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Evaluation of harvest models for Manila clam fisheries in British Columbia

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Abstract

Simple harvest models were used to evaluate the effects of various harvest rates on yields and stock size in Manila clam (*Venerupis philippinarum* [= *Tapes philippinarum*]) fisheries. Models used included the Washington State Department of Fish and Wildlife management program, depuration fisheries in British Columbia, and estimated harvest rates from size-limit fisheries. Data were taken from surveys completed by First Nations for co-management pilot programs.

Because recruitment patterns are not known for Manila clams, we examined effects of various harvest rates on the stock estimated from stock surveys, essentially the initial legal-sized stock and one year's recruitment.

The Washington State model is designed to partition the estimated stock over a four-year harvest period. Size limit models (constant harvest rates of 0.5 to 0.7) have the higher yield, but decrease stock size more quickly than other models. If recruitment is relatively high, size limit fisheries deplete detected stock in 3-4 years, depending on harvest rate. Under medium or low recruitment, size limit fisheries deplete detected stock in 2-3 years. The model employing a constant TAC of 25% of the initial legal stock estimate depletes that stock in 2, 3 or more than 4 years, depending on recruitment level. A 50% TAC model depletes detected stock in 3, 2 or 1 year.

High harvest rates produce high yields, but are more quickly dependent on annual recruitment to maintain harvest levels. Harvests resulting from lower harvest rates show decreased total yield, but greater consistency.

Résumé

On utilise de simples modèles de pêche pour évaluer les effets de divers taux de récolte sur les rendements et la taille des stocks de palourde japonaise (*Venerupis philippinarum* [= *Tapes philippinarum*]). Les modèles utilisés incluent le programme de gestion du Department of Fish and Wildlife de l'État de Washington, les pêches visées par un programme de dépuration en Colombie-Britannique et les taux de récolte estimatifs obtenus dans le cadre de pêches régies par une limite de taille. Les données ont été obtenues par relevés effectués par des Premières nations dans le cadre de programmes pilotes de cogestion.

Étant donné que nous ne connaissons pas les régimes de recrutement de la palourde japonaise, nous avons examiné les effets de divers taux de récolte sur le stock estimé d'après des relevés des populations, essentiellement le stock initial de palourde de taille légale et le recrutement d'un an.

Le modèle de l'État de Washington est conçu de façon à répartir le stock estimatif sur une période de récolte de quatre ans. Les modèles basés sur une limite de taille (à taux de récolte constants allant de 0,5 à 0,7) donnent le rendement le plus élevé, mais ils montrent une baisse plus rapide de la taille du stock que les autres modèles. Si le recrutement est relativement fort, les pêches régies par une limite de taille appauvrissent le stock cerné en 3 à 4 ans, selon le taux de récolte. Le modèle basé sur un TAC constant de 25 % de l'estimation initiale du stock de palourde de taille légale montre un appauvrissement du stock en 2, 3 ou plus de 4 ans, selon le niveau de recrutement, tandis qu'un modèle basé sur un TAC de 50 % réduit le stock cerné en 3, 2 ou 1 ans.

Des taux de récolte élevés donnent des rendements élevés, mais ils dépendent plus rapidement du recrutement annuel pour que soient maintenus les niveaux de récolte. Les captures résultant de taux de récolte moins élevés montrent un rendement total réduit, mais une plus grande uniformité.

Table of Contents

List of Tables

List of Figures

1. Introduction

Commercial fisheries for intertidal clams date to the 1800s, and First Nations peoples have long used butter and littleneck clams and other molluscs for food and ceremonial purposes (Quayle and Bourne 1972; Harbo 1997). Between 1951, when reliable landing statistics began to be collected, and the 1970s, the fishery had a relatively low landed value (Table 1), and was largely supported by the harvest of butter clams (*Saxidomus giganteus*). There were varied minor landings of littleneck (*Protothaca staminea*), razor (*Siliqua patula*), and introduced Manila clams (*Venerupis philippinarum* [= *Tapes philippinarum*]). Since the late 1970s, market preference has shifted to steamer clams (littleneck and particularly Manila clams), and landings and landed values increased remarkably through the early and mid-1980s.

The Manila clam fishery has developed only in the last 15 years and has reached the state where landings have peaked and declined, largely as a result of management actions. Driven by increased value, market demand and low capital investment for fishers to participate, the fishery has become oversubscribed, and numerous closures have been instituted after overharvest of available commercial resources. The fishery has exhausted most, if not all, of the accumulated legal-size biomass in many areas, and landings are now driven by annual recruitment to the fishery (Heizer 1992; Webb and Marcus 1996).

As DFO policies change, outside groups, including depurators, Aboriginal groups and Community Management Boards will be participating in co-management of clam beaches. In most cases where a specific beach is to be considered, the only information they will have to make management decisions is an initial survey.

This paper uses pragmatic models (*fide* Starfield 1997) to examine the effects of different harvest rates on the stock estimated from a single survey. Information available from the survey includes estimates of legal-sized and sublegal-sized portions, age and size composition of the population, and estimated growth rates. We compare yield and resulting stock size from modeled harvests using estimated removals in size limit fisheries, harvest levels suggested by the Washington State model, and harvest rates and allowable catches presently assigned in British Columbia depuration fisheries.

1.1. HISTORY OF THE FISHERY

1.1.1. Catch

While Manila and littleneck clams have been reported in commercial landings since records were kept in 1951, the directed fishery for Manila clams did not develop until the late 1970s (Table 1; Figure 1; Figure 2). Landings increased steadily until 1988, when they peaked at 3,909 t (8.6 million pounds). Prior to 1978, Manila clams accounted for between <1% and 28%, and littlenecks for between 1% and 40%, of total B.C. landings of intertidal clam species. In the same period, total landings of steamer clams (Manila, littleneck and mixed landings combined) never accounted for greater than 58% of total clam landings. For the period 1987-1990 inclusive, steamer clam landings represented greater than 90% of the total clam landings for British Columbia.

Landings decreased after 1988 to approximately 25% of the peak landings, largely due to management actions. However, steamer landings still accounted for more than 80% of total British Columbia intertidal clam yield in 1994.

There are two serious problems with clam catch statistics. Firstly, there is little spatial resolution of reported catches. Catch statistics are captured at Statistical Area or Subarea levels, not landings from individual beaches. It is therefore impossible to link fishery removals from grouped catch statistics to stock estimates for individual beaches. Secondly, these statistics only account for legitimate commercial removals. Thus, there is no accounting of legitimate recreational or subsistence removals, or illegal removals.

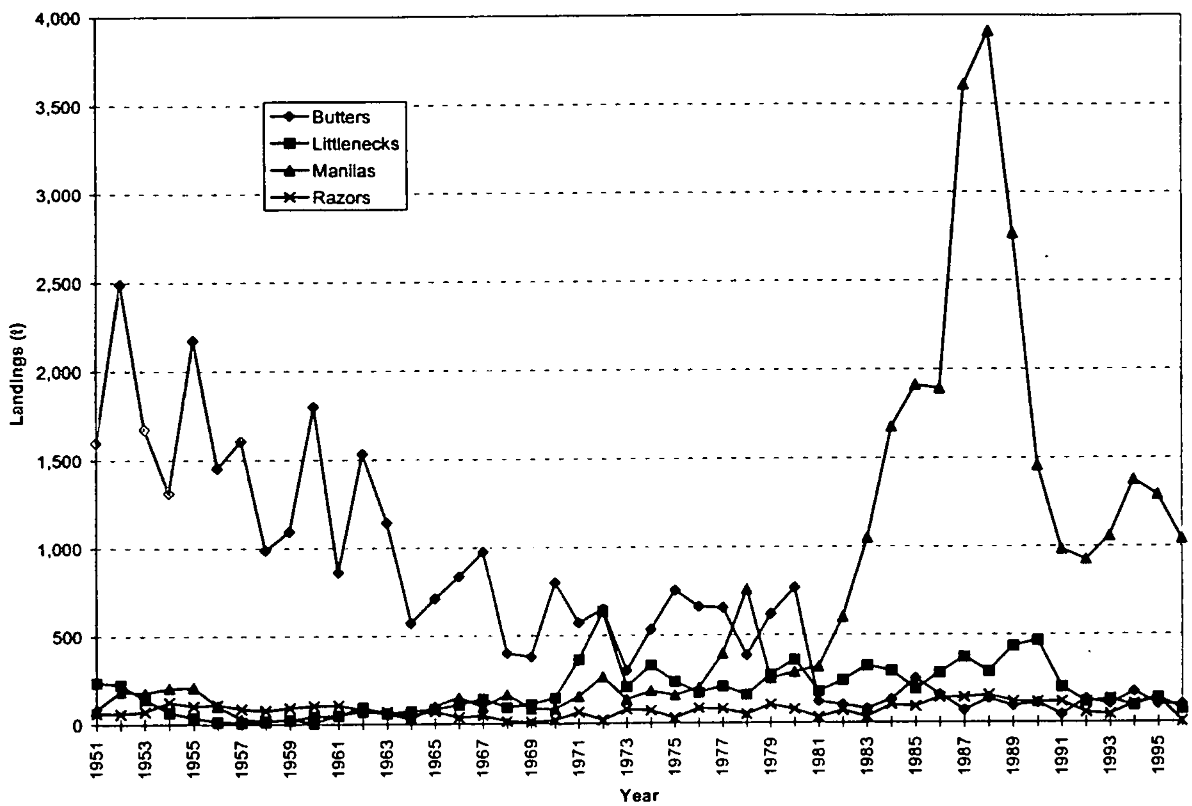

Figure 1. Annual landings of intertidal clams in British Columbia, 1951-1996.

Table 1. Annual British Columbia commercial clam fishery landings and landed values, 1951-1996 (Webb and Marcus 1996).

Year	Butter (t)	Littleneck (t)	Manila (t)	Mixed (t)	Total Steamers (t)	Razor (t)	Landed Value ($000)	Total Landings	Number of Licences
1951	1,597	237	81	65	383	61	$149	2,041	NA
1952	2,490	224	184	65	473	57	$222	3,020	NA
1953	1,674	140	176	20	336	70	$127	2,080	NA
1954	1,314	66	204	5	275	123	$104	1,712	NA
1955	2,170	36	207	3	246	99	$159	2,515	NA
1956	1,454	14	99	0	113	108	$102	1,675	NA
1957	1,606	10	29	11	50	84	$102	1,740	NA
1958	987	18	15	6	39	75	$65	1,101	NA
1959	1,094	22	25	13	60	90	$75	1,244	NA
1960	1,800	41	6	23	70	101	$133	1,971	NA
1961	857	46	48	34	128	104	$76	1,089	NA
1962	1,533	92	69	43	204	77	$139	1,814	NA
1963	1,144	59	59	0	118	67	$103	1,329	NA
1964	570	69	26	1	96	48	$59	714	NA
1965	704	82	97	0	179	68	$106	951	NA
1966	831	105	149	1	255	35	$125	1,121	NA
1967	975	139	92	0	231	46	$163	1,252	NA
1968	399	91	164	15	270	12	$98	681	NA
1969	378	107	81	7	195	8	$85	581	NA
1970	792	144	79	15	238	18	$184	1,048	NA
1971	568	361	153	11	525	62	$235	1,155	NA
1972	645	631	265	1	897	17	$382	1,559	NA
1973	298	207	134	0	341	76	$196	715	NA
1974	531	328	182	0	510	69	$383	1,110	NA
1975	746	236	158	6	400	27	$333	1,173	NA
1976	655	173	199	70	442	82	$340	1,179	NA
1977	649	209	394	59	662	78	$545	1,389	NA
1978	383	159	753	245	1,157	47	$834	1,587	NA
1979	613	273	251	374	898	101	$916	1,612	NA
1980	760	358	288	151	797	75	$1,001	1,632	NA
1981	119	179	318	161	658	30	$737	807	NA
1982	102	242	598	155	995	68	$1,135	1,165	NA
1983	77	324	1,048	279	1,651	31	$1,723	1,759	NA
1984	130	294	1,677	410	2,381	100	$2,757	2,611	NA
1985	251	191	1,913	477	2,581	90	$3,288	2,922	NA
1986	158	284	1,893	371	2,548	142	$3,801	2,848	NA
1987	68	373	3,607	87	4,067	142	$6,755	4,277	NA
1988	134	290	3,909	27	4,226	155	$7,771	4,515	NA
1989	92	433	2,764	159	3,356	117	$6,955	3,565	1,870
1990	109	465	1,456	339	2,260	114	$5,279	2,483	2,068
1991	42	201	982	137	1,320	117	$3,302	1,479	1,949
1992	132	116	923	112	1,151	55	$2,720	1,338	1,814
1993	102	131	1,059	133	1,323	44	$3,371	1,469	1,639
1994	174	94	1,376	87	1,557	105	$4,410	1,836	1,844
1995	101	140	1,292	3	1,435	140	$4,724	1,676	2,448
1996	99	72	1041	2	1,115	1	$3,835	1,215	1,906

1995 and 1996 statistics preliminary.
1993 through 1996 include aboriginal licenced harvest in Area 7 and non-lease depuration harvests.

1.1.2. Effort

Information regarding historic levels of effort in British Columbia's intertidal clam fisheries is scarce. Clam fishers were not required to obtain a clam fishing licence separate from their commercial fishing licence until 1989. Nearly two thousand fishers acquired clam licenses in that year (Table 1). Licence requirements changed in 1990 when fishers under the age of 16 were no longer required to purchase clam licenses. Nevertheless, licence issue increased by 8% to 2,068. Regulations again required commercial diggers under 16 years old to purchase clam licenses in 1995.

Obviously, total participation in the fishery is not the most desirable unit of effort. Quayle (1940) used total landings per digger per tide to quantify catch per unit effort (CPUE), and this standard is still used today.

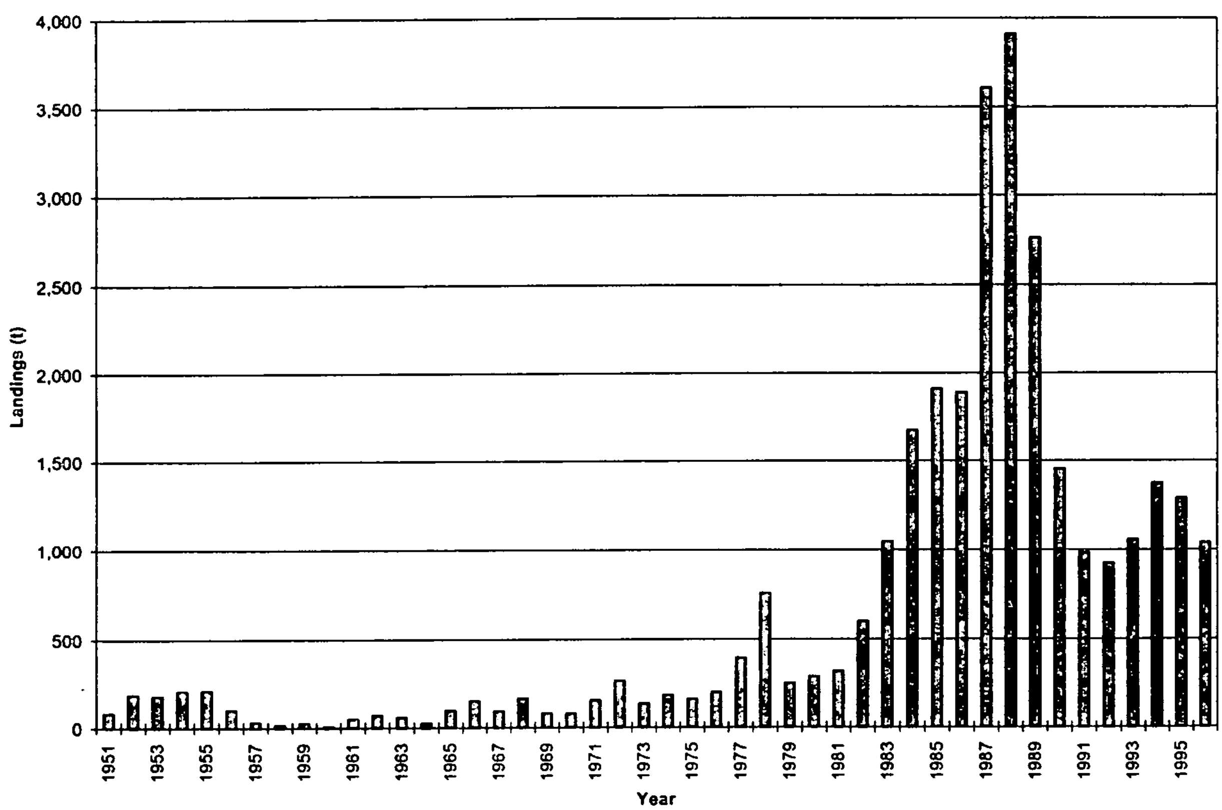

Figure 2. Annual landings of Manila clams in British Columbia, 1951-1996.

1.1.3. Fishery Management

Until recently, intertidal clam fisheries were managed using a minimum size limit, time and area closures and area licensing (Quayle and Bourne 1972; Webb and Marcus 1996). The degree of oversubscription to the clam fishery has led to clam beaches remaining closed to commercial harvest much of the year, except for a small number of closely monitored openings. At industry's request, openings are rotated throughout the various licence areas and throughout the year in an effort to ensure a consistent supply of product to the market. An unfortunate side-effect of this management action is a consistent window of opportunity to move clams into the market from areas that are not open to commercial fisheries. These areas may be closed due to conservation concerns or contamination closures. There are also significant problems of pre-digging and stockpiling product for landing during open periods (R. Webb, DFO Parksville, pers. comm.).

As it became apparent that existing measures were not effective in meeting conservation goals, managers began to closely monitor openings for indications of overharvest of open areas (R. Harbo, DFO, Nanaimo, pers. comm.). Reference limits leading to closure included:

1. increased incidence of sublegal clams in the landed product (beaches were closed if sublegal percentage exceeded 10%);
2. digging in marginal habitats, contaminated areas, or on oyster or clam leases (indicative of depletion of high production areas);
3. decreases in CPUE (digger production per tide) or total effort;
4. increased percentage of littleneck clams in the landings (the fishery is driven by demand for Manila clams, high landings of littlenecks indicates that Manila abundance is decreased); or
5. increased amounts of detritus (sand, mud or rock) in the clam sacks.

Managers' concerns about increased sublegal mortality as a result of repeated digging has also led to limited days open. Openings have been canceled in response to pre-digging of product or removal of product from contaminated areas prior to the commencement of the fishery. Managers track yield from open areas (usually Statistical Areas or clam licence areas) and review closure criteria when yield approaches recent historical levels. Often these yield levels must be adjusted to account for the loss of significant areas to contamination closures. Managers have estimated that this framework results in harvest rates of approximately 60% of the standing legal-sized stock on major beaches (R. Webb, DFO Operations Branch, Parksville, pers. comm.). It has also, however, resulted in very short duration openings, at times less than five open days per year (Webb and Marcus 1996; their Table 2), largely due to high effort levels during each opening.

Quotas have been used in limited situations for management of B.C. intertidal clam fisheries in the past. An annual quota of 100 t was used to control the butter clam fishery at Seal Island from 1942 to 1965 (Neave 1942; Quayle and Bourne 1972; Bourne 1987). The project was discontinued due to problems monitoring landings, and decreased landings and effort.

A quota system was used to manage harvest at Savary Island in Area C between 1978 and 1984 (Bourne and Adkins 1985; Adkins 1992). Quotas were arbitrarily set at 50% of the legal-size stock estimated from annual surveys, with the objective of partitioning the resource between conflicting user groups, not conservation. These measures were discontinued as no biological rationale existed for partitioning the stocks and the cost of establishing and monitoring quotas was prohibitive. After five years of size limit management, Savary Island was closed for conservation reasons during 1990-1993, and managed under a quota when it re-opened in 1994 (Gillespie *et al.* 1995b). The quota was designed to partition the harvest of the legal-size stock over 4 years to buffer a period of poor settlement on the beach.

Under new management policies, specific groups can be allocated individual beaches for harvest. Depuration permits allow certified processing companies exclusive harvest opportunities on beaches which are marginally contaminated by fecal coliform organisms. First Nations groups have been given exclusive harvest allocations for food fishing and communal commercial pilot projects (Bella Bella in the Central Coast; Kulleet Bay, Kuper Island and Squirrel Cove in the Strait of Georgia). The clam fishery in Area C (Sunshine Coast) is a limited entry fishery, thus the beaches are allocated to specific user groups.

The depuration allocation policy includes the requirement for stock assessment and quota-based management. Some beaches are included under a stock assessment program, and are harvested at constant harvest rates (HR's) of 0.25 or 0.50 of stock estimates from annual surveys. Other beaches are assigned long-term total allowable catches (TAC's) derived from baseline stock assessment surveys. TAC's were set at either 25% or 50% of initial legal-sized stock, based on the harvest history of the stock. Those beaches which had been recently harvested before being removed from the conventional commercial fishery (i.e., were already fished down) were considered to be supported primarily by annual recruitment. TAC's for these beaches were set at 50% of initial legal-sized stock. Beaches which had not been fished for at least 2 years, and which had accumulated legal-sized stock were assumed to be unable to sustain the 50% TAC as they were fished down. These beaches were set at 25% of initial legal-sized stock. In either case, these harvest rates were considered to be conservative, relative to the 60% harvest rate estimated in conventional commercial fisheries managed with size limits and fishery-based closure criteria.

1.2. WASHINGTON STATE CLAM MANAGEMENT

Commercial and recreational clam fisheries in Puget Sound and Hood Canal, Washington, are managed with allowable catches derived from survey estimates (Campbell 1996). The Washington State framework derives quotas from stock assessment surveys using a deterministic model. A survey is used to estimate legal and sublegal stock sizes and biological parameters related to growth and recruitment. These parameters are used to set harvest rates which would deplete the standing legal stock and one year's recruitment (essentially those clams detected by the survey) in four years of harvest. However, surveys are conducted annually, and the parameters and harvest rates reset.

2. Methods

2.1. SURVEY DATA

Population characteristics estimated from intertidal clam surveys include:

1. population size, both in numbers and weight, by legal and sublegal size categories, and their associated confidence intervals;
2. age and length frequencies;
3. mean weight of clams by size class; and
4. von Bertalanffy growth parameters (K, t_0 and L_∞), which are used to estimate the age of recruitment to the fishery.

In addition, annual mortality for age classes which are fully recruited to the fishery, and the age class which will recruit in the subsequent year, are estimated (see Section 2.3.1).

2.2. SURVEY METHODS

The surveys at Kulleet Bay, Kuper Island and Squirrel Cove followed the methodology used in Gillespie *et al.* (1995a). In general, survey design involved placement of survey grids (analyzed as strata) over beds of clams which were considered to be harvestable concentrations. The surveys and laboratory processing were completed by Fisheries Guardians and Technicians representing each of the First Nations groups participating in the co-management agreements. We selected 4 populations for evaluation: Inner Kulleet Bay, North Shore Kuper Island, Lamalchi Bay and Squirrel Cove Beach 1.

Inner Kulleet Bay is a wide bay on the north shore of Coffin Point, Vancouver Island, near Ladysmith. North Shore Kuper Island is a narrow beach which extends from Clam Bay westward towards Josling Point. Lamalchi Bay is a protected bay on the south side of Kuper Island, which opens on Stuart Channel. Squirrel Cove Beach 1 is a small beach in Inner Squirrel Cove, Cortes Island.

Laboratory methods follow Gillespie *et al.* (1995b) for biomass and biological sampling of survey collections.

2.3. ANALYTICAL METHODS

2.3.1. Population Characteristics

Analytical methods are derived from Gillespie *et al.* (1995b) and Kronlund *et al.* (1995). Mean density of clams (#/m^2) and mean biomass (kg/m^2) and their associated variances were calculated by species in legal and sublegal size categories from each stratum at each site. These estimates (expressed as either numbers of clams or biomass) were calculated using the modified bootstrap methods outlined in Kronlund *et al.* (1995). Naive bootstrap estimators were used for single stratum designs (*e.g.* Squirrel Cove). Bootstrap estimators modified using the methods of Rao and Wu (1988) and Sitter (1992) were used for stratified designs (*fide* Kronlund *et al.* 1995).

Length and age frequencies were collated from total length and age data, and plotted in S-Plus (StatSci 1995). These frequencies were used to determine the proportion of imminent recruits from the sublegal portion of the population (Section 2.3.2.).

Growth parameters were estimated using the nonlinear least squares fitting routine **nls** in S-Plus (StatSci 1995) to fit length-at-annulus data to the von Bertalanffy growth equation:

$$L_t = L_\infty(1 - e^{-K(t-t_0)}) \tag{1}$$

where L_∞ is the theoretical mean length of the oldest age group (asymptotic length), L_t is length at time t, K is the Brody growth coefficient, and t_0 is the theoretical time at which length equals 0. Length-at-annulus data are preferable to age and length data for estimating growth parameters. The lengths are assigned to the annular marks in the first case, and the latter measurements are often rendered imprecise by inclusion of summer growth since annulus formation (Gillespie *et al.* 1995b).

Age of recruitment to the fishery was calculated as:

$$t = t_0 - (1/K)\log_e(1 - (L_t/L_\infty)) \tag{2}$$

where t_0, K and L_∞ are the estimated growth parameters of the von Bertalanffy equation, and L_t is set to 38 mm.

Natural mortality rates were estimated using Hoenig's (1983) algorithm which estimates total mortality (Z) from the maximum age recorded for the species (T_{max}):

$$\log_e(Z) = a + b(\log_e(T_{\max})). \tag{3}$$

We used his slope and intercept values for molluscs (b = -0.832, a = 1.23) and a maximum observed age of 14 years (Bourne 1987) for Manila clams. It is assumed that Z approaches M when T_{max} is the maximum age of the species, not the maximum age detected in the survey.

The recruitment history of the stock was subjectively evaluated by examining the age frequency plots and comparing relative strengths of year classes. We arbitrarily classified upcoming recruitment as high, medium, or low, based on the density of clams per square meter that would recruit to legal size within the next year. Stocks where pre-recruits were found in densities less than 30 per m^2 were designated as having low recruitment, those with densities from 30 to 70 pre-recruits per m^2 were said to have medium recruitment, and those with densities greater than 70 pre-recruits per m^2 were said to have high recruitment. Based on these criteria, 2 of the 4 stocks considered here are high recruitment stocks, one is medium, and one is a low recruitment stock.

2.3.2. WDFW Harvest Model

We adapted the harvest rate calculations developed by the Washington State Department of Fish and Wildlife (WDFW) (Campbell 1996). The algorithm is based on partitioning the initial legal stock, plus one year's recruitment, over four years of harvest.

The harvest rate is derived by an iterative deterministic method which proceeds as follows:

1. In the survey year, t, estimates of legal-size and pre-recruit populations are established.
2. In subsequent years, the legal-sized stock is reduced by harvest and natural mortality. In the first year's iteration ($t + 1$) only, the legal-sized stock is increased by the contribution of the pre-recruit stock from year t, likewise reduced by one year's natural mortality.

Thus:

$$\tau_{L(t+1)} = \left(\tau_{L(t)} - u(\tau_{L(t)})\right) - v\left(\tau_{L(t)} - u(\tau_{L(t)})\right) + \left(p_R \tau_{S(t)} - v(p_R \tau_{S(t)})\right) \quad (4)$$

$$\tau_{L(t+2)} = \left(\tau_{L(t+1)} - u(\tau_{L(t+1)})\right) - v\left(\tau_{L(t+1)} - u(\tau_{L(t+1)})\right) \quad (5)$$

$$\tau_{L(t+3)} = \left(\tau_{L(t+2)} - u(\tau_{L(t+2)})\right) - v\left(\tau_{L(t+2)} - u(\tau_{L(t+2)})\right) \quad (6)$$

$$\tau_{L(t+4)} = (\tau_{L(t+3)} - u(\tau_{L(t+3)})) - v(\tau_{L(t+3)} - u(\tau_{L(t+3)})) \quad (7)$$

where u is the annual rate of fishing mortality, v is the annual rate of natural mortality, $\tau_{L(t)}$ is the estimate of legal-sized population (# clams) in year t, $\tau_{S(t)}$ is the estimate of sublegal-sized population (# clams) in year t and p_R is the proportion of the sublegal population which will recruit to legal size in year t+1, based on age frequencies and age of recruitment to the fishery (Section 2.4.2 and Equation 3 above). Since the portion of the available population which is harvested is not subject to natural mortality, the mortality rate is applied to the remaining population after the harvest has been subtracted. Notation used by Campbell (1996) for annual harvest and natural mortality rates has been changed here to that used by Ricker (1975).

The WDFW uses a deterministic approximation of the iterative approach (Campbell 1996) to establish the first year harvest rate. The specific case for an age of recruitment of 3 years is:

$$F = \frac{S^3}{p(S^3 + S^2 + S + 1)} \quad (8)$$

where F is the harvest rate, p is the proportion of clams recruited to legal size plus clams one year removed from recruitment to legal size, and S is the annual survival rate of these age classes. The proportion of pre-recruit clams was calculated from the estimated population of sublegal-sized clams, the age of recruitment, and the age frequency sample for the stock, and this estimate is added to the survey estimate of legal-sized clams. Thus, again for an age of recruitment of 3 years:

$$p = \frac{(\tau_L) + ((n_2/(n_1 + n_2))(\tau_S))}{(\tau_L + \tau_S)} \tag{9}$$

where τ_L is the estimate of legal-size population in numbers, τ_S is the estimate of sublegal-size population in numbers, and the n's are numbers at age from the age frequency sample. The annual survival rate was calculated as:

$$S = e^{-Z} \tag{10}$$

where Z is the instantaneous rate of natural mortality.

A spreadsheet for the iterative approach described above was constructed. When the critical biological parameters had been input, the harvest rate was adjusted to satisfy the objective of removal of all legal-size clams plus one year's recruitment in 4 years of harvest.

The potential yield for year t (Y_t) expressed as weight (kg), was calculated as:

$$Y_t = F((\overline{W}_L)(\tau_{L(t)})) \tag{11}$$

where F is the harvest rate, $\overline{W}_L$ is the mean weight of a legal-sized clam from the stock (in kg), and $\tau_{L(t)}$ is the estimated legal-size population on the stock in year t.

The method assumes that:

1. age frequencies and estimated growth parameters are representative of the entire population on the beach;
2. natural mortality occurs only after harvest;
3. mortality rates are equal for all age classes involved;
4. the pre-recruit age class is fully represented in survey samples (survey methods are not size selective); and
5. mean weight of a legal-size clam does not change over the three years of harvest (there is no growth component included in the model).

Our method differs from the WDFW method in that age class strength is assessed directly by ageing samples from the survey, not through the use of an age-length key. Our method calculates the age of recruitment to legal size from the estimated parameters of the von Bertalanffy growth equation, and thus considers different growth characteristics of each stock assessed. Using length-based estimates of age can lead to erroneous assumptions regarding the rate of recruitment in populations where poor growth results in stunting of a large proportion of the population. Most stunted clams would not reach legal size, but are assumed by the WDFW method to grow to legal size in approximately 3 years.

The method responds to various levels of impending recruitment in the following fashion. The harvest rate increases as the ratio of pre-recruited to recruited individuals increases (Table 2). As the ratio of potential recruits to those animals affected by the fishery increases, the fishery is allowed to remove more legal-sized clams, as they will be replenished relatively rapidly. In the case where most of the legal-sized stock has been removed by harvest previous to the assessment, the harvest rate will be relatively high, due to the promise of impending recruitment to legal-size of a large portion of the sublegal-sized stock. However, since the harvest (in terms of numbers of clams) is set in the first year *and remains constant throughout the assessment iteration*, the yield options will be relatively low over the four years of harvest. In the case where the stock on the beach is predominantly of legal-size, as in a period of successive poor settlement years, the harvest rate is low, and the stock is conserved over the four year harvest period. It is vitally important that the survey accurately assess the sublegal portion of the stock, as the ratio of legal to sublegal-size proportions of the population is critical in the determination of harvest rates.

Table 2. WDFW harvest rates predicted for various levels of p with $M = 0.32$ and an age of recruitment of 3 years.

P	Harvest Rate	p	Harvest Rate
0.1	1.28	0.6	0.21
0.2	0.64	0.7	0.18
0.3	0.43	0.8	0.16
0.4	0.32	0.9	0.14
0.5	0.26	1.0	0.13

2.3.3. Baranov Harvest Models

One drawback of the WDFW model is the use of annual mortality rates, and the required decision whether to apply natural mortality before or after the fishing mortality has been calculated. Thus, we evaluated the harvests recommended by the WDFW model for each population using instantaneous rates and Baranov equations for a Type 2 fishery, i.e., a fishery in which fishing and natural mortality operate concurrently (Ricker 1975). As well, each population was modeled at constant harvest rates of 25, 50, 60 and 70% of the available legal-size stock, to simulate harvest rates currently set in depuration fisheries and estimated harvest rates from fisheries governed only by the size limit. The range of harvest limits reflect uncertainty in the actual exploitation of the legal-size stock in non-quota size limit fisheries. It is believed that the actual harvest rate for such fisheries falls between 50% and 70% of the legal-size population. Lastly, each population was modeled with a constant total allowable catch (TAC) of 25% and 50% of the first year stock size (i.e. harvests were set at 25% or 50% of the legal-size stock in the survey year, and then remained constant over the four year period modeled).

A harvest in any particular year is related to values for the estimated legal-sized population in that year, the rate of natural mortality, and the rate of fishing mortality in the equation below :

$$h_i = \frac{(\tau_{L(i)})\,(F_i)\,(1 - e^{-(M+F_i)})}{M + F_i} \qquad (12)$$

where h_i is the harvest in year i, $\tau_{L(i)}$ is the estimate of legal-sized population (# clams) in year i, F_i is the rate of fishing mortality in year i, and M is the rate of natural mortality.

The three types of instantaneous models we used (to simulate the WDFW harvests, to simulate a size limit fishery with constant harvest rates, and to simulate a constant TAC of 0.25 or 0.50 of initial stock size) differed in their choice of harvest size. Each began with values for h_i, M, and $\tau_{L(i)}$ (see Equation 12 above). In order to obtain a value for F_i, we solved equation (12) for F_i, for years i = t, t+1, t+2, and t+3. As this is impossible to do algebraically, the equation was solved numerically.

Population was calculated using the numerically estimated values for F_i as follows:

$$\tau_{L(t+1)} = ((\tau_{L(t)})e^{-(M+F_t)}) + ((p_R \tau_{S(t)})e^{-M}) \tag{13}$$

$$\tau_{L(t+2)} = \tau_{L(t+1)} e^{-(M+F_{t+1})} \tag{14}$$

$$\tau_{L(t+3)} = \tau_{L(t+2)} e^{-(M+F_{t+2})} \tag{15}$$

$$\tau_{L(t+4)} = \tau_{L(t+3)} e^{-(M+F_{t+3})} \tag{16}$$

where $\tau_{L(t)}$ is the estimate of legal-sized population (# clams) in year t, M is the rate of natural mortality, F_i is the rate of fishing mortality in year i, p_R is the proportion of the sub-legal population which will recruit to legal size in year t+1, and $\tau_{S(t)}$ is the estimate of sublegal-sized population (# clams) in year t. Note that unlike the WDFW model, where the mortality rate is applied to the stock after the estimated harvest has been removed, here natural mortality and fishing mortality rates are applied at the same time.

When using an instantaneous model and WDFW harvests, it is likely that the pre-set values for the harvest may exceed the stock size estimate for a particular year, especially year t+3. When such an event occurred, the harvest for that year was limited by the available stock.

Our instantaneous models assume that :

1. age frequencies and estimated growth parameters are representative of the entire population on the beach;
2. natural mortality remains constant over the three years of harvest;
3. the pre-recruit age class is fully represented in the survey samples (survey methods are not size-selective);
4. mean weight of a legal-size clam does not change over the three years of harvest; and
5. natural mortality and fishing mortality operate concurrently.

Each of the models discussed above involves only a portion of the actual population on the beach, as recruitment is factored into the models for only a single year. Because of size selectivity of survey methods and an incomplete understanding of age-specific mortality rates, we cannot predict recruitment from the survey results beyond a single year.

To examine the results of the above models with the entire population, we assumed a constant level of recruitment over the four years. Methods were identical to those described above, except that stock size was increased by recruits for every year of the simulation, not just in the first year. Stock size was estimated as follows:

$$\tau_{L(t+1)} = ((\tau_{L(t)})e^{-(M+F_t)}) + ((p_R \tau_{S(t)})e^{-M}) \tag{18}$$

$$\tau_{L(t+2)} = ((\tau_{L(t+1)})e^{-(M+F_{t+1})}) + ((p_R \tau_{S(t)})e^{-M}) \tag{19}$$

$$\tau_{L(t+3)} = ((\tau_{L(t+2)})e^{-(M+F_{t+2})}) + ((p_R \tau_{S(t)})e^{-M}) \tag{20}$$

$$\tau_{L(t+4)} = ((\tau_{L(t+3)})e^{-(M+F_{t+3})}) + ((p_R \tau_{S(t)})e^{-M}) \tag{21}$$

where $\tau_{L(t)}$ is the estimate of legal-sized population (# clams) in year t, M is the rate of natural mortality, F_i is the rate of fishing mortality in year i, p_R is the proportion of the sub-legal population which will recruit to legal size in year t+1, and $\tau_{S(t)}$ is the estimate of sublegal-sized population (# clams) in year t.

3. Results

On the four stocks examined here, densities of harvestable Manila clams ranged from 23.92 to 64.56 per m^2 (Table 3). This range is similar to that observed on Savary Island during 1987 to 1995, where densities ranging from 6 to 79.1 legal-size clams per m^2 were recorded (Gillespie *et al.* 1995b). Densities of pre-recruit clams on the beaches under study varied similarly, from 4.75 per m^2 on the north shore of Kuper Island to 96.97 per m^2 at Inner Kulleet Bay. Stocks were classified as high, medium or low recruitment based on pre-recruit density (Table 3).

3.1. Inner Kulleet Bay

3.1.1. Survey Results

Seventy-one quadrats were sampled in Inner Kulleet Bay, representing 6 strata totaling 26.6 ha of clam-bearing area (Table 4). The beach supported approximately 21 t (95% confidence limits of 16.2 and 25.9 t) of legal-sized Manila clams, which is less than one t per hectare. The sublegal portion had approximately three times as many clams as the legal portion. Truncation of the age frequency after 6 years and length frequency after 42 mm (Figure 3), Z_{5+} of 1.06 and relatively low mean weight for legal-sized clams are indicative of regular harvest reducing the legal portion of the population. The lack of 2-year-olds in the samples may indicate poor upcoming recruitment, or small clams may have been missed during collection of the survey samples. Growth analyses estimate L_∞ at 49.25 mm, and an age of recruitment of approximately 5 years. Manila clams in Inner Kulleet Bay grow somewhat slower than other populations in the Strait of

Georgia (Bourne 1982), but are not particularly stunted. The density of pre-recruits was 96.97 per m^2, and upcoming recruitment was designated high (Table 3). The relatively high proportion of sublegal clams to legal clams in Inner Kulleet Bay implies that good recruitment will support current fishery production in the short term, and the calculated WDFW harvest rate of 0.41 reflects this.

Table 3. Summary of initial densities of harvestable and pre-recruit Manila clams and recruitment classification from the examples.

Stock	Density of Legals (# clams/m^2)	Density of Pre-Recruits (# clams/m^2)	Recruitment Classification
Inner Kulleet Bay	44.32	96.97	high
Lamalchi Bay	37.12	83.86	high
Squirrel Cove Beach 1	64.56	39.44	medium
North Shore Kuper Is.	23.92	4.75	low

3.1.2. Model Results

Simulations which modeled natural and fishing mortality concurrently using WDFW harvests resulted in a slight decrease in yield (6.6%), as the interaction of natural and fishing mortalities reduced the stock more rapidly than the annual rate model predicted (Table 5). By the fourth year, the stock was unable to support the harvest recommended by the WDFW model.

Not surprisingly, the models with high constant harvest rates resulted in greater yield, and reduced the legal biomass more rapidly than the WDFW model. Yield increased relative to the WDFW model between 4.9% (0.5 HR) and 23.6% (0.7 HR) at Inner Kulleet Bay (Table 5). Instantaneous rates of fishing mortality (*F*) required to achieve these harvest rates were exceedingly high - up to four times the estimated natural mortality rate (*M*). The model with a 0.25 HR showed a yield decrease to 67.1% of the WDFW model.

Stock size increased in year 2 due to relatively high recruitment, but virtually all of the initial stock was depleted after four years. Under size limit models, stock size was reduced to 4.0% of its original size (0.5 HR) or virtually removed (0.7 HR) after four years (Table 5). The 0.25 HR left 21.8% of the initial population on the beach after four years.

The 25% TAC model shows 19.4% of the stock remaining after four years (Table 5). Yield decreased to 61.3% of that predicted by the WDFW model, not surprising since the WDFW model uses a harvest rate considerably greater than 0.25. The 50% TAC model predicts that the stock will be completely removed in the four year period, with incomplete harvest in the fourth year, with a slight increase in yield (by 1.3%) over the WDFW model.

At Inner Kulleet Bay, where a single year's recruitment exceeds the initial legal population, all models show increasing population size when simulated using constant recruitment (Table 6). Simulations of a size limit fishery show increases that range from 172.8% (0.7 HR) to 207.9%

(0.5 HR). The constant TAC models show increases to 340.3% (25% TAC) and 290.6% (50% TAC) of the initial stock size. Yield in most cases is increased over the WDFW model. Size limit simulations show a yield increase of 109.5% (0.5 HR) to 160.5% (0.7 HR). The 25% TAC model shows yield 61.3% of that of the WDFW model, while the 50% TAC model shows a yield increase of 22.6%. Obviously, consistent good recruitment increases both yield and stock size.

Table 4. Stock size and parameter estimates from the 1995 Inner Kulleet Bay clam survey. 95% confidence limits in brackets.

Parameter/Estimate	Value
Survey Area (m^2)	26,600
Number of Quadrats	71
Mean Legal Density (clams/m^2)	44.32 (34.16; 54.72)
Mean Sublegal Density (clams/m^2)	133.56 (87.48; 186.40)
Total Legal Population (clams x 10^3)	1,179 (923; 1,440)
Total Sublegal Population (clams x 10^3)	3,553 (2,175; 4,988)
Mean Legal Biomass (kg/m^2)	0.78 (0.61; 0.96)
Mean Sublegal Biomass (kg/m^2)	1.28 (0.84; 1.75)
Total Legal Biomass (kg)	20,796 (16,162; 25,874)
Total Sublegal Biomass (kg)	33,976 (21,986; 46,825)
K	0.29
L_∞	49.25
t_0	0.19
Age of Recruitment (y)	5.26
Recruit Age Class	5
Z_{5+}	1.06
Mean Weight (g/legal clam)	17.69
WDFW Harvest Rate	0.41

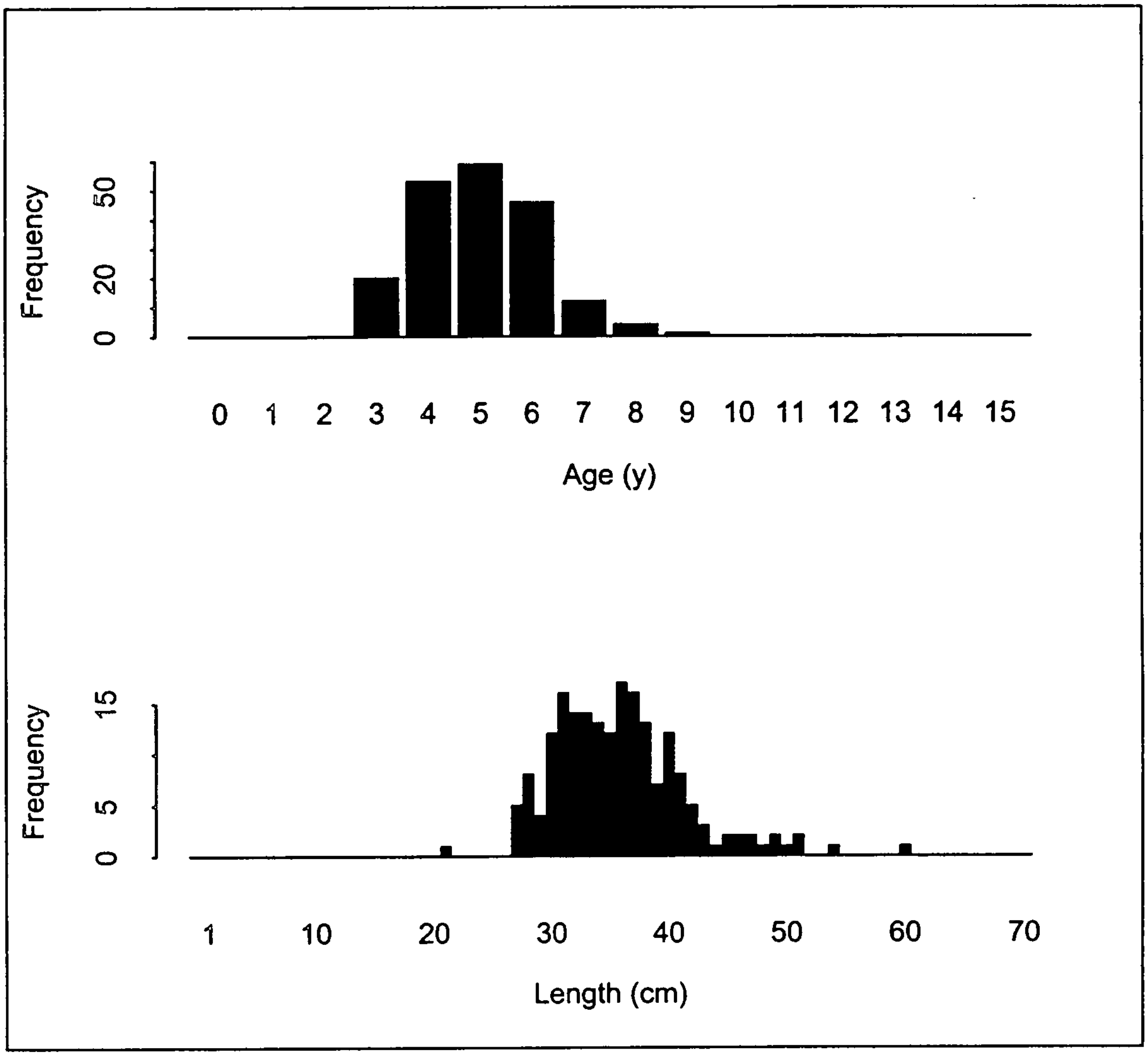

Figure 3. Age and length frequencies of Manila clams from the 1995 Inner Kulleet Bay clam survey.

Table 5. Harvest simulations for Inner Kulleet Bay.

	Stock Size at End of Year				
Model	Initial Size	Year 1	Year 2	Year 3	Year 4
WDFW (HR = 0.41)	1,179,000	2,228,729	1,188,434	481,033	1
WDFW (Inst.)	1,179,000	2,180,587	1,098,309	363,958	1
0.25 HR	1,179,000	2,328,294	1,117,713	536,565	257,582
0.50 HR	1,179,000	2,096,498	594,256	168,443	47,746
0.60 HR	1,179,000	2,007,389	417,280	86,741	18,031
0.70 HR	1,179,000	1,921,823	260,017	35,180	4,760
25% TAC	1,179,000	2,328,294	1,349,736	682,243	229,239
50% TAC	1,179,000	2,096,498	954,118	185,727	1

	Harvest (kg)					
Model	Year 1	Year 2	Year 3	Year 4	Total	% WDFW
WDFW (HR = 0.41)	8,509	8,509	8,509	8,509	34,036	100.0%
WDFW (Inst.)	8,509	8,509	8,509	6,247	31,774	93.4%
0.25 HR	5,214	10,297	4,943	2,373	22,827	67.1%
0.50 HR	10,428	18,544	5,256	1,490	35,718	104.9%
0.60 HR	12,514	21,306	4,429	921	39,170	115.1%
0.70 HR	14,600	23,798	3,220	436	42,054	123.6%
25% TAC	5,214	5,214	5,214	5,214	20,856	61.3%
50% TAC	10,428	10,428	10,428	3,182	34,466	101.3%

Table 6. Harvest simulations for Inner Kulleet Bay with constant recruitment.

	Stock Size at End of Year				
Model	Initial Size	Year 1	Year 2	Year 3	Year 4
WDFW (HR = 0.41)	1,179,000	2,228,729	2,942,544	3,427,938	3,758,007
WDFW (Inst.)	1,179,000	2,180,587	2,860,617	3,324,205	3,640,495
0.25 HR	1,179,000	2,328,294	2,880,021	3,144,880	3,272,028
0.50 HR	1,179,000	2,096,498	2,356,564	2,430,281	2,451,176
0.60 HR	1,179,000	2,007,389	2,179,588	2,215,383	2,222,824
0.70 HR	1,179,000	1,921,823	2,022,325	2,035,923	2,037,763
25% TAC	1,179,000	2,328,294	3,112,044	3,647,151	4,012,583
50% TAC	1,179,000	2,096,498	2,716,426	3,138,343	3,425,903

	Harvest (kg)					
Model	Year 1	Year 2	Year 3	Year 4	Total	% WDFW
WDFW (HR = 0.41)	8,509	8,509	8,509	8,509	34,036	100.0%
WDFW (Inst.)	8,509	8,509	8,509	8,509	34,036	100.0%
0.25 HR	5,214	10,297	12,737	13,908	42,156	123.9%
0.50 HR	10,428	18,544	20,844	21,496	71,312	209.5%
0.60 HR	12,514	21,306	23,134	23,514	80,468	236.4%
0.70 HR	14,600	23,798	25,042	25,211	88,651	260.5%
25% TAC	5,214	5,214	5,214	5,214	20,856	61.3%
50% TAC	10,428	10,428	10,428	10,428	41,712	122.6%

3.2. NORTH SHORE KUPER ISLAND

3.2.1. Survey Results

One hundred eighty-six samples were collected from 17 strata totaling 36.7 ha of clam-bearing area on the north shore of Kuper Island (Table 7). The beach supported approximately 24 t (95% confidence limits of 20.1 and 28.7 t) of legal-size Manila clams, less than one t per hectare. The sublegal portion of the stock is small relative to the legal portion. The age frequency exhibits a gradual decrease from a peak at 5 years, Z_{5+} is 0.39, the length frequency has good representation of size classes greater than 40 mm (Figure 4), and mean size of a legal clam is 29.11 g, all indications of low exploitation rates in the recent past. Growth analyses estimate L_∞ at 61.31 mm and age of recruitment at less than 4 years. While growth, size and age characteristics of the population indicate a lightly harvested stock, the low density of clams argues that this may not be a particularly productive beach. The density of pre-recruits was 4.75 per m^2, and upcoming recruitment was designated low (Table 3). The relatively small sublegal stock is reflected in the low calculated WDFW harvest rate of 0.15.

Table 7. Stock size and parameter estimates from the 1995 North Shore Kuper Island clam survey. 95% confidence limits in brackets.

Parameter/Estimate	Value
Survey Area (m^2)	36,675
Number of Quadrats	186
Mean Legal Density (clams/m^2)	23.92 (19.40; 28.76)
Mean Sublegal Density (clams/m^2)	5.48 (3.88; 7.28)
Total Legal Population (clams x 10^3)	824 (644; 999)
Total Sublegal Population (clams x 10^3)	188 (125; 248)
Mean Legal Biomass (kg/m^2)	0.70 (0.58; 0.84)
Mean Sublegal Biomass (kg/m^2)	0.06 (0.04; 0.07)
Total Legal Biomass (kg)	24,224 (20,138; 28,657)
Total Sublegal Biomass (kg)	1,897 (1,343; 2,501)
K	0.27
L_∞	61.31
t_0	0.27
Age of Recruitment (y)	3.85
Recruit Age Class	4
Z_{5+}	0.39
Mean Weight (g/legal clam)	29.11
WDFW Harvest Rate	0.15

3.2.2. Model Results

Baranov simulations of harvests recommended by the WDFW model showed a slight decrease in yield over the four years (6.8%), as the concurrent operation of natural mortality and harvest reduced the stock more quickly than the annual rate model (Table 8). By the fourth year the stock was unable to support the recommended harvest level.

Constant harvest rate models generally resulted in greater yield from the stocks, and reduced the legal biomass more rapidly (Table 8). Yield relative to the WDFW model increased between 28.1% (0.5 HR) to 49.8% (0.7 HR). The 0.25 HR yielded only 83.7% of predicted WDFW harvests.

Stock size consistently decreased, as poor recruitment in the second year did not replace the harvested animals, and after four years, the initial stock was almost completely depleted. Size limit models reduced the initial stock to 1.0% at 0.5 HR , and removed the entire stock at 0.7 HR after 4 years of harvest. The 0.25 HR model reduced the initial stock to 6.8% of the initial size after 4 years.

The 25% TAC model shows a yield increase of 16.2% over the WDFW model, but the entire population is removed after three years (Table 8). The 50% TAC shows a greater yield (47.8%) but predicts that the stock will be completely removed after two years.

All models showed decreasing stock size when simulated using constant recruitment (Table 9). Size limit models showed yield increases from 53.3% to 82.8% over the constant recruitment WDFW model, while the 0.25 HR managed yield 97.4% of the WDFW model. Constant TAC models showed yield increases of 51.0% and 90.5% over the WDFW model. However, the 25% TAC model predicts insufficient stock in the fourth year to maintain the harvest level, while the 50% model predicts insufficient stock in year two.

Table 8. Harvest simulations for North Shore Kuper Island.

Stock Size at End of Year					
Model	Initial Size	Year 1	Year 2	Year 3	Year 4
WDFW (HR = 0.15)	824,000	585,343	312,136	126,356	25
WDFW (Inst.)	824,000	571,258	287,487	94,951	1
0.25 HR	824,000	507,005	243,391	116,841	56,090
0.50 HR	824,000	345,003	97,792	27,719	7,857
0.60 HR	824,000	282,725	58,771	12,217	2,540
0.70 HR	824,000	222,923	30,161	4,081	552
25% TAC	824,000	507,005	180,544	1	0
50% TAC	824,000	345,003	1	0	0

Harvest (kg)						
Model	Year 1	Year 2	Year 3	Year 4	Total	% WDFW
WDFW (HR = 0.15)	3,677	3,677	3,677	3,677	14,708	100.0%
WDFW (Inst.)	3,677	3,677	3,677	2,672	13,703	93.2%
0.25 HR	5,997	3,690	1,771	850	12,308	83.7%
0.50 HR	11,993	5,022	1,423	403	18,841	128.1%
0.60 HR	14,392	4,938	1,026	213	20,569	139.8%
0.70 HR	16,791	4,543	615	83	22,032	149.8%
25% TAC	5,997	5,997	5,090	0	17,084	116.2%
50% TAC	11,993	9,743	0	0	21,736	147.8%

Table 9. Harvest simulations for North Shore Kuper Island with constant recruitment.

	Stock Size at End of Year				
Model	Initial Size	Year 1	Year 2	Year 3	Year 4
WDFW (HR = 0.15)	824,000	585,343	423,056	312,701	237,660
WDFW (Inst.)	824,000	571,258	398,925	281,718	202,514
Constant 0.25 HR	824,000	507,005	354,829	281,776	246,707
Constant 0.50 HR	824,000	345,003	209,230	170,745	159,836
Constant 0.60 HR	824,000	282,725	170,209	146,820	141,958
Constant 0.70 HR	824,000	222,923	141,599	130,596	129,108
Constant 25% TAC	824,000	507,005	291,982	149,808	111,439
Constant 50% TAC	824,000	345,003	111,439	111,439	111,439
	Harvest (kg)				
Model	Year 1	Year 2	Year 3	Year 4	Total	% WDFW
WDFW (HR = 0.15)	3,677	3,677	3,677	3,677	14,708	100.0%
WDFW (Inst.)	3,677	3,677	3,677	3,677	14,708	100.0%
Constant 0.25 HR	5,997	3,690	2,582	2,051	14,320	97.4%
Constant 0.50 HR	11,993	5,022	3,045	2,485	22,545	153.3%
Constant 0.60 HR	14,392	4,938	2,973	2,564	24,867	169.1%
Constant 0.70 HR	16,791	4,543	2,885	2,661	26,880	182.8%
Constant 25% TAC	5,997	5,997	5,997	4,221	22,212	151.0%
Constant 50% TAC	11,993	9,743	3,138	3,138	28,012	190.5%

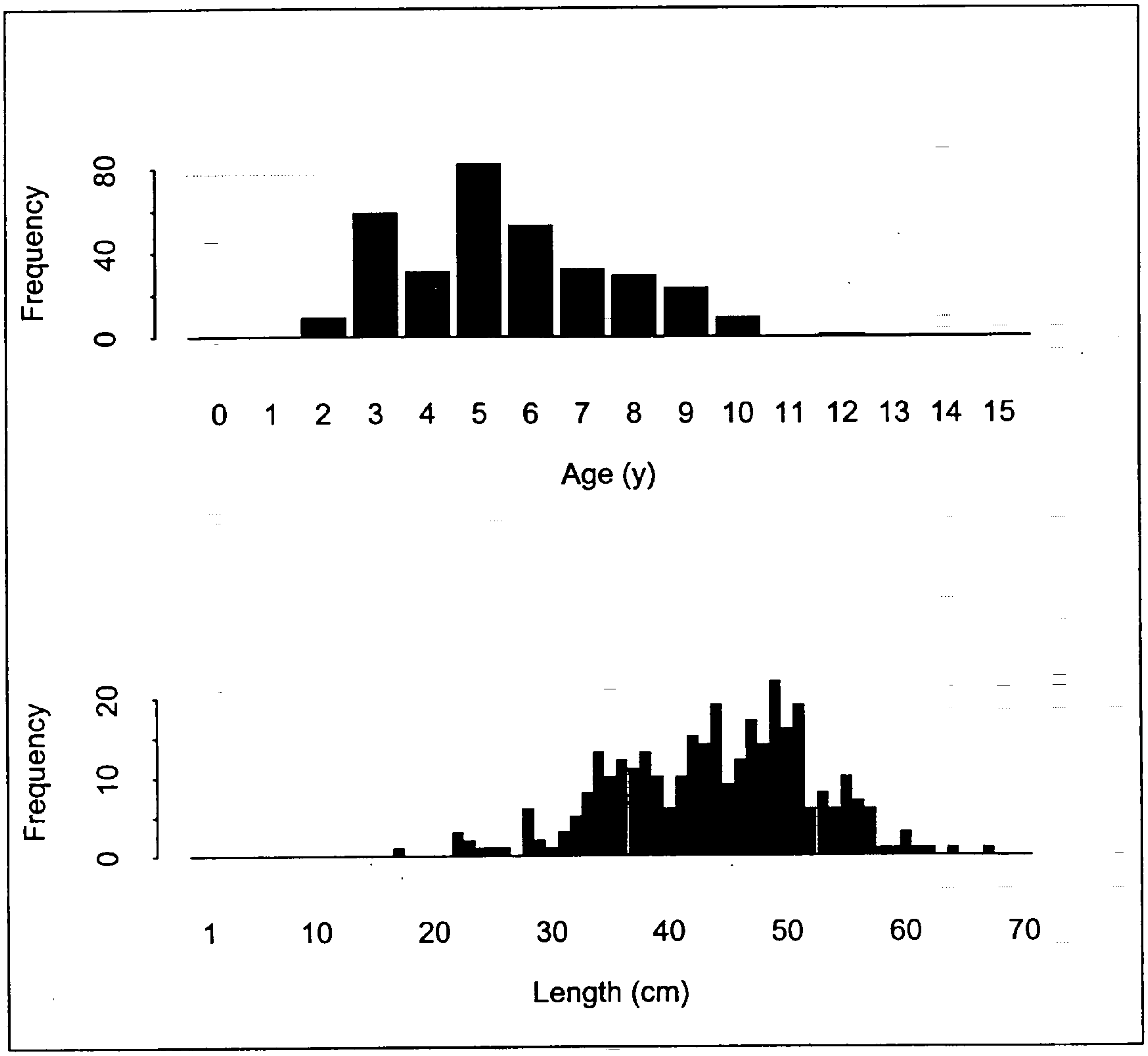

Figure 4. Age and length frequencies of Manila clams from the 1995 North Shore Kuper Island clam survey.

3.3. LAMALCHI BAY

3.3.1. Survey Results

Eighty-eight samples from 5 strata totaling 20.1 ha of clam-bearing area were collected from Lamalchi Bay (Table 10). Lamalchi Bay supports approximately 15 t (95% confidence limits of 12.0 and 18.8 t) of legal-size Manila clams, less than one t per hectare. The legal portion of the stock is small relative to the sublegal portion. The age frequency is truncated sharply at 5 years, Z_{5+} is 1.35, the length frequency still exhibits individuals in the 50-60 mm size classes (Figure 5), and mean weight of a legal clam is low at 20.80 g, all indications of regular exploitation. Growth analyses estimate L_∞ at 62.44 mm and age of recruitment at 3.51 years. Assessment indicates that this stock is heavily exploited, but exhibits healthy growth characteristics. The density of pre-recruits was 83.86 per m^2, and upcoming recruitment was designated high (Table 3). The heavily exploited stock in Lamalchi Bay has a large sublegal stock and good growth characteristics to support the fishery in the short term, thus the calculated WDFW harvest rate is 0.42.

Table 10. Stock size and parameter estimates from the 1995 Lamalchi Bay clam survey. 95% confidence limits are in brackets.

Parameter/Estimate	Value
Survey Area (m^2)	20,125
Number of Quadrats	88
Mean Legal Density (clams/m^2)	37.12 (28.24; 47.08)
Mean Sublegal Density (clams/m^2)	109.88 (82.44; 141.64)
Total Legal Population (clams x 10^3)	745 (546; 948)
Total Sublegal Population (clams x 10^3)	2,246 (1,661; 2,924)
Mean Legal Biomass (kg/m^2)	0.75 (0.58; 0.93)
Mean Sublegal Biomass (kg/m^2)	0.96 (0.70; 1.24)
Total Legal Biomass (kg)	15,211 (12,002; 18,877)
Total Sublegal Biomass (kg)	19,102 (14,123; 24,967)
K	0.29
L_∞	62.44
t_0	0.33
Age of Recruitment (y)	3.51
Recruit Age Class	4
Z_{5+}	1.35
Mean Weight (g/legal clam)	20.80
WDFW Harvest Rate	0.42

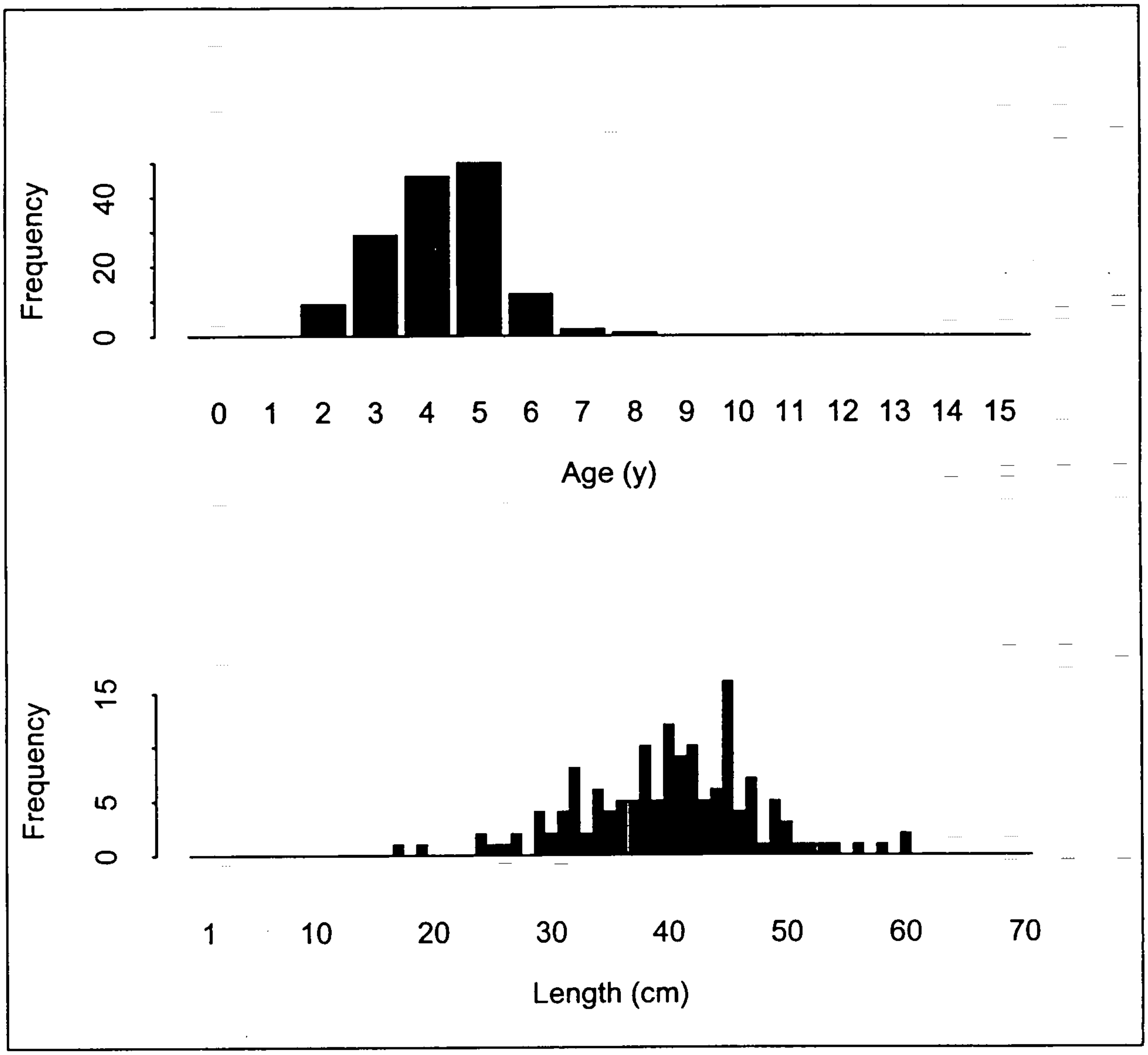

Figure 5. Age and length frequencies of Manila clams from the 1995 Lamalchi Bay clam survey.

Table 11. Harvest simulations for Lamalchi Bay.

Stock Size at End of Year					
Model	Initial Size	Year 1	Year 2	Year 3	Year 4
WDFW (HR = 0.42)	745,000	1,458,168	777,566	314,757	47
WDFW (Inst.)	745,000	1,426,924	718,778	238,282	1
0.25 HR	745,000	1,528,645	733,836	352,283	169,116
0.50 HR	745,000	1,382,175	391,780	111,051	31,478
0.60 HR	745,000	1,325,868	275,611	57,292	11,909
0.70 HR	745,000	1,271,799	172,071	23,281	3,150
25% TAC	745,000	1,528,645	892,080	457,807	162,837
50% TAC	745,000	1,382,175	641,933	142,882	1

Harvest (kg)						
Model	Year 1	Year 2	Year 3	Year 4	Total	% WDFW
WDFW (HR = 0.42)	6,546	6,546	6,546	6,546	26,184	100.0%
WDFW (Inst.)	6,546	6,546	6,546	4,804	24,442	93.3%
0.25 HR	3,874	7,949	3,816	1,832	17,471	66.7%
0.50 HR	7,748	14,375	4,075	1,155	27,353	104.5%
0.60 HR	9,298	16,547	3,440	715	30,000	114.6%
0.70 HR	10,847	18,517	2,505	339	32,208	123.0%
25% TAC	3,874	3,874	3,874	3,874	15,496	59.2%
50% TAC	7,748	7,748	7,748	2,877	26,121	99.8%

Table 12. Harvest simulations for Lamalchi Bay with constant recruitment.

Stock Size at End of Year					
Model	Initial Size	Year 1	Year 2	Year 3	Year 4
WDFW (HR = 0.42)	745,000	1,458,168	1,943,122	2,272,891	2,497,134
WDFW (Inst.)	745,000	1,426,924	1,889,781	2,205,326	2,420,619
0.25 HR	745,000	1,528,645	1,904,839	2,085,433	2,172,129
0.50 HR	745,000	1,382,175	1,562,783	1,613,977	1,628,488
0.60 HR	745,000	1,325,868	1,446,614	1,471,714	1,476,931
0.70 HR	745,000	1,271,799	1,343,074	1,352,717	1,354,022
25% TAC	745,000	1,528,645	2,063,083	2,427,992	2,677,203
50% TAC	745,000	1,382,175	1,812,936	2,106,227	2,306,179

Harvest (kg)						
Model	Year 1	Year 2	Year 3	Year 4	Total	% WDFW
WDFW (HR = 0.42)	6,546	6,546	6,546	6,546	26,184	100.0%
WDFW (Inst.)	6,546	6,546	6,546	6,546	26,184	100.0%
0.25 HR	3,874	7,949	9,905	10,844	32,572	124.4%
0.50 HR	7,748	14,375	16,253	16,785	55,161	210.7%
0.60 HR	9,298	16,547	18,054	18,367	62,266	237.8%
0.70 HR	10,847	18,517	19,555	19,696	68,615	262.0%
25% TAC	3,874	3,874	3,874	3,874	15,496	59.2%
50% TAC	7,748	7,748	7,748	7,748	30,992	118.4%

3.3.2. Model Results

Baranov simulations of predicted WDFW harvest rates (Table 11) indicated a slight decrease in yield (6.7%), as the population is depleted faster when natural and fishing mortality operate concurrently. The decrease is due to stock depletion in the fourth year before the recommended harvest can be taken.

Constant harvest rate models generally increased yield and decreased the life span of the population (Table 11). Size limit harvests increased yield between 4.5% (0.5 HR) and 23.0% (0.7 HR). The 0.25 HR model had the smallest yield, only 66.7% of the WDFW harvest rates.

Size limit models reduced the initial stock to 4.2% of initial size (0.5 HR) , 1.6% (0.6 HR), or removed the stock completely (0.7 HR) after four years of harvest. The 0.25 HR reduced the stock to 22.7% of its initial level after 4 years.

The 25% TAC model reduced the stock to 21.9% of its original value after four years (Table 11). Yield decreased to 59.2% of the WDFW model. The 50% TAC showed a slight yield decrease, and predicted the removal of the entire population after four years.

At the beach at Lamalchi Bay, all models showed population increases when simulation was done using constant recruitment (Table 12). Size limit models with constant recruitment showed a yield increase of 110.7 to 162.0% over the WDFW model, while the 0.25 HR showed a 24.4% increase in yield. Yield from the 25% TAC model was 59.2% of that of the WDFW model, and the 50% TAC model showed an increase of 18.4%.

3.4. SQUIRREL COVE

3.4.1. Survey Results

The beach in Squirrel Cove is small relative to the beaches just summarized (Table 13), only 656 m^2 (0.07 ha). The beach supports approximately 0.8 t (95% confidence limits of 0.5 and 1.1 t), about 1.2 t per hectare. The sublegal portion of the stock is about twice as large as the legal portion. The age frequency peaks at 2 years and is truncated sharply at 5 years, Z_{5+} is 0.80, the length frequency shows a distinct mode about 20 mm (reflecting the abundance of 2-year-olds) and has few individuals greater than 40 mm in length, and the mean weight of a legal clam is 18.81 g (Figure 6), all indications of regular exploitation. Growth analyses estimate L_∞ at 49.02 mm and age of recruitment at just over 4 years. The age of recruitment indicates good growth rates, and the low estimate of L_∞ reflects the lack of large individuals in the population, not stunting. The density of pre-recruits was 39.44 per m^2, and upcoming recruitment was designated medium (Table 3). A relatively low WDFW harvest rate of 0.21 was calculated for Beach 1.

Table 13. Stock size and parameter estimates from the 1995 Squirrel Cove Beach 1 clam survey. 95% confidence limits are in brackets.

Parameter/Estimate	Value
Survey Area (m^2)	656
Number of Quadrats	7
Mean Legal Density (clams/m^2)	64.56 (42.36; 87.40)
Mean Sublegal Density (clams/m^2)	155.44 (85.68; 220.36)
Total Legal Population (clams x 10^3)	42.36 (27.38; 56.54)
Total Sublegal Population (clams x 10^3)	101.96 (56.21; 144.48)
Mean Legal Biomass (kg/m^2)	1.21 (0.76; 1.68)
Mean Sublegal Biomass (kg/m^2)	0.72 (0.44; 1.00)
Total Legal Biomass (kg)	800 (497; 1,137)
Total Sublegal Biomass (kg)	473 (295; 648)
K	0.34
L_∞	49.02
t_0	-0.11
Age of Recruitment (y)	4.33
Recruit Age Class	4
Z_{5+}	0.80
Mean Weight (g/legal clam)	18.81
WDFW Harvest Rate	0.21

Table 14. Harvest simulations for Squirrel Cove Beach 1.

	Stock Size at End of Year				
Model	Initial Size	Year 1	Year 2	Year 3	Year 4
WDFW (HR = 0.21)	42,360	40,460	21,576	8,735	3
WDFW (Inst.)	42,360	39,504	19,885	6,573	1
0.25 HR	42,360	38,009	18,247	8,759	4,205
0.50 HR	42,360	29,681	8,413	2,385	676
0.60 HR	42,360	26,480	5,504	1,144	238
0.70 HR	42,360	23,405	3,167	428	58
25% TAC	42,360	38,009	17,376	3,490	1
50% TAC	42,360	29,681	3,733	1	0

	Harvest (kg)					
Model	Year 1	Year 2	Year 3	Year 4	Total	% WDFW
WDFW (HR = 0.21)	164	164	164	164	656	100.0%
WDFW (Inst.)	164	164	164	118	610	93.0%
0.25 HR	199	179	86	41	505	77.0%
0.50 HR	398	279	79	22	778	118.6%
0.60 HR	478	299	62	13	852	129.9%
0.70 HR	558	308	42	6	914	139.3%
25% TAC	199	199	199	63	660	100.6%
50% TAC	398	398	67	0	863	131.6%

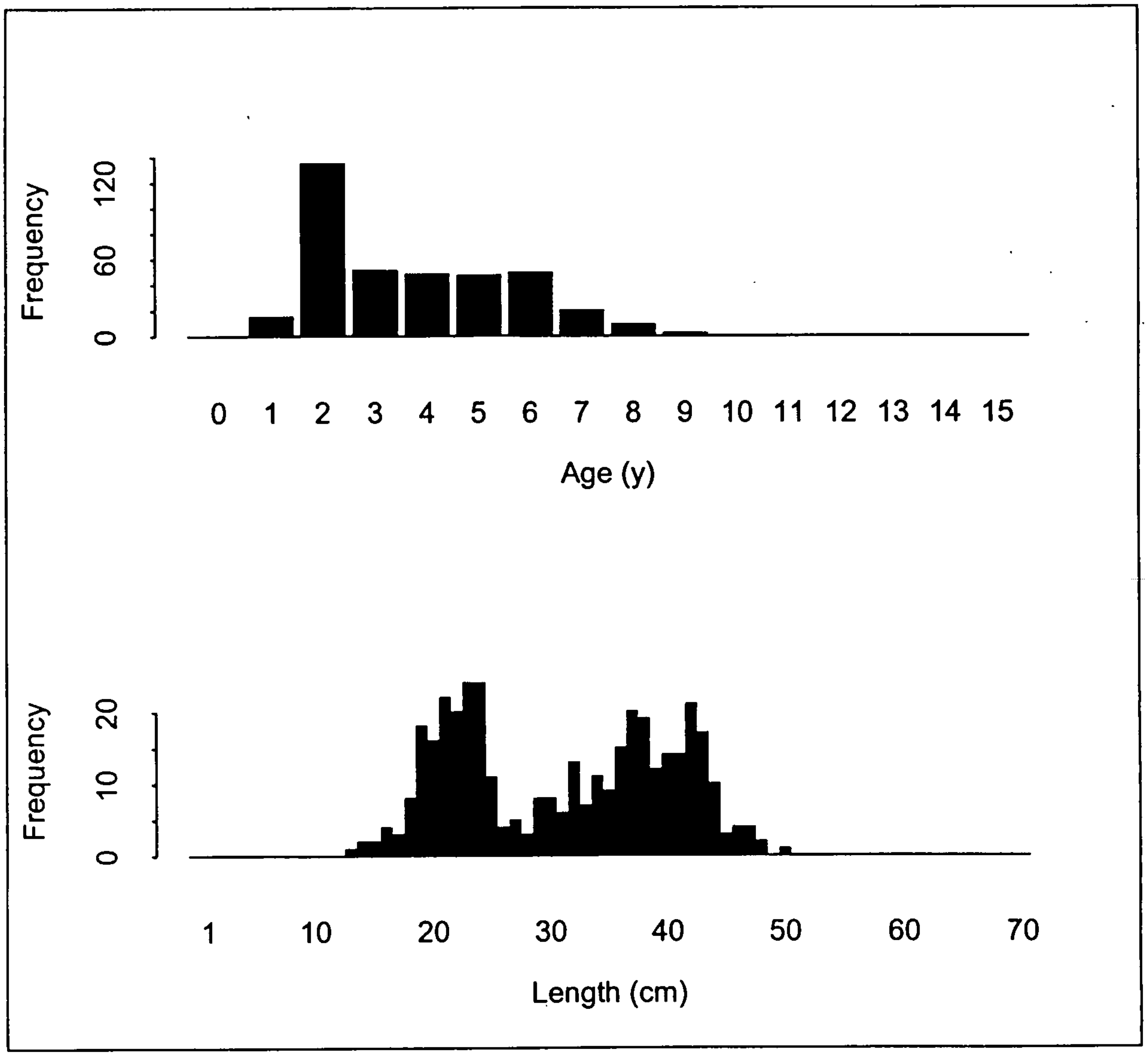

Figure 6. Age and length frequencies of Manila clams from the 1995 Squirrel Cove Beach 1 clam survey.

3.4.2. Model Results

Baranov simulations of WDFW harvest levels showed a slight decease in yield over the four years (7.0%), as the interaction of natural and fishing mortalities reduced the stock more rapidly than the annual rate model predicted (Table 14). The reduced yield is due to depletion of the initial population in the fourth year, prior to the entire recommended harvest being taken.

The constant harvest rate models intended to simulate harvests governed by the size limit resulted in greater yield from the stock, and reduced the remaining legal biomass more rapidly than the WDFW model did. Yield increased relative to the WDFW predicted harvests between 18.6% (0.5 HR) to 39.3% (0.7 HR) (Table 14). The 0.25 HR model demonstrated yield 77.0% of the WDFW model.

Size limit models reduced stock size to between 1.6% (0.5 HR) and 0.1% (0.7 HR) of its initial size after four years of harvest (Table 14). The 0.25 HR depleted the stock to 9.9% of its initial size after four years.

The 25% TAC model shows a slight increase in yield (0.6%) over the WDFW model, but predicts the complete removal of the population after four years (Table 14). The model using a constant TAC of 50% of the initial population shows a 31.6% increase in yield, but predicts that the stock will be removed after three years.

All models show a decreasing stock size when simulations are done using constant recruitment (Table 15). Size limit simulations show increases in yield from 76.5% (0.5 HR) to 114.9% (0.7 HR) over the WDFW model, while the 0.25 HR shows an 8.4% increase in yield. The constant TAC models show increases of 21.3% and 130.6% over the WDFW model. Note, however, that for the 50% TAC model, there is insufficient stock in the fourth year to complete harvest, which becomes reliant on annual recruitment.

Table 15. Harvest simulations for Squirrel Cove Beach 1 with constant recruitment.

	Stock Size at End of Year				
Model	Initial Size	Year 1	Year 2	Year 3	Year 4
WDFW (HR = 0.21)	42,360	40,460	39,168	38,289	37,692
WDFW (Inst.)	42,360	39,504	37,559	36,234	35,331
0.25 HR	42,360	38,009	35,921	34,918	34,437
0.50 HR	42,360	29,681	26,087	25,069	24,780
0.60 HR	42,360	26,480	23,178	22,492	22,350
0.70 HR	42,360	23,405	20,841	20,494	20,447
25% TAC	42,360	38,009	35,050	33,040	31,675
50% TAC	42,360	29,681	21,407	17,674	17,675

	Harvest (kg)					
Model	Year 1	Year 2	Year 3	Year 4	Total	% WDFW
WDFW (HR = 0.21)	164	164	164	164	656	100.0%
WDFW (Inst.)	164	164	164	164	656	100.0%
0.25 HR	199	179	169	164	711	108.4%
0.50 HR	398	279	245	236	1,158	176.5%
0.60 HR	478	299	262	254	1,293	197.1%
0.70 HR	558	308	274	270	1,410	214.9%
25% TAC	199	199	199	199	796	121.3%
50% TAC	398	398	398	319	1,513	230.6%

4. Discussion

Starfield (1997) emphasized the utility of simple, pragmatic models as a tool for focused exploration of specific scenarios, often when data are limited. The models examined here are simple, not meant to fully represent reality, but rather to explore effects of various management policies on the fate of the stock detected in an initial assessment survey.

4.1. Assessment of Models

Major assumptions of the models are that population estimates and biological parameters from the survey are representative of the modeled stock, mortality rates are equal for all age classes and do not change between years and the mean weight of legal-sized clams does not change over the modeling period.

The measured population characteristics are assumed to be representative of the population, as the samples which describe these characteristics are selected randomly from the pool of available samples (Gillespie *et al.* 1995b). If the survey design incorporates only exploited clam beds, then results of age and growth analyses should be representative of the exploited portion of the population. Inclusion of areas which harbor slower growing clams (to maximize the estimate of population size) may decrease growth rate estimates, and hence increase the estimated age of recruitment for the entire population. Surveyors must consider this trade-off when deciding which areas of the beach support harvestable clam beds.

As the strength of impending recruitment greatly affects the results of the simulations, survey design should incorporate as much concern for estimation of the sublegal portion of the population as for the harvestable portion. The size group which represents impending recruitment does not suffer selectivity if the survey has been completed properly. However, some past surveys which used commercial diggers to collect samples have suffered incomplete sampling of sublegal portions of the stock (Gillespie *et al.* 1995a).

Growth as modeled is simplistic, and can greatly affect harvest rates in situations where growth is perceived to be poor. Models assume knife-edge vulnerability at age, which is not true. Size-at-age is available from survey data, and partial vulnerabilities at age could be calculated. The assumption of equal mortality rates for all age classes and constant mean weight of legal size clam are simplifications. More ambitious models can improve these assumptions, but also have more stringent data requirements.

Mean weight of legal size animals in the stock will change over the harvest period, as newly recruited animals are smaller than the harvested animals they are replacing. The difference may be inconsequential if legal stock size is low, and most of the harvestable stock are new recruits. However, if age classes have accumulated in the absence of significant harvest, mean size of a harvested animal will be reduced considerably by intense harvests. Because TAC's are currently allocated as a portion of the biomass, not population size, a reduction in mean size of harvested animals will require that more animals be harvested to meet the TAC. Harvest rates will be underestimated as mean weight decreases.

The simulations discussed in this paper assume that natural and fishing mortalities occur concurrently, unlike the WDFW model. The use of annual rates, with harvest occurring first and natural mortality acting only on the unharvested portion of the stock is unrealistic for clam fisheries. Harvests are not instantaneous, and often are not confined to short periods of time when TAC's are allocated. Harvests can occur much later in the year than the surveys, and thus, natural mortality affects both harvested and unharvested portions of the stock.

The utility of the models is somewhat limited in that they predict behavior of only a portion of the stock during the period of the fishery. Recruitment to the fishery is not factored into the model after the second year. Thus, the results of the analyses deal only with the population detected by a survey, and do not reflect the responses of the entire population at the end of four years.

The models can be used in situations where impending recruitment is known to be low (e.g. Gillespie *et al.* 1995b), or can be useful in examining the effect of harvest on the stock detected in a survey. The model could be used in situations where surveys are done on an annual or bi-annual basis. In these cases, the harvestable stock is reasonably well known from the last survey results.

Simulations using constant recruitment do predict the behavior of the entire stock on the beach, unlike the models discussed above. However, constant recruitment is unlikely to actually occur, as bivalve recruitment patterns are extremely variable (Bourne 1995).

4.2. SIMULATIONS USING REAL DATA

In all cases, the WDFW annual rate model is optimistic relative to the instantaneous models, where harvest and natural mortality are assumed to act concurrently. The WDFW model predicts the survival of more clams than the instantaneous model, and thus also predicts a greater yield than would occur according to an instantaneous model. The WDFW model is designed to spread the harvest over four years, but the instantaneous model predicts that WDFW harvest levels could not be maintained over four years.

Our models of size limit harvests (0.5-0.7 HR) predicted the greatest yields, but most of the stock was removed early. In this situation, many clams that might fall victim to natural mortality are harvested before they can die. Few clams on the beach will grow to be very large - the combination of natural mortality and a high harvest level result in the speedy removal of a cohort once it reaches legal size. On the other hand, the 0.25 HR model leaves clams on the beach for a longer period - a cohort is removed from the beach at a much slower rate.

Depuration quotas are currently set at either 50% or 25% of the standing legal-size stock. Quotas are set at 50% for stocks that have been regularly harvested, and at 25% for those that have seen little harvest recently. The stock in our study with little recent harvest (North Shore Kuper Island) showed that a 25% model exhausts the stock detected in the survey in three years. Other stocks modeled at 50% show that the stock is exhausted by the third or fourth year. If stocks with little recent harvest are modeled with a 50% TAC, the stock can be exhausted in as little as two years.

The 50% TAC model, like the 0.5, 0.6, and 0.7 HR models, predicted a rapid decrease in stock size. This results in a greater dependence on high recruitment to allow continued harvest, and an increased risk of stock depletion due to low recruitment. In the absence of high recruitment, other actions (such as closures) are more likely to be needed to allow the stocks to recover.

Since the situation where recruitment remains constant is extremely unlikely to occur, the constant recruitment model is not particularly useful. However, it does illustrate what might occur if several years of low recruitment occur under high levels of harvest.

Stock responses in constant recruitment models depend heavily on the recruitment level itself. Stocks with constant high recruitment (Inner Kulleet Bay and Lamalchi Bay) showed increasing stock size over the four year period modeled (Table 6, Table 12). However, the constant low recruitment stock (North Shore Kuper Island) demonstrated rapidly decreasing stock size under all harvest models (Table 9). Squirrel Cove Beach 1, with constant medium recruitment, showed less than a 20% decrease under the 0.25 HR model, and 42-52% under the size limit models (Table 15).

Models with a constant TAC of 25% or 50% of the year one legal-size stock cannot maintain their harvest levels for stocks with low recruitment. Stocks with high recruitment have sufficient numbers of pre-recruits entering the fishery each year to maintain harvests, but stocks with low recruitment generally do not (unless the number of legal-size clams on the beach initially is particularly low, especially relative to recruitment).

4.3. HYPOTHETICAL CASES

To investigate how recruitment trends affect the model predictions, we considered three hypothetical stocks, each with an initial population of one million legal-sized clams, at a density of 50 per m^2. The low recruitment stock was assigned 300,000 pre-recruit clams for a density of 15 per m^2, the medium recruitment stock was assigned 1,000,000 (50 per m^2), and the high recruitment stock had 85 pre-recruits per m^2 (1,700,000 clams). The hypothetical examples examine the response of the detected stock from a survey, thus recruitment occurs only in the second year of the simulation. Yields are in terms of number of animals harvested, not weights.

Figure 7 shows total yield over a four year period for each model, and for each hypothetical stock. Although the model choice is clearly important in determining yield, all models show a consistent difference in yield between high, medium, and low recruitment stocks.

Figure 8 shows stock size and cumulative harvest for the hypothetical high recruitment stock. All models show an initial increase in stock size, despite harvesting, due to the high recruitment. The high constant harvest rate models show a rapid decrease in stock size after year 2. At the same time, the cumulative harvest shows a rapid increase for the first year, but very slow increases in following years, as most of the stock has been removed from the beach early in the simulation. This can be contrasted with the 0.25 HR, which demonstrates a much slower decrease in stock size and far lower total harvest. Note that the 25% TAC model shows a steady accumulation in harvest (stable yield), while the 50% TAC model shows a rapidly decreasing stock size and a leveling off of harvest after three years due to a lack of harvestable stock.

The medium recruitment stock showed an increase in stock size after the first year (due to recruitment) for the low harvest level models, and decreases for models with high levels of harvest (Figure 9). With this stock, high constant harvest rate models show rapid decreases in stock size and slow increases in total harvest after the first year, as with the high recruitment stock. Here, though, the TAC models show more rapid decreases in stock size than with the high recruitment stock.

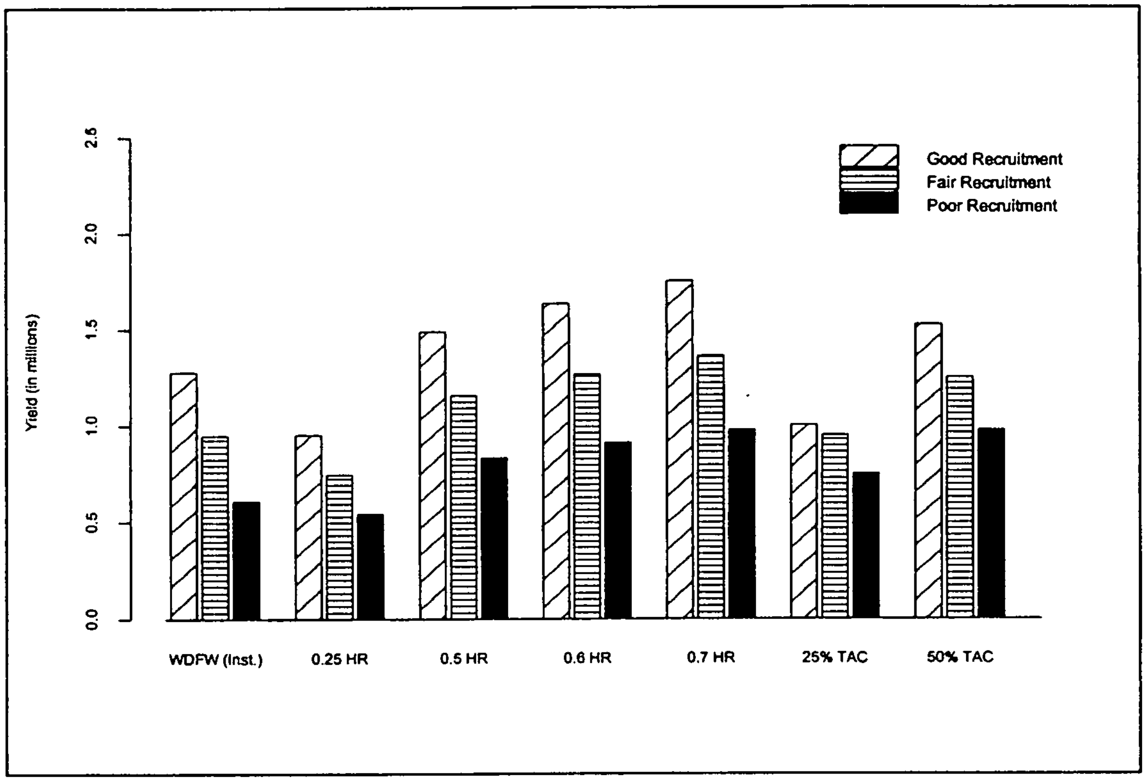

Figure 7. Hypothetical yield from various harvest models at three levels of recruitment.

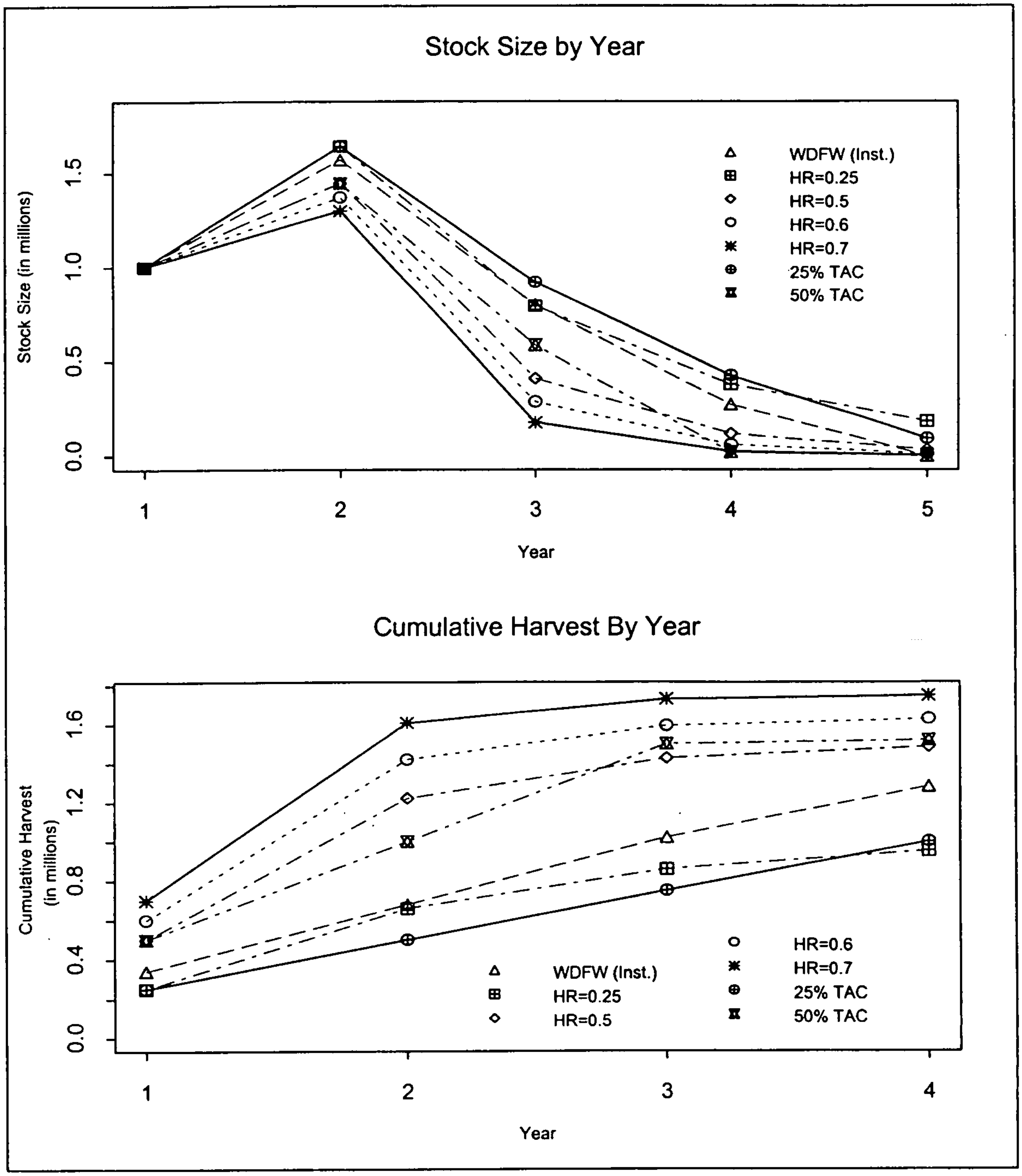

Figure 8. Stock size and yield from various harvest models and a stock with high recruitment.

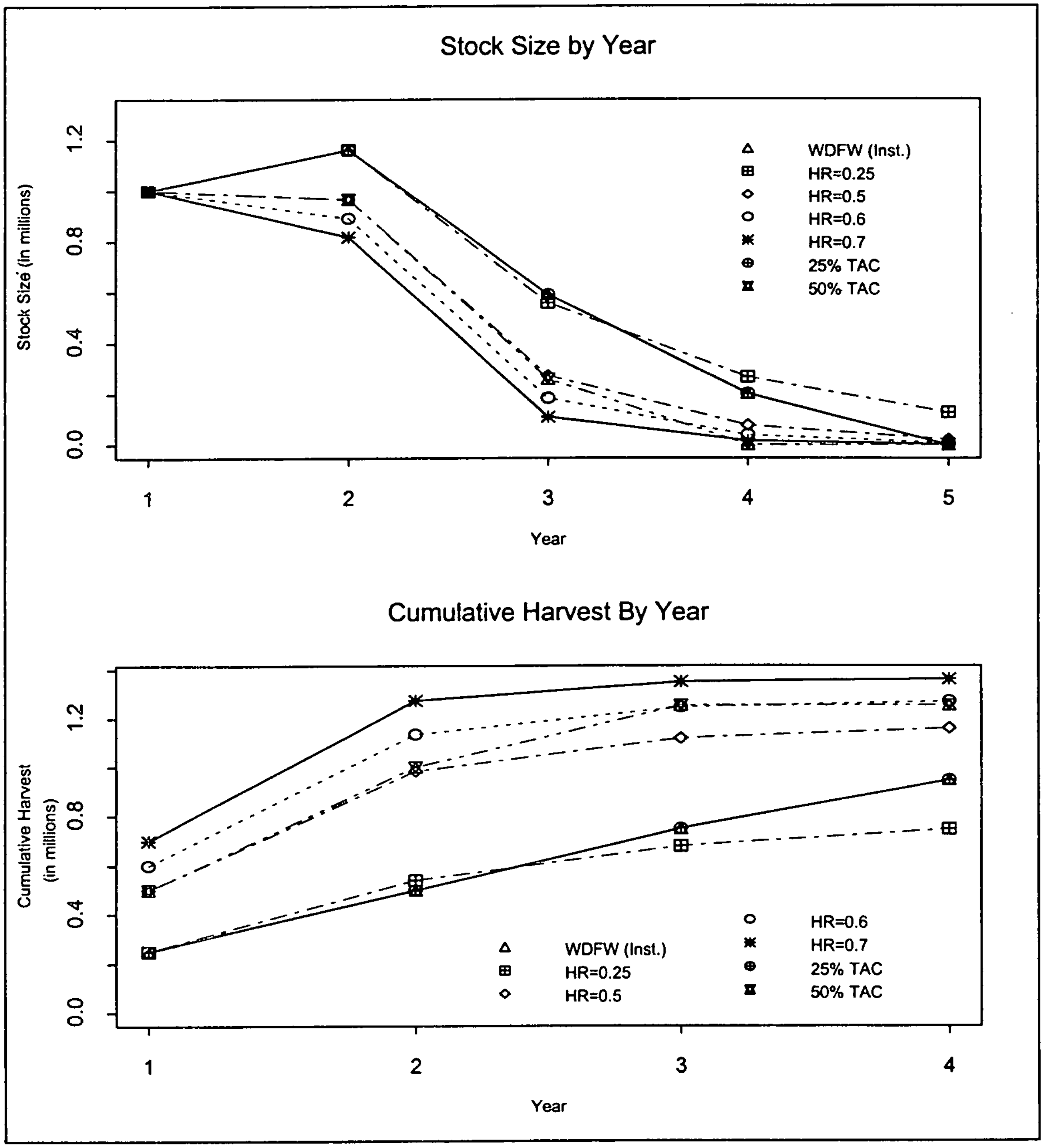

Figure 9. Stock size and yield for various harvest models and a stock with medium recruitment.

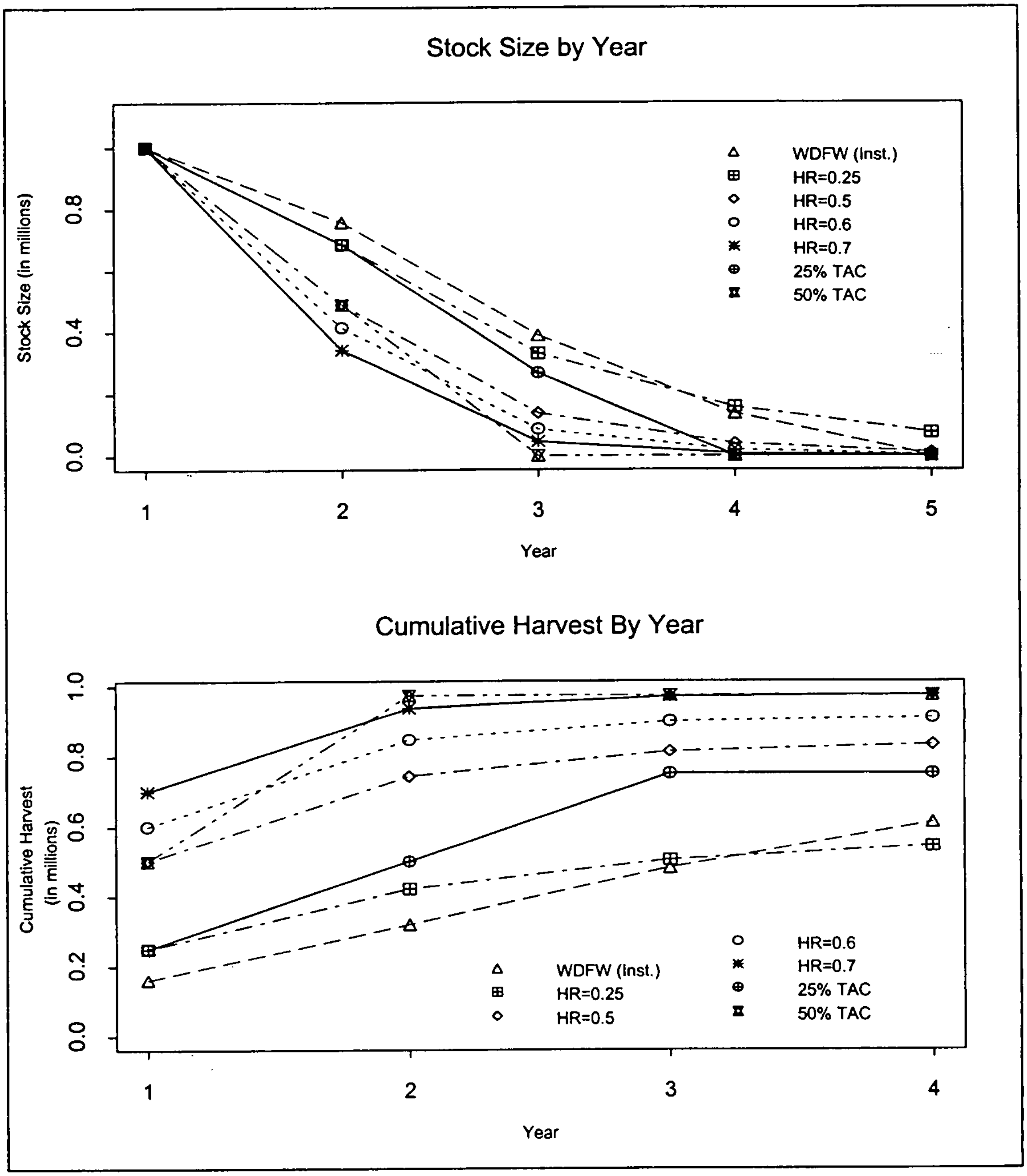

Figure 10. Stock size and yield for various harvest models and a stock with low recruitment.

The low recruitment stock predicted no increase in stock size due to recruitment (Figure 10). As with the high and medium recruitment stocks, a rapid decrease in stock size was seen for high constant harvest rate models, combined with a slow increase in total yield after the first year. Again, the 0.25 HR shows slow decreases in stock size and low overall harvests. For TAC models, the decrease in stock size was more rapid than with high or medium recruitment. The total harvest for the 25% TAC model levels off after three years (due to a lack of stock on the beach, harvests were incomplete), while the 50% TAC model shows incomplete harvests after only two years.

Harvest models such as 0.5-0.7 HR and 50% TAC predict a higher yield, but also a rapid decrease in stock size. Gains in yield are due to harvest of animals from the stock before they can fall victim to natural mortality. These models suggest that a fishery can remove virtually all of the stock detected by a survey in two years of harvest. This effect is less severe if recruitment is high, but occurs nonetheless. The result is a stock that relies almost entirely on annual recruitment, with animals that are of generally small size, since clams are removed from the beach soon after they reach legal size. The effects of low stock levels and reduced mean size of animals on the reproductive potential of the stock are not well understood.

4.4. MORTALITY RATES

In evaluating these harvest rates we must take into account the total mortality rate, not just the harvest rate. For instance, the combination of natural mortality and a harvest rate of 0.5 actually results in the loss of 71.7% of the legal-size stock from the beach in a year (Table 16). A harvest rate of 0.7 would decrease the legal-sized stock by 86.5%. Clearly, regular recruitment is important in size limit fisheries if harvest levels are to be maintained.

Table 16. Mortality rates predicted from harvest simulations.

Harvest Rate	M[1]	F[2]	Z[3]	Total Annual Mortality Rate
0.25	0.381	0.353	0.734	51.99%
0.50	0.381	0.880	1.261	71.65%
0.60	0.381	1.190	1.571	79.21%
0.70	0.381	1.619	2.000	86.47%

[1] Instantaneous natural mortality rate
[2] Instantaneous fishing mortality rate
[3] Instantaneous total mortality rate

Note that the levels of fishing mortality required to achieve annual harvests described by the size limit models range from 2.3 to 4.2 times the natural mortality rate used here. Note also that the natural mortality rate may not include incidental mortality effects from the fishery, or catastrophic episodes, such as winter kills.

4.5. RECRUITMENT

Recruitment level is very important for model results. If we consider the time required for the legal stock size to decrease to a level where it is exhausted (say, less than 10% of its original level), the influence of recruitment is clear. Our data from high recruitment stocks predicts, using a model with a constant 0.25 HR, that it will be possible to maintain the surveyed stock at above 10% of its initial size for more than four years (Table 17). For medium and low recruitment stocks, the stock size decreases to less than 10% in four years. With a constant 0.5 HR, the high recruitment stocks manage four years, while the medium and low stocks can last only three. With a higher HR of 0.7, high recruitment stocks keep their stock at above 10% for three years, but medium and low stocks can maintain the surveyed stock for only two years.

The influence of recruitment is also seen in constant TAC models. Using a constant TAC of 25% of the initial stock size, our high recruitment stocks can maintain the harvest for more than four years, but our data from the medium recruitment stock predict that the harvest level can be maintained for only three years, and low recruitment stocks can only provide two years of complete harvests. With a 50% TAC model, even high recruitment stocks can provide only three years of complete harvests, while medium stocks give two years, and low recruitment stocks have insufficient stock to maintain the harvest past a single year. Thus, a 25% TAC can deplete the surveyed stock in as little as two years, although may provide more than four years of harvest, depending on recruitment. A 50% TAC depletes the stock in anywhere from one to three years.

The harvest rate can also affect the amount of time that survey information is useful for making management decisions, given that we cannot currently model recruitment beyond that which is detectable in the initial survey. The more quickly the detected stock is reduced, the sooner a new survey is required to begin the estimation procedure again. If detected stock can be depleted in 1 or 2 years under high harvest rates (Table 17), then annual surveys are required to set quotas.

Table 17. Life span (yr) of populations estimated from clam surveys under various harvest models.

Model	High Recruitment	Medium Recruitment	Low Recruitment
0.25 HR	> 4	4	4
0.50 HR	4	3	3
0.60 HR	3	3	2
0.70 HR	3	2	2
25% TAC	> 4	3	2
50% TAC	3	2	1

N.B. - For HR models, time to exhaustion taken as number of years before population is less than 10% of its original size. For constant TAC models, time to exhaustion taken as number of years before insufficient stock remains to complete the TAC.

5. Conclusions

The pragmatic models evaluated in this paper provide information on the life span of stocks detected by surveys under various harvest models. Although producing the highest yields, the relatively high total mortality rates in size limit fisheries result in rapid depletion of stocks, and reliance on annual recruitment for future harvests. Relatively short periods (1-2 years) of low recruitment cause depletion of harvestable stocks and require additional management attention.

Reduced harvest rates decrease yield, as a portion of the clams not harvested in a given year will succumb to natural mortality. However, reduced harvest rates promote stability in the fishery, as the harvests are supported by a larger surviving proportion of the previous year's stock, in addition to annual recruitment.

The same pattern is apparent when long-term TAC's are allocated from the initial harvest estimate. Higher harvest rates decrease the time required to entirely remove the initial stock, at which point the fishery is dependent on annual recruitment.

Because recruitment patterns and processes are not well understood in bivalves, and sufficient time series from annual surveys are not yet available, we cannot quantify risks associated with each harvest model. However, reliance on annual recruitment implies a higher risk of having to place additional controls on the fishery should one or two years of low recruitment occur.

If one accepts the proposition that the British Columbia Manila clam fishery did not develop until the late 1970s and 1980s, then reduced yields are not surprising. The prevalent pattern in developing fisheries is one of rapid increase to unsustainable harvest levels, and subsequent efforts to reduce the fishery to a more sustainable level as virgin biomass is depleted (Caddy and Gulland 1983; Gunderson 1984; Francis 1986; Hilborn and Sibert 1988; Hilborn and Walters 1992). To date, these efforts have involved reduced opportunity through time closures in the wild fishery and TAC's in fisheries where specific groups are allocated access.

The current proposals for changes in the clam fishery, including decreased participation (licence limitation) and smaller scale assessment and management (Community Management Boards and pilot fisheries), may provide more opportunities for management through direct control of harvest rather than control of effort. The results of these models can provide preliminary guidance in the development of assessment and management frameworks for specific area or important beaches, particularly in instances where an initial assessment survey is the only information available.

In the short term, repeated assessments of harvested stocks are required to either confirm or modify the input parameters, including growth, mortality rates, recruitment variation, and indirect mortality from the fishery. As better data are accumulated, more sophisticated models can be evaluated.

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References

Adkins, B.E. 1992. Clam surveys at Savary Island, British Columbia 1987 to 1991. PSARC Working Paper I92-06.

Bourne, N. 1982. Distribution, reproduction and growth of Manila clam, *Tapes philippinarum* (Adams and Reeve), in British Columbia. J. Shellfish Res. 2: 47-54.

Bourne, N. 1987. A review of management options and the rationale for size limits in British Columbia's commercial fishery for intertidal clams. p. 123-132. *In*: R.M. Harbo and G.S. Jamieson [eds.]. Status of invertebrate fisheries off the Pacific coast of Canada (1985/86). Can. Tech . Rep. Fish. Aquat. Sci. 1576.

Bourne, N. 1995. Review of stock recruitment relationships in bivalves. PSARC Update Paper I95-02.

Bourne, N. and B.E. Adkins. 1985. Savary Island clam study. p. 69-95. *In*: G.S. Jamieson [ed.]. 1983 and 1984 invertebrate management advice, Pacific Region. Can. Man. Rep. Fish. Aquat. Sci. 1848.

Caddy, J.F. and J.A. Gulland. 1983. Historical patterns of fish stocks. Mar. Policy 7(4): 267-278.

Campbell, W.W. 1996. Procedures to determine Intertidal populations of *Protothaca staminea*, *Tapes philippinarum*, and *Crassostrea gigas* in Hood Canal and Puget Sound, Washington. Wash. Dept. Fish Wildl. Procedures Manual MRD96-01. 27 p. + app.

Francis, R.C. 1986. Two fisheries biology problems in west coast groundfish management. N. Am. J. Fish. Manage. 6: 453-462.

Gillespie, G.E., A.R. Kronlund and G.D. Heritage. 1995a. Intertidal clam stock estimates for selected depuration harvest beaches - 1994. PSARC Working Paper I95-07.

Gillespie, G.E., A.R. Kronlund and G.D. Heritage. 1995b. Assessment of Manila clam (*Tapes philippinarum*) stocks at Savary Island, British Columbia - 1995. PSARC Working Paper I95-12.

Gunderson, D.E. 1984. The great widow rockfish hunt 1980-1982. N. Am. J. Fish. Manage. 4: 465-468.

Harbo, R.M. 1997. Shells and Shellfish of the Pacific Northwest. Harbour Publishing, Madeira Park, B.C. 270 p.

Heizer, S.R. 1992. West coast of Vancouver Island intertidal clam surveys, Areas 23 to 27 - 1989 to 1992. PSARC Working Paper I92-05.

Hilborn, R. and J. Sibert. 1988. Adaptive management of developing fisheries. Mar. Policy 12(2): 112-121.

Hilborn, R. and C.J. Walters. 1992. Quantitative Fisheries Stock Assessment: Choice, Dynamics and Uncertainty. Chapman and Hall, New York. 570 p.

Hoenig, J.M. 1983. Empirical use of longevity data to estimate mortality rates. Fishery Bull. (U.S.) 82: 898-902.

Kronlund, A.R., G.E. Gillespie and G.D. Heritage. 1995. Survey methodology for intertidal bivalves. PSARC Working Paper I95-11.

Neave, F. 1942. The butter clam (*Saxidomus giganteus* Deshayes): studies in productivity. Rep. B.C. Fish. Dept. (1941): 79-81.

Quayle, D.B. 1940. A preliminary report on the British Columbia clam investigation. Rep. B.C. Fish. Dept. (1939): 67-71.

Quayle, D.B. and N. Bourne. 1972. The clam fisheries of British Columbia. Fish. Res. Board Can. Bull. 179. 70 p.

Rao, J.N.K. and C.F.J. Wu. 1988. Resampling inference with complex survey data. J. Am. Stat. Soc. 83: 231-241.

Ricker, W.E. 1975. Computation and interpretation of biological statistics of fish populations. Bull. Fish. Res. Board Can. 191. 382 p.

Sitter, R.R. 1992. A resampling procedure for complex survey data. J. Amer. Stat. Assoc. 87: 755-765.

Starfield, A.M. 1997. A pragmatic approach to modeling for wildlife management. J. Wildl. Manage. 61: 261-270.

StatSci. 1995. S-Plus guide to statistical and mathematical analysis. MathSoft, Inc. Seattle, WA.

Webb, R. and K. Marcus. 1996. Intertidal clams. PSARC Fishery Update 1997. 22 p.