

Do you mix batches of oysters of the same size (even if they are different ages)?

____

What is the maximum time you would keep a batch of oysters (e.g. sell off all remaining oysters at 3.5 years regardless of size)?

____

Do you wait until the end of the production cycle before selling off "culls" (low grade oysters) or do you sell them midway (e.g. prior to final grow out)?

____

Do you receive a purchase order prior to grading for sales?

____

What is the cue for harvesting if the oysters are not at a commercial size or weight (i.e. season)?

____

Do you handle stock other than for grading or harvesting (i.e. to move them to avoid QX disease)?

____

Section C. Variable costs

C1. Variable costs by phase

Variable costs are defined as those costs directly attributable to an activity which vary in direct proportion to the scale of the activity (e.g. increasing costs associated with increasing the number of oysters farmed). Fixed costs are defined as those costs which tend to remain constant regardless of the level of activity of the operation (e.g. administration costs).

The Tables below have examples of what may be considered variable costs. Variable costs specific to your operation may alter (and may include variable costs not stated here). Please use either cost per dozen or per bag (and how many dozen per bag and how many bags sold) or total cost (and provide number of dozen sold) so that we can estimate the economic values associated with different traits.

Table 7a. Costs associated with SPAT collection or purchase

Item		**Cost ($)**
Spat bought	**Hatchery**	
	Wild collection	
Shed (water quality, water pump)		
Labour		
Grading costs		
Other (please specify)		

Table 7b. Costs associated with each NURSERY phase

Item	**Cost ($)**
Upwellers	
Shed (water quality, water pump)	
Labour	
Grading costs	
Other (please specify)	

Table 7c. Costs associated with FIRST STAGE GROW OUT phase

Item	Cost ($)
Trays	
Labour	
Grading costs	
Vehicle and boat running expenses (e.g. fuel, oil, repairs)	
Other (please specify; i.e. anti-fouling paint)	

Table 7d. Costs associated with FINAL STAGE GROW OUT phase

Item	Cost ($)
Trays	
Labour	
QA (depuration)	
Grading costs	
Cartage and freight	
Commission, levies, selling charges	
Vehicle and boat running expenses (e.g. fuel, oil, repairs)	
Other (please specify)	

Table 7e. Costs associated with OTHER phase

Item	Cost ($)

How much have costs fluctuated over time (e.g. + or – 10%)?______________________

____

Has there been a large increase or decrease in costs over the last 10 years (e.g. + or – 10%)?

____

____

C2. Spat collection

Total number of spat purchased or caught________________________________

Hatchery (name and location)____________________________________

Percentage of spat (%)____________

Purchase price ($/1000 spat)_____________

Wild spat

Percentage of spat (%)_________________

Sticks or slats in spat collection area (#)_________________

Oyster spat collected per stick or slat (#)________________

Collection cost ($/1000 spat)_____________

Available spat sold (%)_________________

Price received per 1000 spat ($)_________________

Reason for spat collection method (e.g. availability of suitable hatchery spat, lack of wild caught spat)

____

____

For each method:

Advantages____

____

Disadvantages____

____

Do you find oyster purchasing introduces variation to "own" batch oysters sold at the same time (i.e. prime condition at different times etc., discolouration, different size or weight at the same age)?

____

____

____

Do you regularly buy in additional oysters (not spat) for growing out?____ (please fill in Table 8)?

Table 8. Purchase of stock

	Oyster weight	**Cost ($/dozen, bag etc.)**	**Number (dozens, bags etc)**	**% of total production**
Spat - nursery				
All ins				
Other (please specify)				

What are the reasons for the purchase of stock (e.g. spare lease space, not enough spat caught)?

____

____

C3. Quality assurance (QA)

Do you sell your oysters using name or region branding (please specify)?

____

Do you use a form of 'trace back' (please specify, i.e. batch numbers remain constant through to sale)?

____

What is your water quality status (i.e.conditionally approved; A, restricted; R, specify lease number and status)?____

____

____

Is depuration conducted on- or off- farm (and why)?_______________________

Cost ($/doz)____________________

Section D. Revenue

D1. Returns

Table 9. Price and cost for each production class

Production class	**% of production**	**Total production after losses**	**Price/doz, bag or box, kg**		**Cost/doz bag or box, kg**	
			Average	**Range**	**Average**	**Range**
Plate						
Bistro						
Bottle						
All ins (bags, bulk)						
Returned		NA				
Waste oysters		NA	NA	NA		
Other (please specify)						
TOTAL						

Has there been a large increase or decrease (or fluctuation) in revenue over the last 10 years (e.g. + or – 10%)?

___

___

What production class do you associate as being the biggest risk (e.g. Plate oysters as they are more susceptible to disease but may not be in a suitable condition to sell)?

___

___

D2. Costs and returns

From your answers to these questions, we will be able to calculate costs and returns of your oyster farming business. However, it would be beneficial if you could give a rough estimation of your current variable costs and returns.

Estimation of variable costs (per dozen):___

___

Estimation of returns (per dozen):___

___

Section E. Sale details

E1. Sales and contracts of where you sell your oysters

Table 10. Proportion of oysters sold to various outlets

	Proportion (%)	**Main outlets**		
Production class		**Business type****	**% of that production class sales (e.g. 50% Plate sold to 2 restaurants**	**$/doz**
Plate				
Bistro				
Bottle				
All ins (bags, bulk)				
Other (please specify)				
TOTAL	100%			

** = i.e. direct to restaurants, wholesaler, agent (who sells on to who?), through farmers co-op?

Do you have a target market (grades) or are sales conducted on oyster size, weight or age (or month/season)? Please explain.

If you sell to multiple outlets, do they compete for *your* product (does this result in increased sales or prices)?

Do you have a legal contract (e.g. fixed price) with the sales people or is it a 'loyalty contract'?

Do you have a consistent demand for your oysters over your sale period?

Can you provide a reliable and/or consistent supply over your sale period?

Is there a market for extra production (supply)?

How many sales opportunities on average are relevant to a batch?

Is there a new grading required for each sale opportunity?

OPTIONAL: The following Table is designed to enable us to calculate the costs associated with multiples sales from a given batch (e.g. through additional grading or harvesting costs). This Table relates costs to time to best capture the time effect on sale costs.

Table 11. Costs associated with each sale over time

Sale	Sale date (mm,yy)	Oyster dozens	Oyster age	Oyster weight	Extra costs*	Extra returns*	Total costs	Total returns
1					0	0		
2								
3								
4								
5								
Total								

* from previous sale

E2. Premiums and penalties

Do you process (e.g. value add by opening) any of your own stock (is this already included in the previous costs and returns provided)?

____

What are the premiums associated with this?

____

____

Do any of the following affect price premiums and penalties (or affect the availability to even sell oysters)? Please use $ or % increase or decrease from average sales and explain your answer.

- Reliable and/or consistent supply____

____

- Previous sales (e.g. product quality; meat or shell condition, shell shape, little variation in size)____

____

- Meat yield (how is this determined)____

____

- Timing of supply (i.e. lower prices when glut on the market)________________

____

- Mudworm____

____

- Other management implications (e.g. mechanical grading vs. hand grading on shell shape or condition)

____

Section F. Oyster traits (characteristics)

F1. Pests and diseases

Table 12. Threats that may be an issue to your operations

Threat	Does this affect all your lease sites? (please specify)	Does this affect others in your estuary?	Method of disease/pest detection*	Has it been detected in local estuaries?
Winter Mortality				
QX disease				
Mudworm				
Overcatch**				
Other (please specify)				

* i.e. water tests, biopsy, empty shells (unproven), PCR

**overcatch can include Pacific oysters, Sydney rock oysters and/or mussels

Table 12 cont. Threats that may be an issue to your operations

Threat	Season/month of infection	Season/month of mortality	Approximate mortality (%)***	Production class/es or ages affected
Winter Mortality				
QX disease				
Mudworm				
Overcatch				
Other (please specify)				

***overcatch can contribute to mortality directly or through losses due to treatment (e.g. immersion in hot water). Please include all mortality in this table

Can you use any management methods to reduce any of these threats and what are they (i.e. drying, immersion in hot water, change of growing height, water or meat tests)?

____

____

____

Can you estimate a cost associated with each threat (i.e. moving oysters; labour) or is, for example moving oysters also associated with moving them to fatten or solely for threat control (i.e. is the management specific to the threat)?

____

____

Are there any other costs associated with each loss (e.g. opportunity cost of reduced growth due to growing level or different estuary)?

____

____

How do you manage reduced or improved performance in terms of mortality (e.g. buy less oysters)?

____

What threat do you associate as being the biggest risk (in terms of mortality, frequency of occurrence, decreased revenue)?______________________________

F2. Growth rate

How do you manage reduced or improved performance in terms of growth rate? Would an increase in growth rate affect your management (i.e. would it lead to an increase in the frequency of grading or lower stocking densities, stocking density is defined as the number of oyster per unit area)?

____

____

If growth rate increases, what will you do about the decreasing lease space (would you purchase less stock or stock at higher densities)?

____

____

Are there changes associated with age that may affect sales or prices (i.e. change in shell shape at a given whole weight, change in shell strength)?

____

____

Would an increase in growth rate lead to premiums or penalties? (i.e. oversize oysters, ability for sales at start of season rather than the end of the season, depending on meat condition?)

Do you feel that meat weight is associated with shell size or weight (do you have any supporting data)?

F3. Meat condition

How is condition assessed? (i.e. visually, condition index, using a scoring system)

Do you sell 'out of condition' oysters due to demand (and to what extent, and are there penalties)?

What do you consider to be unsaleable in terms of meat condition?

Are you able to manipulate the meat condition of oysters (and when)? How is this achieved (i.e. change of estuary or lease area)?

Are there other meat characteristics that influence sales (e.g. colour)?

Do you feel that meat condition declines with increasing age (do you have any data to support this)?

F4. Eating quality

Do you sell oysters based on superior eating quality (how is this assessed)?

Do you receive premiums or penalties based on eating quality?

Do younger oysters have superior meat quality to older oysters at the same weight and condition (do you have any data to support this)?

F5. Ranking or importance of oyster characteristics

Please rank these traits/characteristics in order of importance (and the premium you would be willing to pay) to *your* business. If unimproved spat cost $30/1000spat, please allocate a maximum change (premium) in spat price ($/1000 or %) between the traits

Table 13a. Priority of all traits

Trait	Priority	What premium would you be willing to pay for animals that have improved performance for this trait?
Winter Mortality resistance		
QX disease resistance		
Growth rate		
Meat condition		
Eating quality		
Decreased spat mortality		
Decreased nursery mortality		
Decreased grow out mortality		
Shell shape		
Shell length		
Shell colour		
Meat colour		
Shelf life		
Other (please specify)*		
TOTAL	100%	

*if 'other' traits are considered important to your business please name them and state your reasons for considering them important and answer the following Table.

Table 13b. Details of other commercially important traits

Trait	How is the trait assessed and what is preferred?	Do you receive premiums or penalties ($ or % increase/decrease)?	Do you sell oysters based on this trait?

Table 14. Priority of traits which are currently being bred for at the NSW Department of Primary Industries fisheries hatchery at Port Stephens.

Breeding program cost level	Trait	Priority	What would be a fair premium for improved spat ($/1000)?
Lowest	Fast growth		
Medium	Fast growth + winter mortality resistance		
Highest	Fast growth + QX disease resistance		

F6. Meat condition and colour grids (if applicable)

Please indicate the price premium or penalty (+ or - $ or %) of the average value that you would receive for each production class under each percentage meat condition or colour stated (assuming all other aspects are acceptable). This means that $0 values should occur for at least 1 category per production class (as this is the average of your sale oysters for each production class). Also indicate what percent of oysters you sell under each condition or colour category. If your data does not fall neatly into these grids then please change them appropriately.

Table 16. Meat condition grid

Condition	60%		70%		80%		90%		100%	
	$ (+/-)	doz	$ (+/-)	doz	$ (+/-)	doz	$ (+/-)	doz	$ (+/-)	doz
Production class										
Bottle										
Bistro										
Plate										

Table 17. Meat (gonad) colour grid

Colour	Discoloured*		Discoloured*		Grey		Cream		Milky white	
	$ (+/-)	doz	$ (+/-)	doz	$ (+/-)	doz	$ (+/-)	doz	$ (+/-)	doz
Production class										
Bottle										
Bistro										
Plate										

* please specify

Table 18. Meat (mantle) colour grid

Colour	Discoloured*		Discoloured*		Grey		Cream		Milky white	
	$ (+/-)	doz	$ (+/-)	doz	$ (+/-)	doz	$ (+/-)	doz	$ (+/-)	doz
Production class										
Bottle										
Bistro										
Plate										

F7. Availability of industry data

Do you have any data relating to your oysters in terms of age, weight, growth, meat yield, meat quality and any other oyster characteristics?

____

Would you be willing to donate SROs to test oyster characteristics (i.e. meat condition, effect age on eating quality, meat yield). When, how often and how much?

____

Dear Participant,

Thank you very much for taking time to read through this survey. I realise that is quite extensive and detailed and I appreciate your time and effort involved. I will go through the questions with you during my visit.

Myself or Damian Ogburn (who is working on a similar project) will have rung you to see if you were willing to participate in this economic survey, and to find an appropriate time to visit in the next few weeks to go through these questions with you. Sending this survey prior to my visit is so that you can familiarise yourself with this project and think about what data you may need. Your profit and loss statements may benefit us in completing this survey. In addition, please include any significant cash sales or costs (for example, labour). We are more interested in long term trends, rather than short term trends, so averages over time would be useful.

This survey is conducted in confidence and you will not be identified in the final report to FRDC or SOCo. Information obtained from the survey will be used to establish the market sustainability of developing and marketing multiple lines and to determine suitable breeding objectives for different lines. This will then enable SOCo to breed oysters that are better targeted to your requirements.

After the survey is conducted, I may follow up the clarification of some questions with a phone call. I have tried to specify what is required in each question and to define terms. Feel free to contact me (details below) if you have any questions about the survey. I will be travelling from Sunday 9th July to Saturday 29th of July and during that time will be available on my mobile phone (0428 271 322).

Sincerely
Anna

Anna Hansson
Masters of Rural Science Candidate - Sydney Rock oyster (SRO) Project
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AGBU is a joint venture of NSW Department of Primary Industries and UNE
to undertake genetic research and development for Australia's Livestock Industries

Appendix A2

INDUSTRY MANAGEMENT AND COMMERCIALISATION PLAN FOR THE SYDNEY ROCK OYSTER (SRO) BREEDING PLAN

Purchaser survey

Section A. Business details

A1. Business details

Business name (and contact name)________________________________

Address____

____

____

Postal address (if different to above)________________________________

____

____

Phone__________________Mobile__________________________

Fax____________________

Email address__________________

What are your business activities (i.e. processor, wholesaler, retailer)?

Total number of employees (incl. cost of employees (average cost/employee/year)

Full time____________________

Part time____________________

Casual__________________

Total production____________________dozen

Number of outlets________________________

Time buying oysters_______________________

Time at current business_______________________________

A4. Species purchased

Do you buy and sell other species (aside from SROs) of oysters.

____

Why or why not?

____

____

What are the constraints/limitations to selling SROs and species other than SROs?

SROs____

____

Other____

____

What proportion of your *oyster* business is made up of species other than SROs?

____

What proportion of your *total* business is made up of species other than SROs?

____

Section B. Business operations

B1. Size of current operation

Annual purchases (dozens)

All oysters____________________

SROs__________________

Annual sales (dozens)

All oysters____________________

SROs__________________

Please note that the production classes (the grades into which you sell your oysters) and the size of oysters that fit into each production class may vary between oyster businesses. Please use the production classes you use.

Table 1. Timing of operations

Production class	Timing of sales (i.e. what month/s sold)	Sales every year? (please specify range and average per annum)	% of each production class?
Plate			
Bistro			
Bottle			
Other (please specify)			

Do you have any niche markets (i.e. selling under a brand name)?

____

Are sales associated with SRO oyster supply?

____

What months of the year does SRO *supply* increase or decrease?

North coast ____________________________________

south coast ____________________________________

What months of the year does SRO *demand* increase or decrease?

____

Would you accept SROs in previous 'low supply' times?

____

____

Can you substitute SROs with another oyster species at these times?

What species?__________________________________

What grade?____________________________________

____

What proportion?_______________________________

____

What businesses allow this (please name them and state type i.e. restaurant)?

____

____

Are there any other limitations to SRO sales?

Does reduced supply affect your current and future sales and/or contracts (i.e. due to disease)?

Is there a market for consistent increased supply?

How much increased supply would lead to you employing more staff?

Is there a seasonal sale price (please specify)?

Section C. Variable costs
C1. Variable costs by class

Variable costs are defined as those costs directly attributable to an activity which vary in direct proportion to the scale of the activity (i.e. increasing the number of sold). Fixed costs are defined as those costs which tend to remain constant regardless of the level of activity of the operation (e.g. administration costs).

The Tables below have examples of what may be considered variable costs. Variable costs specific to your operation may vary (and may include variable costs not stated here). Please use either cost per dozen or per bag (and how many dozen per bag and how many bags sold) or total cost (and provide number of dozen sold) so that we can estimate the economic values associated with different traits.

Table 2a. Costs associated with each production class that are specific to that class

	Item	**Cost ($)**
Bottle	**Processing**	
	Labour	
	Quality assurance	
	Other (please specify)	

Table 2b. Costs associated with each production class that are specific to that class

	Item	**Cost ($)**
Bistro	**Processing**	
	Labour	
	Quality assurance	

	Other (please specify)	

Table 2c. Costs associated with each production class that are specific to that class

	Item	**Cost ($)**
Plate	**Processing**	
	Labour	
	Quality assurance	
	Cartage and freight	
	Commission, levies, selling charges	
	Vehicle running expenses (e.g. fuel, oil, repairs)	
	Other (please specify)	

Table 2d. Costs associated with each production class that are specific to that class

Other (please specify)	**Processing**	
	Labour	
	Quality assurance	
	Cartage and freight	
	Commission, levies, selling charges	
	Vehicle running expenses (e.g. fuel, oil, repairs)	
	Other (please specify)	

C2. Stock purchases

Table 3. Purchase of stock

	Source/s*	**Number**	**% of total production**	**Reason**
Bottle				
Bistro				
Plate				
Other (please specify)				

* please state farmers, processors, wholesalers etc.

Table 3 cont. Purchase of stock

	Source/s*	Number	% of total production	Reason
Diploid Sydney rock oysters				
Triploid Pacific oysters				
Diploid Pacific oysters				
Other (please specify)				

What are the reasons behind the purchase of stock?
For the different production classes____

____

For Sydney rock or Pacific oysters____

____

For the diploid or triploid oysters____

____

Do you pay more for triploid oysters (please specify)?

____

What are the advantages and disadvantages of these stock?

____

____

Do you find oyster purchasing introduces variation (i.e. prime condition at different times etc., discolouration, different size or weight at the same age)?

____

____

C3. Quality assurance (QA)

Do you belong to a QA organisation (Please specify name)?__________________
Do you sell your oysters with ploidy (i.e. triploid or diploid) specified?

____

Do you or would you expect consumer resistance for triploid species?

____

Do you sell your oysters using name or region branding (please specify)?

____

Do you use a form of trace back (please specify)?

____

Section D. Revenue
D1. Returns

Table 4a. Price paid for each SRO production class

Production class	Cost/doz bag or box, kg	
	Average	Range
Plate		
Bistro		
Bottle		
Other (please specify)		
TOTAL		

Table 4b. Price received for each production class

Production class	% of production	Total production after losses	Product type sold*	Price/doz, bag or box, kg	
				Average	Range
Plate					
Bistro					
Bottle					
Other (please specify)					
TOTAL					

* = i.e. boxed as a half shell, whole, bottled

How much have these prices fluctuated or changed over time (i.e. 10% increase)?_______

What item do you associate as being the biggest risk (and why)?

What are the reasons for processing SROs (i.e.shucked for sale on the half shell, trimming of overcatch)?

Do you do any extra handling on your oysters (please specify grade and percentage)?

Do you suffer any oyster losses during processing, handling or storage and if so why (please specify)?

D2. Costs and returns

From your answers to these questions, we will be able to calculate costs and returns of your oyster farming business. However, it would be beneficial if you could estimate your current variable costs and returns.

Estimation of variable costs (per dozen, annually):________________________________

____

Estimation of returns (per dozen, annually):____

____

Section E. Sale details

E1. Sales and contracts

Table 5. Main suppliers

	Proportion (%)	Main suppliers (i.e. farmers, processors, self)
Plate		
Bistro		
Bottle		
Other (please specify)		

Table 6. Proportion of oysters sold to various outlets

	Proportion (%)	Main outlets		
		Business type**	% of sales	$/doz
Plate				
Bistro				
Bottle				
Other (please specify)				

** = i.e. direct to restaurants or the public?

Do you buy from a preferred estuary?

Do you have a target market (grades) or are sales conducted on oyster size, weight or age (or month/season)? Please explain.

If you sell to multiple outlets, does it create competition for your product?

If you have a contract, is it a fixed price contract or a loyalty contract?

Do you have a consistent demand for your oysters?

Can you provide a reliable and/or consistent supply?

Is there a market for extra production (supply)?

Do you negotiate with your supplier and/or buyer?

E2. Premiums and penalties

Do any of the following affect price premiums and penalties (or the availability to even sell oysters)? Please explain your answer.

- Reliable and/or consistent supply
- Previous sales (i.e. condition etc)
- Product quality consistency (i.e. uneven size or shell shape)
- Poor meat condition (how is this determined)
- When is each species in its best condition (please specify)?
- Meat yield (how is this determined)
- Shell condition (i.e. damaged shells)
- Size (undersize, oversize, big)
- Timing of supply (i.e. lower prices when glut on the market)
- Management implications?
- Ploidy (triploid or diploid)?
- Oyster species?

Section F. Traits

F1. Pests and diseases

Threats that may be an issue to your operations include Winter mortality, QX disease, mudworm and Pacific oyster overcatch. We understand these will affect your supply of SROs. However, do you also find that it affects the on-sale of your oysters?

F2. Growth rate

Are there changes associated with an increase in age that may affect sales or prices (i.e. change in shell shape? Increased or decreased sale price)?

Would an increase in growth rate lead to premiums or penalties? (i.e. oversize oysters, ability for sales at start of season rather than the end of the season, depending on body condition?)

Do you feel that meat size is associated with shell size or weight?

F3. Meat condition

How is condition assessed? (i.e. visually, by weight, other measurements, condition index)

Do you receive premiums or penalties (or maintain sales to purchaser/s) for meat condition?

Can you sell 'out of condition' oysters (and to what extent)?

F4. Eating quality

Do you sell oysters based on superior eating quality?

How is this trait assessed?

Do you receive premiums or penalties based on eating quality?

Do you know the age of the oysters you buy and do younger oysters have superior meat quality to older oysters at the same weight and condition when sold together?

F5. Ranking

Please rank these traits in order of importance (and the price you would be willing to pay).

Table 8. Priority of all traits

Trait	Priority	Would you be willing to pay for improvements in the trait?
Winter Mortality resistance		
QX disease resistance		
Growth rate		
Meat condition		
Eating quality		
Decreased spat mortality		
Decreased nursery mortality		
Decreased grow out mortality		
Shell shape		
Shell length		
Shell colour		
Meat colour		
Shelf life		
Other (please specify)		

Table 9. Priority of traits being bred for at NSW Department of Primary Industries & Fisheries Hatchery

Program cost	Trait	Priority	What would be a fair price for these?
Lowest	Fast growth		
Medium	Fast growth + winter mortality resistance		
Highest	Fast growth + QX disease resistance		

F6. Other

Are there other traits that you feel are important to you business?
If so, please name them and give your reasons for declaring them important
(e.g. shell shape, length or colour, meat colour, shelf life)

Table 10. Details of other commercially important traits

Trait	How is the trait assessed and what is preferred?	Do you receive premiums or penalties?	List the traits in order of priority	Do you sell oysters based on this trait?

Do you have any data relating to your oysters in terms of meat yield, meat quality and any other oyster characteristics?

____

____

G1. Meat condition and colour grids

Please indicate the price (premium +$ or penalty -$) you would receive for each production class under each percentage meat condition or colour stated (assuming all other aspects are acceptable). Also indicate how many dozens of oysters would be sold under each condition or colour category.

Table 12. Meat condition grid

Condition	**50%**		**60%**		**70%**		**80%**		**90%**	
	$ (+/-)	**doz**	**$ (+/-)**	**doz**	**$ (+/-)**	**doz**	**$ (+/-)**	**doz**	**$ (+/-)**	**doz**
Production class										
Bottle										
Bistro										
Plate										

Table 13. Meat (gonad) colour grid

Colour	**Grey**		**Brown**		**Discoloured (please specify)**		**Cream**		**Milky white**	
	$ (+/-)	**doz**	**$ (+/-)**	**doz**	**$ (+/-)**	**doz**	**$ (+/-)**	**doz**	**$ (+/-)**	**doz**
Production class										
Bottle										
Bistro										
Plate										

Table 14. Meat (mantle) colour grid

Colour	**Grey**		**Brown**		**Discoloured (please specify)**		**Cream**		**Milky white**	
	$ (+/-)	**doz**	**$ (+/-)**	**doz**	**$ (+/-)**	**doz**	**$ (+/-)**	**doz**	**$ (+/-)**	**doz**
Production class										
Bottle										
Bistro										
Plate										

Dear Participant,

Thank you very much for taking time to read through this survey. I realise that is quite extensive and detailed and I appreciate your time and effort involved, and understand that you may not be able to answer all questions. Please do not be overwhelmed with the size and detail of this survey as I will go through the questions with you during my visit.

Myself or Damian Ogburn (who is working on a similar project) will have rung you to see if you were willing to participate in this economic survey, and to find an appropriate time to visit in the next few weeks to go through these questions with you. Sending this survey prior to me visit is to familiarise yourself with this project and think about what data you may need. Your profit and loss statements may benefit us in completing this survey. In addition, please include any significant cash sales or costs (for example, labour).

This survey is conducted in confidence and you will not be identified in the final report. Information obtained from the survey will be used to establish the market sustainability of developing and marketing multiple lines and to determine suitable breeding objectives for different lines. This will then enable SOCo to breed oysters that are better targeted to your requirements.

After the survey is conducted, I may follow up the clarification of some questions with a phone call. I have tried to specify what is required in each question and to define terms. Feel free to contact me (details below) if you have any questions about the survey. I will be travelling from Sunday 9th July to Saturday 29th of July and during that time will be available on my mobile phone (0428 271 322).

Sincerely
Anna

~~~~~~

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AGBU is a joint venture of NSW Department of Primary Industries and UNE
to undertake genetic research and development for Australia's Livestock Industries

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Appendix A3

Development of economic models: examples for growth rate and mortality

1) Growth rate

a) Returns =	Large plate (LP):	% LP sold × No. doz sold × LP returns ($/doz)
	+ Plate (PL):	% PL sold × No. doz sold × PL returns ($/doz)
	+ Bistro (BI):	% BI sold × No. doz sold × BI returns ($/doz)
	+ Bottle (BO):	% BO sold × No. doz sold × BO returns ($/doz)
	+ Cocktail (CO):	% CO sold × No. doz sold × CO returns ($/doz)

b) Costs =	Wild spat:	No. doz caught × initial collection cost ($/doz)
	- Hatchery spat:	No. doz bought × purchase cost ($/doz) -
	Grading	(Grading No. × $/grading/doz)
	- Depuration	($/doz)
	- Selling	($/doz) (e.g. commission, packing and freight)

Assumptions:
- No changes to costs
- Weight at sale has a normal distribution thus % sold of each grade class depends on this distribution (oysters sold in five grade classes)
- Standard deviation calculated from CV of 18-20%
- 50 000 – 80% mortality = 40 000 doz produced
- All oysters are sold at the same age (36 mo) and sold over a relatively short and constant growing period
- Costs of the different grade classes are the same
- No processing occurs

Average population weight: 45g; No. grade classes: 5, Spat: hatchery $0.08/doz (significant figures v imp here), N.B. assume no changes to costs

a)	LP:	0.0439 × 40 000 × $9.00/doz = $15 804	$0.3951/doz
	PL:	0.2542 × 40 000 × $7.45/doz = $75 751.6	$1.89379/doz
	BI:	0.4432 × 40 000 × $5.45/doz = $96 617.6	$2.41544/doz
	BO:	0.2246 × 40 000 × $3.90/doz = $35 037.6	$0.87594/doz
	CO:	0.034 × 40 000 × $2.75/doz = $3 740	$0.0935/doz
= $226 950.8			$5.67/doz

Average population weight: 50g; No. grade classes: 5, Spat: hatchery $0.08/doz

a)	LP:	0.1455 × 40 000 × $9.00/doz = $52 380	$1.3095/doz
	PL:	0.3767 × 40 000 × $7.45/doz = $112 256.6	$2.806415/doz
	BI:	0.3563 × 40 000 × $5.45/doz = $77 673.4	$1.941835/doz
	BO:	0.1102 × 40 000 × $3.90/doz = $17 191.2	$0.42978/doz
	CO:	0.01134 × 40 000 × $2.75/doz = $1 247.4	$0.031185/doz
= $260 748.6			$6.52/doz

Economic weight (average population weight 45g to 50g) = $6.52/doz - $5.67/doz =0.85/doz

2) Mortality

Net Returns (NR) = Returns – Initial Costs (spat costs) – Additional Costs (grading, selling costs)

NR = (ns × $surv_{total}$ × R)
– (ns × $surv_{total}$ × spat cost)
– (ns × $surv_{spat}$ × gr1) (ns × $surv_{gp2}$ × gr2) - (ns × $surv_{gp2}$ × gr3)

Where:
NR = net returns overall
ns = No. spat
surv = proportion surviving to growth phase
gr = grading costs (gr3 is inflated as it includes selling costs)
gp = growth phase (as subscripts)

R = average returns = (P_{LP} R_{LP} + P_{PL} R_{PL} + P_{BI} R_{BI} + P_{BO} R_{BO} + P_{CO} R_{CO})

Where:
P = proportion of grade class sold
R = returns for grade class

Scenario a) OVERALL_0.96
Spat cost: $0.96/doz
Grading cost 1: $0.002/doz × 1 = $0.002/doz
Grading cost 2: $0.18/doz × 3 = $0.54/doz
Grading cost 3: $0.18/doz × 3 = $0.54/doz

NR = (ns × $surv_{total}$ × R)
– (ns × $surv_{total}$ × $0.96/doz)
– (ns × $surv_{spat}$ × $0.002/doz) (ns × $surv_{gp2}$ × $0.54/doz) - (ns × $surv_{gp2}$ × $0.54/doz)

Example
Mortality: 20%
Example growth phase where mortality occurs: Spat
R = $6.52/doz

NR = (50 000 × 0.80) ($6.52/doz)	$5.22/doz
- (50 000 × ($0.96/doz/0.80))	$1.20/doz
- (50 000 × 0.80 × $0.002/doz)	$0.0016/doz
- (50 000 × 0.80 × $0.54/doz)	$0.432/doz
– (50 000 × 0.80 × $0.54/doz)	$0.432/doz
$260 800	
- $60 000	
- $80 - $21 600 - $21 600	$0.8656/doz
= $157 520	= $3.15/doz

Mortality: 30%

NR = (50 000 × 0.70) ($6.52)	$4.56/doz
- (50 000 × ($0.96/doz/0.70))	$1.37/doz
- (50 000 × 0.70 × $0.002/doz)	$0.0014/doz

- (50 000 × 0.70 × \$0.54/doz) \$0.378/doz
– (50 000 × 0.70 × \$0.54/doz) \$0.378/doz

\$228 200
- \$68 571
- \$70 - \$18 900 - \$18 900 \$0.7574/doz
= \$121 759 = \$2.44/doz

Economic weight (30%-20% mortality) = \$2.44/doz - \$3.15/doz = -\$0.71/doz

Scenario b) OVERALL_0.04
Spat cost: \$0.04/doz
Grading cost 1: \$0.002/doz × 1 = \$0.002/doz
Grading cost 2: \$0.18/doz × 3 = \$0.54/doz
Grading cost 3: \$0.18/doz × 3 = \$0.54/doz

NR = (ns × $surv_{total}$ × R)
– (ns × $surv_{total}$ × \$0.04/doz)
– (ns × $surv_{spat}$ × \$0.002/doz) (ns × $surv_{gp2}$ × \$0.54/doz) - (ns × $surv_{gp3}$ × \$0.54/doz)

Mortality: 20%
Grading cost 1: \$0.002/doz × 1 = \$0.002/doz
Grading cost 2: \$0.18/doz × 3 = \$0.54/doz
Grading cost 3: \$0.18/doz × 3 = \$0.54/doz
Growth phase where mortality occurs: Spat

NR = (50 000 × 0.80) (\$6.52) \$5.22/doz
- (50 000 × (\$0.04/doz/0.80)) \$0.05/doz
- (50 000 × 0.80 × \$0.002/doz) \$0.0016/doz
- (50 000 × 0.80 × \$0.54/doz) \$0.432/doz
– (50 000 × 0.80 × \$0.54/doz) \$0.432/doz

\$260 800
- \$2 500
- \$80 - \$21 600 - \$21 600 \$0.8656/doz
= \$215 020 = \$4.30/doz

Mortality: 30%
NR = (50 000 × 0.70) (\$6.52) \$4.56/doz
- (50 000 × (\$0.04/doz/0.70)) \$0.06/doz
- (50 000 × 0.70 × \$0.002/doz) \$0.0014/doz
- (50 000 × 0.70 × \$0.54/doz) \$0.378/doz
– (50 000 × 0.70 × \$0.54/doz) \$0.378/doz

\$228 200
- \$3 000
- \$70 - \$18 900 - \$18 900 \$0.7574/doz
= \$187 330 = \$3.75/doz

Economic weight (30%-20% mortality)= \$3.75/doz - \$4.30/doz = -\$0.55/doz

Scenario c) HATCH_0.08
Spat cost: \$0.08/doz
Grading cost 1: \$0.00014/doz × 52 = \$0.01/doz
Grading cost 2: \$0.29/doz × 3 = \$0.87/doz
Grading cost 3: \$0.26/doz × 3 = \$0.78/doz

$NR = (ns \times surv_{total} \times R)$
$- (ns \times surv_{total} \times \$0.08/doz)$
$- (ns \times surv_{spat} \times \$0.01/doz)\ (ns \times surv_{gp2} \times \$0.87/doz) - (ns \times surv_{gp3} \times \$0.78/doz)$

Scenario d) HATCH_0.96
Spat cost: \$0.96/doz
Grading cost 1: NA as spat purchased at a larger size
Grading cost 2: \$0.29/doz × 3 = \$0.87/doz
Grading cost 3: \$0.26/doz × 3 = \$0.78/doz

$NR = (ns \times surv_{total} \times R)$
$- (ns \times surv_{total} \times \$0.96/doz)$
$- (ns \times surv_{gr2} \times \$0.87/doz) - (ns \times surv_{gr3} \times \$0.78/doz)$

Scenario e) WILD_0.04
Spat cost: \$0.04/doz
Grading cost 1: \$0.002/doz × 1 = \$0.002/doz
Grading cost 2: \$0.29/doz × 3 = \$0.87/doz
Grading cost 3: \$0.26/doz × 3 = \$0.78/doz

$NR = (ns \times surv_{total} \times R)$
$- (ns \times surv_{total} \times \$0.04/doz)$
$- (ns \times surv_{spat} \times \$0.002/doz) - (ns \times surv_{gp2} \times \$0.87/doz) - (ns \times surv_{gp3} \times \$0.78/doz)$

Appendix A3

ECONOMIC WEIGHTS FOR DISEASE RESISTANCE IN SYDNEY ROCK OYSTERS

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SUMMARY

Sydney rock oyster farmers and wholesalers surveyed in 2006 provided production and economic data, which were used to construct a profit function for the industry. Economic values, assuming a range of initial mortality levels, were estimated using the partial first derivative of the profit function. Economic values were differentiated for Winter Mortality (WM) and QX disease taking into account the growth phase at which mortality occurred and reported mortality levels for these diseases.

Increased mortality leads to higher costs associated with replacing dead oysters, which is done by attaining additional spat (young oysters). Plus there are additional grading costs, particularly at the later stages of growth, which increased the economic value for mortality occurring in later growth phases. There was little difference in the corresponding economic values between nursery and initial grow out growth phases, but mortality during the final grow out growth phase had large economic values.

For QX disease, the high level of mortality typically occurring in the final growth phase (90%) resulted in an economic value of -\$0.146/% per dozen oysters. No successful management practices are available to manage QX disease. Winter Mortality commonly causes approximately 46% mortality, resulting in an economic value of -\$0.061/%. When management strategies were used to reduce initial mortality levels (between 10% and 30%), economic values were between -\$0.047/% and -\$0.052/% respectively. The difference between the economic values for WM and QX disease resistance show that selecting against mortality from QX disease is more economically important to a breeding program than selecting against WM, assuming similar genetic variation for both diseases.

INTRODUCTION

The Sydney Rock Oyster (SRO: Saccostrea glomerata) has historically been the most important edible oyster in Australia (Brown, 1997). Two biological constraints to SRO production include Winter Mortality (WM) and QX disease ('QLD Unknown'), which are associated with infections by Bonamia roughleyi and Marteilia sydneyi, respectively.

Winter Mortality generally occurs along the NSW coast from Port Stephens (24°S) down to the Victorian border (37°S). Infection occurs in the third winter of an oyster's life, causing mortality rates as high as 80% (Smith, 2000), which is just before many farmed SROs reach market size ((Nell 2001b)). QX disease mostly affects farmers from the Georges River (34°S) to Hervey Bay in Southern QLD (24°S) ((Nell 2001b)). Infection occurs in summer, with up to 90% mortality ((Nell 2001b)). In 1994, QX disease effectively ruined SRO production in the Georges River. The NSW Department of Primary Industries and Fisheries SRO breeding program, aimed at increasing growth rates, was subsequently expanded to include selection against mortality from QX and WM. Recent results show that cumulative mortality was reduced in the lines selected

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* AGBU is a joint venture of NSW Department of Primary Industries and the University of New England

against mortality from QX and WM by 33% and 28% respectively, when compared to control oysters ((Nell and Perkins 2006)).

Future objectives of the SRO breeding program will include an increasing number of commercially important traits. However, currently no estimates of economic weights exist for any traits important for oyster production. This paper will investigate economic weights for generic SRO mortality, and then apply these to specific disease scenarios. Selection against mortality from disease is particularly important to oysters given that the production environment is relatively uncontrolled, thus disease management options are few. In addition, the long production cycle where risk of loss from disease is highest at later growth stages means that farmers are unable to compensate for losses.

MATERIALS AND METHODS

Production and economic data were obtained from a survey of SRO farmers (n=35) and wholesalers (n=5) conducted in 2006. Average returns were estimated from representative prices received and the proportions sold for each grade class. Variable costs included spat purchase, grading, and selling costs. Consultation with industry representatives and available literature was used to cross-check the survey estimates. All costs and returns were estimated on a dollars per dozen ($/doz) basis, as used in industry. Thus, economic values are also expressed on a $/doz basis.

Estimates for costs and returns were used as input variables for a simple profit function that describes profitability for oyster production. The function was:

$$\text{Net Returns (NR)} = [\bar{R} \times (1-m) \times n_s] - [c_s/(1\text{-}m) \times n_s] - [c_g\text{NUR} \times (1-m) \times n_s + c_g\text{IGO} \times (1-m) \times n_s + c_g\text{FGO} \times (1-m) \times n_s] \quad [1]$$

Where: n_s=no. spat; m=mortality; $\bar{R}$ =average returns=$\Sigma_i p_i R_i$ for i=1-5 grade classes; p=proportion sold; R=returns; c_s=spat cost; c_g=grading costs for nursery (NUR), initial (IGO) or final (FGO) growth phases. For simplicity, this paper examines mortality as confined to a single growth phase (e.g. NUR, IGO or FGO), so only one growth phase will have a non-zero mortality. The term $c_s/(1\text{-}m)$ shows that producers generally purchase additional spat to accommodate losses. After expanding with respect to m and removing the scale effect (n_s) the equation becomes:

$$NR = [\bar{R} - \bar{R}\,m] - [c_s/(1\text{-}m)] - [(c_{gNUR} - m_{NUR}\,c_{gNUR}) - (c_{gIGO} - m_{IGO}\,c_{gIGO}) - (c_{gFGO} - m_{FGO}\,c_{gFGO})]$$

The economic weight calculated using the partial first derivative with respect to nursery mortality is:

$$\frac{\delta\,NR}{\delta\,m_{NUR}} = -\bar{R} - [c_s/(1\text{-}m)^2] + [c_{gNUR} + c_{gIGO} + c_{gFGO}]$$

Similarly, partial derivatives can also be derived for mortality occurring in the other growth phases.

RESULTS AND DISCUSSION

The weighted average return ($6.52/doz) was calculated based on an average sale weight of 50g and sales occurring in all grade classes. Acceptable meat condition was assumed. Spat cost was based on purchase costs for hatchery spat ($0.08/doz). Total grading costs were calculated as the sum of the cost per grading and the number of gradings performed in the NUR ($0.007/doz), IGO ($0.87/doz) and FGO ($0.78/doz) growth phases.

The economic value for a 1% change in mortality increases as higher levels of initial mortality are assumed. This is because changes in spat cost per 1% increased in an exponential manner as the assumed initial mortality increased. At higher levels of mortality the contribution of grading costs are low compared to the contributions from spat costs. The economic value expressed per dozen oysters for a change in mortality increased in magnitude from -$0.050/% to -$0.052/% and -$0.138/% for initial mortality levels (NUR and IGO) of 10%, 50% and 90% respectively.

To illustrate differences between the effects of mortality in different growth phases, economic values were also calculated from equation [1] as the difference in net returns per percent change in mortality for initial mortality levels ranging from 0% to 90% (Table 1). Changes in mortality have been shown to be approximately 10% per generation under selection (Nell & Perkins, 2006). As with mortality in the nursery phase, economic values increased in magnitude with increasing mortality level for the IGO and FGO growth phases (Table 1). However, at any given mortality level, economic values for mortality in NUR and IGO were similar but were lower in magnitude than the comparable economic value for the same mortality level in the FGO growth phase. While absolute values were larger in magnitude for the FGO growth phase, the difference between growth phases on a percentage basis diminishes with increasing initial mortality.

The economic value for mortality occurring in later growth phases is higher in magnitude due to the increasing contribution of grading costs from earlier growth phases. In reality, above a certain level of mortality (unknown) it is not economically viable to pick out the live oysters from the dead oysters for grading or sale. This threshold effectively increases mortality to 100%.

Table 1. Economic values ($/doz) per 1% increase in mortality at different initial levels for the three growth phases

Change in mortality (%)	0-1	10-11	20-21	30-31	40-41	50-51	60-61	70-71	80-81	90-91
Nursery	-0.049	-0.050	-0.050	-0.050	-0.051	-0.052	-0.054	-0.058	-0.070	-0.138
Initial grow out	-0.050	-0.050	-0.050	-0.050	-0.051	-0.052	-0.054	-0.058	-0.070	-0.138
Final grow out	-0.058	-0.058	-0.059	-0.059	-0.060	-0.061	-0.063	-0.067	-0.078	-0.146

These results show that the appropriate economic value to place on mortality depends on both the level of mortality and the growth phase in which mortality occurs. This has implications for establishing the economic values relevant to the diseases of QX and WM.

Winter Mortality. Economic values for the FGO growth phase are the most relevant to WM, but the values will vary depending on how farmers manage WM, as different levels of mortality will determine the most appropriate values to be used in any one enterprise. Assuming a WM average of 46% (Nell & Perkins, 2006), this equates to an economic value for mortality of around -$0.061/% (Table 1). However, there are a few alternative strategies that SRO farmers can employ to reduce infection from WM, which may impact on the applicable economic values.

The most common strategy to manage the risk of losses resulting from WM is to sell oysters prior to their third winter. This means that oysters are sold at lighter weight (i.e. receive a lower average return) but also incur lower grading costs. After accounting for both the reduction in returns and the change in grading costs the economic values for WM are decreased in magnitude. For example if the average sale weight is reduced to 45g and there are two fewer FGO gradings, the economic values for a 1% change in FGO mortality are approximately -$0.047/%, for expected initial mortality levels of between 10% to 30%. A second management practice to reduce the impact of WM is to raise the growing height or move oysters upstream prior to their third winter. (Smith et al. 2000)) stated that it was relatively inexpensive to change growing height for controlling WM. From survey data, costs to pick up oysters and put them out was calculated to be $0.14/doz, and can be used as a preliminary cost of moving SROs upstream. If this was cost effective, the economic value for mortality would then depend on the level of protection this strategy conferred (i.e. reduction in mortality). The study by Smith et al. (2000) found that SROs grown above the normal growing height by 150mm and 300mm had significantly lower mortality than those grown at a normal height. Cumulative mortality was reduced from 35% to 17% and 9% for these heights, respectively. After accounting for cost changes economic values would reduce in magnitude to -\$0.049/%, -\$0.050/% and -\$0.052/% at 10%, 20% and 30% initial mortality levels. In summary, the economic values applicable to WM were influenced by both the cost and returns along with the assumed base level for mortality, which was influenced by management strategies to control the disease.

QX disease. Economic values for the FGO phases are relevant for this disease. A 1% increase from an initial value of 80% mortality resulted in an economic weight of -\$0.078/% (Table 1). Net returns were negative when initial mortality reached 80% for the FGO phase, or 90% in any growth phase. At an initial mortality level of 90%, an economic value of -\$0.146 per 1% change in mortality was estimated. With a rapid reduction in mortality levels caused by successful selection for resistance to QX disease, the economic value would also decrease in magnitude exponentially. Farmers in QX affected estuaries can purchase older SROs to on-grow to market weight and sell before the QX high-risk season in autumn ((Nell 2001b)). However, as few farmers implement this strategy, costs and returns for this production system could not be quantified.

CONCLUSIONS

Economic values for mortality depend on both base mortality levels that are assumed for the farm and the growth phase in which mortality occurs. Economic values increased in magnitude with increasing mortality due to increases in both spat and grading costs. These values were relatively stable for a wide range of mortality (0% to 70%), but increased dramatically after this. In addition, the economic values increased in magnitude with increasing growth phase as costs accumulated.

The economic value of -\$0.146/doz per dozen oysters for a 1% change in mortality caused by QX disease is worth more than the corresponding percentage change in mortality caused by WM (-\$0.061/doz). This is due to the very high levels of mortality associated with QX and the lack of an effective management strategy for alleviating the effects of the disease. In contrast, WM causes relatively lower levels of mortality and there are management alternatives available to control this disease. If these management strategies are used to control the effects of WM, the estimate of the economic value reduces in magnitude from -\$0.061/% to between -\$0.047/% and -\$0.052/%. The frequency and success of management interventions for WM has implications for the relative importance of selection against mortality from these specific diseases in the SRO breeding program.

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