A BIOECONOMIC SIMULATION MODEL OF A FISHERY USING AREA BASED MANAGEMENT UNDER UNCERTAINTY

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ABSTRACT

Scallop fisheries are often characterized by variable abundance and periodic mass mortality occurrences. Area rotation is a respected management tool for sedentary species. A bioeconomic simulation model that incorporates the spatial and temporal distribution of scallop beds and fishing effort is presented. The model is user-friendly and was designed for use by fisheries managers and shareholders of the New Zealand Challenger Scallop Enhancement Company Inc. The model combines twenty-one biological models representing rotated and enhanced subareas of various size and productivity, with economics of the scallop fishery. The bioeconomic simulation model is used to evaluate various management strategies including geographic area rotation, daily catch limitations and fleet size. Results indicate that a mixed rotation schedule is optimal but that subarea specific growth rate studies are needed to implement it. Results also indicate that vessels numbers may be higher than needed to take the same amount of fish and that low daily catch limits result in the highest level of NPV but increase effort. In addition, the model is used to evaluate the impact of various types of mass mortality occurrences on the net present value of individual quota under two different rotation schedule scenarios. These simulations suggest that the relatively shorter rotation schedule is preferable in that the time it takes to recover from a mass mortality occurrence is shorter than otherwise. Future research endeavors are described. This research is expected to be useful to scallop and other sedentary species-based fisheries considering area rotation as a key management tool.

Keywords: New Zealand fisheries; ITQ fisheries; bioeconomic model; simulation model; scallops; fisheries management; area rotation; spatial management

BACKGROUND

The New Zealand South Island Scallop Fishery is a largely self-governed fishery with 35 quota owners and approximately 60 vessels ranging in size from 12 to 20 meters. The fishing season opens around August and closes in mid-February. The vessels dredge for New Zealand scallop, *Pecten Novaezelandia*, in Golden Bay, Tasman Bay and the Marlborough Sounds at the northern tip of South Island (shown in Figure 1). Fishing grounds encompass approximately 170,000 hectares. As in other scallop fisheries, annual landings fluctuate greatly from year to year. Figure 2 shows landings since 1959 in the SCA7 scallop fishery. Landings have ranged from a high of 1,246 meatweight tons in 1975 to no landings in 1981 and 1982 when the fishery was closed to enable stock recovery.

An enhancement program began in 1983 when the Ministry of Agriculture and Fisheries (MAF) and industry representatives gained assistance from the Overseas Fishery Co-operation Foundation of Japan to establish a scallop enhancement program using techniques similar to those used in Japan. MAF administered the program and the first seeded scallops were harvested in 1986. In 1989, the rotational fishing regime was introduced. Fishing grounds in Tasman and Golden Bay were divided into ten sectors initially. Each year a decided upon number of sectors were opened to commercial fishing according to scallop size and weight as well as quality indicated by sampling. After being fished, the sector was seeded with scallop spat, caught on longlines holding mesh bags.

The Challenger Scallop Enhancement Company was established in late 1993 to protect fishing and management rights of scallop quota owners. Challenger is now the management entity responsible for meeting the requirements of the 1996 Fisheries Act for the scallop fishery.

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The primary goal of the Challenger Scallop Enhancement Corporation is to "maximize quota value". The Challenger Business Plan states, "Aggregate quota value is recognized as the overall indicator of the financial performance of a fishery and that value encompasses the need to sustain the quantity and quality of scallops fished over time" [1]. Several factors can influence quota value. A study by [2] showed that a relationship exists between quota prices and exogenous variables such as interest rates, output prices and the level of the annual TACC. The study also showed that, in the long run, lease and quota prices are correlated in the New Zealand scallops fishery. Therefore, lease price was considered a possible proxy for quota value for the model described in this paper. However, since lease prices in the scallop fishery often combine scallop profitability expectations with vessel sales or other services, this was not ideal. Therefore, net revenue over time, or net present value per quota was used as a proxy for quota value in construction of the simulation model.

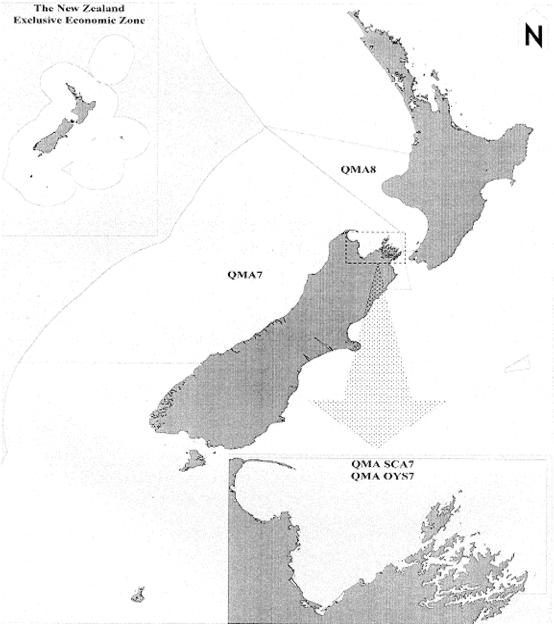

Figure 1. New Zealand EEZ and geographical locations of Golden Bay, Tasman Bay and the Marlborough Sounds. Source: [3]

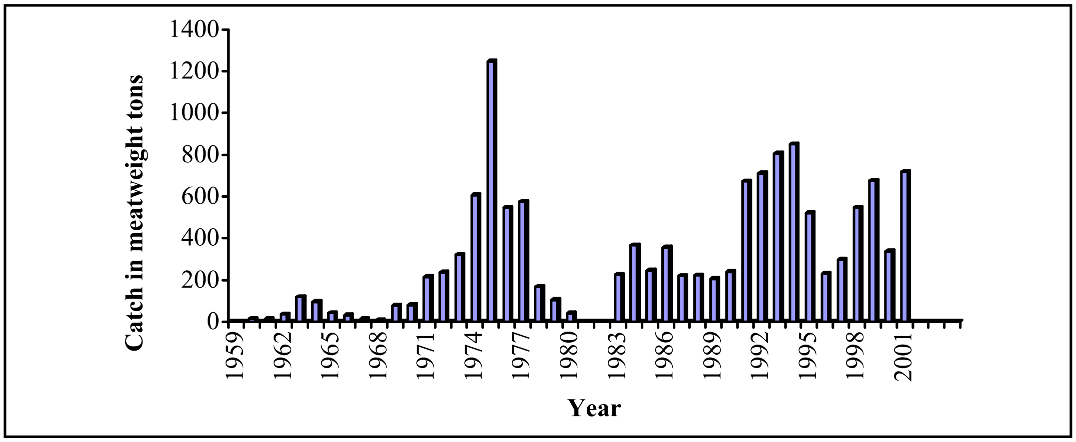

Figure 2. Landings in the SCA7 scallop fishery

Challenger Scallop Fishery Biology and Management

Fleet Composition

Approximately 60 vessels measuring 12 to 20 meters in length fish for scallops with two dredges each. Cluster analysis was used to find groups of vessels with similar characteristics. Length, horsepower, dredge size, number of fisheries each vessel participates in and the number of weeks each vessels remains in the scallop fishery as a percentage of the season length were used to characterize the vessels. Many of the vessels in the scallop fishery also participate in the tuna, finfish and oyster fisheries. However, the scallop fishery is considered the most profitable. Data from 45 vessels over five years was applied to different cluster analysis methods including partitioning around medoids and fuzzy partitioning. Results indicated that there were three distinct groups of vessels. Table I shows the average characteristic values of each grouping.

Table I: Average vessel characteristics and vessel operation data by cluster.

Number of vessels in cluster	Average Length (feet)	Average Horsepower	Average Dredge Size (meters)	Number of fisheries participated in	Weeks spent in the fishery/ season length
Cluster 1 - 25	39.56	115.2	2 x 2.32	2.1	83%
Cluster 2 - 7	47.0	183.7	2 x 2.37	1.9	81%
Cluster 3 - 13	48.4	257.1	2 x 2.36	2.0	80%

Results seemed to indicate that the smallest vessels stay in the scallop fishery the longest each year before leaving for the tuna fishery. They also participate in the largest number of different fisheries. The largest vessels leave the fishery the earliest each year. Although the model was structured to enable the tracking of individual vessels, lack of data necessitated using the clusters identified above.

Market for Scallops

Approximately 50% of landed scallops in the Challenger fishery are exported. The exported product consists of the abductor muscle and roe attached. Larger scallops receive a premium price for meatweight kilograms of scallops less than 80-count. Challenger Scallops is attempting to adjust management of the scallop fishery to produce scallops large enough to receive the premium price offered on exports. The main management tools include area rotation, enhancement, a daily meatweight catch limit per quota, daylight fishing only and a five-day fishing week.

CHALLENGER SCALLOP BIOECONOMIC SIMULATION MODEL

Bioeconomic models often use equations that incorporate the dynamic pool assumption in the biological component of the model. This assumption assumes that the biological resource is distributed uniformly and that after harvest occurs, the stock redistributes itself so that there are no geographic gaps or concentrations in the population. This may be a valid assumption for species that are highly mobile. However, the dynamic pool assumption is not always valid for application to models of sedentary species [4]. Low mobility species like scallops, are often patchily distributed, have low mobility between patches and therefore don't redistribute. Growth and mortality vary even between small distances. [4] suggest two alternative approaches to apply when building biological models for sedentary species. The first is to divide the larger area into independent units to allow for heterogeneity in stock distribution, mortality and growth rates [4]. The second is "integrating the effects of different environmental regimes on the spatial structure of the population, spatial heterogeneity of fishing effort, biological interactions, and the implications of economic factors and human attitudes" [4]. The first approach was used in the model described here.

Structure of the Bioeconomic Simulation Model

A glossary of symbols is listed in Table II and mathematical equations describing the essential population dynamics is reported in Table III. The equations describe a fishery in which recruitment is determined with a biological submodel that produces an influx of eggs within a defined range every year. The eggs are distributed at uniform density over all scallop fishing grounds. Each of the current nine fishing areas is divided into two, three or four subareas. These divisions were made based on estimated growth rates. Further, some portion of each subarea was classified as unfished based on GIS stock assessment data[a]. Scallop population growth by subarea is tracked using twenty-one age-structured models. Scallop stock size and individual growth are tracked for five years for five age classes on a weekly basis. Vessels are distributed to subareas with the highest revenue per meter and harvest depends on dredge efficiency, subarea scallop density and fishing effort. Fishery profitability in the aggregate and by vessel group is determined through a series of accounting relationships.

Table II: GLOSSARY OF SYMBOLS

Endogenous variables:	
ACE	Actual Catch Entitlement
B	Biomass of minimum size and larger scallops in tons
BC	Possible biological catch
C	Catch in biomass
D	Density of scallops per square meter
F	Fishing mortality of minimum size and larger scallops
FC	Total fixed costs
H	Area fished in hectares
L	Total diesel cost
LC	Possible legal catch
MTWT	Meatweight of a single scallop in grams
N	Population
PS	Primary spat
R	Revenue
SGB	Number of subareas open in Golden Bay
SOPEN	Total number of subareas open
STB	Number of subareas open in Tasman Bay
V	Vessels
VC	Total variable costs
WS	Wild spat
Exogenous variables and constants:	
asub	Hectares of fishing ground per subarea
be	Vessel berthage cost
clm	Landed kilograms meatweight allowed per quota
cr	Average conversion ratio of meatweight to greenweight
crew	Crew cost
de	Dredge efficiency
df	Days fished each week
dg	Price of diesel/liter in Golden Bay
ee	Vessel electrical and electronics cost
gear	Gear purchase, maintenance and repairs cost
hf	Hours fished each day each week
hgb	Hours to steam to Golden Bay from Tasman Bay
i	Incidental and discard mortality
ins	Vessel insurance cost
k	Annual growth rate
knots	Speed in knots during a tow
levy	Levy on landings that pay for Challenger operations
Lnf	Maximum age a scallop attains
lph	Liters used per hour per vessel

m	Natural mortality
mh	Meters dredged per hour
mkmd	Meters covered per knot per minute per dredge
mr	Maintenance and repairs cost
mt	Minutes it takes to complete a typical tow
nd	Number of dredges used per vessel
permit	Permit cost
pd	Price of diesel/liter in Tasman Bay
ph	Phone cost
r	Age at which scallops in a subarea reach minimum size requirement
s	Sorting mortality
st	Stores cost
th	Number of tows made per hour
tq	Total quota remaining in the fishery
Indices:	
a	Age in years (*a* = 1, 2, …, A)
w	Week (*w* = 1, 2, …, W)
s	Subarea (*s* = 1, 2, …, S)
t	Time in years (*t* = 1, 2, …, T)
c	Vessel cluster (*c* = 1, 2, …, C)

Table III: List of Equations Used in the Simulation Model

Annual recruitment of spat	$N_{s,a=1,t=1,w=5} = PS_{s,t} + WS_{s,t}$	(Eq. 1)
Numbers at age by subarea	$N_{s,a,t,w} = N_{s,a=>r,t,w-1} * \left(\exp(-F_{s,t,w} - i - m)\right) + N_{s,a<r,t,w-1} * (1 - \exp(-F_{s,t,w})) * \exp(-s - m)$	(Eq.2)
Density in numbers by subarea	$D_{s,t,w} = \sum_a N_a / 10{,}000$	(Eq.3)
Fishing mortality by subarea	$F_{s,t,w} = \left(de * mh * df * hf * V_{s,t,w}\right) / asub$	(Eq.4)
Biomass of legal size scallops	$B_{s,a,t,w} = \left((N_{s,a,t,w} * MTWT_{s,a,t,w}) / 1000\right) / 1000$	(Eq.5)
Meatweight of individual scallops	$MTWT_{s,a,t,w} = e^{-15.6+3.955\ln(LENGTH_{s,a,t,w})}$	(Eq.6)
Length of individual scallops	$LENGTH_{s,a,t,w} = Lnf * (1 - \exp(-k / 52))$	(Eq.7)
Possible biological catch	$BC_{s,t,w} = \sum_a B_{s,a,t,w} * \left(F_{s,t,w} / (F_{s,t,w} + m + i)\right) * \left(1 - \exp(-F_{s,t,w} - m - i)\right) * 1000$	(Eq.8)
Possible legal catch	$LC_{s,t,w} = clm * cr * df * tq * (V_{s,t,w} / \sum_s V_{s,t,w})$	(Eq.9)
Catch in biomass by subarea	$C_{s,t,w} = \min(LC_{s,t,w}, BC_{s,t,w})$	(Eq.10)
Meters per hour	$mh = knots * nd * mt * th * mkmd$	(Eq.11)
Total revenue by vessel cluster	$R_{t,w,c} = \sum_z (p_{t,z} * C_{t,w,c,z})$	(Eq.12)

Total diesel cost by vessel cluster	$L_{t,w,c} = (dg * lph_c * df * hf_w * V_{t,w,c} * (SGB_{t,w} / SOPEN_{t,w})) +$ $(hgb * dg * lph_c * V_{t,w,c} * (SGB_{t,w} / SOPEN_{t,w})) +$ $(hgb * pd * lph_c * df * hf_w * V_{t,w,c} * (STB_{t,w} / SOPEN_{t,w}))$	(Eq.13)
Total weekly variable costs	$VC_{t,w,c} = L_{t,w,c} + levy + ACE_{t,w,c} + crew_c$	(Eq.14)
Total weekly fixed costs	$FC_{t,w,c} = (permit + gear) * V_c + ins_c + ee_c +$ $mr_c + ph_c + be_c + st_c$	(Eq.15)
Total weekly net returns by vessel cluster	$\prod_{t,w,c} = R_{t,w,c} - VC_{t,w,c} - FC_{t,w,c}$	(Eq.16)

Enhancement

To mimic egg distribution in the model, a submodel that produced a variable influx of eggs within a defined range was used. This type of submodel was chosen over more complicated recruitment models because it is thought to more closely resemble reality. A national park located within Golden Bay protects a portion of the parent stock of scallop. Because the national park waters are excluded from scallop dredging, this parent stock is thought to provide a consistent, somewhat stable supply of eggs each year. For this reason, a recruitment model that produces a consistent number of eggs within a certain range was developed.

The eggs develop into either wild or enhanced spat depending on whether they settle on natural benthic material or spat catching equipment. In the model, wild spat are distributed uniformly across all fishing grounds; however, the eggs only settle when density falls below a specified population density. In reality, spat would only be able to survive where there is sufficient food availability. This is thought to be determined by scallop density.

Several factors are considered by Challenger Scallops in deciding what subareas to chosen for enhancement or at what levels the chosen areas are enhanced. Typically, "An area that is suitable for scallop enhancement is one where the costs of enhancement will not exceed the estimated benefits (taking into consideration the various risks encountered)" [3]. Factors assessed when selecting seeding sites include: natural recruitment already settled, bottom type (silty bottom types produce a higher survival rate), predator density, incidental mortality risk (areas chosen with low oyster dredge and trawl activities), growth potential, quantity of source spat and area available for seeding, location of source spat (to minimize time our of water during transportation to seeding area), efficiency of recapture (to minimize dead shell sorting), risk of mass mortality, environmental sensitivity (some area have been identified as having particular scientific and ecological importance [3]. Given these factors considered each year, typically two to three areas are chosen for enhancement annually [5].

Due to a lack of ecological data, the model was not structured to consider all of these factors. At the beginning of a simulation run, the model allows the user to choose whether they would like a particular subarea to be reviewed for enhancement eligibility each year[b]. The model user identifies at what density of scallops enhancement is possible. Enhanced spat are seeded into the three least dense subareas open in any given year. The model enhances a maximum of two subareas each year with primary spat (juvenile scallop extracted from spat bags) and a maximum of one subarea each year with secondary spat (older juvenile scallop dredged from the ocean floor after falling off of spat bags).

Once scallop settle, twenty-one age-structured models are used to track the scallop subarea populations over five years which is believed to be the maximum age scallop reach before dying of natural mortality.

Fishery Economics

Distribution of Fishing Effort

The scallop model presented in this paper distributes fishing effort sequentially according to the economic value of spatial abundance within each subarea. A submodel created with Visual Basic macros were used to distribute fishing vessels over all open fishing subareas within a given week. In the model, the number of subareas open in any given year depends on the rotation schedule given by the user to that subarea. The number of subareas fished of the subareas open was determined in the following way. First, a value per meter was determined for each open subarea based on price according to average meatweight, availability for harvest based on scallop size and biomass per meter. Next, possible biological catch was determined based on biomass and fishing mortality for each subarea. Then, economic expectations of biomass and their associated possible biological catch are ranked from highest to lowest. The macros determine the number of subareas that would be fished if every vessel in the fleet took either all that was biologically available or legally allowed assuming that as many vessels as possible will go to the most economically valuable subareas. Vessels are distributed as a percentage based on biological availability for a subarea divided by the sum of the biological availability of all areas open. That is, the portion of the fleet distributed to a specific subarea is equal to the biological availability in that particular subarea to the aggregate biological availability of all subareas fished that week. This process is repeated each week of the fishing season. As a result, the number of subareas fished each week increases as the season progresses due to decreasing biological availability.

Fleet Costs and Earnings

Fleet costs and earnings were collected through a mail survey of permit holders in the scallop fishery. Single page cost surveys were sent to 43 people with a 49% response rate. Weekly diesel cost was calculated by estimating the number of vessels going to each bay each week multiplied by the bay specific price of diesel per liter, liter per hour diesel use by vessel cluster type, days fished each week, hours fished each day and the number of subareas being fished in a particular bay as a portion of open subareas.

Vessel Exit

In the model, all fifty-eight vessels participate in the scallop fishery for the first seven weeks. This information was based on observations by fisheries managers. Thereafter, vessel clusters exit the model for the year if average cluster revenue falls below a specified minimum amount of revenue needed to operate the fishing vessel. The revenue per week at time of vessel exit was collected from survey data and through personal conversations with fishermen with different sized vessels.

SIMULATION METHODS

The scallop model uses Excel and Visual Basic macros to conduct simulations. Previous research focused on finding the optimal overall rotation schedule, number of vessels in the fleet and daily catch limits (trip limits). Current research is focused on finding the optimal rotation strategy given the possibility of different types of mass mortality occurrences.

PREVIOUS RESEARCH - RESULTS AND DISCUSSION

Rotation

The model was run for fifty years under fixed three, four and mixed-year rotation schedules under fishery parameters estimated to reflect current fishery conditions. Under all rotation schedule scenarios, all but seven of twenty-one subareas are opened every three or four years. These seven subareas are not rotated and are open for potential harvest every year. This is based on historical management practices, which were created to allow for “as-available” harvest of subareas with low productivity and highly variable growth rates.

Under the three-year rotation scenario, all but the seven subareas opened for harvest each year are opened every three years. Under the four-year rotation scenario, all but the seven subareas opened for harvest each year are opened every four years. Subarea openings are staggered so that not all subareas are opened together in the same year. The mixed-year rotation schedule scenario sets the model to open subareas for harvest the year at which that subarea's scallop stock attains the legal size in the first seven weeks of the season. Under the mixed year settings, eight subareas are set to a three-year rotation schedule, six are set to a four-year rotation schedule and the remaining seven are not rotated. The subareas assigned three and four-year rotation schedules were chosen based on estimated subarea growth rates.

Catch and catch size category, average aggregate profitability and net present value per quota are listed in Table IV for each rotation schedule. There are two catch size categories: tons of "scallops equal to or greater than 12.5 grams" each and tons of "scallops less than 12.5 grams" each. Approximately 12.5 grams is the average size of a scallop in a meatweight kilogram of 80-count scallops. These scallops receive a premium price in the export market.

Table IV: Rotation Schedules Simulation Results in Metric Tons and New Zealand Dollars.

Rotation Schedule	Total Catch (t)	Scallops equal to or greater than 12.5 g (t)	Scallops less than 12.5 g (t)	Average Aggregate Profit ($NZ)	NPV per quota ($NZ)
Three year	576	98	479	$4,912,096	$164,801
Four year	430	348	82	$4,371,205	$154,054
Mixed year	**622**	**102**	**520**	**$5,273,438**	**$178,907**

The results indicate that the mixed-year rotation schedule scenario yields the greatest tonnage of catch, the highest average aggregate profits and the highest NPV. The four-year rotation schedule resulted in the shortest season (17 weeks) and the mixed rotation schedule had the longest (22 weeks). The four-year rotation had the lowest diesel costs due to the smaller number of subareas open each year. Although the mixed-year rotation appears optimal, subarea specific growth rate information is needed for implementation. The profit information in Table IV may be useful in determining whether growth rate estimation research is worthwhile to pursue. Currently, subareas are harvested when information from the annual stock assessment indicates they are ready for harvest. That is, no particular rotation schedule is strictly adhered to. This avoids the necessity of growth rate research but it increases the likelihood of high catch variability from year to year.

Fleet Size

The model was run for fifty years under various fleet sizes ranging from two to sixty in increments of ten vessels under the mixed rotation schedule scenario. The number of vessels within each cluster remained at a constant approximate proportion according to the cluster analysis results. The daylight hours restriction was relaxed allowing vessels to fish for up to 24 hours per day. Effort in the form of quota was shifted to the remaining number of vessels as vessel numbers decreased. All other regulations remained the same including daylight fishing only. Table V shows the results of those simulation runs. The results showed that total catch, average aggregate profit and NPV peak at twenty vessels. The results indicate that twenty vessels could take the same catch (if not more, with a longer season) as the current approximate sixty vessels and earn a total average aggregate profit of approximately $729,000 more each year, or approximately $950 more per quota held. This assumes the thirty vessels can be used to take the same amount of scallops as sixty vessels. Also, with twenty vessels, the season lasts longer than with sixty vessels. This increases the percentage of larger scallops caught as a portion of total scallops landed due to the fact that many scallops don't reach the average weight that receives the upper price tier until halfway through the fishing season. With sixty vessels, the season is shorter than with twenty vessels since catch per vessel for each cluster is relatively smaller and the revenue levels at which the vessels can no longer cover costs are approached sooner.

Table V: Fleet Size Simulation Results in Metric Tons and New Zealand Dollars.

Number of vessels	**Total Catch (t)**	**Scallops equal to or greater than 12.5 g (t)**	**Scallops less than 12.5 g (t)**	**Average Aggregate Profit ($NZ)**	**NPV per quota ($NZ)**
2	214	81	132	$2,270,182	$68,047
5	397	126	271	$4,080,090	$120,211
10	573	147	426	$5,656,020	$169,551
20	**657**	**129**	**529**	**$6,166,875**	**$185,716**
30	662	110	552	$6,017,286	$181,010
40	651	106	546	$5,778,705	$174,279
50	649	102	548	$5,585,330	$168,284
60	650	99	551	$5,437,958	$163,836

Catch Limitation

Catch limitation is the greenweight tonnage per quota or ACE held that a vessel is allowed to land. Catch limits were established in the fishery to control the amount of scallops coming into a processing facility each day. The catch limit is established by a group of processors each year based on the estimated workforce available for the season, since scallop shucking is labor intensive. Again, the model was run for fifty years with catch limitations of 100 to 200 greenweight tons at increments of ten greenweight tons per quota held under the mixed-rotation schedule scenario. Table VI shows the results from these simulation runs. Changes in the catch limit influence several aspects of the model. For example, a lower catch limit lengthens the fishing season by forcing catch to be taken at a slower rate which increases total catch and catch of larger scallops but also increases vessel operation costs relative to a large catch limit which shortens the season. A large catch limit results in lower aggregate catch but lower operational costs.

Table VI: Catch Limitation Simulation Results in Metric Tons and New Zealand Dollars.

Number of vessels	**Total Catch (t)**	**Scallops equal to or greater than 12.5 g (t)**	**Scallops less than 12.5 g (t)**	**Average Aggregate Profit** (1000s $NZ)	**NPV per quota** (1000s $NZ)
100	**658**	**128**	530	$5,081	$138
110	658	118	541	$5,180	$141
120	650	107	543	$5,219	$142
130	650	104	546	$5,316	$145
140	651	104	547	$5,408	$147
150	648	100	548	$5,442	$148
160	641	97	544	$5,442	$148
170	647	100	547	$5,527	$151
180	651	101	550	$5,603	$153
190	649	98	551	$5,612	$153
200	647	97	549	**$5,629**	**$153**

A catch limit of 100 greenweight kilograms per quota results in the highest total catch and the highest catch of large scallops. However, average profits are largest under a catch limit of 200 vessels due to the relationship between a shorter season and lower operational costs (which decrease with increasing catch limits).

CURRENT RESEARCH – RESULTS AND DISCUSSION

For simplicity, the model simulations reported above did not account for the occurrence of mass mortality instances. However, the New Zealand Challenger Scallop Fishery does experience mass mortality occurrences about once every 10 years [5]. Current research incorporates mass mortality occurrences of various kinds and examines catch and profit under different rotation schedules for each type of mass mortality occurrence. Specifically, the project seeks to answer the following questions: What rotation schedule strategies should be used under different mass mortality occurrence assumptions? Is there a dominant rotational strategy to take depending on the types mass mortality occurrences that manifest in an ecosystem?

The model was run for 25 years under 3 and 4-year rotation schedules. Table VII shows the results of these simulations under various mass mortality situations. Comparing the 3-year and 4-year rotation schedules under the situation of no mass mortality occurrences, the 3-year rotation schedule offers the highest total catch in metric tons, the larger number of small scallops, the highest and most stable average aggregate profit and the highest NPV. The 4-year rotation schedule offers the largest number of large scallops. In an environment that experiences mass mortality occurrences on all fishing grounds equally and simultaneously, the 3-year rotation schedule provides a higher catch and higher average aggregate profit but with greater instability relative to the 4-year rotation schedule. In an environment that experiences mass mortality occurrences in two consecutive years, the 3-year rotation schedule offers the highest average aggregate profit and NPV. In an environment that experiences mass mortality occurrences affecting each bay at different times, again the 3-year rotation strategy yields the highest catch, number of small scallops, average profit, and NPV. The 3-year rotation strategy is dominant due to it quicker recovery time from mass mortality occurrences.

Table VII: Different Rotation Schedules Under Various Mass Mortality Occurrences.

Simulation	Total Catch (MT)	Larger Scallops (MT)	Smaller Scallops (MT)	Average Aggregate Profit ($NZ)	NPV ($NZ)
Environment 1: No mass mortality *occurrences.*					
3-year rotation	**862**	158	**704**	**$7,334,239**	**$134,458**
4-year rotation	583	**478**	105	$6,033,524	$112,998
Environment 2: Two mass mortality occurrences *affecting each bay equally (Yrs. 8 & 17) and simultaneously.*					
3-year rotation	**786**	143	**643**	**$6,638,791**	**$116,668**
4-year rotation	512	**418**	93	$5,207,063	$93,848
Environment 3: Two consecutive mass mortality occurrences *affecting each bay equally (Yrs. 8 & 9) and simultaneously.*					
3-year rotation	**798**	142	**656**	**$7,023,124**	**$117,017**
4-year rotation	526	**429**	97	$5,366,513	$94,394
Environment 4: Two mass mortality occurrences affecting each bay at different times *(Tasman Bay: Yrs. 8 & 17, Golden Bay: Yrs. 10 & 19)*					
3-year rotation	**600**	115	**484**	**$5,932,199**	**$80,580**
4-year rotation	399	**328**	71	$5,054,904	$69,226

FUTURE RESEARCH ENDEAVORS

After the occurrence of an especially severe mass mortality occurrence, fisheries managers may feel pressure to deviate from a set rotation schedule or abandon rotation schedules altogether to avoid several subsequent years of relatively small catch and low profits. While this lessens the severity of profit shortfalls in the short-run, if rotation schedules are abandoned entirely, in the long-run the benefits made possible with implementation of rotation schedules will be lost. Future research will attempt to answer the following questions pertaining to this research area:

- Should a change in the rotation schedule strategy be made once a mass mortality occurs under the situation where a single mass mortality affects each bay equally?
    - Examine rotation under stochastic mass mortality and the best adaptive strategy to take after a mass mortality occurrence.
    - Analyze a no rotation option as a rotation strategy and as a strategy to implement after mass mortality occurrences.

The gear used to harvest scallops is often perceived as causing relative large environmental impacts in some fisheries. Future research will attempt to conduct the following tasks pertaining to environmental impacts, mitigation methods, and their economic tradeoffs:

- Would implementation of management measures that lessen incidental mortality be economically beneficial?
    - Assess the impact of different levels of incidental mortality through sensitivity analysis (more incidental mortality occurs under short rotation schedules and no rotation strategies).
    - Analyze the net benefits and tradeoffs of increasing or decreasing the minimum legal scallop size.

CONCLUSIONS

Results from previous research indicate that a mixed rotation schedule scenario that assigns subarea rotation schedules based on subarea specific growth rate information is optimal in this fishery under the model assumptions. When fishing ground subareas are opened for harvest at the average size needed to fetch the premium price, then average profits and the NPV are optimal. Although this finding seems logical, it requires subareas specific growth rate information and some complex modeling exercises to ensure that revenues are relatively stable from year to year. Subarea-specific growth rates vary from year to year requiring multiyear data collection efforts.

Results from previous research also suggest that the fleet size in the modeled fishery may be larger than needed to harvest the same amount of scallops than are currently being harvested. Approximately twenty vessels were found to optimize aggregate profits and NPV in the model. Various catch limitation scenarios were tested. The results don't indicate a clear advantage in average profitability or NPV of one catch limitation over another. However, there could be some advantages to either a low catch limitation resulting in vessels fishing longer each year than otherwise that allows for harvest of scallops just reaching the minimum size limit or larger size toward the end of the season, or a high catch limitation resulting in vessels staying for a relatively short number of weeks each year and lowering vessel operation costs and dredge impacts.

Results from current research indicate that under the assumptions used, the relatively shorter 3-year rotation schedule is advantageous for fisheries with various types of mass mortality occurrences. It is advantageous for catch maximization goals, profit maximization goals or goals that seek to maximize long term economic value based on NPV. However, fisheries with limited market opportunities for smaller scallops may have to opt for 4-year rotation schedules.

In every case shown, there is not a large difference between the average aggregate profit under mixed, 3, or 4 year rotation strategies allowing for other objectives besides profit maximization to perhaps influence decision making. For example, the 4-year rotation schedule often results in a shorter season than under the 3-year rotation schedule and therefore, lower fixed and variable costs. If fishery participants would like a shorter season than that indicated by the 3-year rotation schedule, then the 4-year rotation schedule may be optimal. If new information was found on the severity or how often mass mortality incidents occur and this information was incorporated into the model, results could change.

The importance of the type of model used here is stressed given the increasing role of fishermen and other stakeholders in resource management.

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ENDNOTES

[a] The subareas were determined by dividing the fishing grounds within each bay into geographical regions with the same growth rate based on GIS data from annual biomass surveys and personal communication with a fishery manager. Hectares within a subarea that consistently failed to yield a sufficient density of scallops during the biomass surveys were excluded from the modeled fishing grounds. In this way, the model accounts for patchy distribution of scallop beds where fishing effort is applied to productive scallop beds and areas known for very low population are left unfished. The model allows the user to change the size, number and growth potential of the subareas since they are assumed to change over time.

[b] Some areas are never enhanced due to high natural mortality or low growth.