Trading on extinction: An open-access deterrence model for the South African abalone fishery

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South African rhinoceros (e.g. *Diceros bicornis*) and abalone (*Haliotis midae*) have in common that they both are harvested under open-access conditions, are high-value commodities and are traded illegally. The difference is that a legal market for abalone already exists. An open-access deterrence model was developed for South African abalone, using Table Mountain National Park as a case study. It was found that illegal poaching spiked following the closure of the recreational fishery. The resource custodian's objective is to maximise returns from confiscations. This study showed that a legal trade results in a 'trading on extinction' resource trap, with a race for profits, an increase in the probability of detection *after* a poaching event and the depletion of populations. In contrast with HS Gordon's seminal article (J Polit Econ 1954;62:124–142), profit maximisation does not automatically improve the sustainability of the resource. Under certain conditions (e.g. a legal trade with costly enforcement), profit maximisation may actually deplete abalone populations. The article also has implications for rhino populations, as a legal trade is currently proposed.

Introduction

The South African abalone (*Haliotis midae*) fishery is experiencing a crisis. Illegal harvesting of abalone has escalated dramatically in recent years, to such an extent that the fishery was closed between 2008 and 2010.[1] Several reasons for this escalation have been presented. For example, Raemaekers et al.[2] argue that both the rise in abalone prices in the 1990s and the failure to include traditional fishers in the reform process, were drivers for the collapse in the fishery. Muchapondwa et al.[1], however, found that drug use and corruption were major factors in the illegal trade in abalone.

The abalone fishery has a number of important features that characterise systems of illegal exploitation. Firstly, there is what is known as open-access to the resource. Here open-access implies that entrants have relatively free access to the resource and that species are subject to low levels of protection and enforcement and are subject to poaching.[3] Secondly, the authorities seek to restrict access to the resource by patrolling the fishery, arresting offenders and enforcing some sort of penalty for the offence. Thirdly, the fishery is characterised by a complex system.[2] This characterisation requires some form of integrated modelling to develop not only the biological dynamics of the abalone population, but also the dynamics of fishing effort.

Therefore, a model is developed here to capture each of these three features. The model is an open-access deterrence model and is developed using system dynamics modelling. Optimisation is used to calibrate the model to fit the historical data, so that unknown biological parameters may be estimated. A unique feature of the model is that it encapsulates decision-making by the resource custodian (in this case, the marine authority), thus enabling one not only to assess the implications for management of the abalone fishery, but also to see the potential implications for rhino management, as both rhino management and abalone management contain a number of similar features that will be discussed. The model is then used to answer 'what if' type policy questions to improve the sustainability of the abalone population.

Study site

The model is developed for the Table Mountain National Park in the Western Cape, South Africa, which falls within Zone E (Figure 1). Before the park was proclaimed in 2004, it was known as the Cape Peninsula National Park. In the same year the coastal waters surrounding the park were proclaimed as a marine protected area. However, fishing is still allowed in certain areas. This area was selected because it is close to an urban area (the City of Cape Town), has a good mix of legal fishing and illegal fishing, and is in close proximity to a number of fishing communities. The western areas of South Africa house some of the last remaining viable abalone populations, as many of the abalone populations to the southeast of the study area have already been depleted.

The model

Model attributes

The model comprises four features: (1) open-access modelling of poacher–population interactions using the Gordon–Schaefer model; (2) a deterrence model of poacher behaviour based on Becker's optimal enforcement model; (3) the marine authority's response to poaching; and (4) modelling of the fishery as an integrated complex system.

Open-access modelling

The Gordon–Schaefer open-access model is well described in the literature.[4,5] Changes in stocks are a function of a biological growth f(x) less harvests (h):

$$\dot{x}=f(x)-h \qquad \text{Equation 1}$$

Figure 1: Map of the study site, showing Zone E within the context of other abalone fishing zones in the Western Cape Province of South Africa.

Most frequently, f(x) is the logistic function although other density-dependent variants are possible.[6] The harvests are represented by the standard Schaefer production function, which is a linear function of effort (E) and stock size (x):

$$h(E,x) = qEx. \qquad \text{Equation 2}$$

Here q is the catchability coefficient. Effort dynamics under open-access harvesting is a function of profitability, where greater profits attract additional entrants and fewer profits discourage entrants:

$$\dot{E} = \emptyset\pi, \qquad \text{Equation 3}$$

where π is a profit function relating prices to costs and is an adjustment parameter determining the rate at which effort adjusts to changes in profitability. In this model, an adapted adjustment parameter $n' = \emptyset p$ is used, where p is the unit price of abalone, expressed as USD/tonnes. Costs on the other hand are a function of the effort expended in order to catch the resource.

Economics of crime and punishment

In a seminal article by Nobel laureate Gary Becker, it is argued that the supply of offences is a function of the probability of conviction per offence, and also the punishment per offence.[7] The model has many applications in the economics literature. One example is an application to the economics of fraud by Van Heerden et al.[8] This theory has been applied to fisheries by Sutinen and Anderson[9], and more recently by Kuperan and Sutinen[10]. The Becker model was also used by Muchapondwa et al.[1] to model the abalone fishery in South Africa.

Marine authority’s objective

A unique feature of the model is the way that the marine authority’s response to the poaching crisis is modelled. According to Goga[11], up to 30% of the marine authority’s operating budget is obtained through the sale of confiscated abalone on the open market. Revenues from the trade in abalone therefore play an important role in enforcement efforts. This role is modelled in the study by adopting a standard neoclassical approach, where the aim of the marine authority is to adapt enforcement effort in order to maximise the revenues obtained through the sale of confiscated abalone, subject to the constraints imposed by the abalone population as well as poaching effort. Some would argue that it is inappropriate for an authority tasked with resource conservation to maximise revenues from confiscations. However, this is very much aligned with the current emphasis of environmental authorities on sustainable resource use initiatives rather than conservation per se. It is therefore necessary to test the feasibility of this profit maximising objective for the sustainability of abalone stocks.

System dynamics modelling

The abalone fishery in South Africa may be viewed as a complex system, with many actors and role players. A system dynamics modelling approach provides a way of capturing those dynamics. A model was constructed to capture the interactions between poachers, the crew members, boat owners and the abalone population (Figure 2). The historical data span from 1980 to 2007, a time period of 27 years. The model is projected forward to the year 2100 to consider the effects of different management strategies on the dynamics of both abalone stocks and fishing effort.

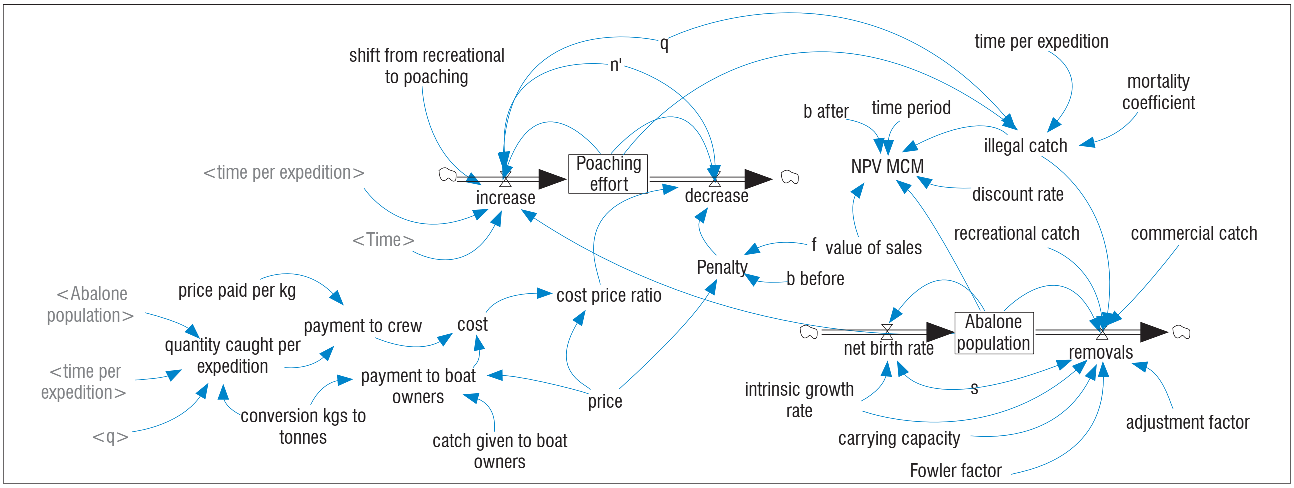


Figure 2: Stock flow diagram for the abalone fishery.

Data

The data were derived from a number of sources. Edwards and Plagányi[12] was the primary source of time series data on commercial catch per unit effort (CPUE) and commercial, recreational and illegal catches from 1980 to 2007. CPUE was standardised using a general linear modelling technique to eliminate differences between catch rates that are a result of any factor besides chance or differences in abundance (for example see Allen and Punsly[13]). These data were supplemented by data on illegal catches from 2003 to 2005[14] which were taken from confiscation records in Table Mountain National Park. In order to derive an estimate for the total illegal catch it was necessary to divide these amounts by the proportion of confiscations (b^D). It is unlikely that this proportion would be higher than 0.25, as data from Zones A to D suggest a range of between 0.06 and 0.25 (see Brandão and Butterworth[15]). In order to generate a lower bound estimate for illegal catch, the maximum proportion of confiscations was assumed to be 0.25. Therefore, illegal catch for the years 2003 to 2005 is estimated using:

$$\text{Illegal catch}_t = \text{Confiscations}_t / b^D, \text{ for } t = 2003,..,2005, \quad \text{Equation 4}$$

where $b^D = 0.25$ (Table 1). For the 2007 fishing season, it was assumed that trends in other zones were indicative of the situation in Zone E. The illegal catch in Zones A to D amounted to 927 tonnes in 2007[15] and the total allowable catch (TAC) was 125 tonnes[16].

Table 1: Exogenous parameters used in the South African abalone fishery model

Parameter	Symbol	Value	Unit	Reference
Price of abalone for poachers	p	22 000	US dollars/tonne	De Greef and Raemaekers[31]
Time per expedition	T_E	240	Minutes/expedition	De Greef[17]
Biomass in base year (1980)	X_{1980}	1484	Tonnes	Edwards and Plagányi[12]
Poaching effort in base year (1980)	E_{1980}	10	Expeditions	Own calculations
Time frame of historical data for commercial catches	T_C	27	Years	Edwards and Plagányi[12]
Time frame of historical data for recreational catches	T_R	23	Years	Edwards and Plagányi[12]
Shift from recreational to poaching		290	Expeditions/year	Optimisation
Penalty for repeat offender	f	2000	US dollars	De Greef[17]
Price paid to crew and carriers for abalone		5	US dollars/kilogram	Calculation based on De Greef and Raemaekers[31]
Catch given to boat owners	c_B	10	Kilograms/expedition	De Greef and Raemaekers[31]
Commercial catch coefficient		0.0055	Dimensionless	Calculation based on Edwards and Plagányi[12]
Catchability coefficient	q	9.3e-007	1/minutes	Edwards and Plagányi[12]
Proportion of confiscations	b^D	0.25	Dimensionless	Maximum based on Brandão and Butterworth[15]
Probability of detection prior to offence	b	0.025	Dimensionless	Assumption (tested through sensitivity analysis)
Adjustment coefficient	n’	0.44	Expeditions/tonnes/year	Optimisation
Carrying capacity	k	1710	Tonnes	Edwards and Plagányi[12]
Fowler (curvilinear) factor	z	0.88	Dimensionless	Optimisation
Intrinsic growth rate	r	0.1	Dimensionless	Edwards and Plagányi[12]
Discount rate	δ	0.01	1/year	Assumption (tested through sensitivity analysis)
Value of sales	V^A	1800	US dollars/tonnes	Goga[11]

The TAC in Zone E was 12 tonnes in 2007, so apportioning by TAC gives an estimated illegal catch in Zone E of 89 tonnes in 2007 (12/125*927). Table 2 shows the poaching data for 2003–2007, estimated in this way. The methodology is coarse but shows that illegal fishing has increased dramatically over the period since 2003. The anecdotal evidence supports this assertion.[1,2,16]

Illegal fishing effort is estimated by dividing CPUE data[12] into the illegal catch for that year. The CPUE data are for commercial fisheries. In the absence of other available data, it is necessary to assume that the CPUE for the illegal fishery would be similar. CPUE is expressed as kg/min. This unit was converted from a time-based measure of effort to a measure such as the number of fishing trips by dividing by the average length of a fishing trip.

Table 2: Estimates (tonnes) of illegal abalone catch, 2003–2007

Year	Catch
2003	5.8
2004	27.5
2005	68.7
2006	–
2007	89.0

Model equations

The exogenous parameters, values and references used are given in Table 1. The model equations are given in Table 3. The associated endogenous parameters are given in Table 4. The model comprises three components. The first component, the abalone population model, is a density-dependent logistic fisheries model. Fowler's density-dependent term was included to capture the effect of non-linear density dependence, following Milner-Gulland and Leader-Williams[6]. The logistic function has precedence in modelling South African abalone dynamics in Zone E[12], thereby enabling access to specific biological parameters for this growth function. However, no known study has modelled the non-linear density-dependence factor for South African abalone. But it is possible to use optimisation to estimate the value of the density-dependent term by minimising the difference between the model data and the historical data using the historical data published in Edwards and Plagányi[12], supplemented by the data in Table 1. The same technique is also used to estimate the value of the adjustment parameter n'.

The second component to the model is the fishing catch. Three types of fishing effort were present in the model over the historical period of the study (1980–2007). A recreational fishery was present during most of the time period, but was closed in 2004. A commercial fishery is also present in the study area, with the catch dependent on a TAC allocation determined annually by the fisheries authorities. In both these fisheries, catch is a function of the abalone abundance only. Naturally, however, recreational catches were set at zero from 2004 onwards. The illegal poaching, on the other hand, follows a standard Schaefer production function (Table 3). In other words, it is a function of the catchability coefficient, poaching effort and the available abalone population.

Table 3: Equations for the South African abalone fishery model

Cost for a diving expedition (US dollars per expedition):	**Revenue from sales of abalone confiscations:**
$c=p_C+p_B$	$\pi_t^M= b^D h_t^I V^A$
Payment to crew (US dollars per expedition):	**Illegal harvests in time t:**
$p_C=A_P^C Q_t^A$	$h_t^I= C_t^I X_t$
Quantity caught (kilograms per expedition):	**The decrease in poaching effort is:**
$Q_t^A=qvT_E X_t$ where v is a conversion rate from kilograms to tonnes	$\frac{dE}{dt} = n'E \left(\frac{c}{p} + \frac{bf}{p}\right)$
Payment to boat owners (US dollars per expedition):	**Growth in the abalone population is:**
$p_B= \frac{pc_B}{v}$	$\frac{dX}{dt} =srX$
Illegal catch coefficient:	**Removals from the abalone population:**
$C_t^I=mqT_E E_t$	$\frac{dX}{dt} =sX(\frac{rX^z}{k^z}+C_t^I+C^C+C_t^R)$
Commercial catch coefficient:	**Net present value of sales from confiscations:**
$C^C= \frac{\frac{1}{T_C} \sum_{t=1980}^{2007} h_t^c}{X_{1980}}$	$\pi(\delta,t)= \sum_{t=1}^{120} \frac{\pi_t^M}{(1+\delta)^n}$
Recreational catch coefficient:	**The increase in poaching effort:**
$C_t^R= \frac{\frac{1}{T_R} \sum_{t=1980}^{2003} h_t^R}{X_{1980}}$ $=0.03, t \leq 2003$ $=0$ otherwise	$\frac{dE}{dt} =n'C_t^I X_t$ for $t \neq 2004$ $\frac{dE}{dt} =n'C_t^I X_t + C_R^I$ for $t = 2004$

Table 4: Endogenous variables in the model for the South African abalone fishery

Parameter / endogenous variable	Symbol	Unit
Commercial harvests in time t	h_t^c	Tonnes
Recreational catch coefficient in time t	C_t^R	Dimensionless
Illegal harvests in time t	h_t^I	Tonnes
Recreational harvests in time t	h_t^R	Tonnes
Poaching effort in time t	E_t	Number of expeditions
Abalone biomass in time t	X_t	Tonnes
Illegal catch coefficient in time t	C_t^I	Dimensionless
Payment given to boat owners	p_B	US dollars/expedition
Payment given to crew	p_C	US dollars/expedition
Quantity of abalone caught per expedition in time t	Q_t^A	Kilograms/expedition
Revenue from abalone confiscation in time t	π_t^M	US dollars/year
Enforcement costs for marine authority	c^M	US dollars/year

Illegal fishing is subject to enforcement effort by authorities. A third component to the model, therefore, is the authorities' response to illegal poaching. In standard deterrence models, there is one probability of detection that *prevents* illegal activity. However, in the South African abalone fishery, there are two detection probabilities, both of which are important to the model. The first probability is the one reported above, and the second is the probability of detection following an illegal poaching event. Once poaching occurs, abalone cannot be returned to the wild and an increase in the probability of detection after poaching therefore does not improve abalone populations. The seizure of illegally caught abalone by fisheries authorities is the most commonly reported on in the literature. In our model, therefore, there is both a probability of detection that prevents illegal harvesting, and a probability of detection that results in the seizure of abalone assets.

According to Goga[11], fishery authorities sell abalone seized after illegal poaching. There is therefore an incentive to rather improve the probability of detection *following* an illegal poaching event, than to improve the probability of detection *prior* to a poaching event. Another factor to consider in the model is the penalty for transgression. Although abalone is confiscated, an additional penalty is levied. Some studies report high penalties and prison sentences for offenders. However, a recent study in Hangberg[17] found that a fine levied to a repeat offender to prevent the possibility of a prison sentence was a mere ZAR20 000 (equivalent to USD2000 at the time at which the fine was imposed).

The marine authority's problem, according to neoclassical economic principles, is to maximise the present value of revenues from the confiscation of illegal catch:

$$PV=\int_0^{\infty} e^{-\delta t} b^D h_t^I(x,E) V^A dt, \qquad \text{Equation 5}$$

where δ is the discount rate, b^D is the probability of detection after a poaching event, $h_t^I(\bullet)$ is abalone confiscations and V^A is the market value of abalone sales.

The change in abalone population ($\dot{x}$) is a function of the population growth rate f(x) less harvests:

$$\dot{x}=f(x)-h^I(E,x)-h^L(x), \qquad \text{Equation 6}$$

where $h^I(E,x)$ is the catch from illegal harvesting which is a function of poaching effort (E) and stock size x, and $h^L(x)$ is the catch from legal harvesting which is only a function of stock size.

The change in poaching effort ($\dot{E}$) is a function of profitability from illegal harvesting $\pi(\bullet)$:

$$\dot{E}=\O\pi(b,f;E,\overline{c},\overline{p}). \qquad \text{Equation 7}$$

The objective of marine authorities is to vary the probability of detection prior to a poaching event (b) and the magnitude of the fine (f) in order to maximise the present value of revenues (costs (c) and prices (p) are held constant). The system dynamics model is used to solve this problem, using a discrete time variant of the net present value problem (Table 3).

Results

Baseline simulation

The model captures the increase in the illegal poaching of abalone from 2003 onwards. This increase occurred despite greater enforcement of marine fisheries zones. In 2005, Operation Neptune and Operation Trident ended, as did the Environmental Courts. Although these initiatives were in the Overberg, poaching in the Table Mountain National Park doubled from 27.5 tonnes to 68.7 tonnes (Table 2). This model indicates that, for the given parameter values, poaching has continued to increase.

The model provides a reasonably good fit to the illegal catch, effort and abalone abundance time series between 1980 and 2007 (Figure 3a–e). Figure 3 indicates that illegal fishing spiked after the closure of the recreational fishery. The increase in illegal poaching (Figure 3b) mirrors the declines in recreational fishing (Figure 3a). Recreational fishing peaked at approximately 120 tonnes, whereas illegal fishing peaked at approximately 90 tonnes.

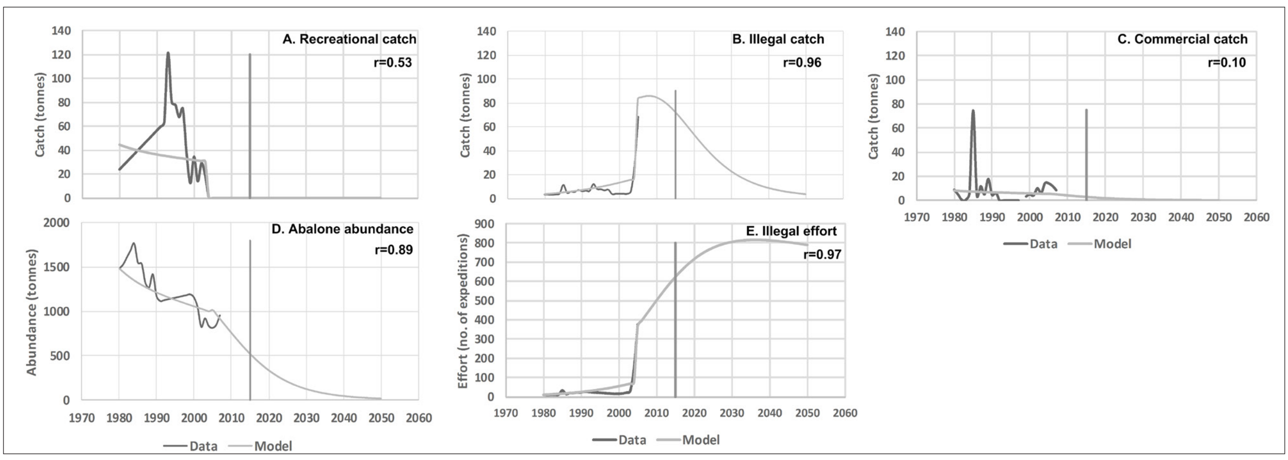


Figure 3: Baseline simulations showing how the model outputs of catch, abundance and effort replicate the historical data. The vertical line in each graph indicates the 2015 estimates.

Figure 3c indicates that, historically, the commercial fishery sectors have played a relatively small role in overall fishery catches. However, the most significant outcome of the model is that abalone stocks appear to have continued to decline since 2007, and are currently less than half of carrying capacity (Figure 3d). The decline in the illegal catch that is expected from 2015 onwards, it seems, is largely because of the lack of availability of abalone (Figure 3d) and spikes in poaching effort since 2003 (Figure 3e). According to the model, if current trends persist, abalone populations in Table Mountain National Park will be functionally extinct by 2050.

Policy simulations

The resource manager's challenge is to maximise the present value of abalone seizures by varying the probability of detection prior to a poaching event, as well as the fine for a transgression. One way of doing this is by patrolling no-take areas and also monitoring the departure of boats from the harbours.

It is important to emphasise that the following results hold for a resource manager's discount rate of less than 0.04 (4%). This is a model outcome. The marine authorities must place a high time preference on future stocks of abalone, in other words the sustainability of the resource. However, one would expect this from authorities that are custodians of abalone stocks.

The effect of varying the probability of detection prior to a poaching event (b) and the level of the fine (f) under costless enforcement are shown in Figure 4 in three figures: a bubble plot (Figure 4a), a line plot (Figure 4b) and an XY plot (Figure 4c).

The bubble plot (Figure 4a) indicates that the resource manager's profitability is maximised for high values of b and low values of f, and also low values of b and high values of f. Counter-intuitively, high values of both f and b result in the lowest net present values (NPVs) for resource managers, although these would result in the highest long-term abundance of abalone stocks.

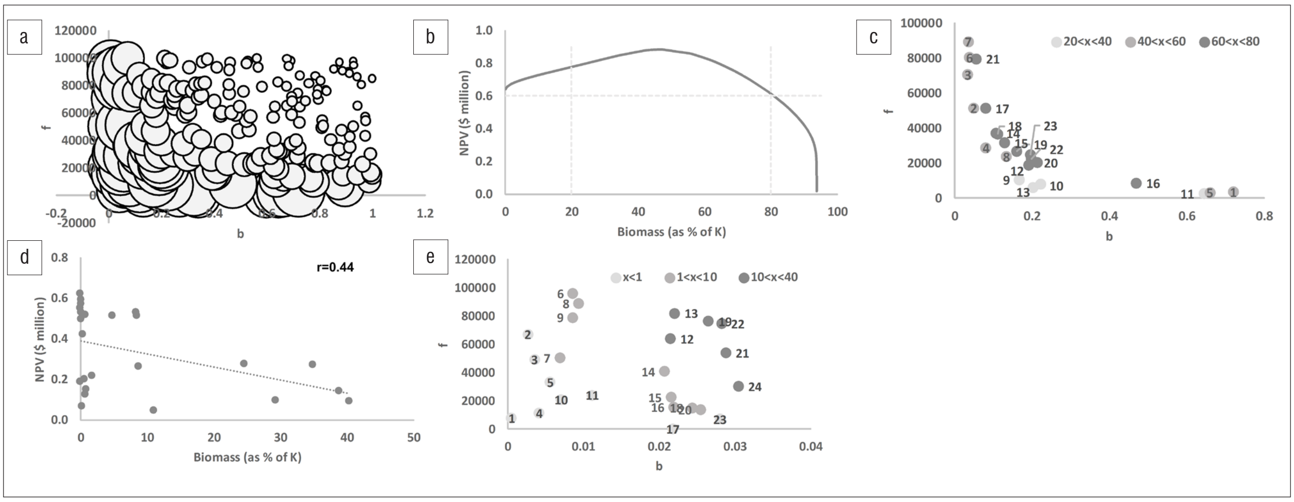
The line plot (Figure 4b) indicates that the marine authorities' NPV is maximised at an abalone abundance of approximately 50% of carrying capacity (0.47K). This value equates more or less to the stock density at maximum sustainable yield for the density-dependent logistic growth function (0.49K). The XY data plot of b and f (Figure 4c) indicates that the highest NPV is achieved for a high probability of detection (b) and a low fine (f). Taken together, this implies that improving the probability of detection prior to a poaching event produces a sustainable stock density in the abalone fishery, while also maximising profits for the marine authority.

The first series of policy simulations assumes that enforcement is costless. A simple cost function was added to the marine authority's decision problem:

$$c^M = bWc, \qquad \text{Equation 8}$$

where W is the enforcement effort of the marine authority. Enforcement costs are therefore an increasing function of the probability of detection prior to a poaching event (b). In the absence of other data, it is assumed that the enforcement costs per unit effort for the marine authority are the same as the cost per unit effort for the poaching vessel (c), and that the marine authority patrols once a day. Profit maximisation under this function is achieved by minimising the probability of detection prior to a poaching event, while maximising the level of the fine. The maximum payoff is USD0.63 million, compared with USD0.88 million under the zero enforcement cost outcome. However, at this level of enforcement effort the abalone population declines to zero by 2050, compared with populations stabilising at 47% of carrying capacity under the zero enforcement cost profit maximisation scenario.

As for the baseline, a Monte Carlo simulation was employed by varying the probability of detection prior to a poaching event (b) and the magnitude of the fine (f). This simulation indicated that only 3% of outcomes resulted in a positive NPV for the marine authority. Plotting these NPVs against biomass (from an ensemble of 750 realisations – Figure 4d) shows that, in contrast with the model of costless enforcement, profits for the resource authority are highest when stocks are allowed to deplete, and decline linearly as the biological population increases in relation to its carrying capacity. The XY plot under costly enforcement (Figure 4e) indicates that NPVs are highest under low probabilities of detection (b) and lowest under high probabilities of detection (although in absolute terms these probabilities of detection are much lower than under the costless enforcement scenario). Under costly enforcement, therefore, profit maximisation results in an unsustainable abalone population compared with profit maximisation under costless enforcement, and an incentive to minimise the probability of detection prior to a poaching event, compared with costless enforcement where there is an incentive to increase the probability of detection prior to a poaching event.



Note: (4a) Bubble size indicates NPV at year 2100; (4c and e) colour shades indicate abalone abundance as a percentage of carrying capacity (K), numbers indicate NPV rank, with 1 being the highest NPV.

Management variables: b is the probability of detection prior to an offence and f is the magnitude of the fine.

Figure 4: Simulations of the effect of management variables on marine authorities net present value (NPV) under (a–c) *costless* enforcement and (d,e) *costly* enforcement.

Sensitivity analysis

In order to test the sensitivity of the model outcomes to the new data on illegal catch in Zone E, the model was re-run using the illegal poaching data from Edwards and Plagányi[12] and the shift from recreational to poaching in the model was set at zero. The model outputs were then compared with the new historical data for abalone abundance and illegal poaching effort (Figure 5). Figure 5 indicates that the sensitivity analysis replicates the decline in abalone abundance relatively satisfactorily (Figure 5a), and tracks changes in effort relatively accurately until around 1992 (Figure 5b). Thereafter, the model predicts a continued increase in poaching effort, whereas the data show a decline in poaching effort from 1993 onwards.

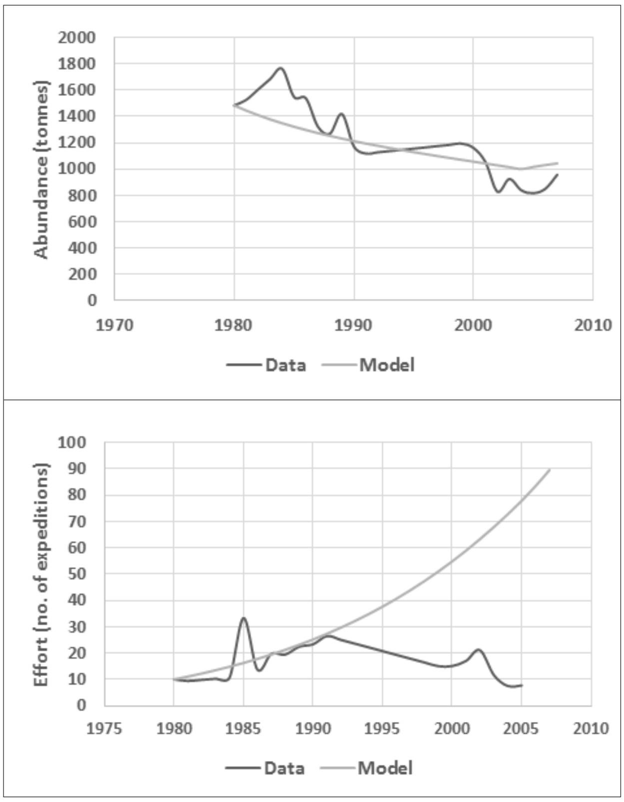


Figure 5: Sensitivity plots for (a) abalone abundance and (b) poaching effort.

There are therefore some discrepancies between the model and the published historical data under the sensitivity run. However, more recent data in Brill and Raemaekers[14] suggests that confiscations alone could be much higher than these published data. For example, Brill and Raemaeker's data indicate that reported confiscations in Zone E amounted to 17.2 tonnes of shucked abalone in 2005 (own calculations based on their data), which is considerably higher than the 1.4 tonnes reported in Edwards and Plagányi[12] for the same period. Furthermore Brill and Raemaeker's data exclude undetected poaching events, so the possibility exists that poaching is even higher in Zone E than these estimates. Their data span the years 2000 to 2009, and therefore do not include the period from 1993 to 1999. Their data do, however, indicate a growing trend in confiscations over these 9 years, although this would only indicate an increase in illegal catch (and poaching effort as effort is proportional to catch in the Schaefer production function – see Equation 2) over that period if b^D was stable or declining over that same period. Plagianyi et al.[18] published time series data of a policing effort index which could provide an indication of likely changes in b^D over time. The data show that the policing index remained constant between the years 2000 and 2004, but then decreased by 20 percentage points in 2004 and remained at this lower level until 2008. This finding indicates that illegal catch (and poaching effort) may have increased by even more than that modelled in this study (see Equation 4 – a decreasing b^D implies an increase in illegal catch and poaching effort). However, this index is for Zones A to D and one can therefore not categorically state that the same trends would be observed in Zone E. In conclusion, there still is much uncertainty over the historical data, and further work in this area would be beneficial.

In spite of these uncertainties, the sensitivity analysis indicates that abalone abundance will decline, reaching functional extinction by 2080, which is slightly longer than that for the baseline model (2050). The model is therefore robust in predicting declines in abalone abundance, irrespective of whether or not there is a spike in illegal catches following the closure of the recreational fishery.

Implications for rhino conservation

There are many similarities between the abalone fishery and rhino conservation in South Africa. Both abalone and rhino horn are high-value commodities for which there is considerable demand on the Asian markets. Although abalone can be sold legally for about ZAR350/kg (USD35/kg wet 'in shell' weight), black market prices are considerably higher, with recent estimates at approximately ZAR2500/kg (USD250/kg). However, the trade in abalone is high volume. It was recently estimated that the illegal trade in abalone in the Eastern Cape Province of South Africa alone was worth USD50–100 million annually.[19] The rhino horn trade fetches considerably higher prices, approximately USD65 000/kg in 2013, with some studies indicating prices as high as USD100 000/kg, but volumes are lower. Given that one horn weighs about 3 kg, and about 1000 rhinos were poached in South Africa in 2013, the implied illegal trade in rhino horn in South Africa was worth USD200–300 million in 2013.

Other similarities between the abalone fishery and rhino horn trade include that both products are relatively easy to transport; both species are slow-growing species and do not propagate easily; and as resources, they are difficult to protect – rhinos inhabit large areas that are often not adequately fenced off and abalone live in the ocean and consequently there are large areas of coastline to patrol. In sum, these types of resource demonstrate many features of an open-access system.

One notable difference between abalone and rhinos is that the abalone fishery in South Africa is characterised by a legal and illegal trade, whereas rhino horn is currently only traded illegally. However, there are strong lobby groups advocating for the legalisation of rhino horn trade. Observing the behaviour of the South African government as far as the South African abalone fishery is concerned therefore gives one some indication of how the government might respond if rhino horn were legally traded. There are, then, some important lessons that could be learnt from the abalone fishery.

The abalone fishery study indicates that it is important to distinguish between the probability of detection *prior* to the poaching offence, and the probability of detection *following* the poaching offence. Legalisation of trade in rhino horn would provide incentives to the South African government to increase the probability of detection *following* a poaching event. In the short term, this approach would not help to protect rhino populations, as the rhino would have already been killed. This approach will result in a race for rhinos and a 'trading on extinction' scenario in which profits are maximised over the short term to the detriment of the rhino population. This is similar to the 'banking on extinction' hypothesis of Mason et al.[20], except that instead of stockpiling, goods are sold on the open market. Over the long term, the effect of changing the probability of detection after a poaching event for rhinos is uncertain. However, changing the probability of detection after a poaching event for abalone fisheries has not deterred poachers over the long term. In fact, poaching appears to have increased over the periods of heightened enforcement effort between 2000 and 2005. The solution for escaping the 'trading on extinction' scenario is to improve the probability of detection *prior* to a poaching event.

Under costless enforcement, profit maximisation provides an incentive to reduce the probability of detection prior to a poaching event, which results in a sustainable resource stock approximately at maximum sustainable yield. However, under costly enforcement, there is no economic incentive for resource custodians to improve the probability of detection prior to a poaching event. The abalone model indicates that the long-term sustainability of the resource is highly questionable under the following conditions: (1) a wildlife resource is subject to high levels of poaching; (2) there is a legal as well as an illegal trade in the resource; (3) the trade is highly lucrative; (4) profit maximisation principles are pursued by resource owners/custodians; and (5) enforcement is costly. Most of these conditions also hold for rhinos, were a legal trade to be allowed. A limitation of the abalone model is that only confiscation revenues, and not other sources of income, are included. For game farms or reserves, alternative sources of income such as that from de-horning and tourism may influence the outcome of the model. Some work has been done in this regard (see discussion section), although further work is required.

It is important also to recognise that a fundamental difference between abalone and rhinos is that abalone's primary benefit is through consumption. On the other hand, rhinos have a significant direct non-consumption benefit, namely tourism value. However both rhinos and abalone have a potential indirect non-consumptive benefit through ecosystem functioning. As Waldram et al.[21] indicate, rhinos may reduce sward height in grasslands, thereby reducing the extent of bushfires in savanna regions. Abalone, on the other hand, relies on the sea urchin *Parechinus angulosus* as a refugia for juveniles,[22] and therefore a well-functioning ecosystem is crucial to the survival of abalone. However, the removal of abalone may affect the emergence of epibenthic communities, as well as predatory fish diets.[23] Therefore, tourism in both the marine environment as well as the savanna areas may be affected indirectly through an overall degeneration of ecosystem functioning associated with the disturbance of the ecological system. An assessment of a legal trade in both rhino horn and abalone should therefore also take these non-consumptive benefits into consideration.

Discussion

It has been shown here that a trading on extinction incentive exists in the management of abalone stocks. This finding implies that there is an incentive for wildlife authorities to maximise short-term revenues at the expense of the long-term sustainability of the abalone population. A similar effect was observed by Crookes and Blignaut[24] in their model of the trade in rhino horn. They found that, although a legalisation of the trade increased the profitability of game farms significantly compared with a no-trade scenario, profits were higher under a policy outcome that resulted in the local extinction of the rhino population compared with profits under a sustainable supply of rhino. This outcome was a result of the fact that demand for rhino horn needed to decrease for sustainability to be achieved, which meant that the price of rhino horn would fall compared with demand from unsustainable supply.

It may seem paradoxical that a wildlife authority would have as its objective profit maximising, rather than another objective such as welfare maximisation, so two branches of literature are briefly discussed in support of this conclusion. Firstly, there is a significant body of literature that suggests that governments are motivated by profits when it comes to wildlife management. For example, Mayoral-Phillips, in his review of protected areas management in southern Africa, indicated that 'Governments, institutions, experts and stakeholders are rigidly following the rhetoric of "wildlife pays, wildlife stays", a form of wildlife privatisation of the commons'[25(p.11)]. This privatisation does not imply that a national resource is placed in private sector hands, but rather implies that private sector principles of profit maximisation are applied (for example see De Fraja and Delbono[26]).

Other studies have also confirmed that there is a detrimental effect on the environment if the principles of profit maximisation are applied by government in certain instances. Bárcena-Ruiz and Garzón[27] showed that when there are both government and private firms in product markets the environmental damage is greater than in the case of only private sector firms competing. Beladi and Chao[28] also found a detrimental effect on the environment if government follows profit maximising principles. This outcome is a consequence of the failure of the government sector to prevent environmental damage when it acts as a monopoly, because they argue that it is characterised by inefficient management (see also Wang and Wang[29]). In all these examples, however, environmental impact is measured in terms of pollution emissions. This study is the first one known to observe this trend in abalone, and there is now a growing body of literature to suggest that profit maximisation under a legalised trade in wildlife may be detrimental to the sustainability of the wildlife populations. This is true at least for rhinos and abalone, and further work is required to establish whether or not this conclusion holds in other wildlife sectors as well.

Conclusions

An open-access deterrence model for the abalone fishery in Table Mountain National Park (Zone E) was presented here. Fishing has moved westwards in recent years, because many areas of the Overberg region are now so depleted that some areas no longer contain viable populations. This study is therefore important, as it provides a tool for marine authorities to better manage abalone populations. Under current conditions, abalone populations in Table Mountain National Park could be depleted by 2050, as a result of a spike in illegal fishing effort following the closure of the recreational fishery in 2003.

In contrast with Gordon's seminal article[30], profit maximisation may not always result in the improved sustainability of wildlife populations. In the case of rhinos and abalone, a legalised trade must be accompanied by secondary policies, for the sustainability of the resource to be achieved. For rhinos, this secondary policy is consumer behaviour modification that reduces demand,[24] whereas for abalone, it is improving the probability of detection prior to an offence. Under costly enforcement, the market does not provide the incentives to adopt these secondary policies, because profits are higher without them. If there is a legalised trade then there is an incentive for resource owners to switch to a non-sustainable (but profit maximising) solution – termed the 'trading on extinction' effect. There is a need to emphasise and promote the non-consumptive benefits of the resources in question, as well as, in the case of abalone, address the causes of poaching rather than the consequences of poaching.

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