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Bioeconomics of a Marine Disease

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January 2014

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Bioeconomics of a Marine Disease

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Abstract

We study the economic impact of the viral disease AVG, its stochastic transmission across abalone reefs in southern Australia, and the optimal management response as AVG approaches an uninfected reef. Using conservative estimates of the virulence and mortality rates associated with the disease, we find it optimal to maintain the pre-AVG steady-state biomass on reef j until AVG has reached reef $j-1$. The size of the optimal harvest when AVG has reached reef $j-1$ is significant, ranging from 85% of the pre-AVG steady-state stock plus its annual growth, to 100% when the mortality rate associated with the virus reaches 80%. Increases in the probability of transmission, P, also increase the size of the drawdown but to a lesser extent than the mortality rate. A regime shift in the intrinsic growth rate following infection also plays a central role in determining the level of pre-emptive harvesting.

Keywords: fisheries, bioeconomics, marine pathogens, disease transmission, epidemiology, optimal management.

JEL classification: Q2 (Renewable Resources and Conservation); Q22 (Fishery; Aquaculture)

1 Introduction and Overview

In December, 2005, several aquaculture facilities in Western Victoria, Australia, experienced unusually high mortality (up to 90%) in their stocks of farmed abalone. In February, 2006, the cause of that mortality spike was identified as a herpes-like virus never seen before in abalone in Australia. In May, 2006, the virus was reported in wild stocks near one of the aquaculture facilities. By early August, 2006, high abalone mortalities were reported in wild stocks five kilometers west and 12 kilometers east of the initial outbreak. The spread of what is now known as Abalone Viral Ganglioneuritis (AVG), through December, 2009, is shown in Figure 1 below. See Corbeil *et al.* (2010).

Figure 1: Spread of AVG (dark shading) by December, 2009, from Port Fairy, in December, 2005.

A class action has been brought against the State of Victoria and Southern Ocean Mariculture (SOM), on behalf of a group of abalone license holders. The suit alleges that effluent from SOM contained the AVG that subsequently spread to wild stocks of abalone. (AVG causes inflammation of nervous tissue and interferes with the abalone's ability to adhere to reefs and to feed.) The class action further alleges that the Victorian government was negligent in failing to (1) require appropriate biosecurity measures at SOM when it initially licensed their operations, and to (2) stop the discharge of effluent after the virus had been identified and declared an "exotic" disease on February 7th, 2006.

AVG has now spread to more than 280 km of coastline in the Western Zone of Victoria's abalone fishery. Some remnant abalone populations on reefs infected early in the pandemic are exhibiting slow recovery. See Mayfield *et al.* (2011). A critical question is whether these remnant populations have developed immunity to AVG, or whether they were simply lucky to have escaped the initial pandemic and would be susceptible to AVG should it reappear. Preliminary research by Crane *et al.* (2013) indicates that remnant populations remain susceptible to AVG. If this conclusion is correct, it may have profound implications for the future management of Victoria's wild abalone fishery. Specifically, if AVG can be viewed as a threat comparable to a forest fire, with some small but positive probability that it will occur in the next year, then the optimal harvest of abalone on a particular reef may depend on the proximity of AVG and whether the size of the abalone population prior to the arrival of AVG will influence the likelihood of its spread or the speed of recovery. There is the potential for countervailing effects. A large abalone population, when AVG arrives, may result in an increased probability of transmission to the next reef. In other words, would intensive harvesting of abalone prior to the arrival of AVG create a "firebreak?" At the same time, a large abalone population may result in a larger surviving population from which to start recovery.

In the next section we briefly describe the biology of abalone and the regulations that govern the wild fishery in Victoria, Australia. In Section 3 we develop a bioeconomic model where AVG induces a regime shift as it stochastically spreads along a coastline. In Section 4 we specify functional forms and parameter values for a representative reef in a system of J indentical reefs. Section 5 presents the results of extensive stochastic simulation, reporting the distribution of arrival times of AVG in our multi-reef system, the pre- and post-AVG population dynamics, and the distribution of discounted net revenue. Section 6 concludes.

2 Biology and Regulation of the Abalone Fishery in Victoria, Australia

Individual reefs in Southern Australia often contain biologically-independent abalone populations. This results from the fact that abalone are relatively immobile and that reefs may be spatially separated by sandy substrate which results in an oceanographic barrier to the mixing of eggs and sperm across meta-populations. McShane (1995) models the likelihood of mixing as declining exponentially with the distance between any two reefs.

Different reefs may be more or less hospitable to abalone, causing variation in (1) shell length at age, (2) possibly the age at sexual maturity, (3) egg production per female, and (4) weight of the foot muscle or "meat." Properly prepared, the meat of an abalone is regarded as a delicacy by some consumers who are willing to pay $100 or more for a single 150 gram serving. The biological independence of small-scale, meta-populations creates a very difficult, spatially-complex, management problem; where optimal management may require reef-specific *legal minimum shell lengths*, LMLs, and *total allowable catch caps*, TACCs. See Prince *et al.* (2008).

The abalone fishery in Victoria is a limited entry, individual-transferable-quota (ITQ) fishery. Management by reef-specific TACCs began on April 1st, 1988. Wild stocks of abalone are harvested by divers who own a license or are employed by a license holder. There are currently 71 licenses in the fishery (14 in the Western Zone, 34 in the Central Zone, and 23 in the Eastern Zone). Only one diver, per license, may be in the water harvesting abalone. Divers use "hookah gear", where air is supplied through a hose connected to a compressor on the deck of a support vessel. A deck hand monitors the compressor, keeps the boat positioned over the diver, and will haul up legal-sized abalone that are pried from a reef with a chisel-like iron bar.

Unless deeply in debt, license holders have an economic incentive to prevent overfishing. Associations of license holders and divers, such as the *Western Zone Abalone Diver's Association*, or WADA, have ocassionally specified *voluntary* minimum shell lengths and *voluntary* total allowable catch caps if they feel the legal minimum shell size or the legal TACCs might result in overfishing. This creates the rare situation where, for some reefs, the license holders might be more conservative than the managers! See Prince *et al.* (2008).

Reef-specific TACCs are assigned for a quota year that runs from April 1st to March 31st of the following year. Harvested abalone are transported in sealed bins to a licensed processor. Within one hour after landing, a diver must register his catch with *Fisheries Victoria* via an *Integrated Voice Response System*, or IVR, providing his diver ID, total weight of his catch, and the reef ID where the abalone were harvested. The licensed processor receiving that catch must also call the IVR to get the assigned catch number. This system allows *Fisheries Victoria* to monitor and cumulate landings during the quota year for each reef. When cumulative harvest equals the TACC for a particular reef, the fishery is closed on that reef for the remainder of the quota year. The IVR system also allows *Fisheries Victoria* to track harvested abalone through the supply chain. Most harvests of wild or farmed abalone are processed and shipped to wholesalers in Hong Kong, Japan, and China.

Prior to the spread of AVG, the wild fishery in the State of Victoria supported total landings of greenlip and blacklip abalone ranging from $1,328$ to $1,437$ metric tons, with a landed value of 46 to 70 million Australian Dollars (AD) per quota year. See Table 1. From the 06/07 season through the 10/11 season, the landings of abalone monotonically declined from $1,261$ metric tons to 781 metric tons.

Table 1: Quota Years, Landings (Metric Tons), Landed Value (Millons of AD), and Average Price (AD/kg) for Abalone from the State of Victoria, Autralia.

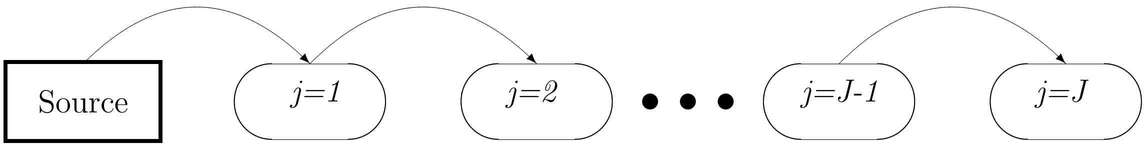
Quota Years	Landings	Landed Value	Average Price
00/01	1,436	70.387	49.02
01/02	1,437	62.486	43.48
02/03	1,384	53.658	38.77
03/04	1,426	46.549	32.64
04/05	1,358	60.181	44.32
05/06	1,328	49.735	37.45
06/07	1,261	45.932	36.43
07/08	1,195	37.983	31.78
08/09	1,001	26.556	26.53
09/10	942	21.933	23.28
10/11	781	23.873	30.56

Source: Australian Fisheries Statistics (2003 - 2012) and
http://www.dpi.vic.gov.au/fisheries/commercial-fishing/
commercial-fishing-production-2011/abalones-catch-effort

3 A General Bioeconomic Model

Suppose there are $j = 1, 2, \ldots, J$ reefs containing abalone along a stretch of coastline, as shown in Figure 2. For simplicity we will assume that the spread of the disease is uni-directional. Our model is easily modified to allow for simultaneous bi-directional spread (east and west), as was the case with AVG in Western Victoria. We also assume that the disease can only spread one reef per period.

Figure 2: Spread of Disease to Subsequent Reefs, from a Source at Left, Spreading to the Right.



The infection status of reefs in period t are indicated by the binary variables $B_{j,t}$, where $B_{j,t} = 0$ indicates that the j^{th} patch is not infected in period t, while $B_{j,t} = 1$ indicates that the j^{th} patch is infected in period t, $t = -1, 0, 1, \ldots, T$. We assume that infection is permanent (irreversible), so that $B_{j,t+1} \geq B_{j,t}$. With uni-directional spread, and assuming no jumps of more than one reef per period, $B_{j,t} \geq B_{j+1,t}$. We assume none of the reefs to be infected initially, so that $B_{j,-1} = 0$ for $j = 1, 2, \ldots, J$. The "front" of the disease will be at patch j in period t if $B_{j,t} = 1$ and $B_{j+1,t} = 0$. The status of the Source is indicated by $B_{0,t}$.

Once the source becomes infected, $B_{0,-1} = 1$ and it is possible that reef $j = 1$ may become infected in $t = 0$. It is assumed that AVG will spread stochastically, according to a probability vector with $1 > P_j > 0$ where

$$P_j = Pr(B_{j,t+1} = 1 \mid B_{j,t} = 0, B_{j-1,t} = 1). \tag{3.1}$$

Smaller values for P_j have the effect of slowing the spread. Also, if $B_{j-1,t} = 0$, then $Pr(B_{j,t+1} = 1 \mid B_{j,t} = 0, B_{j-1,t} = 0) = 0$.

Prior to the arrival of AVG we assume that the biological productivity of reef j can be described by a net growth function $F_j^0(X_{j,t})$ and that

$$X_{j,t+1} = X_{j,t} + F_j^0(X_{j,t}) - Y_{j,t} \tag{3.2}$$

where $X_{j,t}$ is the biomass of the abalone population and $Y_{j,t} \geq 0$ is the amount harvested from reef j in period t; both measured in metric tons. If the j^{th} reef becomes infected for the first time at the start of period t, there is a significant mortality hit (die off) and subsequent biological productivity is permanently impaired (a regime shift has occurred) as indicated by

$$X_{j,t+1} = [1 - (B_{j,t} - B_{j,t-1})M]X_{j,t} + F_j^1([1 - (B_{j,t} - B_{j,t-1})M]X_{j,t}) - Y_{j,t}. \tag{3.3}$$

In Equation (3.3), $1 > M > 0$ is the one-time mortality hit when AVG first arrives at a reef at the start of period t. When $B_{j,t+1} = B_{j,t} = 1$, the surviving abalone population is less productive because $F_j^1(X_{j,t+1}) < F_j^0(X_{j,t+1})$.

Define $G_j^1(X_{j,t}) = [1 - (B_{j,t} - B_{j,t-1})M]X_{j,t} + F_j^1([1 - (B_{j,t} - B_{j,t-1})M]X_{j,t})$ and $G_j^0(X_{j,t}) = X_{j,t} + F_j^0(X_{j,t})$. It is then possible to combine Equations (3.2) and (3.3), allowing the infection indicator, $B_{j,t}$, to determine how $X_{j,t+1}$ is to be computed. Specifically

$$X_{j,t+1} = (1 - B_{j,t})G_j^0(X_{j,t}) + B_{j,t}G_j^1(X_{j,t}) - Y_{j,t}. \tag{3.4}$$

In month t, let net revenue, summed over all reefs, be given by

$$N_t = \sum_{j=1}^{J} p_t Y_{j,t} - Q_t C_t \tag{3.5}$$

where p_t is the "beach price" per kilogram for abalone in period t, Q_t are the number of active license holders in month t, and C_t is the sum of variable and fixed costs for the average license holder in month t.

Let $\rho_m = 1/(1+\delta_m)$ be the monthly discount factor, where $\delta_m > 0$ is the monthly rate of discount. Recall that the spread of AVG is a stochastic process. Even with P_j fixed, the arrival time of AVG to a particular reef is a random variable and therefore discounted net revenue will also be a random variable. Let $s = 1, 2, \ldots, S$ be a simulation index, where S denotes the number of stochastic simulations to be conducted. The present value of net revenues for simulation s can be computed as

$$N_s = \sum_{t=0}^{T} \sum_{j=1}^{J} \rho_m^t [p_t Y_{j,s,t} - Q_t C_t] \tag{3.6}$$

where $Y_{j,s,t}$ is the harvest from reef j, in simulation s, in month t. The evolution of the abalone population and optimal harvest on each reef may be different from simulation s to simulation s' because the arrival time of AVG to each reef may be different. One can plot distributions (histograms) of the arrival time of AVG to each reef and the distribution (histogram) for discounted net revenue, N_s for $s = 1, 2, \ldots, S$.

4 A Simple Specification

The Stochastic Spread of AVG

Suppose there are $J = 22$ reefs and our analysis covers $T = 96$ months. Our model of uni-directional spread, with a maximum jump of one reef per month, requires the specification of $P_j = Pr(B_{j,t+1} = 1 \mid B_{j,t} = 0, B_{j-1,t} = 1)$. Suppose that $P_j = P = 0.4$. This assumption results in closed-form expressions for the probability density functions (PDFs) and the cumulative density functions (CDFs) for the arrival time of AVG at reef j when it is currently at the source in $t = -1$. In Table 2 we show the PDFs for reefs $j = 1, 2, 3, 4, 5, 6$.

The pattern which emerges in Table 2 allows us to infer that the PDF for reef j becoming infected at $t \geq 0$ is given by

$$Pr[j, t] = \frac{P^j (1-P)^{t-(j-1)} \prod_{i=0}^{j-2} (t-i)}{(j-1)!} \tag{4.1}$$

Table 2: The probability Reef j will become infected in month $t \geq 0$ given $B_{0,-1} = 1$.

j	Pr[j,t]
1	$(1-P)^t P$
2	$(1-P)^{t-1} P^2 t$
3	$(1/2)(1-P)^{t-2} P^3 (t-1)t$
4	$(1/6)(1-P)^{t-3} P^4 (t-2)(t-1)t$
5	$(1/24)(1-P)^{t-4} P^5 (t-3)(t-2)(t-1)t$
6	$(1/120)(1-P)^{t-5} P^6 (t-4)(t-3)(t-2)(t-1)t$

with the CDF given by

$$Pr[j, t \leq \tau] = \sum_{t=0}^{t=\tau} Pr[j, t] \tag{4.2}$$

In Figures 3, and 4, we show the probabilities that AVG will arrive in month t at reefs $j = 1$, and $j = 2$, 6, 14, and 22 respectively, when $P_j = P = 0.4$ and $B_{0,-1} = 1$. The expected theoretical arrival time at reef j is given by $(j - P)/P$. For $P = 0.4$, we can expect the virus to arrive at $j = 1$ on average 1.5 months after its detection at the source, and for the AVG to advance on average every 2.5 months. Thus, the expected arrival times at reefs 2 and beyond are $t = 4$, $t = 6.5$, $t = 9$, etc... In Table 3, we list the mean, median, and standard deviation of the AVG arrival time for all reefs in $S = 2,000$ stochastic simulations. The mean arrival times in our simulations are consistent with theoretical predictions.

A key aspect of the diffusion process described by Equation (4.1) is the distance of the source from an uninfected reef. In fact, what matters is the distance of an uninfected reef from the AVG front. Suppose that the front is at reef $j - 3$ at the start of month t. We can reset month t to be $t = 0$ and reef $j - 3$ to be the source. Then, $Pr[j - (j - 3), t] = Pr[3, t]$. This feature will be extremely helpful when trying to determine optimal harvest (behavior) as AVG moves closer to an uninfected reef.

Logistic Net Growth Before and After the Arrival of AVG

We assume logistic net growth with $F_j^0(X_{j,t}) = r_j^0 X_{j,t}(1 - X_{j,t}/K)$ prior to the arrival of AVG at reef j and $F_j^1(X_{j,t}) = r_j^1 X_{j,t}(1 - X_{j,t}/K)$ after the arrival of AVG. For our exploratory analysis we assume that all $J = 22$ reefs are identical with $r_j^0 = r^0 = 0.030$ before the arrival of AVG, and $r_j^1 = r^1 = 0.018$ after the arrival of AVG. Note, these r-values are monthly intrinsic growth rates.

Figure 3: Probability of AVG Arrival at Reef $j = 1$ in Month t.

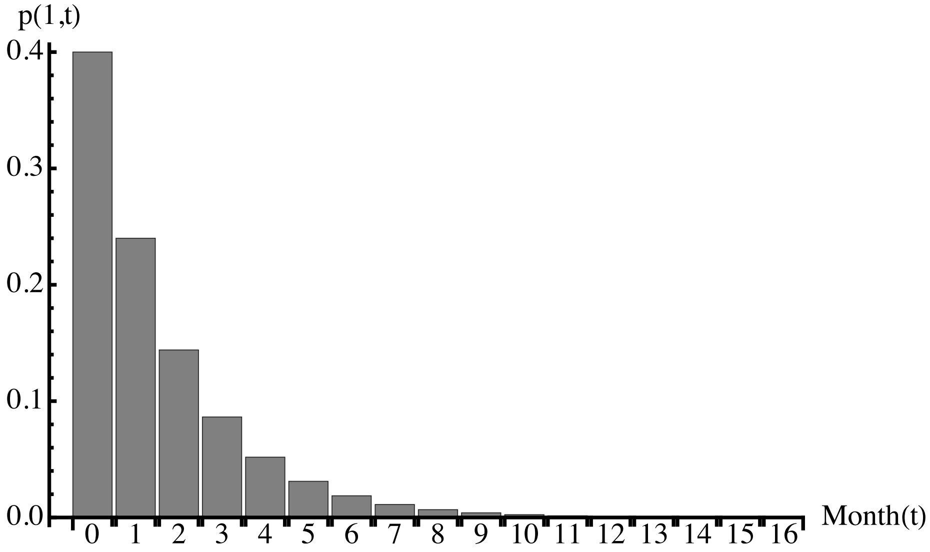


Figure 4: Probability of AVG Arrival at Reefs $j = 2,6,14$ and 22 in Month t.

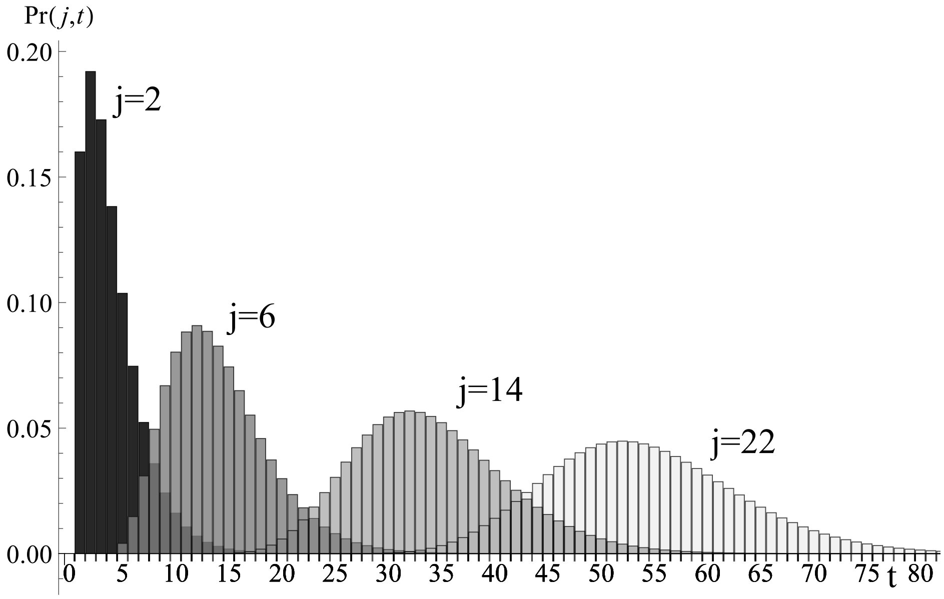


Table 3: The Mean, Median, and Standard Deviation of AVG Arrival Time for All $J = 22$ Reefs based on $S = 2,000$ Simulations.

Reef Number	Mean Arrival Time	Median Arrival Time	Standard Deviation
1	1.564	1	2.008
2	4.050	3	2.748
3	6.544	6	3.295
4	9.145	8	3.807
5	11.620	11	4.276
6	14.186	14	4.737
7	16.672	16	5.081
8	19.181	19	5.484
9	21.641	21	5.823
10	24.112	24	6.091
11	26.618	26	6.382
12	29.177	29	6.676
13	31.640	31	6.950
14	34.082	33	7.204
15	36.577	36	7.473
16	39.045	38	7.788
17	41.562	41	8.035
18	44.137	44	8.327
19	46.664	46	8.506
20	49.259	49	8.699
21	51.747	51	8.971
22	54.242	54	9.227

We assume that carrying capacity on our representative reef is $K = 180$ mt, and that it is unchanged by AVG. Because Equation (3.6) is linear in harvest, $Y_{j,s,t}$, and harvest cost does not depend on stock size, the optimal steady-state biomass before the arrival of AVG can be shown to be $X^0_{SS} = K(r^0 - \delta_m)/(2r^0)$ mt and that the optimal steady-state harvest will be $Y^0_{SS} = K((r^0)^2 - \delta^2_m)/(4r^0)$. Suppose that the monthly discount rate is $\delta_m = 0.01$. Then, the values for r^0, K, and δ_m imply that before the arrival of AVG the optimal steady-state biomass on our representative reef is $X^0_{SS} = 60$ mt which will support an optimal steady-state monthly harvest of $Y^0_{SS} = 1.2$ mt. When AVG reaches our representative reef, and the intrinsic growth rate permanently drops to $r^1 = 0.018$, the new optimal biomass and monthly harvest will be $X^1_{SS} = K(r^1 - \delta_m)/(2r^1) = 40$ mt and $Y^1_{SS} = K((r^1)^2 - \delta^2_m)/(4r^1) = 0.56$ mt, respectively. We also know that if the biomass drops below X^1_{SS} after the arrival of AVG, it will be optimal to set the TACC to zero, *i.e.*, $Y_{j,s,t} = 0$, so as to move $X_{j,s,t}$ up to X^1_{SS} as rapidly as possible. In other words, if $X_{j,s,t} < X^1_{SS}$, it is optimal to adopt a moratorium on harvest until $X_{j,s,t} \geq X^1_{SS}$.

Net Revenue

Our model assumes that there are $Q = 14$ abalone licenses and that license holders, or their designated diver, can access any reef at the same marginal cost. With 22 identical reefs producing 1.2 mt of abalone per month, total monthly production would be 26.4 mt when summed over all reefs. This would imply an annual production of 316.8 mt.

The “beach price” is set at $p = \$30/kg$. The monthly, steady-state, harvest of 26.4 mt would imply a monthly, gross revenue of $\$792,000$ for the fishery and an average monthly revenue of $\$56,571$ per license. The cost of fishing a license during a typical month is the sum of variable opportunity costs for time and monthly fixed costs that are independent of the hours spent working a license. We assume a monthly cost function where $C = \omega h + \phi$, where $\omega = \$60/hour$ is the opportunity wage for a commercial diver, $h = 80$ $hours$ are the number of hours spent working an abalone license in a typical month, and $\phi = \$5,000$ is a monthly fixed cost for maintaining a boat, truck, trailer, equipment, insurance, interest payments, and bookkeeping. These parameter values imply a monthly cost per license of $C = \$9,800$ and a monthly *net revenue* of $N^0_t = \$46,771$ per license. Annual net revenue per license would be $N^0_a = \$561,252$.

Table 4: Parameter or Benchmark, Definition, Value.

Parameter	Definition	Value
$J = 22$	Number of Reefs	$j = 1, 2, \ldots, 22$
$T = 96$	Number of Months	$t = 0, 1, 2, \ldots, 96$
$S = 2,000$	Number of Simulations	$s = 1, 2, \ldots, 2,000$
P	Monthly Jump Probability to Next Reef	0.4
r^0	Monthly Intrinsic Growth Rate, *Pre-AVG*	0.030
r^1	Monthly Intrinsic Growth Rate, *Post-AVG*	0.018
K	Reef Carrying Capacity, *Pre- and Post-AVG*	180 *mt*
X^0_{SS}	Steady-State Biomass/Reef, *Pre-AVG*	60 *mt*
X^1_{SS}	Steady-State Biomass/Reef, *Post-AVG*	40 *mt*
Y^0_{SS}	Steady-State Harvest/Month/Reef, *Pre-AVG*	1.2 *mt*
Y^1_{SS}	Steady-State Harvest/Month/Reef, *Post-AVG*	0.56 *mt*
Y^0_t	Total Monthly Harvest, *Pre-AVG*	26.4 *mt*
Y^0_a	Total Annual Harvest, *Pre-AVG*	316.8 *mt*
Y^1_t	Total Monthly Harvest, *Post-AVG*	12.32 *mt*
Y^1_a	Total Annual Harvest, *Post-AVG*	147.84 *mt*
M	AVG Mortality Rate	0.40
p	Beach Price	$\$30,000/mt$
h	Hours Worked/License/Month	80 *hours*
ω	Opportunity Wage/hour	$\$60/hour$
ϕ	Fixed Cost/License/Month	$\$5,000$
Q	Number of Licenses in Western Zone	14
δ_a	Annual Discount Rate	0.12
δ_m	Monthly Discount Rate	0.01
C	Monthly Cost/License	$\$9,800$
N^0_t	Monthly Net Revenue/License *Pre-AVG*	$\$46,771$
N^0_a	Annual Net Revenue/License *Pre-AVG*	$\$561,252$
V^0	Value of a License *Pre-AVG*	$\$4,723,871$
N^1_t	Monthly Net Revenue/License *Post-AVG*	$\$16,600$
N^1_a	Annual Net Revenue/License *Post-AVG*	$\$199,200$
V^1	Value of a License *Post-AVG*	$\$1,676,600$

Are the above numbers plausible? With an annual net revenue per license of $N^0 = \$561,252$ we can calculate the value of a license in a steady-state fishery prior to AVG as $V^0 = (1+\delta_a)N^0/\delta_a$, where $\delta_a = 0.12$ would be a reasonable estimate for the annual rate of discount during the heydays of the fishery, $2000 - 2006$. These values imply that $V^0 = \$4,723,871$. On March 27th, 2006, an inquiry about the purchase price of an abalone license in the State of Victoria, elicited an estimate of $\$5 - 6$ *million.* Our license value of $V^0 = \$4.7$ million falls just below this range.

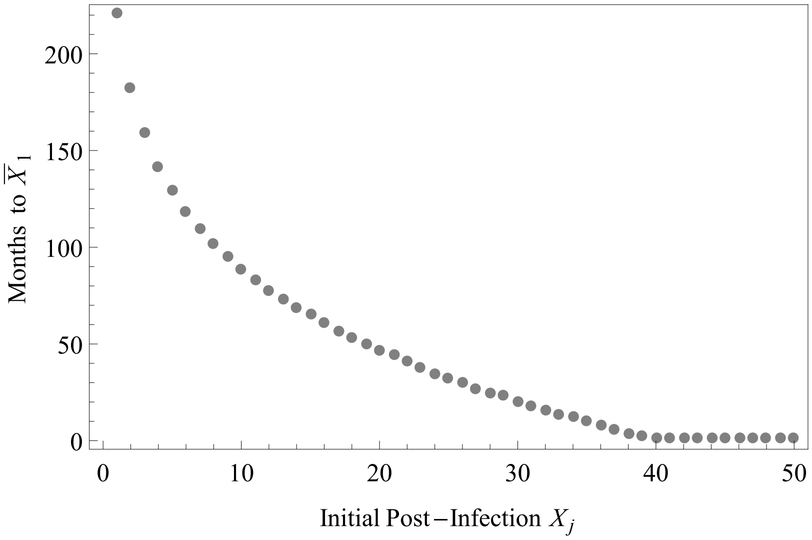
After the arrival of AVG, our representative reef, at its new steady state, is producing 0.56 *mt* per month and the fishery as a whole is producing 12.32 *mt* per month. This implies an annual harvest of 147.84 *mt*. At a beach price of $\$30/kg$, the fishery is generating a monthly gross revenue of $\$369,600$ and annual gross revenue of $\$4,435,200$. For a license holder with the same monthly cost of $\$9,800$, monthly net revenue has dropped to $N_t^1 = \$16,600$ and annual net revenue has fallen to $N_a^1 = \$199,200$. The value of a license *post-AVG*, when $\delta_m = 0.01$, is now $V^1 = (1+\delta_m)N^1/\delta_m = \$1,676,600$. Parameter values and present value calculations are summarized in Table 4.

5 Preliminary Results

Expected Discounted Revenue with AVG
In this section we present preliminary results focusing on the reduction in the present value of revenue and profits caused by the sequential spread of AVG. There are at least two ways to estimate the financial consequences of AVG. In a world without AVG, the present value of revenues from a representative reef would be $\$3,636,000$ *AD*. Similarly, if we assume that harvesting costs for the 14 license holders are equally distributed across all reefs, the net present value of profits for a representive reef without AVG is $\$3,006,127$. These numbers serve as a benchmark for comparison with the expected losses from AVG. The stochastic arrival of AVG at a given reef produces a distribution of losses for each reef. Reefs that are more distant from the source suffer smaller losses on average since AVG tends to arrive later.

The first, and easiest way to compute the potential losses from AVG is to assume that managers set allowable harvest at $Y_{SS}^0 = K((r^0)^2 - (\delta_m)^2)/(4r^0)) = 1.2$ in all periods prior to the arrival of AVG (all biomass and harvest numbers are measured in metric tons). When AVG reaches a reef in month t, biomass drops from its steady state value of $X_{SS}^0 = 60$ to $(1-M)X_{SS}^0 = 36$ and we assume that a moratorium on fishing is immediately imposed. Thus, the biomass in $t+1$ will be $X_{t+1} = (1-M)X_t + r^1(1-M)X_t(1-(1-M)X_t/K) = 36.518 < X_{SS}^1 = 40$. As long as $X_{t+1} < X_{SS}^1$, the moratorium remains in place. With an initial population of 60 and $M = 0.4$ it would take eight months for the stock to recover to the post-AVG steady state level. A Most Rapid Approach Path would normaly call for harvesting to resume in the month before it would naturally reach X_{SS}^1, with the corresponding harvesting level tailored to avoid overshooting of the steady state. Because of the existence of fixed costs, however, it turns out that waiting the extra month is always beneficial. Figure 5 shows the number of months it takes for different population levels to recover from the time of infection to the post-AVG optimal stock.

Figure 5: Duration of Moratorium as a function of Post-Infection Biomass



In the case of the initial post-AVG population at 36 mt, the moratorium lasts 8 month ($t = 0$ to 7) and in the ninth month, the stock is $X_{t+8} = 40.30$. The first post moratorium harvest is $(X_{t+8} + r^1 X_{t+8}(1 - X_{t+8}/K) - X^1_{SS}) = 0.866mt$. This adjusts the stock to its post-virus steady state and corresponding new harvest level $Y^1_{SS} = 0.56$. Because all reefs are identical, arrival of the virus triggers the same eight-month moratorium, followed by one period of adjustment and resumption of fishing. The only difference between reefs is the anticipated arrival time of the virus.

This scenario assumes that harvest is not changed from Y^0_{SS} even if the virus has been detected at other reefs. We refer to this as the "myopic" scenario, and it will be compared with the expected present value of revenue when optimally modifying the level of harvest prior to the arrival of AVG. Determining the optimal harvest on reef j in month t when the front for AVG is at reef $j - k$ will require the solution of a dynamic optimization problem using stochastic dynamic programming. We report the results of the myopic scenario first.

Recall from Equation (3.6) that the present value of revenue from reef j in simulation s can be calculated as $R_{j,s} = \sum\limits_{t=0}^{\infty} \rho^t_m p_t Y_{j,s,t}$. We ran $S = 2,000$ simulations. Starting with an infected source in $t = -1$, the virus infects reef 1 in $t = 0$ with probability

$P = 0.4$, in which case the moratorium is immediately imposed and no harvesting takes place until the reef has recovered to its post-AVG equilibrium level. With probability $(1 - P)$, the virus does not arrive at the first reef in $t = 0$ and at least one period of harvesting takes place.

Table 5 reports the impact of AVG on expected revenue and profits for each of the 22 reefs based on the simulation data. These numbers are computed over an infinitely long time horizon (i.e. they assume that the post-AVG steady state harvesting is infinitely maintained after the end of the moratorium). The financial values are net present values at $t = 0$.

Table 5: Expected Present Value of Reef Revenue, Profits, and AVG-Induced Losses Myopic Management - 2,000 simulations over 22 Reefs.

Reef Number	Expected Net Present Revenue	AVG-Induced Revenue Reduction	Expected Net Present Value of Profits	AVG-Induced Profit Reductions
1	1,606,864	2,029,136	1,024,453	1,981,674
2	1,656,111	1,979,889	1,072,547	1,933,580
3	1,704,317	1,931,683	1,119,626	1,886,501
4	1,753,344	1,882,656	1,167,507	1,838,621
5	1,798,794	1,837,206	1,211,893	1,794,234
6	1,844,745	1,791,255	1,256,770	1,749,358
7	1,888,232	1,747,768	1,299,239	1,706,888
8	1,930,973	1,705,027	1,340,980	1,665,147
9	1,971,882	1,664,118	1,380,933	1,625,195
10	2,012,050	1,623,950	1,420,161	1,585,967
11	2,051,764	1,584,236	1,458,946	1,547,181
12	2,091,299	1,544,701	1,497,557	1,508,571
13	2,128,420	1,507,580	1,533,809	1,472,318
14	2,164,356	1,471,644	1,568,905	1,437,223
15	2,200,170	1,435,830	1,603,881	1,402,247
16	2,234,669	1,401,331	1,637,573	1,368,555
17	2,269,076	1,366,924	1,671,175	1,334,952
18	2,303,331	1,332,669	1,704,629	1,301,498
19	2,336,230	1,299,770	1,736,759	1,269,369
20	2,369,160	1,266,840	1,768,919	1,237,208
21	2,399,850	1,236,150	1,798,890	1,207,237
22	2,429,884	1,206,116	1,828,222	1,177,905

Table 5 shows that the expected present value of revenue and profits are lower, and therefore the reduction in the expected present value is greater, the closer a reef is to the source of the virus. The total reduction in the present value of revenue over all $J = 22$ reefs sums to \$34,846,479 AD. These results critically depend on (1) the distributions of arrival times when $P_j = P = 0.4$, (2) that the intrinsic growth rate is $r^0 = 0.03$ before the arrival of AVG and drops to $r^1 = 0.018$ after the arrival of AVG, (3) that the mortality rate when AVG arrives is $M = 0.4$, and (4) that there are $J = 22$ identical reefs along our stretch of coastline. Finally, profit levels are also sensitive to assumptions made about the costs attributed to each reef during the moratorium and beyond. The numbers shown in Table 5 assume that no costs are attributed to reef j during the moratorium, and that they revert to their original level once the reef reopens, despite the lower harvesting level. In reality, some operators may continue to incur some or all of their fixed costs during a moratorium, but may also spend less on production once harvesting must be lowered to the post-AVG level. While these two effects counteract each other, they could be modeled more precisely if more accurate information was available on the industry's adjustments to reef closure and recovery.

Stochastic Dynamic Programming and Optimal Harvest with the Threat of AVG
The myopic approach of harvesting Y^0_{SS} until the arrival of the virus turns out to be a suboptimal strategy. In this section we develop and solve the Stochastic Dynamic Programming problem of maximizing the net present value of harvesting from reef j, when the state of the system can be described by the stock level X_t on reef j and the location of the AVG front is at reef $j - k$. The Bellman Equation is an optimality condition for determining the harvest on reef j, Y_t when waiting for AVG. The Bellman Equation requires that the optimal Y_t to

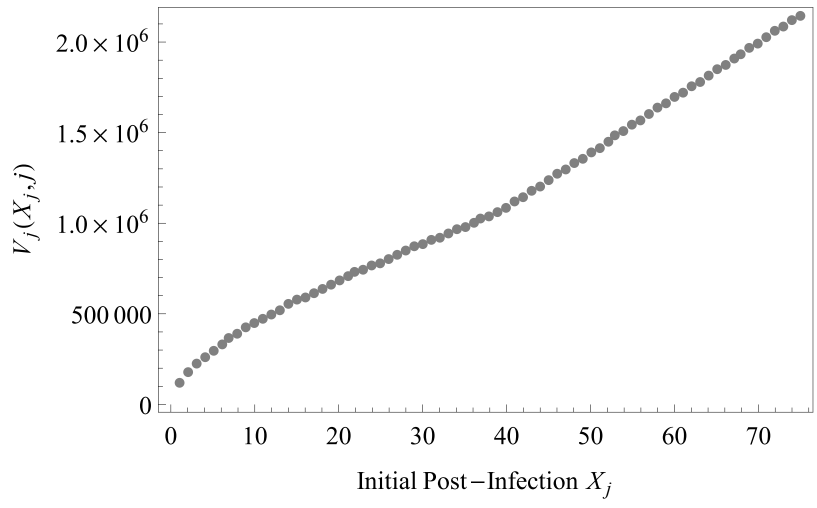
$$\begin{aligned}\underset{\{Y_t\}}{Max}\, V_{j,t}(X_t, j-k) = {} & pY_t - Q_tC_t/J \\ & + P\rho V_{j,t+1}\left(X_t + F^0(X_t) - Y_t, j-k+1\right) \\ & + (1-P)\rho V_{j,t+1}\left(X_t + F^0(X_t) - Y_t, j-k\right)\end{aligned} \tag{5.1}$$

Equation 5.1 defines $V_t(X_t, j-k)$ as the value of reef j at time t given that the current stock is X_t and the virus is $j-k$ reefs away. If we know that the virus is $j-k$ reefs away when the harvesting decision is made (*i.e.* before we observe if the virus has jumped a reef at the beginning of the period, $t+1$), harvesting Y_t produces a monthly profit $pY_t - Q_tC_t/J$ and leads to a stock $X_{t+1} = X_t + F^0(X_t) - Y_t$ at the beginning of period $t+1$. With probability P, the virus will then jump from reef $j-k$ to $j-k+1$ at the beginning of $t+1$. A different way of saying this is that with probability P, reef j will have to be considered from the perspective of a reef with stock X_{t+1}, but where harvesting in the next period will have to be chosen with the knowledge that the virus has arrived at reef $j-k+1$. Consistent with our previous definition, the value of this reef would be $V_{j,t+1}\left(X_t + F^0(X_t) - Y_t, j-k+1\right)$ which must be discounted back one period for consistency in summimg dollars across time. On the other hand, there is a probability $(1-P)$ that the virus will remain at $j-k$ at the beginning of period $t+1$. The value of the resulting stock in $t+1$ (prior to next period's harvesting decision but after the state of the virus is observed) is $V_{j,t+1}(X_t + F^0(X_t) - Y_t, j-k)$ to which the discount factor is also applied.

The problem takes on a slightly different flavor when the virus reaches reef $j-1$. After the harvest decision in time t, the probability P refers to the likelihood that reef j will be infected at the beginning of next period. If infection occurs, mortality takes place and the moratorium is imposed until recovery to the post-AVG steady state stock when harvesting resumes. Hence, with probability P, the value of the stock will be $V_{j,t+1}((1-M)(X_t + F^1(X_t) - Y_t), j)$.

For any given set of parameters, these values can be computed for any initial post-AVG stock. For our chosen parameters and a founding post-AVG biomass of 36, the value of the just infected reef is $1,003,720$AD. Figure 6 shows more generally how this value increases with a greater initial post-AVG stock. Initial stocks lower than 40 require a moratorium and growth of the stock prior to the resumption of fishing. This explains the concave shape of the post-AVG value function up to $X_j = 40$. Post-infection founding populations at or above $X^1_{SS} = 40$ do not require a moratorium since the infection leaves more abalone on the reef than are required to sustain the post-AVG steady-state fishery. Since all of the excess is taken immediately in the MRAP solution, the marginal value of a unit of stock is simply the price it fetches discounted one period. This produces a linear function above the stock of 40.

Figure 6: Value at the time of infection of a newly infected reef



Note that any expression of $V(\bullet)$ produced with the algorithm is consistent with the timing of events whereby harvesting decisions are made after observing the state of infection. Thus, the optimal value and harvesting decisions for $t = 0$ are continuation values conditional on the virus not having moved at the beginning of $t = 0$. The expected value of the same reef when the virus is discovered at the source (*i.e.* at t=0, but before knowing if it will infect reef 1 in t=0) can then be obtained as $\mathrm{V}^s_{j,0} = PV_{j,0}\,(X_0, j-k+1) + (1-P)V_{j,0}\,(X_0, j-k)$. For reef $j = 1$, $V_{j,0}\,(X_0, j) = ((1-M)(X_0), j)$ is the value of the reef at the time of infection (at the end of $t = 0$).

The solution to Equation 5.1 is approximated by solving the equation recursively over a finite time horizon ($T = 15$ for $k = 1$, then for $k > 1$). The terminal assumption is that if the virus has not jumped from one reef to the next in T months, it arrived with probability one in T+1. Such a truncation is necessary since it could, in theory, take an infinite amount of time for the virus to infect the next reef. However, the probability that the front of the infection does not move for 15 months is equal to $(1-P)^{15}$, which for $P = 0.4$ amounts to 0.00047. The error introduced by the truncation of the problem should therefore have an imperceptible impact on the expected profits and optimal harvest levels.

The numerical algorithm proceeds through the following steps, starting with the reef closest to the front of the infection ($j-1$):

1. Beginning with month T and repeating backward
    (a) Take in turn each value of $X_t \in [1, K]$
        i. For each possible harvesting levels in the discretize grid $Y_t \in [0, X_t + F^0(X_t)]$, compute $V_{j,t}(X_t, j-k)$ as per Equation 5.1 and the particuliarities described above if $k = 1$.
        ii. Identify the harvesting level $Y^*_t(X_t)$ that maximizes $V_{j,t}(X_t, j-k)$;
        iii. Retain in memory the optimal harvest $Y^*_t(X_t)$ and corresponding value $V^*_{j,t}(X_t, j-k)$;
        iv. Estimate a continuous function $Y^*_t(X_t)$ from the pairs $(X_t, Y^*_t(X_t))$
    (b) Estimate a continuous function $V^*_{j,t}(X_t, j-k)$ from the pairs $(X_t, V^*_{j,t}(X_t, j-k))$.

The estimation of continuous functions from the grid of possible X and Y values makes it possible for the numerical algorithm to consider choosing a time path that is not restricted to the discrete grid, and one thus obtains a better numerical approximation of the true solution. It is also computationally far more efficient. Once this process has reached $t = 0$, the known initial stock level can then be used to calculate $V^*_{j,0}(X_0, j-k)$, and the previously recorded value $Y^*_t(X_t)$ recalled as the optimal harvesting level. From there, one can iterate forward using $X_{t+1} = X_t + F^0(X_t) - Y^*_t(X_t)$ to recover the optimal harvesting rates at reef j. The resulting time paths and associated values are optimal solutions conditional on the virus not advancing in time t. Since $V^*_{j,0}(X_0, j-k)$ is also conditional on the information that the virus has not advanced at $t = 0$, obtaining the unconditional value of the reef at the true begining of time requires making the adjustment discussed in conjunction with Equation 5.1.

We solved the Stochastic Dynamic Problem for all combinations of $P \in [0.1, 0.9]$ and $M \in [0.1, 0.9]$ each in intervals of 0.1. Table 6 provides an example of the resulting output for the first two reefs (presenting the first 10 periods).

Table 6: Optimal Harvesting Program For Reef $(j-2)$ and $(j-1)$ - $P = M = 0.4$

Time since AVG arrival at $j-2$	X_{j-2}	Y_{j-2}	Time since AVG arrival at $j-1$	X_{j-1}	Y_{j-1}
0	60	1.2210	0	60	58.381
1	59.979	1.1970	1	2.8192	0.2070
2	59.9818	1.2001	2	2.6955	0.1535
3	59.9814	1.1998	3	2.6216	0.1260
4	59.9815	1.1998	4	2.5732	0.1096
5	59.9814	1.1998	5	2.5300	0.0990
6	59.9814	1.1998	6	2.5158	0.0918
7	59.9814	1.1998	7	2.4983	0.0868
8	59.9814	1.1998	8	2.4855	0.0831
9	59.9814	1.1998	9	2.4759	0.0804
10	59.9814	1.1998	10	2.4687	0.0784

Reefs further away from the virus have solutions qualitatively identical to reef $j-2$ in Table 6 and so are not shown. Taken together, the solutions yield four interesting results.

1. It is optimal to depart from the pre-AVG steady-state optimum only when AVG arrives at the neighboring reef, thereby causing a direct threat of infection to reef j in the following period. [1]

2. When AVG arrives at the neighboring reef, it is optimal to significantly drawdown (harvest) the abalone population even if the probability of arrival of AVG in the

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[1] Technically speaking, the results of Table 6 for $j-2$ prescribe a small deviation from the steady state stock of 60 *mt* and the corresponding harvesting rate of 1.2. However, there is no apparent theoretical reason for doing so. Our conjecture is that this is an artifact of solving this problem over a finite time period and imposing an artificial terminal condition, as well as the unavoidable approximations that numerical computation imposes. The level of error is probably far less than the real uncertainty surrounding our parameter estimates.

next period is small. Table 6 illustrate this process. As long as the virus remains at $(j-2)$, it shows that the stock should be kept at its steady state level. At some random point in time, the AVG will jump to the neighboring reef. The jump changes the state of infection for reef j from $j-2$ to $j-1$. For the purpose of reading the Table 6, the time of arrival at $(j-1)$ is reset to $t=0$, and we read the optimal harvest level from the first row of the new state of infection. If the stock was previously kept at it steady state level of 60, $Y^*_{j-1} = 58.38$, or more than 97% of the biomass present of the beginning of the period.

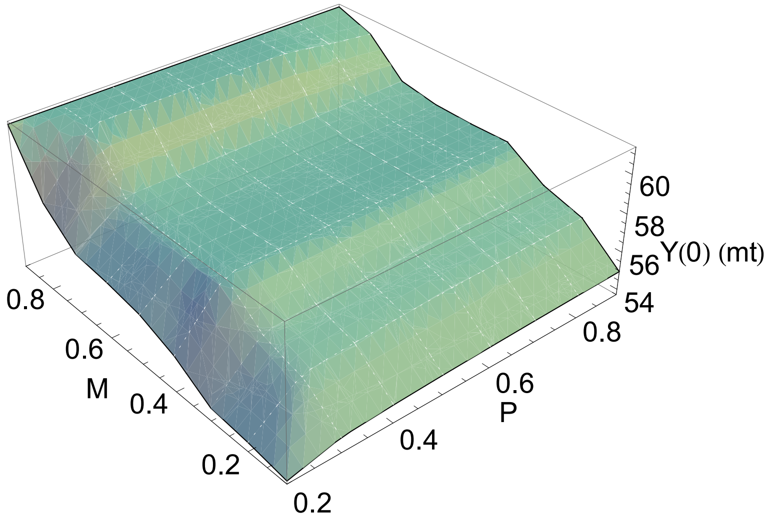
Table 7 and Figure 7 show how drastic the optimal harvest (drawdown) of the population on reef j should be once the risk of infection becomes imminent (i.e. when the virus arrives at $j-1$). Regardless of the mortality or risk of transmission, the vast majority of the stock should be harvested. Furthermore, with mortality rates of 80 and 90%, a complete depopulation of the of the reef becomes optimal. The reasons for the dramatic reduction of the stock prior to its arrival can be traced primarily to two reasons: 1) the long term impact of AVG on the rate of growth r; and 2) how the mortality rate affects the costs and benefits of immediate harvesting through its interplay with the length of the moratorium. It is important to note that if harvest costs increase as biomass is reduced, the size of the drawdown would likely be less.

Table 7: Optimal Harvesting Level at reef j upon infection of reef $j-1$

		M								
		$\frac{1}{10}$	$\frac{2}{10}$	$\frac{3}{10}$	$\frac{4}{10}$	$\frac{5}{10}$	$\frac{6}{10}$	$\frac{7}{10}$	$\frac{8}{10}$	$\frac{9}{10}$
	1/10	51.03	52.75	55.45	56.36	57.72	57.76	61.20	61.20	61.20
	2/10	53.86	54.18	54.38	55.56	56.29	56.62	56.83	58.28	61.20
	3/10	54.50	56.13	56.81	58.34	58.30	58.33	58.66	61.20	61.20
	4/10	54.64	56.33	56.93	58.38	58.34	58.38	58.70	61.20	61.20
P	5/10	54.74	56.43	57.02	58.42	58.38	58.42	58.74	61.20	61.20
	6/10	54.81	56.53	57.10	58.44	58.40	58.45	58.78	61.20	61.20
	7/10	54.87	56.57	57.16	58.47	58.42	58.47	58.80	61.20	61.20
	8/10	54.92	56.61	57.21	58.49	58.44	58.49	58.83	60.84	61.20
	9/10	54.96	56.64	57.25	58.50	58.46	58.52	58.85	60.55	61.20

First, imagine that the virus did not kill any abalone $(M=0)$ but still affected the reproduction rate. In this context, the arrival of the virus at reef j would shift the steady state population from 60 to 40. Given our assumptions about the profit function, it would be optimal to immediately harvest all stocks in excess of 40, adjusting the stock to its new steady-state level. This would not necessarily proceed entirely before the infection, but the probability of arrival combined with discounting should lead to the drawdown beginning before the infection is

Figure 7: Optimal Drawdown as a Function of P and M



detected. We can conclude from this that an important proportion of the stock reductions observed in Table 7 are the result of the effect the virus has on the growth rate alone.

Of course, the virus does kill a proportion of the stock. To see clearly how this affects the optimal harvesting decisions, consider first a mortality rate approaching 100%. With the reef almost completely decimated when the virus arrives, it makes economic sense the to harvest the entire reef. The problem is reduced to choosing between harvesting and selling the natural capital for a profit in now or seeing it destroyed by the virus, with no benefits to show for it. (There are some benefits of holding on to some biomass since the virus arrives next period only with some probability P. However, since $X_{SS}^0 = 60$ corresponds to 50 months of steady state harvesting, the financial risk of maintaining a high stock is simply too high. This explains why the probability of transmission has a minor impact on the optimal harvesting rate).

As the mortality rate decreases, however, one must consider how much more to harvest beyond the approximately 20 *mt* to be harvested due to the impact of the virus on r. Thus, let's consider whether or not one should reduce the stock below 40 when the mortality rate is $M = 0.2$. With the stock at 40 when the virus arrives, the population drops to 32 at the beginning of the moratorium. It would take a moratorium of 16 months for the stock to recover. If we further reduced the stock to 39 prior to infection, the moratorium would be two months longer. Thus, the benefits of keeping the marginal tonne is roughly two months of harvesting at the Y^1_{SS}. If $P = 0.4$, the virus will arrive and moratorium will be imposed on average in $1/P = 2.5$ months. Therefore, the two years of additional benefits from conserving the stock would be collected on average 18.5 months into the future. For our parameters, the present value of these benefits is $\$4,564$. One the other hand, harvesting immediately would generate immediate revenues of $\$30,000$. Even if a licensee incurred a full year's costs to harvest this tonne, the immediate net profits would only be reduced to $\$21,200$, far above the benefits of conserving that tonne. One should conclude that it is beneficial to harvest the marginal tonne and bring the stock below 40.

Figure 5 is useful in understanding the benefit-cost tradeoffs associated with the impact of the mortality rate. For population levels close to 40 before the arrival of the virus results in a biomass of $(1 - M)40$ afterwards. Further reducing the population results in a relatively small extension of the moratorium. As the post-virus biomass is reduced to very low levels, however, the additional moratorium time becomes increasingly large. Thus, the marginal cost of further reductions in the stock becomes larger and eventually exceeds the benefits of harvesting prior to the arrival of the virus. We note, however, that the large marginal increases in the length of the moratorium (the steep part of the curve in Figure 5 are associated with very low biomass (i.e. $X < 10$). This explain why most optimal harvesting plans take the stock to very low levels, but also why very large mortality rates make it optimal to fully depopulate the reef.

3. The size of the drawdown only increases slightly as P increases;

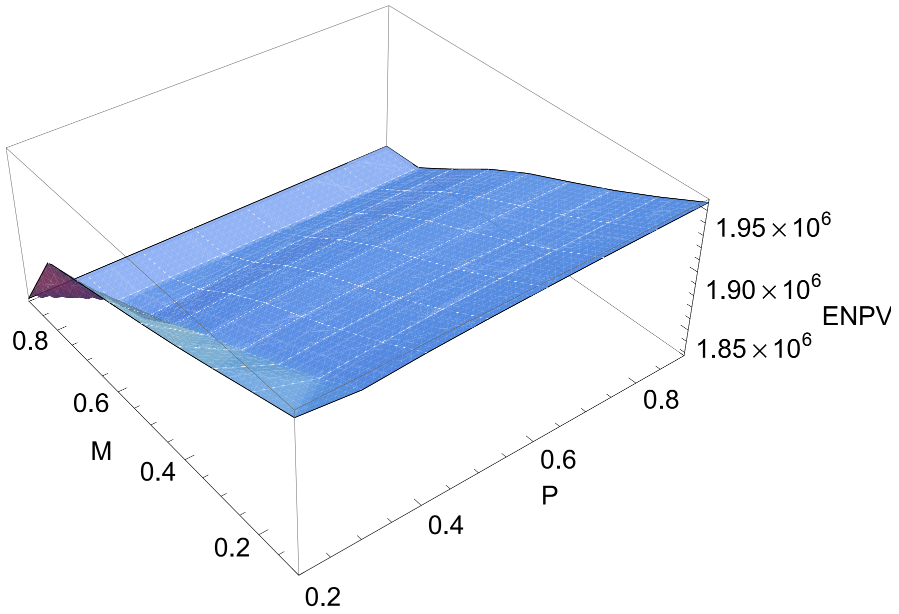
4. As the AVG mortality rate, M, increases, keeping P constant, the size of the drawdown increases initially ($M = 0.3, 0.4$) then stabilizes before increasing again for larger values of M. Non-smooth marginal variations are often observed in discrete-time programming.

Figure 7 shows that the magnitude of the drawdown is far more sensitive to the mortality rate M than the probability of transmission, P. This can be traced back to the double impact of the the virus on both r and M. We have already pointed out that regardless of P and M, the eventual arrival of the virus will trigger the need for a drawdown due to the regime switch. Thus, keeping M constant and varying the probability of arrival has little effect on the optimal drawdown. On the other hand, increasing M while keeping P constant is increasing the amount of abaloine biomass that will be lost if not harvested. It therefore pays to react to a greater mortality rate by increasing the proportion of the initial stock harvested in the drawdown.

Increasing either P or M decreases the expected value of any reef j but the ability to react pre-emptively and optimally to the expected arrival of the virus makes a large difference in the resulting value of a reef. Figures 8 and 9 illustrate the difference.

Figure 8 represents the net present value of a reef when the virus arrives at $j-1$ conditional on having the option to draw the stock down in that period. On the other hand, Figure 9 assumes that the virus could unexpectedly arrive at reef j in that period. The abilty to harvest heavily from the stock avoids large losses. For instance, with $P = M = 0.4$, the NPV is \$1.90 million if it possible to optimally draw the stock down and only \$1.53 million if the presence of the virus is not known or if no action is taken before its arrival. In the more likely scenario that $P = M = 0.9$, the difference is \$1.83 million vs. $\$480,040$.

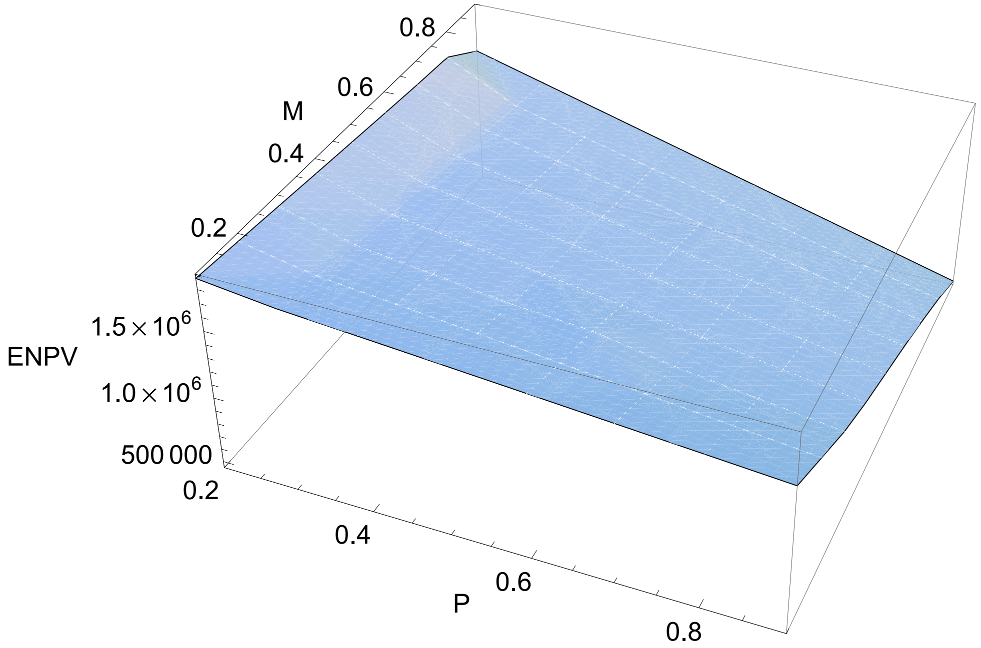
Figure 8: Conditional Expected Value of Reef j, $X = 60$ when AVG arrives at $j-1$



The optimal solution derived above can also be used to obtain distributions of the expected value of profits for all reefs using the simulation data. These results for $P = M = 0.4$ were obtained by applying the optimal harvesting solution to the simulation data. The optimal harvesting program begins immediately upon the virus being detected at reef $j-1$ and continues until reef j gets infected (recall, however, that reef 1 can be infected without prior warning in $t = 0$). The results are presented in Table 8. It shows that the optimal management regime results in significant increases in profits when compared to the myopic management regime of harvesting steady state levels until the arrival of the virus.

We can also sum up the net present value of each of the twenty two reefs in a particular simulation to obtain a distribution of the net present value of the entire fishery in that simulation. Dividing by the number of licensees provides the economic value of an

Figure 9: Unconditional Expected Value of Reef 1 at $t = 0$



average license in that simulation. Figure 10 draws the histogram of the NPV of a license under both the optimal and myopic management regimes. It shows that the optimal management regime of drastically reducing the stock always strictly dominates the myopic management regime. The mean NPV of a license is \$3.323 million AD when optimal harvesting is employed, but only \$2.293 million AD under myopic harvesting. Considering that the average pre-AVG license is worth \$4.724 million AD, roughly 58% of AVG losses can be avoided by choosing to systematically reduce the size of the stock. Said differently, the myopic regime results in a loss of 52% of the entire fishery's value while the optimal approach limits the losses to roughly 30% of the pre-AVG value of the abalone fishery when $P = M = 0.4$.

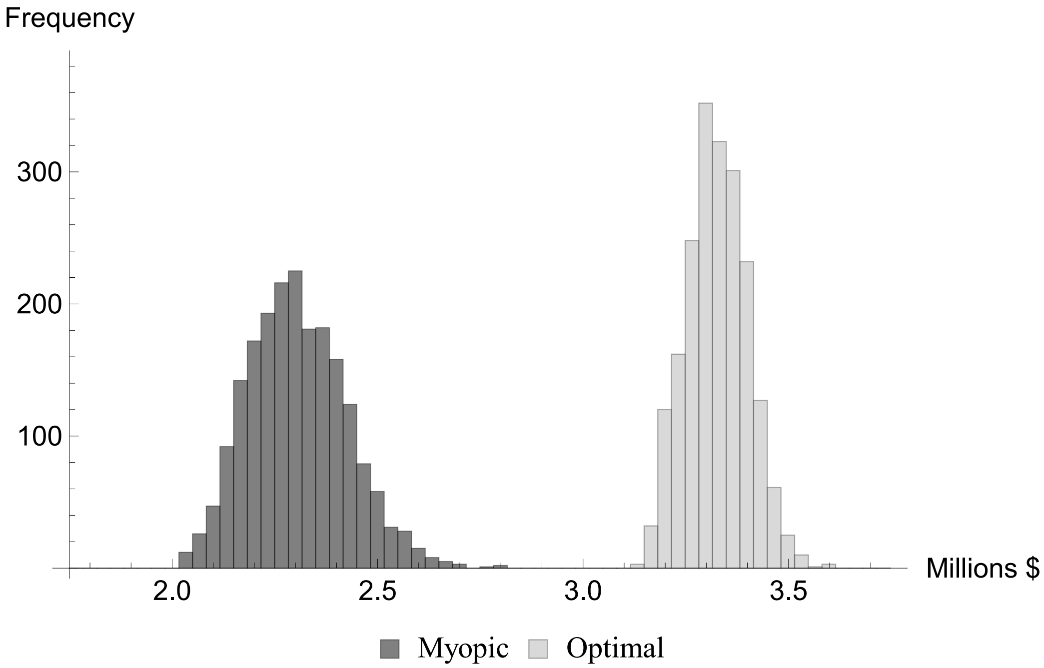
Discrete Regime Shift and Allee Effect

We also solved the model (1) without regime shift (the net growth function is unchanged after the arrival of AVG) and (2) when net growth exhibits an Allee effect with critical depensation. The presence of a regime shift, resulting in impaired (lower) net growth, does significantly affect size of the size of the harvest (drawdown) when AVG is one reef away. Consider the row where $P = 4/10$ in Table 7 and $M = 8/10$. The optimal harvest with the prospect of a regime shift is $Y_t = 61.2$ (i.e. complete elimination of the stock). Without a regime shift the harvest is reduced to $Y_t = 53.48$. If we denote the harvest with regime shift by Y_t^R and harvest without regime shift by Y_t^W, then $Y_t^R > Y_t^W$ and the difference, $(Y_t^R - Y_t^W)$, is larger for lower values of M. Compared to the situation with a regime shift, the value of a license would be

Table 8: Expected Present Value of Reef Profits Optimal Vs. Myopic Management - $2,000$ simulations over 22 Reefs.

Reef Number	Mean Profits (Optimal)	Mean Profits (Myopic)	Difference
1	1,542,540	1,024,453	518,087
2	1,911,518	1,072,547	838,971
3	1,937,989	1,119,626	818,363
4	1,963,374	1,167,507	795,868
5	1,990,558	1,211,893	778,665
6	2,014,567	1,256,770	757,797
7	2,039,757	1,299,239	740,518
8	2,063,149	1,340,980	722,169
9	2,086,442	1,380,933	705,510
10	2,108,435	1,420,161	688,274
11	2,129,926	1,458,946	670,979
12	2,151,125	1,497,557	653,569
13	2,172,887	1,533,809	639,078
14	2,193,001	1,568,905	624,096
15	2,212,189	1,603,881	608,309
16	2,231,629	1,637,573	594,056
17	2,250,014	1,671,175	578,839
18	2,268,386	1,704,629	563,757
19	2,286,995	1,736,759	550,237
20	2,304,501	1,768,919	535,582
21	2,322,708	1,798,890	523,817
22	2,339,229	1,828,222	511,007

Figure 10: Net Present Value of a License - Optimal vs. Myopic Harvest Policy



30% higher without a regime shift when $P = M = 0.1$, and nearly 200% higher when $P = M = 0.9$.

It was suggested to us by a marine biologist (Kevin Lafferty, personal communication) that growth effects following virus infections are more likely to be transient and take the form of an Allee effect. It was also suggested that reef dynamics likely impose a critical population at around 10% of carrying capacity. We therefore replaced the logistic growth function with a net growth function exhibiting critical depensation. Specifically $F_j^0(X_{j,t}) = F_j^1(X_{j,t}) = rX_{j,t}(X_{j,t}/K_1 - 1)(1 - X_{j,t}/K_2)$, where $K_2 = 180$, $K_1 = 20$. We completed the calibration of the function by setting the growth parameter to $r = 0.0065028$. This is the growth rate required to make this model deliver the same steady state harvest level of 1.2 mt per month assessed in the original model. By extension, the two models produce the same pre-AVG license value. Solving the model for $P = M = 0.4$, indicates that it is optimal to harvest the entire stock immediately (from its new steady state stock level of 104). This is a far more aggressive policy than the drawdown with a logistic growth function and discrete regime shift and it reflects two important differences between the two models, both of which make keeping positive stocks less beneficial. First, if the drawdown and subsequent AVG mortality brought the population to between zero and $K_1 = 20$, net growth would then be negative, making it optimal to immediately remove all remaining abalone. The AVG mortality being significant makes it financially attractive to avoid this situation. This means a drawdown that brings the population below $K_1/(1-M)$ will almost always be less valuable than a complete harvesting of the reef. In addition, recovery times under the Allee effect model tend to be much slower than under the original model. This increases the length of the moratorium that follows AVG, providing an additional incentive to completely remove abalone from the reef prior to the arrival of AVG.

6 Discussion

This paper presents a spatial bioeconomic model dealing with the stochastic spread of a disease that induces a regime shift in the net growth of a renewable resource. This stylized model was motivated by the spread of AVG along the coastline of Victoria, Australia. There is much that we do not know about AVG, abalone biology, and the cost of participating in the wild fishery. Our model and results may not accurately depict the biological or financial consequences of AVG. The objective of this paper was to develop a model that would (1) stimulate discussion between biologists and economists, (2) suggest modifications that might make it more realistic, (3) identify the data needed to more accurately predict the biological and economic consequences of AVG (or other marine diseases), and (4) determine how resource managers might respond to future pandemics that threaten valuable marine resources. We briefly review the results from this paper and then discuss three important areas of fundamental uncertainty (1) the possibility of an irreversible regime shift; (2) the form of the cost function and optimal adaptive management; and (3) the stochastic spread of AVG.

Results
(1) Our model of the stochastic spread of AVG was strictly sequential, with a given probability that AVG would jump from its current front on reef $j-1$ in period t to reef j in period $t+1$. When the probability of that jump is the same between all reefs, there are analytic expressions for the probability density functions and cumulative distributions that reef j will become infected in period $\tau > t$ when reef $j-k$ is infected in period t.

(2) In our model, it is optimal to maintain the pre-AVG steady-state biomass on reef j until AVG has reached reef $j-1$. Because drawdown of the stock is optimal (as opposed to building up the stock before the arrival of AVG), one period provides sufficient time to harvest healthy abalone before the possible arrival of AVG.

(3) The size of the optimal drawndown (harvest) on reef j when AVG has reached reef $j-1$ is significant, ranging from 85% of the pre-AVG steady-state stock plus growth $(X^0_{SS}+r^0X^0_{SS}(1-X^0_{SS}/K))$ up to 100% for values of $M \geq 0.8$. See Table 7. Increases in P also increase the size of the drawdown but to a lesser extent than M. So the mortality inflicted by a disease that threatens a valuable marine resource is important in determining the optimal adaptive response when the disease spreads.

(4) Our model can be calibrated to yield plausible license values prior to AVG and one can compute the distribution of license values post-AVG under myopic behavior (no drawdown) and under optimal drawdown on reef j when AVG has reached reef $j-1$. Optimal drawdown before the arrival of AVG reduces the financial loss to license holders in the wild fishery by almost 22%.

Irreversible Regime Shift

The model in this paper assumed that a post-AVG world would involve a permanent shift to a regime of lower biological productivity. We do not know if this will be the case, but the history of abalone populations in other marine ecosystems would seem to indicate a transition to a less productive, less resilient resource. The possibility of regime shift is purely speculative in the current model. Removing the regime shift from our model illustrated how it can be a significant source of losses associated with AVG. On the other hand, a model with cubic function that embodies both an Allee effect that more perniciously affect growth as well as a critical population threshold shows that both exacerbate the cost of AVG to the fishery and leads to optimal eradication of the stock.

Cost Functions and Adaptive Response

Resource economists are interested in optimal allocation over time and space. When a model is stochastic, so that the level of state variables in the future depend in part on the realization of random variables, optimal allocation will typically involve finding an optimal *feedback policy* using dynamic programming. In our current model of AVG, one of the state variables is the location of the AVG front and the adaptive feedback policy for reef j tells us how much should be harvested, given the current biomass on reef j, and the proximity of AVG. As noted previously, there are two opposing incentives. One incentive is to harvest healthy abalone before AVG reaches reef j. The other is to leave more biomass, which would increase the surviving biomass, and hasten the recovery and reopening of the fishery. The form of the cost function is important in determining optimal steady-state biomass, both pre- and post-AVG, and the level of drawdown (harvest) when AVG is imminent. In our current model the cost of fishing is essentially a fixed cost and does not depend on the level of harvest or reef biomass. This structure had analytic advantages in determining pre- and post-AVG optimal biomass and implied that the optimal approach to a new steady-state optimum would be most rapid. The nature of the cost function for license holders and divers in the wild fishery is not known and could significantly change our results. In particular, the result that it is optimal to wait until the virus is at reef $j-1$ to draw down the stock is largely dependent on the assumption that the cost of harvesting does not vary with population density or more than proportionally with harvesting level. If it were the case that attempting to remove all or a very large proportion of the remaining stock raised the average cost per abalone harvested significantly, it could become optimal to drawdown the stock over more than one month.

Stochastic Spread of AVG

The analysis of AVG assumed it was spread by wind and current along the Victorian coast. After introduction at a source, this process was viewed as exogenous to the model. The location of reefs might require different probabilities, based on the distance between reefs down-wind or down-current from the AVG front An unanswered question is whether biomass prior to the arrival of AVG on a reef, and thus the viral-laden material after the arrival of AVG, might influence the probability of a jump to the next reef. An alternative to the exogenous model in this paper would be a dynamical system similar to a host-parasite model where AVG and marine species interact over time and space and where the virus emerges at a certain host density, and then dies out when host density drops below a threshold. It is worth noting however, that a model in which higher abalone density increases viral load in the water column, and therefore the probability of transmission between reefs, would provide even greater incentives to reduce reef populations prior to the arrival of the AVG.

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