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A bioeconomic model for Hooker's sea lion bycatch in New Zealand*

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The New Zealand Ministry of Fisheries constrains the incidental capture of Hooker's sea lions in trawl nets of the southern squid fishery by closing the season once an upper limit on sea lion deaths is reached. The regulatory measure is in fact a limit on effort because the number of sea lion deaths is calculated from an estimated mortality rate per standard unit of effort measured in tows. During recent years, vessels have been observed to increase the median time per tow, suggesting that the industry is expanding the capacity of an unregulated input in response. This paper formalises the current situation analytically by constructing a bioeconomic model that captures the idiosyncrasies of the squid fishery and the imposed regulation. Reducing the regulatory constraint to an isoperimetric problem can show how the current management regime may skew incentives leading to the observed increase in tow time. An extension to the current regulatory framework by introducing a spatial dimension to the estimated sea lion mortality rate may lead to more efficient behaviour. Despite retaining an upper limit on sea lion deaths, the profit-maximising squid industry is given the incentive to increase effort in areas of high squid density relative to sea lion density.

Key words: bioeconomic model, regulation, sea lion bycatch, squid fishery.

1. Introduction

Harvesting activities by commercial vessels resulting in the unintended and incidental catch of marine mammals have been occurring for centuries (Read *et al*. 2006). The practice of discarding captured animals dead (or mortally injured) when they have no economic value or are protected by law is known as bycatch (Hall 1996). Read *et al*. (2006) estimate the global bycatch to be in the hundreds of thousands of marine mammals, primarily because of the rapid growth of fisheries worldwide over the last decade, with significant demographic effects on local marine mammal populations.

Tuna–dolphin interactions in the eastern tropical Pacific were probably one of the most widely publicised problems, where fishers set large seines on dolphins to fish on associated schools of tuna (Alverson and Hughes 1996). The problem of bycatch is not unique to marine mammals. Other species that

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suffer from interactions with commercial vessels include sea birds in longline fisheries (e.g. Gilman *et al.* 2005), turtles in nets and longline fisheries (e.g. Watson *et al.* 2005), large sharks (e.g. Lewison *et al.* 2004) and other less charismatic species (Casey and Myers 1998).

Aspirations to reduce the level of marine mammal bycatch rest on the FAO code of conduct for responsible fisheries (FAO 1995), encouraging responsible and sustainable fisheries management and explicitly discouraging the practice of discarding. Operational measures to reduce bycatch are limited to either a reduction on effort or on the bycatch-per-unit effort (Hall 1996). The former is a costly solution often imposed indirectly by enforcing spatial and temporal closures, such as in the tuna–dolphin program (Hall 1998), while the latter relates to technological changes in gear and other equipment; for example, requirements for turtle excluder devices on trawlers have had a marked positive impact on turtle mortality (Magnuson *et al.* 1990). Other measures include changes in the deployment and retrieval of fishing gear (for example deploying longlines at night reduces seabird bycatches (Loekkeborg 1998)) and training of fishers to provide them with the information to avoid conditions favouring high bycatch levels (Hall *et al.* 2000).

This paper analyses the bycatch problem of the rare Hooker's sea lion, which pursues the same prey as commercial fishers when harvesting arrow squid by trawl nets around the sub-Antarctic islands, 350 km south of the New Zealand mainland. Population levels of sea lions have dropped by more than 40 per cent over the past 10 years with now < 10,000 individuals of the endemic species left (Southland Times 2010). Currently, the New Zealand Ministry of Fisheries constrains the incidental capture of sea lions in trawl nets by closing the fishing season once an upper limit on sea lion deaths is reached, where the calculated number of sea lion deaths is based on an estimated mortality rate per standard unit of effort. The calculation leans on measures developed in the US marine mammal management scheme where estimated bycatch rates are applied to some measure of total fishing effort to derive total bycatch levels (Read *et al.* 2006).

This paper draws attention to the fact that the Ministry of Fisheries' upper limit on sea lion deaths, and in particular the calculation of this upper limit as a function of the total units of effort in a season, is in fact an indirect limit on fishing effort. The finding is in line with Hall (1998) who notes that a total bycatch limit is often a costly solution by indirectly constraining fishing effort. The squid industry has to forgo revenue streams as a result of the premature closure of the fishing season once the upper limit on sea lion deaths is reached. During recent years, vessels have been observed to expand the capacity of a standard unit of effort, indicating that the industry may be trying to circumvent regulation rather than focus on avoiding sea lion capture.

The current situation is analysed by constructing a bioeconomic model that reflects the idiosyncrasies of the fishery. The squid fishery is best modelled by a single-cohort model, and the effects of regulation are analysed by reducing the regulatory constraint to an isoperimetric problem. The model is able to show how the current management regime provides incentives leading to the observed expansion of fishing capacity. An extension to the current regulatory framework by taking spatial differences in sea lion density into consideration adds flexibility and may lead to more efficient behaviour. Despite retaining an upper limit on sea lion deaths, the profit-maximising squid industry is accorded spatial flexibility in its response to the regulatory limit and given the incentive to increase harvest activity in zones of high squid density relative to sea lion density. The more effective the Ministry of Fisheries and/or squid industry becomes in integrating the spatial dimension into regulation, the greater the scope for maximising economic gains and the less pressure there will be on expanding the capacity of the defined effort unit.

Section 2 provides a brief summary of sea lions as a bycatch to the squid fishery, section 3 proposes a single-cohort model to capture the characteristics of the squid fishery, section 4 illustrates the dynamic optimisation problem of the squid industry, section 5 models the effects of regulation, section 6 provides policy advice by presenting a spatial model and numerical analysis, section 7 provides a short discussion and section 8 concludes.

2. Squid and sea lions

The squid fishery is managed by an individual transferable quota (ITQ) system, New Zealand's rights-based management response to dwindling inshore stocks since 1986. Each year the Ministry of Fisheries sets a total allowable commercial catch (TACC) in each of the four quota management areas (QMAs) for squid, and the ITQs are well-defined rights to harvest a percentage share of this TACC. Owners can buy (sell) parts of their ITQ holdings[1] to increase (reduce) their landings. The amount an owner is allowed to catch within the next fishing year is known as an annual catch entitlement (ACE). To enhance flexibility of the system, ITQ owners may lease all or part of their ACE to other fishers. The result is that anyone may enter the industry by buying ITQs or leasing ACE at any time. The underlying theory is that owners of such ITQs may trade or lease them freely in a competitive market, generating price signals that provide important information on the profitability and sustainability of the fishery.[2] Figure 1 shows the squid QMAs SQU1J (jig fishing only), and SQU1T, SQU6T and SQU10T (trawl fisheries but can be jigged) (Chilvers 2008).

Squid fishing in New Zealand goes as far back as in the late 1970s, mainly by jigging. In 2008 arrow squid was one of the top 10 export species, worth $NZ 71 million (Seafood Industry Council (SeaFIC) 2010). A large fraction of this catch is derived nearly exclusively by trawl from SQU6T, an area

[1] ITQs are subject to certain restrictions on aggregation and foreign ownership (Ministry of Fisheries 2010).

[2] Newell *et al.* (2005) find support for a competitive market for economically important fish stocks in New Zealand and conclude that its ITQ system is a potentially effective instrument for efficient fisheries management.

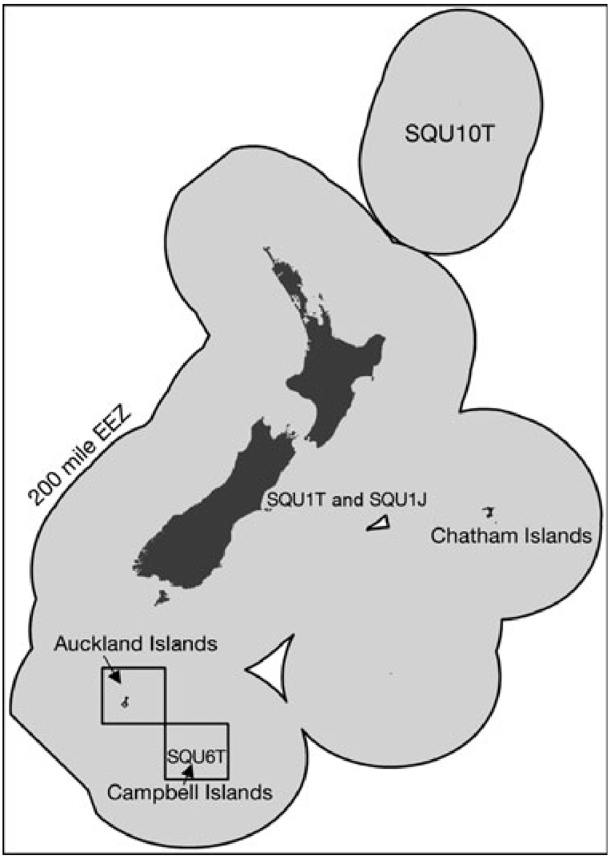

Figure 1 Quota Management Areas for New Zealand's squid fisheries. Replicated from Chilvers (2008), Fig 3 (with permission from the author and the Ministry of Fisheries).

south of the New Zealand mainland. Trawling activity focusses on waters surrounding the Auckland Islands, which lie within SQU6T, due to being relatively accessible for squid vessels and leading to little finfish bycatch. The TACC for SQU6T has been historically above actual landings and has remained unchanged since 1997–1998; however, recent management measures to protect the rare Hooker's sea lion (*Phocarctos hookeri*) have constrained landings (Ministry of Fisheries 2009).

The Hooker's sea lion is endemic to New Zealand, with its main breeding grounds confined to the Auckland Islands (MarineBio 2009).[3] The main food source consists of fish, squid and octopus, and individuals can live up to 18–23 years. In New Zealand, sea lions are classified as a threatened species and are also listed as vulnerable on the IUCN Red List, primarily because of the limited number of breeding sites (Breen and Kim 2005).

[3] Small numbers are also found on other sub-Antarctic islands and on isolated beaches of the southern New Zealand coastline.

The operation of the fishery coincides spatially and temporally with the foraging and breeding behaviour of sea lions that prey on squid. Sea lions are most frequently caught by arrow squid trawl vessels in the SQU6T fishing grounds around the Auckland Islands and capture usually results in the drowning of the animals (Breen and Kim 2005). The impact of the bycatch mortality on the population size is debated; however, the Ministry of Fisheries has enacted a regulatory measure to constrain the incidental capture of sea lions, the analysis of which constitutes the main subject of this paper.

3. The single-cohort model

The New Zealand squid fishery reflects the unique biological characteristic of the arrow squid *Nototodarus sloanii* found in the south of New Zealand. Unlike other pelagic fish, arrow squid live for 1 year and exhibit rapid growth in the latter stages of their life cycle, during which fishing occurs (Breen and Kim 2005).

Wilson and Soboil (2006) present a combined squid and sea lion model to test alternative management strategies for squid harvesting in New Zealand. The authors treat the squid stock as a lumped parameter problem represented by a Verhulst logistic growth function, which they couple with a 'die off' function[4] to reflect the rapid death of squid once it reaches the age of one. Logistic growth presupposes a yearly standing stock where the rate of reproduction is proportional to the existing population and the amount of available resources. However, given the biological idiosyncrasies of squid, the problem is more accurately represented by the single-cohort model of Beverton and Holt (1957). All squid individuals hatch between July and August and spawn once in their lifetime in the months of June and July shortly before they die. This means every squid fishing season is based on a completely new stock with individuals of the same age (Ministry of Fisheries 2009). Fishing occurs between January and May and is conducted almost entirely by trawl with little finfish bycatch. Recruitment is highly variable and influenced largely by environmental and oceanographic variables.[5] This implies there is little statistical correlation between recruitment and spawning biomass, and predicting yearly biomass levels is difficult (Ministry of Fisheries 2009).

Following Clark's (2005) exposition of the Beverton–Holt single-cohort model and adapting it to reflect the biological characteristics of the squid fishery, the change in the number of squid, $N(t)$, alive in a given cohort at time t can be expressed as

[4] The rate of squid 'die off' is modelled as a rapidly increasing function of age by using a large exponent on age.

[5] Arrow squid recruitment is subject to large environmental variability owing to changes in upwelling, nutrient loads and primary production blooms.

$$\frac{\mathrm{d}N(t)}{\mathrm{d}t} = -[M(t) + F(t) + F_s]N(t) \tag{1}$$

$$N(0) = R \tag{2}$$

where $M(t)$ represents the natural mortality rate, $F(t)$ the fishing mortality rate, F_s the rate of squid being preyed upon by sea lions and R recruitment (assumed to be a given constant). The predation effect of sea lions on squid, F_s, is negligible and dropped in further analysis. Equation (1) distinguishes itself from the Beverton–Holt single-cohort model by making natural mortality $M(t)$ a time-dependent variable (as opposed to some assumed constant M). This is to reflect the rapid change in natural mortality towards the end of the life cycle, where all squid die by the age of one. The total biomass of the squid cohort, $B(t)$, is defined as

$$B(t) = N(t)w(t) \tag{3}$$

where $w(t)$ measures the time-dependent average weight of squid.[6] The natural biomass of squid, $B_0(t)$, (where $F(t) = 0$) is given by

$$B_0(t) = \mathrm{R}\mathrm{e}^{-M(t)t}w(t) \tag{4}$$

By differentiating Equation (4) with respect to time t, one can derive the age $t = t_0$ (here in terms of months) at which the natural biomass of squid attains its maximum value.

$$\frac{\dot{w}}{w} = \dot{M}t + M(t) \tag{5}$$

Equation (5) shows that, given natural mortality is assumed to be a function of time in Equation (4), t_0 depends both on the *change* of natural mortality over time, $\dot{M}$, multiplied by the number of months, t, and on natural mortality, $M(t)$. Similar to Wilson and Soboil's (2006) representation of the rate of die off, one can model $M(t)$ as a function of age according to

$$M(t) = \Omega t^{y} \tag{6}$$

where Ω takes the value of a constant and γ is a relatively large exponent so as to ensure death of all squid by month 12. In practical terms, this means that the natural biomass $B_0(t)$ function follows a strong peak-shaped pattern with a slow take off and a sharply decreasing drop close to the end of month 12.

[6] Weight is typically represented by a Bertalanffy weight function (see Ministry of Fisheries (2009) for estimated Bertalanffy weight parameter values of squid).

4. Dynamic optimisation

New Zealand deepwater interests are combined in a single, efficient management company since 2005. The Deepwater Group Ltd. represents the amalgamated interests of 14 deepwater companies fishing for hoki, squid and orange roughy. Shareholders agree to and fund an annual business plan based on their quota holdings (shareholders in the Deepwater Group hold about 97 per cent of the quota in the squid trawl fishery areas SQU1T and SQU6T) (The Deepwater Group 2008). This approach ensures proportionate representation among shareholders in decision-making and in governance. The Deepwater Group explicitly aims to optimise economic value and facilitate economies of scale across the management of deepwater fisheries, including the liaison with the Ministry of Fisheries and other marine stakeholders.[7] For example, the Deepwater Group voluntarily withdrew most vessels before the upper limit on sea lion deaths was met in 2000–01 and introduced sea lion exclusion devices on all deepwater vessels fishing for squid in response to regulatory measures (Ministry of Fisheries 2009).[8] Given that squid fishing interests are represented by the Deepwater Group, the fishers' management problem can be modelled as that of a private, single-owner fishery, hereafter referred to as the (squid) industry.

The dynamic analysis of the Beverton–Holt model assuming a single owner becomes complex and analytically intractable when maximising harvest of an age-structured population with many cohorts. However, as every squid fishing season is based on individuals of the same age, one can resort to the simple dynamic optimisation of a single-cohort harvest when no regulation is imposed. Allowing $F(t)$ to vary over time ($0 < F(t) \leq F_{\max}(t)$), Clark (2005) formulates the problem as one of maximising the present value, PV, of the net benefits from harvest of a squid cohort discounted[9] at a rate δ as

$$\mathrm{PV} = \int_0^\infty \mathrm{e}^{-\delta t}[pN(t)w(t) - c]F(t)\mathrm{d}t \tag{7}$$

The price of squid, p, and the cost coefficient, c, are assumed constant. The objective function (7) is maximised in continuous time with an infinite time horizon subject to Equation (1), where $F(t)$ constitutes the control variable and $N(t)$ the state variable.[10] Following the standard bang–bang approach to

[7] The Deepwater Group (2010). Available from URL: http://www.deepwater.co.nz [accessed 20 June 2010]

[8] Deepwater fishing interests for squid were represented by a single submission in response to the Ministry of Fisheries' 2008–09 SQU6T Squid Operational Plan (The Deepwater Group 2008).

[9] Sea lions have no commercial value and so do not appear in the industry's maximisation problem.

[10] Prior to sea lion regulation, Ministry of Fisheries (2009) data indicate the squid TACC has not been an active harvesting constraint and is therefore not part of the maximization problem.

this linear control problem, the results show that the singular solution $N^*(t)$ is not qualitatively affected by the assumption of a time-dependent natural mortality rate $M(t)$. The optimal path of squid population can be restated from Clark (2005) as

$$N^*(t) = \frac{\delta c}{pw(t)\left[\delta + M(t) - \frac{\dot{w}(t)}{w(t)}\right]} \tag{8}$$

If $B^*(t) = N^*(t)\, w(t)$, Equation (8) can be restated as

$$B^*(t) = \frac{\delta c}{p\left[\delta + M(t) - \frac{\dot{w}(t)}{w(t)}\right]} \tag{9}$$

However, given Equation (6), the optimal biomass path, $B^*(t)$, distinguishes itself in that it intersects the natural biomass curve, B_0, relatively late in the life cycle of the species and displays a sharp decline in line with the peak-shaped pattern of the natural biomass curve. Figure 2 provides a visual example[11] of what the natural and optimal biomass paths may look like based on estimates of biological parameters of squid (provided by the Ministry of Fisheries 2009).[12]

The Beverton–Holt single-cohort model assuming time-dependent natural mortality is able to explain the behaviour of a profit-maximising industry adequately. Squid hatch between July and August every year are left to increase in natural biomass until 6 months or so later and are then intensively harvested from January to May, shortly before they die in June and July. Squid landings data obtained from the Ministry of Fisheries illustrate harvesting intensity in SQU6T over recent years. Figure 3 shows that average monthly landings between 2001 and 2009 rise in February (1699 tonnes), peak in March and April (with 7324 and 7593 tonnes, respectively) and decline again in May (2749 tonnes) to negligible takings in June and July, after which average landings are zero. The squid industry takes the biological idiosyncrasies of arrow squid closely into consideration and adjusts fishing intensity and timing accordingly to maximise profits.

5. The effect of regulation

The bycatch of Hooker's sea lions in the southern squid fishery has motivated a number of regulatory measures by the New Zealand Ministry of

[11] Refer to Figure 9.9, p. 283 in Clark (2005) for comparison to biomass paths assuming a constant M.

[12] The values in Figure 2 are hypothetical. Known biological estimates are calibrated by scaling unknown parameters such as Ω and γ from Equation (6) to fit the lifespan of squid and historical harvest estimates. As expected, sensitivity trials show that the peak shaped property of B_0 derives primarily from the value of the assumed exponent γ.

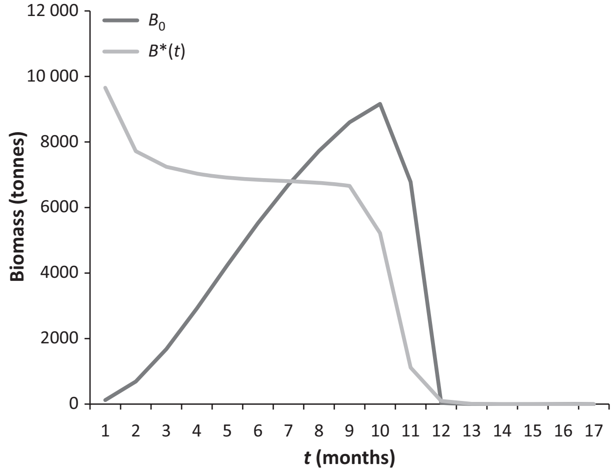

Figure 2 Natural and optimal biomass path of arrow squid.

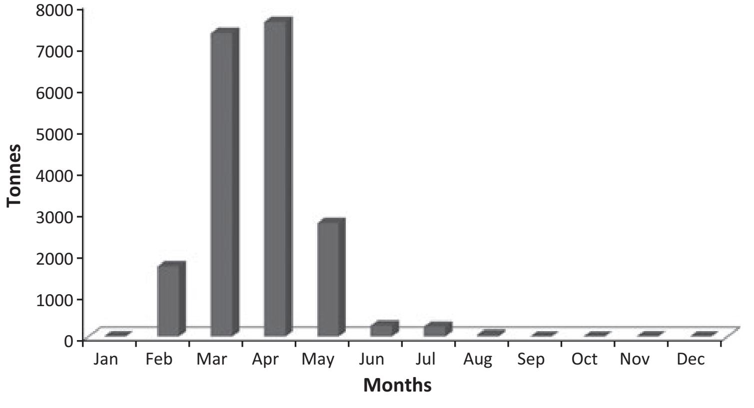

Figure 3 Average landings of arrow squid 2001–2009, by month.

Fisheries, the most significant of which was enacted in 1992, known as the SQU6T Sea Lion Operational Plan. The regulatory measure imposes a yearly upper limit (or bycatch quota) on the number of sea lion deaths upon which the squid fishing season will be closed. This upper limit, called 'fishery-related mortality limit' (FRML), is based on a proxy of the fatal interaction between squid vessels and sea lions (Ministry of Fisheries 2008). By analysing effort data between 2003 and 2006, the Ministry calculated a strike rate of 5.65 per cent (meaning for every 100 tows undertaken by squid trawl vessels, 5.65 sea lions are presumed killed and counted against the FRML).

Every year the Minister has to choose from a series of harvest control rules that vary in the value of the FRML and the associated fishing opportunities foregone as a result of closing the fishing season prematurely. These harvest control rules are determined on the basis of a complex biological model known as the Breen–Kim model.[13] The Minister decided to set a FRML of 113 sea lions for the 2008–09 fishing season, predicting an estimated loss of 419 tows forgone for the squid fishery.

The application of a bycatch quota on sea lions is controversial. Conservation agencies demand a zero 'kill quota', claiming sea lion populations are small and declining and the Breen–Kim model is associated with large uncertainties. The squid industry is equally dissatisfied, pointing out that the squid fishery is one of New Zealand's most valuable export fisheries. Export values have peaked around NZ$ 172 million in 2004 but dropped to NZ$ 71 million in 2008 and 2009.

The industry has made voluntary efforts to mitigate the incidental capture of sea lions (The Deepwater Group 2008). For example, all vessels are voluntarily using a 'sea lion escape device' (SLED) in their trawl nets, which provides an escape hole for sea lions to swim out of the net. However, the effectiveness of such escape holes is controversial (Breen and Kim 2005).

The central question that motivates this study is whether the current regulation provides the appropriate incentives for the squid industry to avoid the capture of sea lions. If society wishes to protect sea lions as well as promote industry profitability, the cost of capturing sea lions during harvesting activities has to be internalised so that the industry can respond in an efficient manner. The following provides an indication that the current regulation fails to do so. The Ministry had to increase the strike rate from 5.3 per cent to 5.65 per cent in the 2008–09 season to take account of an increase in the median time per tow (Ministry of Fisheries 2008). It was observed that over a time span of 3 years, the median tow length had increased steadily from approximately 4 to 5.8 h.

This is to be expected given the way the regulation is implemented. The FRML of 113 sea lions is in fact an *imposed restriction on effort*; a strike rate of 5.65 per cent implies 5.65 sea lions are presumed dead for every 100 tows.[14] It follows that an upper limit of 113 sea lions represents a maximum cumulative number of 2000 tows per season, $\bar{v}$, which applies to the squid industry as a whole. The effect of imposing a binding restriction on effort leads to the following maximisation problem

$$\mathrm{PV} = \int_0^\infty e^{-\delta t}[pN(t)w(t) - c]q\bar{h}\bar{v}(t)\mathrm{d}t \tag{10}$$

[13] The Breen–Kim model is a sea lion population model developed in 2003 by biologists Paul Breen and Susan Kim of the National Institute of Water and Atmospheric Research Ltd., Wellington, New Zealand.

[14] Vessels with SLED are given a discount rate reducing the strike rate of 5.65–3.67 per cent. Virtually, all squid vessels have a SLED, but for the purpose of this analysis, a rate of 5.65 per cent is assumed.

$$\int_0^\infty v(t) \le \bar{v} \tag{11}$$

The squid fishery, represented by the Deepwater Group Ltd., aims to maximise the net benefits from squid harvest according to Equation (10) subject to the effort constraint in Equation (11). Equation (10) restates Equation (7) with the difference in representing the fishing mortality variable $F(t)$ as a product of the catchability coefficient q (assumed constant) and fishing effort $E(t)$ (Beverton and Holt 1957). In the case of a trawl fishery, effort $E(t)$ can be measured by the product of the duration per tow $\bar{h}$ and the number of tows at time t, $v(t)$. To increase fishing efficiency, trawling vessels generally maximise the standard duration per tow subject to limiting factors such as fish quality. The variable $\bar{h}$ is assumed constant in the short term (during a fishing season) and measured by the median number of hours per tow. Effort $E(t)$ in Equation (10) is defined as

$$F(t) = qE(t) = q\bar{h}v(t) \tag{12}$$

where $v(t)$ is the control variable. The constraint in Equation (11) reflects the imposed effort restriction; once the cumulative number of tows during the fishing season reaches $\bar{v} = 2000$, the fishery will be closed.

Equation (12) obliterates the usual biological constraint shown by Equation (1) as long as it is binding, meaning as long as the optimal cumulative number of tows $\int_0^\infty v^*(t)$ that would have been undertaken in absence of regulation is bigger than the imposed effort restriction, $\int_0^\infty v^*(t) > \bar{v}$, the problem becomes one akin to the extraction of exhaustible resources (according to the Ministry of Fisheries (2009) the FRML has been an active constraint in the squid fishery over the last few years). The industry no longer focusses on determining the effort $v^*(t)$ that maximises Equation (10) but aims to find an optimal effort path for the amount of tows determined by $\bar{v}$ in Equation (11) (akin to an optimal path of exhaustible resource extraction).

The maximisation of Equation (10) subject to (11) is an isoperimetric problem implying a constant co-state variable $\bar{\mu}$, regardless of the type of equality condition (Chiang 1992). The Lagrangian integrand L is defined as

$$L = e^{-\delta t}[pN(t)w(t) - c]q\bar{h}v(t) - \bar{\mu}v(t) \tag{13}$$

and maximised with respect to the control variable $v(t)$ to yield the following solution

$$e^{\delta t}\bar{\mu} = [pN(t)w(t) - c]q\bar{h} \tag{14}$$

The economic interpretation of Equation (14) may provide insight as to why the median tow length, $\bar{h}$, has been observed to increase. Recalling that $\bar{\mu}$

is a constant, Equation (14) describes the condition that the marginal net benefit of effort $[pN(t)w(t) - c]q\bar{h}$ has to grow at the rate δ along an optimal path. The co-state variable $\bar{\mu}$ thus represents the initial value of $[pN(t)w(t) - c]q\bar{h}$, and the industry can increase this initial value (and thus compounded profits) by increasing the *value of* $\bar{h}$. In the common solution path of exhaustible resources, agents have no control over the initial condition.[15] However, in the case where effort is composed of both tow duration and tow frequency but the effort restriction only applies to the latter, the regulatory constraint sets the incentive to divert profit-maximising behaviour to the expansion of median tow length. Equation (14) formally demonstrates the observed incentive to expand the capacity of an unregulated input resulting from an effort-based restriction.

6. Policy advice

6.1. A spatial model

How can the Ministry of Fisheries implement regulation that provides the industry with the appropriate incentive to internalise the cost of sea lion capture during harvest activity? The Ministry of Fisheries has put extensive work into devising and applying the concepts of strike rate and FRML, and its efforts likely reflect society's wish to limit sea lion mortality in absolute terms. The following policy advice focusses on a solution within the existing regulatory framework that accords the industry spatial flexibility in its response to a given FRML.

Sea lion bycatch is affected by temporal variation owing to feeding commitments of pups onshore. The concentration of sea lions at sea is highest during the squid-harvesting season, and there is little the Ministry of Fisheries can do to change the temporal pattern of fishing behaviour without unduly constraining harvest.

However, data collected by the Ministry of Fisheries show sea lion bycatch is also affected by spatial variation (see for example Thompson and Abraham 2009). Both squid and sea lion populations are heterogeneously distributed, and their catchability varies *within* SQU6T. A system of zone-dependent strike rates to approximate variations in sea lion catchability may present a feasible policy option. The following analysis illustrates the resulting incentives when catchability coefficients, cost coefficient and the control variable vary spatially within SQU6T.

$$\mathrm{PV} = \int_0^\infty \mathrm{e}^{-\delta t} \sum_{j=1}^{2} [pN(t)w(t) - c_j] q_j \bar{h} v_j(t)\,\mathrm{d}t \qquad (10^*)$$

[15] See for example equation (6.47″), p. 150 in Chiang (1992).

$$\int_0^\infty \frac{\mathrm{d}s(t)}{\mathrm{d}t} = -\left[m + \sum_{j=1}^{2} \theta_j v_j(t)\right] s(t) \geq \text{FRML} \qquad (11^*)$$

Equation (10*) is a restatement of Equation (10) but differs as follows; q_j indicates squid catchability in zone j and depends on squid density.[16] The cost coefficient c_j varies across zones and is a decreasing function of squid catchability.[17] The control variable $v_j(t)$[18] represents the number of tows in zone j at time t. Assuming a two-zone model ($j = 1, 2$), the industry's problem is to maximise the *sum* of net benefits from squid harvest across both zones.

The constraint in Equation (11*) differs notably from Equation (11). For a given FRML, Equation (11*) represents the constrained cumulative decrease in the sea lion population $s(t)$ during a fishing season, $\int_0^\infty \mathrm{d}s(t)/\mathrm{d}t,$ caused by natural mortality, m, and sea lion fishing mortality summed across zones, $\sum_{j=1}^{2} \theta_j v_j(t)$ (where θ_j represents sea lion catchability). Note the term $\theta_j v_j(t)$ excludes the median number of hours per tow to reflect the fact that regulation specifies sea lion mortality as a function of tow frequency rather than tow duration. The Lagrangian integrand L is defined as

$$L = \mathrm{e}^{-\delta t} \sum_{j=1}^{2} [pN(t)w(t) - c_j] q_j \bar{h} v_j(t) - \bar{\mu}\left[m + \sum_{j=1}^{2} \theta_j v_j(t)\right] s(t) \qquad (15)$$

and maximisation gives

$$\mathrm{e}^{\delta t}\bar{\mu} = \frac{\sum_{j=1}^{2}(pN(t)w(t) - c_j)\bar{h}q_j}{\sum_{j=1}^{2}\theta_j s(t)} \qquad (16)$$

Equation (16) shows that the co-state variable $\bar{\mu}$ is equal to the initial value of the right hand side. The median tow length $\bar{h}$ remains in the solution; however, the industry can increase the initial value not only in terms of $\bar{h}$ but also by seeking out zones with high squid catchability q_j relative to sea lion catchability θ_j (indicating relative densities). The numerator represents the economic rent per tow in zone j, while the denominator shows the sea lion bycatch per tow, which corresponds to the Ministry of Fisheries' calculated strike rate. Variations in sea lion bycatch per tow across zones because of varying catchability θ_j can be approximated by zone-dependent strike rates.

[16] Rearranging Equation (12) and adding the subscript j gives $q_j = \frac{F_j(t)}{E_j(t)}$, which can be interpreted as the fishing mortality per unit of effort, thus reflecting variations in density across zones (Beverton and Holt 1957).

[17] The maximisation problem of a single cohort in Equation (7) with $F(t) = qE(t)$ as a control variable implies that the cost coefficient c is a constant fraction $c = \frac{\alpha}{q}$ (see Clark 2005, p. 38). It follows $c_j = \frac{\alpha}{q_j}$.

[18] Alternatively, the control variable can be defined as a function of both time t and zone j, $v(t, j)$. This adds mathematical complexity, for example a two-stage modeling approach can be applied where the solution of the spatial problem (first stage) is optimised over time (second stage).

A lower strike rate implies a higher maximum number of allowable tows (see p. 11 for derivation of implied maximum tows). It follows that for a two-zone model with two *different* strike rates, the implied maximum will vary according to the choice of harvesting location. For example, a lower strike rate in zone 1 implies a higher maximum number of allowable tows when all harvesting activity occurs in zone 1 rather than zone 2. The choice of harvest location determines the applicable strike rate and thus the implied maximum. Based on the zone-dependent strike rates, varying combinations of cumulative tows in zones 1 ($v_{c1}(t)$) and 2 ($v_{c2}(t)$) will determine the overall effort restriction $\bar{v}(v_{cj})$ according to

$$\bar{v}(v_{cj}) = v_{c1}(v_{c2}) + v_{c2} \tag{17}$$

$$v_{c1} = a - bv_{c2} \tag{18}$$

The coefficients a and b are derived by the zone-dependent strike rates; $\bar{v}(v_{cj}) = v_{c1} = a$ when $v_{c2} = 0$ (where a represents the maximum number of allowable tows derived by the strike rate in zone 1) and $\bar{v}(v_{cj}) = v_{c2} = \frac{a}{b}$ when $v_{c1} = 0$ (where $\frac{a}{b}$ represents the maximum number of allowable tows derived by the strike rate in zone 2).

Taking spatial differences in sea lion density into consideration adds flexibility to an imposed FRML. The industry can actively influence the implied level of effort restriction by its choice of harvest zone. However, potential economic gains from harvesting in a 'low' strike rate zone (implying a high maximum number of allowable tows) may be negated by lower squid densities in the same zone.

Equation (16) shows that target species and bycatch densities matter relative to each other. The ratio of economic rent per tow to sea lion bycatch per tow equates to *economic rent per captured sea lion* in zone j. This shows that rent maximisation under a policy of zone-dependent strike rates focusses on obtaining the highest profit per regulatory unit. The industry can increase the initial value of $\bar{\mu}$ by increasing harvest activity in the zone with the highest *economic rent per captured sea lion*. In fact, Equation (16) implies zones 1 and 2 are perfect substitutes for each other, which means rent is maximised when all of the tows are expended in the zone with the higher *economic rent per captured sea lion*. In practice, variables not captured in the objective function may prove prohibitive to such a corner solution, but economic gains may still be made from moderate changes in the distribution of effort across zones, as shown by the following numerical analysis.

6.2. Numerical analysis

Chilvers *et al*. (2005) and Chilvers (2008) report that the number of trawl tows undertaken by the squid fishery varies between years, but that their locations are similar. There appear to be two dominant fishing zones within

SQU6T, an area southwest of the Auckland Islands ($j = 1$) and an area north/northwest of the Auckland Islands ($j = 2$). Zone 1 records 44 per cent of all tows undertaken between 2001 and 2004, leading to 39 per cent of the total squid catch (by weight) and 28 per cent of all recorded sea lion captures. Zone 2 represents the remaining 56 per cent of all tows undertaken, leading to 61 per cent of total squid catch and 72 per cent of all sea lion captures. Kim *et al*. (2004) and the Ministry of Fisheries (2009) provide data on the total amount of effort (6171 tows), squid catch (56,278 t) and bycatch (305 sea lions) in SQU6T for the corresponding time frame.

The first three rows of Table 1 summarise the data on total effort, catch and bycatch and show the corresponding calculated levels for zones 1 and 2 based on the information above. The status quo column reflects the current policy of a strike rate that is invariant to space within SQU6T and serves as a benchmark. The columns for zones 1 and 2 reflect the hypothetical scenario of a policy of zone-dependent strike rates.

The gathered data provide the necessary information to derive numerical values for the numerator and the denominator of Equation (16). The reported values are rounded,[19] which may lead to some deviations when replicating calculations.

Squid catch per tow (t) under the status quo is found by dividing total squid catch (t) by the total number of tows between 2001 and 2004 $\left(\frac{56{,}278}{6171} = 9.12\right)$. Note that the value of 9.12 t represents the average amount of squid catch per tow during those years. The corresponding values in zones 1 and 2 are 8.08 $\left(= \frac{21{,}948}{2715}\right)$ and 9.93 $\left(= \frac{34{,}330}{3456}\right)$. Revenue per tow (\$NZ) is calculated by multiplying the export price[20] of squid, \$NZ 2219, by squid catch per tow. Cost estimates are difficult to come by for fishing companies in New Zealand because there are no official reporting requirements or accessible records. Aotearoa Fisheries Ltd, a stakeholder of the Deepwater Group, provides annual reports online from 2005 to 2010 detailing yearly total revenue and net surplus for the Deepwater Group (Aotearoa Fisheries Limited 2010).[21] Based on this information, total costs represent on average 85 per cent of total revenue (std. dev. 4 per cent).[22] We apply this percentage to estimate cost per tow (\$NZ) in Table 1. The economic rent per tow under the status quo is then \$NZ 3036, and \$NZ 2691 and \$NZ 3307 in zones 1 and 2, respectively. These values represent the numerator of the initial value $\bar{\mu}$ in Equation (16).

[19] Spreadsheet available on request from the author.

[20] The NZ Seafood Industry Council (SeaFIC) has provided official monthly export values of squid (\$NZ) and weight (kg) between 2001 and 2004, which allows the calculation of an average export price of \$NZ 2219/t.

[21] Annual reports prior to 2005 are not available.

[22] Total revenue and net surplus in the annual reports apply to harvest across all deepwater species, of which squid is approximately 20 per cent in export value. The information suffices for the current example where estimating costs as any given percentage of revenue allows costs to vary spatially and enables the comparison of economic rent under different policies.

Table 1 Numerical analysis

	Status quo *SQU6T*	Policy of zone-dependent strike rates	
		Zone 1	Zone 2
Effort (number of tows)	6171 (*total*)	2715 (*44% of total*)	3456 (*56% of total*)
Squid catch (t)	56,278 (*total*)	21,948 (*39% of total*)	34,330 (*61% of total*)
Sea lion bycatch	305 (*total*)	85 (*28% of total*)	220 (*72% of total*)
Squid catch per tow (t)	9.12	8.08	9.93
Revenue per tow ($NZ)	20,238	17,938	22,045
Cost per tow ($NZ)	17,202	15,247	18,738
Economic rent per tow ($NZ)	3036	2691	3307
Sea lion bycatch per tow = strike rate (*implied maximum number of allowable tows*)	0.05 (*1760*)	0.03 (*2766*)	0.06 (*1369*)
Economic rent per captured sea lion ($NZ)	61,420	85,549	52,036
Economic rent ($NZ)	5,434,531	4,527,340–7,442,775 (*min. – max.*)	

Sea lion bycatch per tow under the status quo is found by dividing total sea lion bycatch by the total number of tows ($\frac{305}{6171} = 0.05$), and in zones 1 and 2 accordingly ($\frac{85}{2715} = 0.03$ and $\frac{220}{3456} = 0.06$). These values represent the denominator in Equation (16) and are representative of the strike rates. The status quo strike rate of 0.05 implies a maximum number of 1760 allowable tows for the season, while the strike rates of 0.03 and 0.06 in zones 1 and 2 imply a maximum number of 2766 and 1369 tows, respectively.

The second to last row shows the values for the *economic rent per captured sea lion* under the status quo ($NZ 61,420) and for zones 1 and 2 ($NZ 85,549 and $NZ 52,036). The potential economic gains arising from zone-specific *economic rent per captured sea lion* values are shown in the last row of Table 1. During a given squid fishing season between 2001 and 2004, the industry generated an average economic rent of $NZ 5,434,531 under the status quo (economic rent per tow × implied maximum number of allowable tows[23]). However, under a policy of zone-dependent strike rates, economic rent could have been as low as $NZ 4,527,340 (min.) or as high as $NZ 7,442,775 (max.), depending on the choice of harvest zone. Table 2 illustrates how this range is determined.

The first column shows the maximum number of allowable tows determined by Equation (17). The second column shows the cumulative number of tows expended in zone 2, while the cumulative number of tows in zone 1 is a

[23] The economic rent can also be derived by multiplying economic rent per captured sea lion by the average yearly FRML of 87 sea lions.

Table 2 Potential economic gains from a policy of zone-dependent strike rates

Maximum number of allowable tows ($\bar{v}(v_{cj})$)	Cumulative no. of tows in zone 2 (v_{c2})	Cumulative no. of tows in zone 1 (v_{c1} (v_{c2}))	Percentage of tows in zone 1 (%)	Economic rent ($NZ)
2766	0	2766	100	7,442,775 (max.)
2154	600	1554	72	6,165,010
1760	986	775	44	5,434,531 (status quo)
1542	1200	342	22	4,887,244
1369	1369	0	0	4,527,340 (min.)

function of tows in zone 2 according to Equation (18). The fourth column shows the number of tows that are expended in zone 1 as a percentage of the maximum, which is useful when comparing the distribution of effort between policies. The last column provides the economic rent (economic rent per tow × cumulative number of tows, summed across zones).

The first row illustrates the corner solution inferred from Equation (16). *Economic rent per captured sea lion* is higher in zone 1 and economic rent is maximised when all tows are expended in zone 1 ($v_{c2} = 0$). In this case, the maximum number of allowable tows is implied by the strike rate in zone 1 ($\bar{v}(v_{cj}) = v_{c1} = a = 2766$). By expending 100 per cent of the maximum allowable tows in zone 1, the industry can generate a *maximum* economic rent of $NZ 7,442,775 (= 2691 × 2766 + 3307 × 0). Conversely, the last row shows that expending all tows in zone 2 ($v_{c1} = 0$) leads to a number of 1369 allowable tows ($\bar{v}(v_{cj}) = v_{c2} = \frac{a}{b} = 1369$)[24] and a *minimum* economic rent of $NZ 4,527,340 (= 2691 × 0 + 3307 × 1369).

The remaining rows illustrate varying combinations of cumulative tows in both zones, for example, the second row shows the case when 72 per cent of all tows are expended in zone 1, leading to a maximum of 2154 allowable tows and an economic rent of $NZ 6,165,010. For 44 per cent of tows in zone 1 (third row), the distribution of effort corresponds to the status quo, yielding an economic rent of $NZ 5,434,531. It represents the benchmark of comparison, and any distribution of effort that involves < 44 per cent of tows in zone 1 leads to lower levels of economic rent (see fourth and last row).

7. Discussion

The numerical analysis exemplifies the incentives provided by a policy of zone-dependent strike rates. *Economic rent per captured sea lion* in zone 1 is higher than in zone 2, and the industry can actively influence the level of implied effort restriction and economic rent by raising harvest activity in zone 1. For any distribution of effort that involves more than 44 per cent of

[24] It follows $a = 2766$ and $b = 2.02$ in Equation (18) ($v_{c1} = 2766 - 2.02v_{c2}$).

tows in zone 1, the industry is able to increase average economic returns and improve on the status quo.

The numerical analysis of the two predominant fishing zones around the Auckland Islands is a very first step to illustrating the incentive mechanism. The more effective the Ministry of Fisheries and/or industry become in establishing distinct zones and devising zone-dependent strikes accordingly, the greater the scope for maximising economic gains and the less pressure there will be on expanding the capacity of unregulated inputs such as the median duration of tows. However, further issues have to be addressed to make the policy operational.

For example, the two zones in this analysis are treated as unconnected. Little is known about the ecology and movement patterns of arrow squid (Stark *et al.* 2005), and intensive fishing in one zone may lead to changes in squid migration patterns and correlated sea lion densities in adjacent zones. The numerical analysis shows that economic gains may be made from even moderate changes in the distribution of effort across zones, but such gains may vary temporally in a dynamic setting. Ideally, the zone-dependent strike rates should be moving averages that are updated periodically to reflect nontrivial changes in both squid and sea lion densities. This raises the issue of transaction costs.

Currently, all commercial fishing for deepwater species are subject to detailed reporting requirements, such as date, time, starting location and finishing location of tows (lat/long), weight of target species catch/non-target catch and vessel characteristics. The Ministry of Fisheries devotes substantial resources to monitoring and enforcement (observer coverage on trawl vessels has ranged from 22 per cent to 99 per cent since 2000 (Thompson and Abraham 2009)) and maintains a sophisticated database with a public user face.[25] The reporting of sea lion bycatch is already a requirement; however, the interpretation and application of zone-dependent strike rates may lead to added transaction costs. An automated system that continues to update the industry about the implied maximum allowable tows based on reported catch and bycatch data may present one solution to keep transactions costs low.

The analysis rests on the simple premise of introducing a zone-dependent strike rate into the existing regulatory framework. Theoretically, the imposition of the FRML is still tied to measures of effort and subject to the perils of effort-based restrictions; however, by according the industry spatial flexibility in its response to the regulatory limit, the policy may offer a cost-effective solution as a first step towards better fisheries management.

8. Conclusion

The history of fisheries management has clearly shown that input restrictions distort incentives for fishers to circumvent regulatory measures rather than

[25] See for example NABIS for a spatial and visual representation of biological and fisheries management data in New Zealand; http://www.nabis.govt.nz/Pages/default.aspx

focus on efficient ways to address the underlying issue of rent dissipation. The limited entry program for the British Columbia Salmon in 1968 leading to capital stuffing is just one of the many examples of overcapitalisation (Wilen 2000).

The same finding applies to the Ministry of Fisheries' upper limit on sea lion deaths, which indirectly restricts the total number of tows squid vessels may undertake during a fishing season. A bioeconomic model for sea lion bycatch captures the effects of the current regulatory framework analytically and shows that a policy of zone-dependent strike rates provides the industry with the spatial flexibility to respond to a total bycatch limit more efficiently.

In the long run, ever increasing higher spatial resolutions of harvest zones in SQU6T could prove effective in fully internalising to the squid fishery the cost of killing sea lions. Any given number of tows and resulting bycatch provide an instant sea lion mortality rate associated with a specific location that directly affects the level of implied effort restriction. Fishers have an intimate knowledge of their fishing area, and the industry is given the appropriate incentive to maximise economic rent by effecting an effort distribution that avoids sea lion capture relative to squid availability. This may provide a first step towards addressing society's conflicting objectives of conservation and utilisation.

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