
Bioeconomics of a Marine Disease

Jon M. Conrad, *Cornell University*; Daniel Rondeau, *University of Victoria*

ABSTRACT

We study the adaptive harvest of healthy stocks of shellfish that are faced with the risk of high natural mortality from a disease that is spreading along a coastline. This was the situation when Abalone Viral Ganglioneuritis (AVG) spread along the coast of Victoria, Australia in 2006. Abalone mortality on some reefs was thought to have been as high as 90%. In the face of an approaching virus, how should stocks at different reefs be managed? A stochastic, spatial bioeconomic model allows us to examine how optimal preemptive stock reductions are influenced by: (1) the probability of spread, (2) the mortality induced by AVG when it reaches a previously uninfected reef, (3) the form of the harvest cost function, and (4) a regime shift to lower biological productivity, post-AVG.

Key words: Fisheries, adaptive management, bioeconomics, marine pathogens, stochastic disease transmission, epidemiology, optimal management.

JEL Codes: Q2, Q22.

INTRODUCTION AND OVERVIEW

In December, 2005, Southern Ocean Mariculture (SOM) 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 was identified as a herpes-like virus never seen before in abalone in Australia. The virus causes inflammation of nervous tissue and interferes with the abalone's ability to adhere to reefs and feed. In May, 2006, the virus was reported in wild stocks in Taylors Bay near SOM. By early August 2006, high abalone mortality was reported in wild stocks up to 5 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 1.¹

A class action suit was brought against SOM and the State of Victoria, on behalf of a group of abalone license holders, divers, and processors. The action alleged that effluent from SOM contained the AVG that subsequently spread to wild stocks of abalone and that the State of Victoria failed to exercise its "duty of care" by not shutting down SOM after the virus was identified.

In an interesting sequence of legal decisions, the plaintiffs and SOM reached a court-approved settlement on October 14, 2013. The financial terms of that settlement remain confidential. Then, on November 7, 2013, Supreme Court Justice David Beach dismissed the class action against the State of Victoria. The judge argued that the State of Victoria did not owe exclusive duty of care to the plaintiffs, but needed to balance that duty with the eco-

Jon M. Conrad is a professor, Dyson School of Applied Economics and Management, Cornell University, 409 Warren Hall, Ithaca, NY 14853 USA (email: jmc16@cornell.edu). **Daniel Rondeau** is a professor, Department of Economics, University of Victoria, Victoria, British Columbia, Canada V8W 2Y2 (email: rondeau@uvic.ca).

1. See Corbeil et al. (2010) for additional discussion on the spread of AVG.

Received December 16, 2014; Accepted March 5, 2015; Published online July 13, 2015. <http://dx.doi.org/10.1086/681546>

Marine Resource Economics, volume 30, number 4. © 2015 MRE Foundation, Inc. All rights reserved.
0738-1360/2015/3004-0003\$10.00.



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

economic interests of SOM. Further, the judge found uncertainty about causation. The appearance of AVG in the farmed stocks at SOM in December of 2005, and in wild stocks in April and May of 2006, may have been caused by AVG being present in Taylors Bay, as opposed to it originating in the effluent from SOM. The decision is being appealed.

Regardless of the ultimate legal outcome, the presence of a highly virulent, lethal virus at various distances from healthy reefs raises the question of how to best manage abalone stocks on those reefs prior to the arrival of AVG. Specifically, if AVG is spreading along a coastline, at what distance from the “infection front” does it become optimal to draw down the stock at an uninfected (currently healthy) reef? How does: (1) a reef’s distance from the AVG front, (2) the probability of AVG jumping to the next reef along a coastline, (3) the mortality inflicted by AVG, and (4) the form of the cost function governing harvest, affect the timing and level of drawdown from the pre-AVG, steady-state stock?

In addition to proximity, probability of spread, mortality, and cost of drawdown, there is a potential for regime shift, as in Polasky, deZeeuw, and Wagener (2011). Some remnant abalone populations on reefs infected early in the pandemic are exhibiting slow recovery (Mayfield et al. 2011). Preliminary research by Crane et al. (2013) indicates that remnant populations remain susceptible to AVG. If this is correct, surviving populations may have lower intrinsic growth rates with potentially profound implications for the future management of Victoria’s wild abalone fishery.

What are the contributions of this article? We develop spatial bioeconomic models that are particularly suited for analyzing the spread of a pathogen across valuable meta-populations. To our knowledge, this article is the first examination of the role of optimal preemptive harvest and the factors that influence the level and location of harvest; including the: (1) likelihood that the disease will jump to the next meta-population, (2) mortality rate induced by the pathogen when it reaches a previously uninfected population, (3) role of linear and nonlinear (stock-dependent) harvest costs, and (4) presence or absence of a regime shift to lower biological productivity, post-infection. Stochastic dynamic programming is used to determine the level of preemptive harvest. Our numerical results provide a benchmark for future research on pathogens affecting biological resources. We numerically observe that increases in either the probability of a jump (P) or the rate of mortality (M) increase preemptive harvest, but pre-

emptive harvest is more sensitive to the mortality rate. Linear harvest cost allows preemptive harvest to be delayed until the pathogen has reached the adjacent meta-population. Nonlinear, stock-dependent harvest costs require optimal preemptive harvest to begin when the pathogen is more distant. A regime shift further increases the level of preemptive harvest. Our models and numerical analysis provide new insights to the adaptive management of renewable resources faced with the risk of mortality by a marine disease.

In the next section we review the emerging literature on spatial-bioeconomic models. In the third we briefly describe the biology of abalone and the regulations that govern the wild fishery in Victoria, Australia. In the fourth section we develop a bioeconomic model where AVG induces a regime shift as it stochastically spreads along a coastline. In the fifth section we specify functional forms and parameter values for a representative reef in a system of J identical reefs. This is followed by the results of simulation, stochastic dynamic programming, and sensitivity analysis. The final section concludes.

SPATIAL-DYNAMIC PROCESSES, DISEASE, AND REGIME SHIFT

Wilen (2007) defines a spatial-dynamic model as involving a “biophysical process that generates potentially predictable patterns that evolve over space and time.” When an economic dimension is added to such a model it raises questions not only about the optimal timing and intensity of economic actions, but also about the *location* of those actions. Thus, in a spatial-bioeconomic model one is not only concerned with the optimal timing and level of harvest of a renewable resource, but also with the location of harvests within a geographical area. Smith, Sanchirico, and Wilen (2009) deconstruct spatial-bioeconomic models into the: (1) reaction-diffusion equation (or equations) describing net growth over time and the movement of biomass (or individuals) across space, (2) geometry and boundaries of the relevant space, and (3) net benefit from harvesting the renewable resource at different times, locations, and densities. They develop a discrete-space, discrete-time, spatial-dynamic model for the Gulf of Mexico reef fishery and show how parameters of the reaction-diffusion equations might be estimated from economic data.

The earliest reaction-diffusion models were partial differential equations (PDEs), continuous in time and space. Only the simplest PDEs have analytic solutions, providing a closed-form equation that specifies the density of a species at different points in space in the future. Optimization or management of a resource that continuously evolves over time and space is a particularly daunting problem. Advances have been made by Lenhart and Bhat (1992) and Lenhart, Liang, and Protopopescu (1999), who look at spatial-dynamic systems for managing wildlife and the way habitat and boundaries alter multi-species dynamics.

One of the earlier applications of spatial-dynamic systems in resource economics was concerned with the establishment of marine reserves where an area might be designated as a “no fishing zone.” The economic analysis of marine reserves requires a spatial-bioeconomic model as discussed by Smith and Wilen (2003, 2004). Optimality of a marine reserve can arise in a “sink-source-spatial-system,” where it is optimal to have “a corner solution” with no fishing in the reserve. No fishing is optimal because the marine reserve is more valuable as a source of biomass to other locations. See Conrad and Smith (2012) for a numerical example where a marine reserve is economically optimal in a three-patch, spatial system.

More recently Brock and Xepapadeas (2008) examine stability and instability in an infinite-horizon optimal control problem with reaction and diffusion in continuous time. The co-state

equation becomes a PDE. Depending on the discount rate and the curvature of the current-value Hamiltonian, diffusion may destabilize a problem that would be characterized as saddle-point stable without diffusion. They consider three examples where the: (1) amount and location of phosphorus loading in a shallow lake affects the density and location of algae, and thus pollution damage, (2) evolution of biomass density in space and how that density influences the cost of harvest (i.e., harvest cost exhibits *stock effects*), and (3) optimal harvest in time and space in a Ramsey-Solow renewable resource model without stock effects.

Spatial-dynamic processes are especially relevant to the study of infectious disease in human, plant, insect, and animal populations. The starting point is often the classic Susceptible-Infected-Recovered (SIR) epidemiological model, which has been a workhorse for analyzing disease dynamics (Anderson and May 1979, 1986). The SIR model is particularly well suited to study problems in which the location of infected and susceptible individuals and their interaction is a critical determinant of disease transmission. The mechanism of spread is often crucial to understanding a disease and formulating effective policies to limit its economic costs. Spatial models of disease have been used to analyze the annual flu cycle, Severe Acute Respiratory Syndrome (SARS), the spread of measles, and the West Nile virus, all in human populations. Horan et al. (2010) provide a review of the literature on disease dynamics in nonhuman animal systems.

Finally, there is a relatively small but relevant literature concerned with the economics of irreversible “regime change” in biological and environmental systems. Clark (1976) examines the collapse of a fishery when net growth exhibits an Allee Effect (depensation). Cropper (1976) analyzes environmental management (pollution control) when there is a risk of economic collapse if the stock pollutant crosses an unknown threshold. Reed (1987, 1988, 1989) examines the protection of forest or other vulnerable natural resources that face the risk of stochastic destruction or collapse. Carpenter, Ludwig, and Brock (1999) consider the possibility of irreversible eutrophication of a lake from the runoff of phosphorus fertilizers used in agriculture. Janssen, Anderies, and Walker (2004) look at strategies for managing rangeland when there are multiple stable attractors representing different plant “portfolios.” More recently, and more closely related to our model of AVG and abalone, Polasky, deZeeuw, and Wagener (2011) consider optimal harvest in a fishery when the level of harvest increases the probability of a regime shift to lower biological productivity.

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 that largely prevents 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. Differences across reefs and the independence of populations can cause variations in: (1) shell length at age, (2) age at sexual maturity, (3) egg production per female, and (4) weight of the foot muscle or “meat.” 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 (Prince, Peters, Gorfine, and Day

2008). The model we develop below will abstract from these reef variations to focus on the broad outlines of optimal management and specifically optimal preemptive harvest.

The abalone fishery in Victoria is a valuable, limited entry, Individual Transferable Quota (ITQ) fishery. Properly prepared, the meat of an abalone is regarded as a delicacy by some consumers who are willing to pay AUD100 or more for a single 150 gram serving. 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 were 71 licenses in the fishery prior to the AVG outbreak (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.

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 tally 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 mt, with a landed value of AUD46–70 million per quota year. See table 1. From the 06/07 season through the 10/11 season, the landings of abalone declined from 1, 261 to 781 mt.

Table 1. Quota Years, Landings (Metric Tons), Landed Value (Millions of AUD), and Average Price (AUD/kg) for Abalone from the State of Victoria, Australia

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) with Australian Bureau of Agricultural and Resource Economics and Sciences (2003-2012).

In our model the spread of AVG is exogenous, driven by winds and currents. By 2006, Fisheries Victoria required divers to clean and disinfect their gear before diving at a new reef. It was thought that the divers themselves might vector the disease to uninfected reefs. If this were the case, one would have expected to see jumps by AVG beyond the current front. To our knowledge, this was not observed. So, the assumption of exogenous forces spreading the disease seems reasonable.

THE MODEL

Suppose there are $j = 1, 2, \dots, J$ reefs harboring abalone along a stretch of coastline, as shown in figure 2. For simplicity, we focus on a model with uni-directional spread of a disease and where the disease can only jump one reef (to the next reef) per period. The assumption of unidirectional spread does not affect the questions we seek to address (relating to the spatial location, timing, and extent of optimal preemptive harvest). Allowing the disease to skip a reef and jump non-sequentially further down the coastline would make the determination of optimal drawdown via stochastic dynamic programming far more difficult.

Denote the infection status of a reef in period t by the binary variables $B_{j,t}$, where $B_{j,t} = 0$ indicates that the j^{th} reef is not infected in period t , while $B_{j,t} = 1$ indicates that the j^{th} reef is infected in period t , $t = -1, 0, 1, \dots, T$. 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 $B_{j,-1} = 0 \forall j$. The “front” of the disease will be at reef 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 $0 < P_j < 1$ where $P_j = P_r(B_{j,t+1} = 1 \mid B_{j,t} = 0, B_{j-1,t} = 1)$. Smaller values for P_j have the effect of slowing the spread. Finally, if $B_{j-1,t} = 0$, then $P_r(B_{j,t+1} = 1 \mid B_{j,t} = 0, B_{j-1,t} = 0) = 0$.

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:

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

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). The apparent absence of disease resistance in survivors implies that the subsequent productivity of an infected reef is permanently impaired. This regime shift is modeled here by a change in the growth function:

$$X_{j,t+1} = [1 - (B_{j,t} - B_{j,t-1})M]X_{j,t} + F_j^1([1 - (B_{j,t} - B_{j,t-1})M]X_{j,t}) - Y_{j,t}. \tag{2}$$

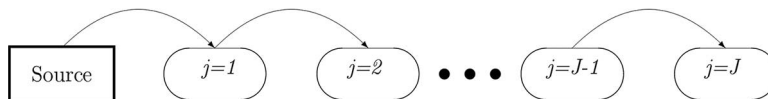


Figure 2. Rightward, Sequential Spread of Disease from Source to Reefs

In equation 2, $0 < M < 1$ 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 1 and 2, allowing the infection indicator, $B_{j,t}$, to determine how $X_{j,t+1}$ is to be computed. Specifically, $X_{j,t+1} = (1 - B_{j,t})G_j^0(X_{j,t}) + B_{j,t}G_j^1(X_{j,t}) - Y_{j,t}$.

We assume fishery managers set TACCs to maximize the net present value of the fishery. We view the managers as myopic because during the pandemic there appeared to be no departure from biomass-based specification of the TACCs on uninfected reefs, regardless of their proximity to the AVG front.

Net revenue from reef j in period t is given by:

$$\pi_{j,t} = pY_{j,t} - C_j(X_{j,t}, Y_{j,t}) - \psi_{j,t}, \tag{3}$$

where p is the “beach price” per metric ton for abalone, $C_j(X_{j,t}, Y_{j,t})$ is the variable cost of harvesting $Y_{j,t}$ when the abalone population is $X_{j,t}$, and $\psi_{j,t}$ are the fixed costs for all divers working that reef in month t , pro-rated to reef j . Thus, if Q denotes the number of license holders and each licensee has to incur a monthly fixed cost, FC , to operate, total fixed costs pro-rated to reef j are equal to $\psi_{j,t} = FC \cdot Q/J$. Because there is very little information allowing us to estimate reef-specific, stock-dependent cost functions, we begin our analysis with a simple linear cost model. We will then consider a richer, non-linear cost specification. With a linear cost function, net revenue from reef j in month t becomes:

$$\pi_{j,t} = (p - c)Y_{j,t} - \psi_{j,t}. \tag{4}$$

We refer to $(p - c)$ as the net beach price. Net revenue in month t , summed over all reefs, is $N_t = \sum_{j=1}^J ((p - c)Y_{j,t} - \psi_{j,t})$. Let $\rho = 1/(1+\delta)$ be the monthly discount factor, where $\delta > 0$ 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. Therefore, discounted net revenue will also be a random variable. Below, we present both simulation results and optimal results obtained from stochastic dynamic programming. For the simulations, let $s = 1, 2, \dots, S$ be a simulation index number where S is the total number of stochastic simulations conducted. The present value of net revenues for simulation, s , can then be computed as:

$$N_s = \sum_{t=0}^T \sum_{j=1}^J \rho^t [(p - c)Y_{j,t,s} - \psi_{j,t}], \tag{5}$$

where $Y_{j,t,s}$ is the harvest from reef j , in month t in simulation s . The horizon length for all simulations is $t = 0, 1, \dots, T$. The evolution of the abalone population and harvest on each reef may be different from simulation s to simulation s' because the arrival time of AVG at each is stochastic.

A SIMPLE SPECIFICATION

THE STOCHASTIC SPREAD OF AVG

Suppose there are $J = 22$ reefs, $T = 96$ months, and that the virus has been initially observed ($t = -1$) at the source. With uni-directional spread, where the virus jumps at most one reef

per month, the earliest time that the virus could arrive at reef j is $t = j - 1$, provided that the virus advanced one reef in every period. For all other time periods ($t \geq 0$), the probability of AVG arriving at reef j is given by the Probability Density Functions (PDFs):

$$Pr[B_{j,t} - B_{j,t-1} = 1] = \frac{P^j(1-P)^{t-(j-1)} \prod_{i=0}^{j-2} (t-i)}{(j-1)!} \tag{6}$$

and the Cumulative Density Functions (CDFs), giving the probability that reef j has been infected by $t = \tau$:

$$Pr[B_{j,\tau} = 1] = \sum_{t=0}^{\tau} Pr[B_{j,t} - B_{j,t-1} = 1]. \tag{7}$$

Figure 3 shows the probabilities that the AVG will arrive in month t at reefs $j = 2, 6, 14,$ and 22 , respectively, when $P_j = P = 0.4$ and AVG is at the source (i.e., $B_{0,-1} = 1$ and $B_{1,-1} = 0$). The virus advances to the next reef every $(1/P)$ months on average, and the expected arrival time at reef j is $(j - P)/P$. Thus, for $P = 0.4$, the virus arrives at $j = 1$ at $t = 1.5$, on average. We would expect AVG to reach reefs 2, 3, and 4 at $t = 4, t = 6.5,$ and $t = 9$, respectively. The virus is expected to arrive at reef $j = 22$ in month 54, on average. Our results for 2,000 simulations presented below closely match theoretical expectations. For instance, the mean arrival time is 4.050 at reef 2 and 54.242 at reef 22.

A key aspect of the diffusion process, described by equation 6, is the distance of the source from an uninfected reef. Suppose we are interested in reef j and that the virus has reached reef $j - 3$ at the start of month t . We can use equation 6 and re-index month t to $t = 0$ and reef $j - 3$ to be the source in order to calculate the probability that reef j will be infected in $\tau > 2$ months from now (the probability is zero for $\tau \leq 2$). This is given by $Pr[B_{j,t+\tau} - B_{j,t+\tau-1} = 1] =$

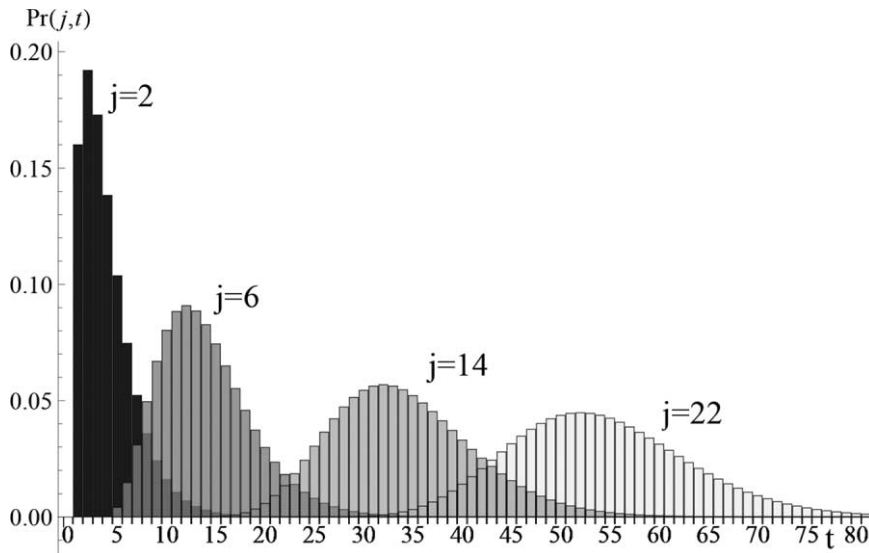


Figure 3. Probability of AVG Arrival at Reefs $j=2, 6, 14,$ and 22 in Month t

$Pr[B_{j,t} - B_{j,t+\tau-1} = 1]$. This feature will prove helpful when trying to determine the optimal drawdown 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.

We assume that carrying capacity on a representative reef is $K = 180$ mt, and that it is unchanged by AVG. Because equation 5 is linear in harvest, $Y_{j,t,s}$, and harvest cost does not depend on stock size, the optimal steady-state biomass before the arrival of AVG requires $F_j^0(X_{j,t}) = \delta$. This implies $X_{ss}^0 = K(r^0 - \delta)/(2r^0)$ mt. The corresponding optimal steady-state harvest is $Y_{ss}^0 = K((r^0)^2 - \delta^2)/(4r^0)$. Suppose that the monthly discount rate is $\delta = 0.01$. Then, the values for r^0 , K , and δ imply that before the arrival of AVG the optimal steady-state biomass at a representative reef is $X_{ss}^0 = 60$ mt which will support an optimal steady-state monthly harvest of $Y_{ss}^0 = 1.2$ mt. When AVG reaches a reef and the intrinsic growth rate permanently drops to $r^1 = 0.018$, the new optimal steady-state biomass and monthly harvest become $X_{ss}^1 = K(r^1 - \delta)/(2r^1) = 40$ mt and $Y_{ss}^1 = K((r^1)^2 - \delta^2)/(4r^1) = 0.56$ mt, respectively. We also know that if the biomass drops below X_{ss}^1 after the arrival of AVG, a Most Rapid Approach Path (MRAP) is optimal and the TACC is set to zero; i.e., $Y_{j,t} = 0$, so as to move $X_{j,t}$ up to X_{ss}^1 as rapidly as possible.

NET REVENUE

Our model assumes that there are $Q = 14$ abalone licenses and that license holders can harvest from any reef at constant 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 in the pre-AVG fishery.

The “net beach price” (p-c) is set at AUD30,000/mt. The monthly, steady-state harvest of 26.4 mt would imply a monthly gross revenue of AUD792,000 for the fishery and an average monthly revenue of AUD56,571 per license. The cost of fishing a license during a typical month is first assumed to consist of monthly fixed costs per license equal to AUD9,800. These are expenses for maintaining a boat, truck, trailer, equipment, insurance, interest payments, and bookkeeping. This translates into a monthly cost per reef equal to $\psi_{j,t} = \text{AUD}6,236$ and a monthly *net revenue* per license of $N_i^0 = 46,771$. The annual net revenue per license is therefore AUD561,252.

Are the above numbers plausible? With monthly net revenue per license of AUD46,771 we can calculate the value of a license in a steady-state fishery prior to AVG as $V^0 = (1 + \delta)N_i^0/\delta$. Assuming $\delta = 0.01$ for the monthly rate of discount during the heydays of the fishery, 2000–2006, these values imply that $V^0 = \text{AUD}4,723,871$. On March 27th, 2006, an inquiry about the purchase price of an abalone license in the State of Victoria, elicited an estimate of AUD5–6 million. Thus our license value of AUD4.7 million falls just below this range. As a result, our estimates of expected losses from AVG might be viewed as conservative.

After the arrival of AVG, a representative reef at its new steady state would produce 0.56 mt per month and the fishery as a whole would produce 12.32 mt per month. This implies an

Table 2. Parameter or Benchmark, Definition, and Value

Parameter	Definition	Value
$J = 22$	Number of reefs	$j = 1, 2, \dots, 22$
$T = 96$	Number of months	$t = 0, 1, 2, \dots, 96$
$S = 2,000$	Number of simulations	$s = 1, 2, \dots, 2,000$
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_{ss}^0	Steady-state biomass/reef, Pre-AVG	60 mt
X_{ss}^1	Steady-state biomass/reef, Post-AVG	40 mt
Y_{ss}^0	Steady-state harvest/month/reef, Pre-AVG	1.2 mt
Y_{ss}^1	Steady-state harvest/month/reef, Post-AVG	0.56 mt
Y_t^0	Total monthly harvest, Pre-AVG	26.4 mt
Y_a^0	Total annual harvest, Pre-AVG	316.8 mt
Y_t^1	Total monthly harvest, Post-AVG	12.32 mt
Y_a^1	Total annual harvest, Post-AVG	147.84 mt
M	AVG mortality rate	0.40
$(p - c)$	Net beach price	AUD30,000/mt
κ	Cost parameter, stock-dependent costs	AUD22.96
Q	Number of licenses in Western Zone	14
δ	Monthly discount rate	0.01
ψ	Monthly cost/license	AUD9,800
N_t^0	Monthly net revenue/license Pre-AVG	AUD46,771
V^0	Value of a license Pre-AVG	AUD4,723,871
N_t^1	Monthly net revenue/license Post-AVG	AUD16,600
V^1	Value of a license Post-AVG	AUD1,676,600

annual harvest of 147.84 mt. At the net beach price of AUD30,000/mt, the fishery is generating a monthly gross revenue of AUD369,600. For each license holder, monthly net revenues are $N_t^1 = 16,600$, and the net present value of a license *post-AVG* is now $V^1 = (1 + \delta)N_t^1/\delta = 1,676,600$. Parameter values and present value calculations are summarized in table 2.

RESULTS

EXPECTED DISCOUNTED REVENUE WITH AVG

In this section we present 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 AUD3,636,000. 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 representative reef without AVG is AUD3,006,127. These numbers serve as a benchmark against which we can compare revenues and net profits when the arrival time of AVG is stochastic.

First we compare the potential losses from AVG by assuming that the fishery manager sets allowable harvest at $Y_{ss}^0 = K((r^0)^2 - (\delta)^2)/(4r^0) = 1.2$ 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 , with mortality rate $M = 0.4$, 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 im-

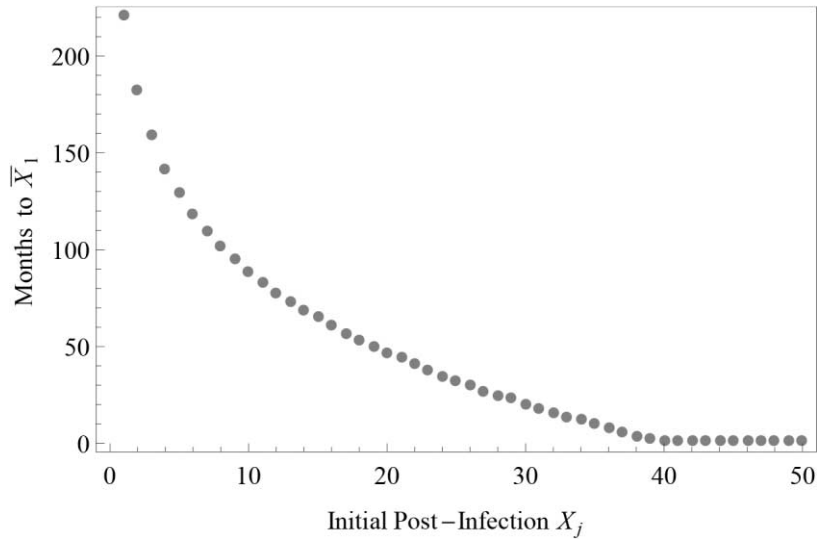


Figure 4. Duration of Moratorium as a Function of Post-Infection Stock Size

posed to allow the stock to recover to the new regime’s steady state ($X_{SS}^1 = 40$). The MRAP would normally 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 the new steady state. Because all costs are fixed costs, it turns out that waiting the extra month is always beneficial and we, therefore, compute results after allowing a slight overshoot. Figure 4 shows the number of months it takes for different population levels to recover from the time of infection to the post-AVG optimal, steady-state stock.

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

This scenario assumes that harvest is not changed from Y_{SS}^0 , even if the virus has been detected at nearby 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. This will give us a benchmark from which to determine the magnitude of avoided losses when an optimal policy is adopted instead.

REDUCTION IN REVENUE UNDER MYOPIC MANAGEMENT

The present value of revenue from reef j in simulation s can be calculated as $R_{j,s} = \sum_{t=0}^{\infty} \rho^t p Y_{j,t,s}$. 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.

Figure 5 shows the impact of AVG on expected revenue and profits for each of the 22 reefs, based on simulation. The height of the bars indicate present value (at $t = 0$), computed over an infinitely long time horizon assuming that the post-AVG steady state is maintained after the end of the moratorium. The expected present value of revenue and profits are lower the closer a reef is to the source of the virus. Reefs further away simply benefit from an extended period of harvest at pre-AVG levels and longer delays before the moratorium and regime shift to lower productivity. Total net present revenue for all $J = 22$ reefs under myopic management amounts to AUD45.1 million, a loss of AUD34.8 million (or 43.6% of the fishery's revenue potential). This result critically depends on: (1) the distributions of arrival times when $P_j = P = 0.4$; (2) the intrinsic growth rates of $r^0 = 0.03$ before the arrival of AVG and $r^1 = 0.018$ after the arrival of AVG; (3) the mortality rate, $M = 0.4$, when AVG arrives; and (4) that the $J = 22$ reefs are identical. Profit levels are also sensitive to the assumptions made about the costs attributed to each reef during the moratorium and beyond. The numbers illustrated in figure 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 steady-state harvest level. In reality, it could be that some or all operators continue to incur their fixed costs during a moratorium. If so, true losses would exceed those presented here.

STOCHASTIC DYNAMIC PROGRAMMING AND OPTIMAL HARVEST WITH THE THREAT OF AVG

The myopic approach of harvesting Y_{ss}^0 until the arrival of the virus turns out to be a sub-optimal strategy. In this section we discuss and report the numerical results of a stochastic

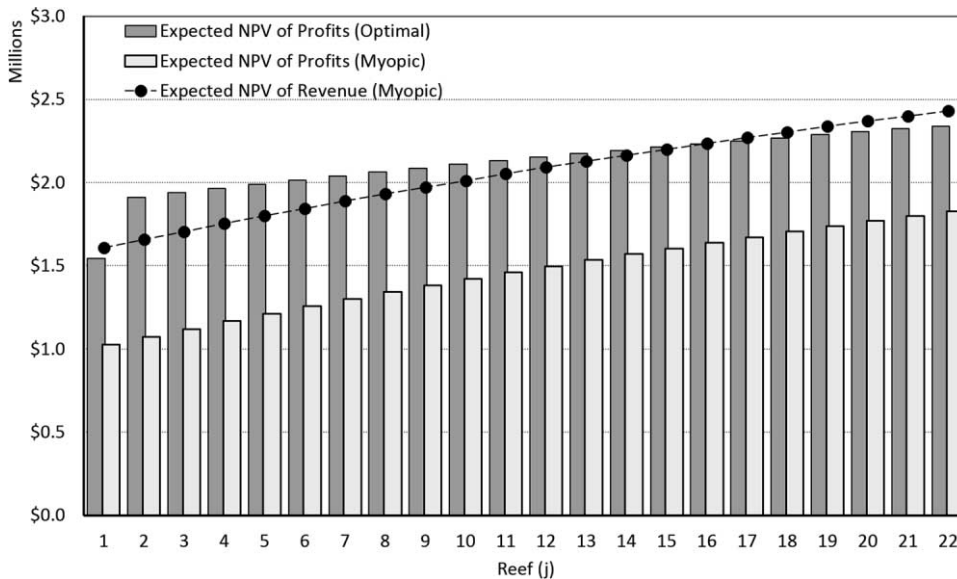


Figure 5. NPV of Revenue and Profits per Reef

dynamic program to maximize the expected net present value of harvest from reef j .² For this reef, the relevant state of the system is the biomass, $X_{j,t}$, and the location of the AVG front, $j-k$. For simplicity, we suppress subscript j on X and Y and let the relevant variables denote the harvest at reef j . The Bellman equation requires that the optimal Y_t satisfy:

$$\begin{aligned}
 V_{j,t}(X_t, j-k) = & \text{Max}_{Y_t} [(p-c)Y_t - \psi \\
 & + \rho P V_{j,t+1}(X_t + F^0(X_t) - Y_t, j-k + 1) \\
 & + \rho(1-P) V_{j,t+1}(X_t + F^0(X_t) - Y_t, j-k)].
 \end{aligned}
 \tag{8}$$

Equation 8 defines $V_{j,t}(X_t, j-k)$ as the value of reef j at time t given that the current stock is X_t and the virus is at reef $j-k$. The harvest decision at time t is made after observing the virus front and the period's natural growth. Harvesting Y_t produces a profit $(p-c)Y_t - \psi$ and leads to a stock $X_{t+1} = X_t + F^0(X_t) - Y_t$ at the beginning of period $t+1$ (before the next opportunity for the virus to jump). With probability P , the virus will indeed progress from reef $j-k$ to $j-k+1$ at the beginning of period $t+1$. With probability $(1-P)$ the virus remains at reef $j-k$, but now with the stock at $X_{j,t+1}$. The second term on the right-hand-side of equation 8 is then the discounted expected value in $t+1$ if AVG has moved one reef closer, while the third term is the discounted expected value in $t+1$ if AVG remains at reef $j-k$.

The problem takes on a special flavor when the virus reaches reef $j-1$. After the harvest decision at time t , the probability P refers to the likelihood that reef j actually becomes 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 $V_{j,t+1}((1-M)X_t + F^1((1-M)X_t) - Y_t, j)$ and with probability $(1-P)$ it will be $V_{j,t+1}(X_t + F^0(X_t) - Y_t, j-1)$.

$V_{j,t+1}(\cdot)$ can be computed for any post-AVG stock. For instance, for an initial post-AVG stock of 36 (i.e., remaining stock after mortality impacts a stock previously at $X_{ss}^0 = 60$), the value of the just-infected reef is AUD1,003,720. Figure 6 shows how $V_{j,t+1}(\cdot)$ increases with a greater post-AVG stock. Post-AVG stocks lower than $X_{ss}^1 = 40$ require a moratorium and growth of the stock prior to the resumption of harvest. This explains the concave shape of the post-AVG value function up to $X_{j,t} = 40$. Post-infection stocks at or above 40 do not require a moratorium and all excess is immediately harvested in the MRAP. The marginal value of a unit of stock in excess of X_{ss}^1 is simply the net price it fetches. This produces a linear relationship for stock above 40.

The solution to equation 8 is obtained by solving the equation recursively over a “jump-time horizon” of τ . If the virus has remained at reef j over the entire horizon, we assume a terminal condition whereby the virus arrives with probability one in month $\tau+1$. In the case of the linear cost function, we report results based on $\tau = 15$ as it results in rapid computation without affecting the results. In theory, it could take an infinite amount of time for the virus to infect the next reef. However, the probability that the infection front does not move for 15 months is equal to $(1-P)^{15}$. With $P = 0.4$, $(1-P)^{15} = 0.00047$.

The numerical algorithm proceeds by backward induction in time and forward induction in reefs (starting with the reef in state $j-1$, closest to the virus). For each stock level on a

2. The dynamic programming code in *Mathematica* is available from the second author upon request.

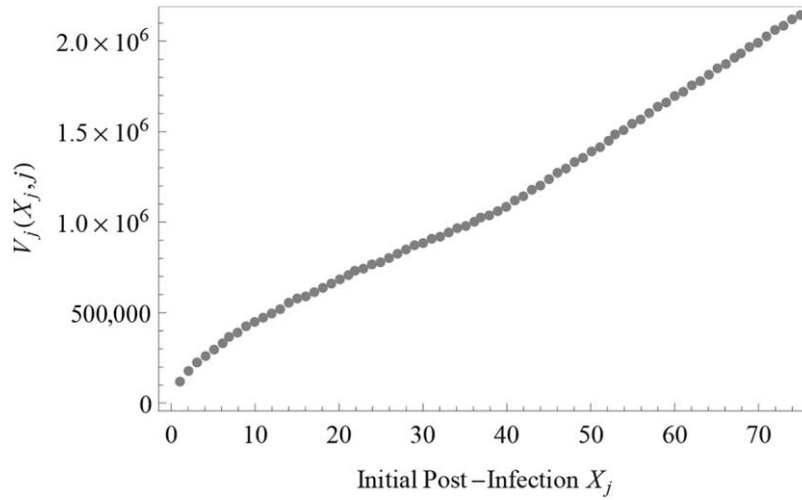


Figure 6. Value at the Time of Infection of a Newly Infected Reef

grid, a finer grid of possible harvesting levels is considered. The harvesting level, $Y_t^*(X_t)$, that maximizes the expected net present value of the remainder of the program, produces the intermediate value $V_{j,t}^*(X_t, j - k)$. From the estimated points $(X_t, Y_t^*(X_t), V_{j,t}^*(X_t, j - k))$, two cubic splines are constructed. The first links any stock, X_t , for a given reef to the corresponding optimal harvesting level. The second gives the corresponding value function $V_{j,t}^*(X_t, j - k)$. Once this process has reached $t = 0$, the initial stock level can then be used to iterate the solution forward and determine the optimal harvesting policy in the “continuation region” (i.e., when the virus does not advance next period). Once the optimization is completed for the reef at $j - 1$, the same procedure is repeated for the next reef where the virus is at $j - 2$ in $t = 0$. Note that when the virus jumps next, this reef switches from virus state $j - 2$ with a stock X_t to a virus state $j - 1$ with a stock $X_t + F^0(X_t) - Y_t$. Simply put, the reef initially at $j - 2$ becomes a reef at $j - 1$, but with a stock level resulting from one month of harvesting without an immediate threat of infection. The optimal strategy for the entire fishery is, therefore, obtained by computing the optimal solution from $j = 1$ to $j = 22$. This optimal solution provides the TACC for each reef conditional on the virus not advancing. The time path of harvesting for a given reef is finally obtained as a series of backward and forward movements. Starting from its geographical index, reef j remains in the continuation region of the initial state of the virus at the source (harvesting forward in time along this optimal program), until the virus jumps to reef 1, at which point the managed reef takes on the persona of reef $j - 1$, using its continuation region as the optimal policy to follow forward in time until the virus advances again. The optimal continuation policies allow the determination of harvest for any given realization of random jumps by the virus.

The stochastic dynamic program was solved for all combinations of $P \in [0.1, 0.9]$ and $M \in [0.1, 0.9]$ in increments of 0.1 for each. Table 3 provides an example of the resulting output for the first two reefs (showing the first 10 periods). Reefs further away from the virus have solutions qualitatively identical to reef $j - 2$ in table 3 and are not shown.

Taken together, the solutions yield three main results:

Table 3. Optimal Harvest Reefs ($j - 2$) and ($j - 1$), $P = M = 0.4$, and Linear Costs

Time Since AVG Arrival at $j-2$			Time Since AVG Arrival at $j-1$		
	X_{j-2}	Y_{j-2}		X_{j-1}	Y_{j-1}
0	60	1.22	0	60	58.38
1	59.98	1.20	1	2.82	0.21
2	59.98	1.20	2	2.70	0.15
3	59.98	1.20	3	2.62	0.13
4	59.98	1.20	4	2.57	0.11
5	59.98	1.20	5	2.53	0.10
6	59.98	1.20	6	2.52	0.09
7	59.98	1.20	7	2.50	0.09
8	59.98	1.20	8	2.49	0.08
9	59.98	1.20	9	2.48	0.08
10	59.98	1.20	10	2.47	0.08

1. With linear costs, it is not optimal to depart from the pre-AVG steady-state optimum until AVG arrives at the neighboring reef, causing a direct threat of infection to reef j in the following period.
2. When AVG arrives at the neighboring reef, it is optimal to significantly drawdown (reduce) the abalone population even if the probability of arrival of AVG in the next period is small. Table 3 provides the details. As long as the virus remains at ($j - 2$), the stock should be kept approximately at its steady-state level. The right-hand side of the table allows one to read the optimal harvesting level of reef 1 at $t = 0$ (when the virus is one reef away) and the stock is 60. As previously indicated, it also gives the optimal harvesting level for any other reef along the coast in the period when the virus arrives at the neighboring reef, when the stock is maintained at the pre-AVG optimal level. We observe that the optimal harvest, upon infection of the adjacent reef, is very aggressive with $Y_{0,j-1}^* = 58.38$, or more than 97% of available biomass (stock plus growth).
3. Starting from low values, increases in either M or P increase the size of preemptive harvest. Close inspection of the numbers in table 3 reveals that optimal preemptive harvest is more sensitive to changes in the mortality rate than to changes in the probability of a jump to the next reef.

FURTHER INSIGHTS

Table 4 shows how drastic the optimal harvest (drawdown) of the population on reef j should be once AVG reaches reef $j - 1$. Even modest mortality rates and transmission probabilities imply that it is optimal to harvest a significant portion of the pre-AVG, steady-state stock. Furthermore, with mortality rates of 80 and 90%, a complete harvest of the stock becomes optimal. This dramatic drawdown can be attributed to: (1) the long-term impact of AVG on the intrinsic rate of growth r (the regime shift), and (2) the effect that higher mortality rates have on the length of the moratorium.

As a thought experiment, suppose that: (1) the virus did not kill any abalone (i.e., $M = 0$), (2) the probability of the jump to reef j in $t + 1$ is $P = 1$, and (3) the regime shift still occurs. The only impact of the virus arriving at reef j is to shift the steady-state population from 60 to 40. This would result in an immediate adjustment of the stock to its new steady state (but

Table 4. Optimal Harvest at Reef j upon Infection of Reef $j - 1$

		M								
		$\frac{1}{10}$	$\frac{2}{10}$	$\frac{3}{10}$	$\frac{4}{10}$	$\frac{5}{10}$	$\frac{6}{10}$	$\frac{7}{10}$	$\frac{8}{10}$	$\frac{9}{10}$
P	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
	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

only once the virus arrives, rather than preemptively). Thus, it is possible that a significant proportion of the stock reductions observed in table 4 are the result of the regime shift alone.

In reality, the virus does kill a significant proportion of the stock. To see how this affects the optimal harvesting decision, consider instead a mortality rate approaching 100%. It would now make economic sense to harvest the entire reef. The choice is between harvesting and selling the natural capital for a profit in period t or risking that it will be destroyed by AVG, yielding zero net revenue. The pre-AVG, steady-state stock of $X_{ss}^0 = 60$ corresponds to 50 months of steady-state harvesting. Therefore, the reality is that the financial risk of maintaining a high stock is simply too great, even with a relatively small value for P . This would explain why P has a smaller effect on optimal preemptive harvest than M .

Now ask the question: is it optimal to harvest an additional metric ton beyond the $Y_t = X_{ss}^0 - X_{ss}^1 = 20$ due to the regime change? Suppose that $M = 0.2$. 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 metric tons prior to the arrival of AVG, the moratorium would be two months longer. Thus, the marginal benefit of not harvesting the marginal ton is roughly equivalent to harvesting Y_{ss}^1 two months sooner. For our parameters, the present value of these benefits is AUD4,564. On the other hand, harvesting the marginal ton would generate immediate marginal net revenues of AUD30,000. Even if a licensee incurred a full year's costs to harvest this marginal ton, the immediate net profits would still be AUD20,200, far above the AUD4,564 of conserving that ton. One should conclude that it is beneficial to harvest the marginal ton and to draw down the stock below 40 under almost any circumstances.

Figure 4 is useful in understanding the benefit-cost tradeoffs associated with the impact of the mortality rate. A population level close to 40, before the arrival of the virus, results in a biomass of $(1 - M)40$ afterward. A further reduction in 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 stock reductions becomes larger and eventually exceeds the benefits of harvesting prior to the arrival of AVG. We note, however, that the large marginal increases in the length of the moratorium (the steep part of the curve in figure 4) are associated with very low biomass levels (i.e., $X_t < 10$). This helps explain why most optimal harvesting plans take the stock to very low levels and also why very large mortality rates make it optimal to fully harvest the reef.

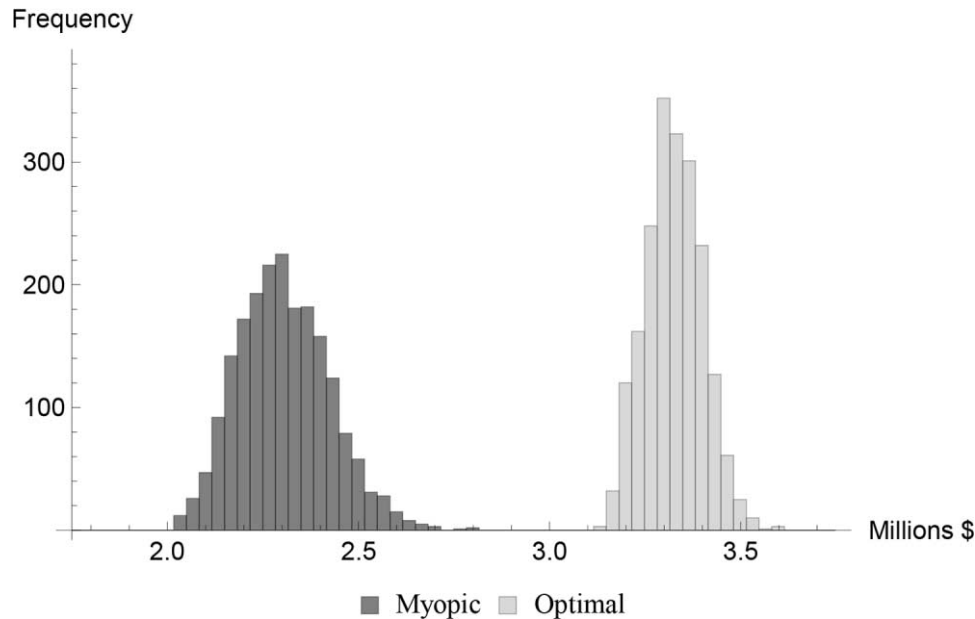


Figure 7. Net Present Value of a License, Optimal vs. Myopic Harvesting

While increasing either P or M decreases the expected value of any reef j , the reduction is smaller if optimal preemptive harvest is adopted prior to the arrival of AVG. The optimal harvesting program begins immediately when the virus is detected at reef $j - 1$ and continues until reef j gets infected. (Recall, however, that reef 1 can be infected, without warning, in $t = 0$). The results are presented in figure 5. It shows that the optimal management approach results in significant increases in the expected present value of reef profits when compared to myopically waiting for the arrival of AVG.

After computing the solution to the dynamic programming problem, we can return to the simulations and compute the net present value for each of the 22 reefs when harvest is myopic and when it is optimally preemptive. We can then compute the net present value of a license. Figure 7 draws the histogram of the NPV of a license over the 2,000 simulations. It shows that the value of a license under optimal management strictly dominates license value under the myopic harvesting regime. The expected NPV of a license is AUD3.32 million when optimal drawdown is employed, but only AUD2.29 million under myopic harvesting, and there is not a single realization in which myopic management outperforms optimal drawdown. For $P = M = 0.4$, the myopic regime results in a loss of 52% of the fishery's value, while the optimal approach limits losses to roughly 30% of the pre-AVG value of a license.

DISCRETE REGIME SHIFT AND THE ALLEE EFFECT

We also solved the linear cost model without regime shift (the net growth function is unchanged after the arrival of AVG) and when net growth exhibits an Allee effect with critical depensation. The presence of our regime shift significantly affects the size of the harvest (drawdown) when AVG is one reef away. Consider table 4 where $P = 4/10$ 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 .

It was suggested to us by a marine biologist³ that the net growth for abalone might exhibit critical depensation, with a minimum viable population at approximately 10% of the carrying capacity. We, therefore, replaced the logistic growth function with $F_j^0(X_{j,t}) = F_j^1(X_{j,t}) = rX_{j,t}(X_{j,t}/K_1 - 1)(1 - X_{j,t}/K_2)$, 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, pre-AVG, as in the original model. Solving the model for $P = M = 0.4$ indicates that it would be 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. It reflects two important differences between the net growth functions. 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. Significant AVG mortality 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 critical depensation tend to be much longer than under logistic net growth. This increases the length of the moratorium that follows after the arrival of AVG, thus providing an additional incentive to remove the entire stock prior to the arrival of AVG.

SENSITIVITY OF THE SOLUTION TO THE MAGNITUDE OF THE NET BEACH PRICE

Given the degree of uncertainty about the fishery's cost structure, we now explore the sensitivity of the drawdown to the net beach price, $(p - c)$. Recall that in the results reported above, the net beach price was set at AUD30,000/*mt*. As alternatives, we computed the optimal drawdown for values of $(p - c)$ ranging from AUD20,000 to 300,000 per *mt* of abalone, when $P = M = 0.4$. All other parameters were unchanged. Table 5 reminds us that with $(p - c) = \text{AUD}30,000/\text{mt}$ the optimal drawdown is 58.38. It also shows that the optimal drawdown is remarkably insensitive to variations in the net beach price. Cutting the price by one third increases the drawdown by just over 1%, while increasing the price by a factor of 10 reduces the drawdown to 51.62, or less than 12%. The insensitivity of the optimal drawdown to $(p - c)$ indicates that drastic measures (large preemptive harvests) are required when rents are threatened by AVG under a linear cost structure.

NON-LINEAR HARVESTING COSTS

In this subsection we specify a nonlinear (stock-dependent) cost function and analyze its effect on optimal preemptive harvest. In most discrete-time models, the stock level at the start of the period inversely influences the cost of harvest. In our specification, we assume that costs increase during the month as divers reduce the stock from $X_{j,t} + F(X_{j,t})$ to $X_{j,t} + F(X_{j,t}) - Y_{j,t}$. This is likely to be the case in an abalone fishery where initial harvest removes more visible

3. Kevin Lafferty, personal communication, 2013.

Table 5. Optimal Harvest on Reef j when AVG is detected at $j - 1$, Linear Costs

$p - c$	Y
20,000	59.00
30,000	58.38
60,000	54.96
90,000	53.67
180,000	52.14
300,000	51.62

abalone and subsequent harvest, later in the month, requires exploring crevices, thus requiring more dive time. Specifically, we assume that total variable costs are given by:

$$C_j(X_{j,t}, Y_{j,t}) = \int_{X_{j,t}+F(X_{j,t})-Y_{j,t}}^{X_{j,t}+F(X_{j,t})} \frac{\kappa_j Y_{j,t}}{Z_t} dZ_t = \kappa_j Y_{j,t} \text{Ln} \left[\frac{X_{j,t} + F(X_{j,t})}{X_{j,t} + F(X_{j,t}) - Y_{j,t}} \right], \tag{9}$$

where $\kappa_j > 0$ is a cost parameter for reef j . It can be shown that the optimal steady-state stock on a representative reef ($\kappa_j = \kappa \forall_j$) must satisfy the golden rule:

$$F'(X) + \frac{\kappa F(X)^2 [F'(X) + 1]}{X[F(X) + X][p - \kappa F(X)/X - \kappa \text{Ln}([F(X) + X]/X)]} = \delta. \tag{10}$$

We retain logistic net growth and the parameters $r^0 = 0.030$, $r^1 = 0.018$, and $K = 180 \text{ mt}$. We set the gross beach price to $p = \text{AUD}30,000/\text{mt}$ and require that the NPV of a pre-AVG license and fixed costs remain unchanged at $\text{AUD}4,723,871$ and $9,800$, respectively. Under these conditions, we calculate $\kappa = \text{AUD}22.9553$, with corresponding steady-state values (from the golden rule) at $X_{ss}^0 = 60.0009$ and $Y_{ss}^0 = 1.2$; $X_{ss}^1 = 40.0007$ and $Y_{ss}^1 = 0.56$. The nonlinear, stock-dependent cost function, even with this relatively low value for κ , will cause the marginal cost of harvest to increase as the stock is drawn down on any uninfected reef.

The optimal harvesting regime for the base case $P = M = 0.4$ is shown in the right panel of table 6. We note both similarities and differences when comparing these results with the linear cost results previously shown in table 3. First, there is a significant drawdown on a reef immediately threatened with AVG (when the virus is at reef $j - 1$). The stock is brought from the initial steady state of 60 to 18.95, with only small adjustments afterward.

Table 6. Optimal Harvest Reefs ($j-2$) and ($j-1$), $P = M = 0.4$, Stock-Dependent Costs

Time Since AVG Arrival at $j-2$			Time Since AVG Arrival at $j-1$		
	X_{j-2}	Y_{j-2}		X_{j-1}	Y_{j-1}
0	60.00	2.74	0	60.00	42.25
1	58.46	1.29	1	18.95	0.74
2	58.35	1.19	2	18.72	0.49
3	58.34	1.18	3	18.73	0.50
4	58.34	1.18	4	18.73	0.50
5	58.34	1.18	5	18.73	0.50

Second, while this is very close to a most rapid approach path, it is worth noting that the resulting stock is substantially higher than that observed with the linear cost function. This less aggressive harvesting policy is consistent with costs that increase rapidly with the fraction of the stock harvested in a given period. This makes it both more expensive to rapidly draw down the stock and dynamically efficient to preserve higher stocks in order to lower future harvesting costs (provided AVG does not advance).

The third observation is that, unlike the solution with linear costs, increasing the marginal cost of harvest within a period provides incentives to actively manage more distant reefs for the eventual arrival of AVG. For the current parameters, this effect is relatively small as observed in the left panel of table 5 for reef $j - 2$. The reefs at $j - 3$ and beyond (not shown) are also affected, but with increasingly smaller stock adjustments.

We investigate the importance of the cost assumptions further by shifting harvesting costs away from fixed costs and towards marginal costs. Doing so reveals a richer picture of the optimal management regime. We proceed by recalibrating the model yet again, this time by setting monthly fixed costs to $\psi = \text{AUD}5,000$. Keeping the NPV of a license constant forces an increase in the marginal cost parameter to $\kappa = \text{AUD}254,732$, with steady-state stock and harvest levels increasing to $X_{ss}^0 = 71.78$ and $Y_{ss}^0 = 1.29$, pre-AVG; and $X_{ss}^1 = 49.27$ and $Y_{ss}^1 = 0.64$, post-AVG.

The shift to lower fixed costs and higher marginal costs increases preemptive harvest at more distant reefs. Figure 8 shows how to optimally manage the 10 reefs closest to the virus in the continuation region (i.e., under the assumption that the AVG virus does not jump at any point during the time horizon).⁴ The lower solid line is the optimal path for $X_{j-1,b}$ the reef immediately threatened by the AVG, assuming that AVG does not advance. The next one up is for the $j - 2$ reef, and so on.

Comparing the adjustment paths when the virus is at $j - 1$ for the two different non-linear cost specifications, we note that the initial stock reduction is substantially smaller due to the increase in the marginal cost of harvesting within a period. The counterweight of this result is that if the virus does not arrive at the reef at the beginning of subsequent periods, significant harvesting continues to take place. Overall, optimal management of the $j - 1$ reef with increasing marginal costs calls for reducing the stock to a steady state of approximately 14.58 (i.e., if the reef remains free of infection) compared to 18.73 with the smaller non-linear costs. While increasing marginal costs makes conservation more valuable (higher stocks reduce the marginal cost of harvesting in the future if AVG does not advance), they also make total harvest itself less valuable. On net, the reduced value of future harvest exceeds the marginal stock effect and results in a lower steady state along the continuation path (when AVG does not advance). The optimal continuation paths for the reefs when AVG remains at $j - 2$ to $j - 10$ are shown in figure 9, which clearly illustrates how the optimal response to the virus now calls for significant stock reductions at more distant reefs. This is naturally traced to the cost savings that are realized when harvesting smaller proportions of the stock over several periods.

Figure 9 repeats the continuing adjustment paths for the reefs at $j - 1$ and $j - 10$, but also shows three additional paths. Each represents a simulation of the optimal management of a reef initially in steady state and 10 reefs away from the virus. Each simulation shows how the

4. These results were computed over a time horizon of 48 months. For clarity, only the first 26 months are shown.

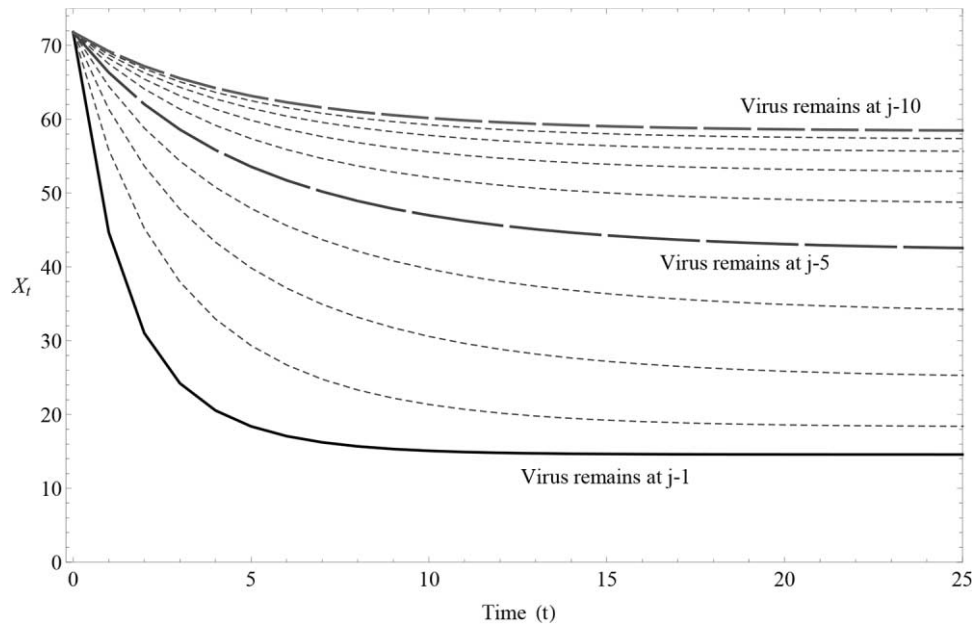


Figure 8. Optimal Management of the 10 Reefs Closest to the AVG Front, Non-Linear Costs, $\psi = \text{AUD}5,000$, $\kappa = \text{AUD}254,732$

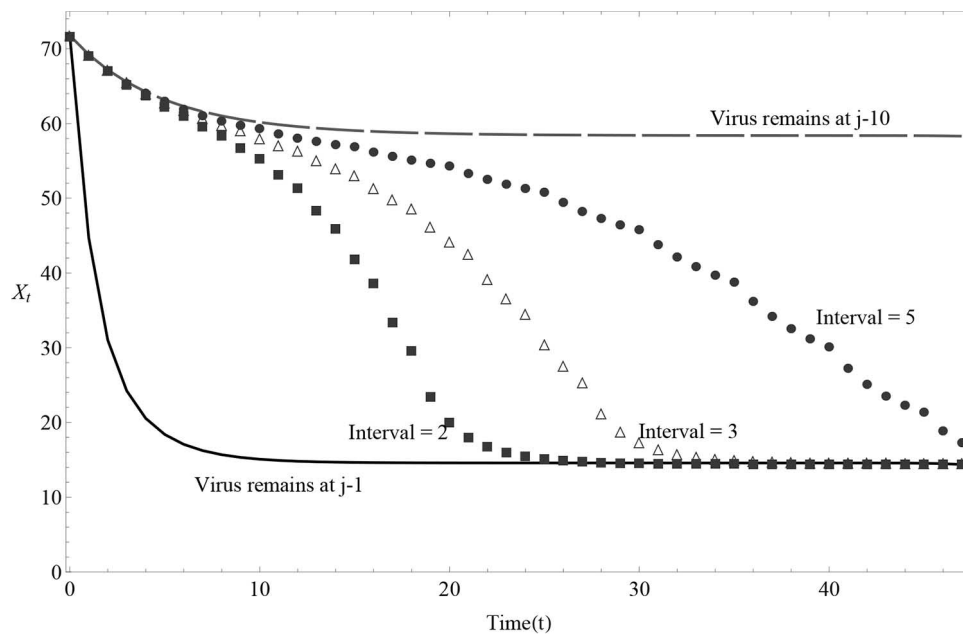


Figure 9. Optimal Harvest of Reef $j -10$, with Jumps, Non-linear Costs, $\psi = \text{AUD}5,000$, $\kappa = \text{AUD}254,732$

reef would actually be managed if the AVG front (randomly) happened to advance at a fixed interval of time (e.g., every two, three, or five months). To illustrate, take the path labeled “Interval=5.” In this simulation, the virus is 10 reefs away at $t = 0$ and the reef has an initial stock of 71.78. Thus, the reef is initially managed along the $j - 10$ path until $t = 4$, when AVG jumps to the next reef. The reef which was formerly $j - 10$ is now $j - 9$, and the change in the AVG front calls for an immediate increase in the rate of harvest (relative to what it would have been had the virus not advanced). At $t = 4$, harvesting is now dictated by the optimal $j - 9$ policy, where the stock at the beginning of $t = 4$ is understood to be the initial stock of the now $j - 9$ reef. The optimal harvesting level continues to be read off of the $j - 9$ policy curve until the virus jumps again. In this simulation, this happens at $t = 9$, when the $j - 9$ reef becomes a $j - 8$. This forces an increase in harvesting and a reduction in the expected time of arrival. This continues until the virus is one reef away, at which point the continuation path for the $j - 1$ reef with a realized stock of $X_{j-1,t}$ is followed until AVG finally infects that reef. With an interval of 5, the reef follows the $j - 1$ path on for the last two periods shown in the graph. For simulations with intervals of 2 and 3, this happens at $t = 18$ and $t = 27$, respectively. Any realization of jumps could be used to simulate the time paths for reef-specific harvest and $X_{j-k,t}$ in a similar fashion.

DISCUSSION

This article presents a spatial bioeconomic model dealing with the stochastic spread of a marine disease in a patchy environment. The 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 models and analysis are offered in the hopes they might: (1) stimulate discussion between biologists and economists, (2) suggest modifications that might make subsequent models more realistic, (3) identify the data needed to more accurately predict the biological and economic consequences of AVG (or other marine diseases), and (4) help determine how resource managers should respond to future pandemics that threaten valuable marine resources. We briefly review the results and then return to the intriguing possibility of endogenous conditional probabilities for transmission.

RESULTS

1. In our uni-directional model of AVG, with a fixed probability that AVG jumps from its current reef to the next reef, there are analytic expressions for the probability density functions and cumulative distributions that reef j will become infected in period $\tau > t$.
2. With linear harvesting costs, it is optimal to maintain the pre-AVG steady-state biomass on reef j until AVG has reached reef $j - 1$ and poses a threat of infection in the next period. Since stock reductions are optimal (as opposed to building up the stock before the arrival of AVG) and marginal costs are constant, a single period provides sufficient time to harvest healthy abalone before the possible arrival of AVG.
3. In the linear model, the size of the optimal preemptive 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 ($X_{SS}^0 + r^0 X_{SS}^0 (1 - X_{SS}^0 / K)$) up to 100% for values of $M \geq 0.8$. See

table 4. Increases in P also increase the size of the drawdown, but to a lesser extent than M . Thus, the mortality inflicted by a disease that threatens a valuable marine resource appears to be highly important in determining the optimal adaptive response as the disease spreads.

4. Even for conservative estimates of the speed of transmission and mortality imposed by the virus, we find that the AVG imposes significant losses on the fishery. A 40% risk of transmission and 40% mortality rate resulted in more than a 50% reduction in the value of the fishery when no preemptive harvests are adopted. Optimal management was shown to reduce losses to roughly 30% of the pre-AVG value of the fishery.
5. In the linear model, optimal solutions do not show great sensitivity to variations in the net beach price ($p - c$).
6. With nonlinear, stock-dependent harvest costs, optimal management calls for adjustments of the stock at more distant reefs. The degree of preemptive adjustments is sensitive to changes in the marginal cost parameter, κ .

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 imply different probabilities, based on the distance between reefs downwind or downcurrent from the AVG front. An important unanswered question is whether abalone biomass prior to the arrival of AVG on a reef (and thus the viral-laden material resulting from the infection) might influence the probability of a jump to the next reef. An alternative to the exogenous model herein would be a model where abalone density influences the conditional distributions, $P_{j+1,t+1} = P_j(X_{j,t})$. A model in which higher abalone density increases the viral load in the water column, and therefore the probability of transmission to the next reef, would likely provide even greater incentives to reduce reef populations prior to the arrival of the AVG, similar to the creation of firebreaks when fighting wildfires.

REFERENCES

- Anderson, R. M., and R. M. May 1979. "Population Biology of Infectious Diseases, Part I." *Nature* 280:361–67.
- . 1986. "The Invasion, Persistence, and Spread of Infectious Disease within Animal and Plant Communities." *Philosophical Transactions of the Royal Society B* 314:533–570.
- Australian Bureau of Agricultural and Resource Economics and Sciences. 2003–2012. "Australian Fisheries Statistics 2003–2012." <http://daff.gov.au/abares/publications>.
- Brock, W., and A. Xepapadeas. 2008. "Diffusion-Induced Instability and Pattern Formation in Infinite-Horizon Recursive Optimal Control." *Journal of Economic Dynamics & Control* 32:2745–87.
- Carpenter, S. R., D. Ludwig, and W. Brock. 1999. "Management of Eutrophication in Lakes Subject to Potentially Irreversible Change." *Ecological Applications* 9(3):751–71.
- Clark, C. W. 1976. *Mathematical Bioeconomics: The Optimal Management of Renewable Resources*. NY: John Wiley & Sons.
- Conrad, J. M., and M. D. Smith. 2012. "Nonspatial and Spatial Models in Bioeconomics." *Natural Resource Modeling* 25(1):52–92.
- Corbeil, S., A. Colling, L. M. Williams, F. Y. K. Wang, K. Savin, S. Warner, B. Murdoch, N. O. Cogan, T. L. Sawbridge, M. Fagan, I. Mohammad, A. Sunarto, J. Handlinger, S. Pyecroft, M. Douglas, P. H.

- Chang, and M. S. J. Crane. 2010. "Development and Validation of a *TagMan*[®] PCR Assay for the Australian Herpes-Like Virus." *Diseases of Aquatic Organisms* 92:1–10.
- Crane M. S. J., S. Crobeil, L. M. Williams, K. A. McColl, and V. Gannon. 2013. "Evaluation of Abalone Viral Ganglioneuritis Resistance among Wild Abalone Populations along the Victorian Coast of Australia." *Journal of Shellfish Research* 32:67–72.
- Cropper, M. L. 1976. "Regulating Activities with Catastrophic Environmental Effects." *Journal of Environmental Economics and Management* 3(1):1–15.
- Department of Environment and Primary Industries, State Government Victoria. 2012. "Abalone Catch and Effort." <http://www.depi.vic.gov.au/fishing-and-hunting/commercial-fishing/abalone/abalone-catch-and-effort>.
- Horan, R. D., E. P. Fenichel, C. A. Wolf, and B. M. Gramig. 2010. "Managing Infectious Animal Disease Systems." *Annual Review of Resource Economics* 2:101–24.
- Janssen, M. A, J. M. Anderies, and B. H. Walker. 2004. "Robust Strategies for Managing Rangelands with Multiple Stable Attractors." *Journal of Environmental Economics and Management* 47(1):140–62.
- Lenhart, S., and M. Bhat. 1992. "Application of a Distributed Parameter Control Model in Wildlife Damage Management." *Mathematical Models and Methods in Applied Sciences* 4:423–39.
- Lenhart, S., M. Liang, and V. Protopopescu. 1999. "Optimal Control of Boundary Habitat Hostility for Interacting Species." *Mathematical Models and Methods in Applied Sciences* 22:1061–77.
- Mayfield, S., R. McGarvey, H. K. Gorfine, H. Peters, P. Burch, and S. Sharma. 2011. "Survey Estimates of Fishable Biomass Following a Mass Mortality in an Australian Molluscan Fishery." *Journal of Fish Diseases* 34:287–302.
- McShane, P. 1995. "Estimating the Abundance of Abalone: The Importance of Patch Size." *Marine and Freshwater Research* 46:657–62.
- Polasky, S., A. deZeeuw, and F. Wagener. 2011. "Optimal Management with Potential Regime Shifts." *Journal of Environmental Economics and Management* 62:229–40.
- Prince, J. D., H. Peters, H. Gorfine, and R. W. Day. 2008. "The Novel Use of Harvest Policies and Rapid Visual Assessment to Manage Spatially Complex Abalone Resources (Genus *Haliotis*)." *Fisheries Research* 94:330–38.
- Reed, W. J. 1987. "Protecting a Forest Against Fire: Optimal Protection Patterns and Harvest Policies." *Natural Resource Modeling* 2:23–54.
- . 1988. "Optimal Harvesting of a Fishery Subject to Random Collapse." *IMA Journal of Mathematics Applied in Medicine & Biology* 5(3):215–35.
- . 1989. "Optimal Investment in the Protection of a Vulnerable Biological Resource." *Natural Resource Modeling* 3:463–80.
- Smith, M. D., J. N. Sanchirico, and J. E. Wilen. 2009. "The Economics of Spatial-Dynamic Processes: Applications to Renewable Resources." *Journal of Environmental Economics and Management* 57(1):104–21.
- Smith, M. D., and J. E. Wilen. 2003. "Economic Impacts of Marine Reserves: The Importance of Spatial Behavior." *Journal of Environmental Economics and Management* 46(2):183–206.
- . 2004. "Marine Reserves with Endogenous Ports: Empirical Bioeconomics of the California Sea Urchin Fishery." *Marine Resource Economics* 19(1): 85–112.
- Wilen, J. E. 2007. "Economics of Spatial-Dynamic Processes." *American Journal of Agricultural Economics* 89(5):1134–44.