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Search and destroy: a bioeconomic analysis of orange roughy fisheries on seamounts in New Zealand.

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ABSTRACT

This paper develops a bioeconomic model that captures the underlying incentives driving the serial depletion of pristine seamounts. The determinants under New Zealand's Quota Management System relate to unit cost savings from bottom trawling for orange roughy on seamounts, where catch rates are high, for a constrained yearly catch, yielding superior rent and driving the continued search for pristine seamounts. Despite known patterns of seamount depletion, catch and effort data collected by the New Zealand Ministry of Fisheries lack information on the bathymetry of harvesting locations. We provide descriptive statistics of the Ministry's data on catch, effort and location between 2001 and 2010, which examine associations between high catch rates and pristine seamounts. The bioeconomic model formalises the expected gains of unit cost reductions and shows that bottom trawling activity on pristine seamounts ceases only when the expected reduction in harvest costs is equal to the search cost per unit of harvest. We contend that New Zealand's policies to date to protect seamounts do not address the spatial determinants of rent appropriation under the quota system and that the imposition of a 'seamount' fee levied on the bottom trawlers' harvest activities may provide a way to internalise the cost of seamount destruction more effectively. Such a policy has a number of advantages, the most important of which is that the fee ties the impacts of habitat destruction to the choice of fishing method, thereby providing an impetus to develop and adopt more selective fishing practices.

Keywords: orange roughy; seamount; bioeconomic model; policy.

INTRODUCTION

The deep ocean is one of the last great wildernesses.

(Roberts 2002, p. 242)

In 1994 the United States Committee on Fisheries proclaimed "habitat alteration by the fishing activities themselves is perhaps the least understood of the important environmental effects of fishing" (National Research Council 1994). Most notably, deep sea bottom trawling has continued to attract international attention because of its wide-scale effects on fragile benthic habitats.

The reasons why we should care about fragile habitats are twofold; fishing worldwide has evolved in response to a long history of regulatory intervention aimed at regulating exploitation with commercial fishers as the main stakeholders. Input and output controls are applied in an effort to manage single species. However, an increasing call for a paradigm shift to a more holistic approach known as ecosystem-based management highlights the growing need to incorporate non-fishing stakeholder interests (see Curtin and Prellezo 2010 for overview of the extensive literature). People attribute value to particular marine habitat for a variety of reasons and the impacts of fishing on non-target species and wider ecosystems are increasingly causing concern. The second reason relates to the fact that there is a large gap between the scientific knowledge of how fishing practices affect benthic habitats, and how these effects in turn influence commercial fish stock levels in the long term (Armstrong and Falk-Petersen 2008). Output and input controls for single species do not address the negative externality that is generated by the impact of fishing equipment on the wider ecosystem (Reiss et al. 2010).

Bottom trawling on deepwater species such as orange roughy in New Zealand waters is a prime example of the growing concern about the destructive impacts of fishing on benthic habitat. The fish form dense aggregations on restricted topographic features such as seamounts, which are associated with high levels of cold water corals and have become an important focal point for fishing (Clark 2001; Ministry of Fisheries 2011b). Bottom trawling has the effect of destroying the extremely slow growing cold water coral irreversibly, often leaving behind barren landscapes with crushed remains of coral skeleton spread over the area (Costello et al., 2005; Fossa et al., 2002; Freiwald et al. 2004;

Roberts 2002). Little is known about the role of topographic features in the life history of orange roughy and how the loss of benthic habitat affects long term fish stock levels, but data analysis shows rapid declines on seamount catch rates over time, where fishing moves progressively from fished to unfished seamounts, exhibiting a pattern of serial depletion (Clark 1999). Seamounts, though biological in nature, may for all purposes be treated as non-renewable on a human time-span.

This paper develops a bioeconomic model that captures the underlying incentives driving the serial depletion of pristine seamounts. The determinants under New Zealand's Quota Management System relate to unit cost savings from bottom trawling for orange roughy on seamounts, where catch rates are high, for a constrained yearly catch, yielding superior rent and driving the continued search for pristine seamounts. Despite known patterns of seamount depletion, catch and effort data collected by the New Zealand Ministry of Fisheries lack information on the bathymetry of harvesting locations. We provide descriptive statistics of the Ministry's data on catch, effort and location between 2001 and 2010, which examine associations between high catch rates and pristine seamounts. The bioeconomic model formalises the expected gains of unit cost reductions and shows that bottom trawling activity on pristine seamounts ceases only when the expected reduction in harvest costs is equal to the search cost per unit of harvest. We contend that New Zealand's policies to date to protect seamounts do not address the spatial determinants of rent appropriation under the quota system and that the imposition of a 'seamount' fee levied on the bottom trawlers' harvest activities may provide a way to internalise the cost of seamount destruction more effectively. Such a policy has a number of advantages, the most important of which is that the fee ties the impacts of habitat destruction to the choice of fishing method, thereby providing an impetus to develop and adopt more selective fishing practices.

The next section provides some background on orange roughy fisheries on seamounts, followed by descriptive statistics, the bioeconomic model, a policy discussion and the conclusion.

BACKGROUND

Originally known as slimeheads, orange roughy (*Hoplostethus atlanticus*) received their current name during the 70’s to increase gastronomic appeal (Lacquet and Pauly 2008) deriving from the fact that they turn orange after death (the fish has a reddish body and bluish-tinged belly when alive and is also known as red roughy or deep sea perch). Orange roughy are a relatively large deep sea demersal species with a maximum length and weight of 75 cm and 7 kgs, respectively. They inhabit continental slopes between depths of 500 and 1500 m and can be found worldwide (Francis and Clark 2005; Kotlyar 1996). Distinct biological characteristics of orange roughy include slow growth, extreme longetivity (exceeding 100 years), late age of maturity, low natural mortality and fecundity and formations of localised aggregations, which are common to many deep sea species making them vulnerable to “boom and bust” cycles of fisheries exploitation (Francis and Clark 2005; Koslow et al. 2000). The investment in deepwater fisheries is likened to an unregulated ‘gold rush’ performance where the low productivity of deepwater stocks and high logistic costs present a considerable risk to the industry, which is offset by high prices for the species (Watson and Morato 2004). Fishing turns into ‘mining’ operations rather than sustainably managed fisheries (Watson and Morato 2004), of which orange roughy is an example. The initial development of such fisheries is rapid and extremely profitable (the so called fishing-down phase), but is followed by a dramatic decline in catch levels and sustained low catch volumes in the long term.

Reported landings from FAO data in Figure 1 illustrate the fishing-down phase for orange roughy worldwide. The first commercial fishery was developed in 1979 in New Zealand, and subsequently in Australia, the Indian Ocean, the Atlantic, Namibia and the Southeast Pacific. Total catches have peaked in 1990 at over 90,000 tonnes, followed by a marked and steady decline in catches to about 13,000 tonnes in 2009. New Zealand has been the dominant player in the world market, being the sole harvester for the first ten years since the fishery’s inception, and supplying an average of 67% of the global production between 1989 and 2009. Despite the marked decline in catches in recent years, orange roughy continues to be one of New Zealand's top 10 export species worth $NZ 49 million[1] in the year ending December 2010 (SeaFIC 2010).

[Insert Figure 1 here]

One of the characteristics that make orange roughy so susceptible to commercial exploitation is their tendency to form dense aggregations on restricted topographic features such as seamounts and underwater canyons (Clark 1999; Koslow et al. 2000; Lorance et al. 2002). In New Zealand very little is known about the conditions that lead to aggregations on seamounts, presumably serving the purpose of 'feeding and spawning' (see e.g. Clark 1999; Ministry of Fisheries 2011b). A meta-analysis by Clark et al. (2001) shows the region, depth of peak and slope of seamounts in New Zealand waters to have a significant effect on orange roughy stock sizes but the physical, biological and oceanographic characteristics of the approximately 800 known seamounts are poorly understood. However, it is generally known that seamounts are sites of high biological productivity due to upwellings of nutrient rich waters and are important areas of biodiversity (Rowden et al. 2005). Analyses of camera data show them to be covered by a relatively large amount of stony coral habitat[2] (generally known as cold water corals), especially near the peaks (Clark and Rowden 2009).

Seamounts are economically important areas because they allow for high catch rates[3] leading to reductions in harvesting costs and have over time become an important focus for orange roughy fisheries in New Zealand, along with fisheries for black oreo (*Allocyttus niger*) and smooth oreo (*Pseudocyttus maculates*) which are found at similar depths and locations. Harvest occurs by bottom trawl only, which has been likened to the clear cutting of a forest (Wattling and Norse 1998). The effects of using heavy trawl gear have long been known (Clark and O'Driscoll 2003) and the impacts on non-mobile, extremely slow growing taxa such as cold water coral are considered irreversible (Koslow 1997). Bottom trawling has been observed to become rapidly concentrated over a relatively small area of seamount topographies in New Zealand (Smith 2001; Clark and O'Driscoll 2003) and a

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[1] The average exchange rate in 2010 was 1 US$ = 1.388 NZ$ (http://www.irs.gov/).

[2] Comprising coral species such as *Solenosmilia variabilis* and *Madrepora oculata*.

[3] The catch rate is defined as the catch per unit of effort over a specified time interval (FAO 2003).

study by Clark and Rowden (2009), which compares camera data of unfished with fished seamounts, concludes the former to possess a relatively large amount of cold water coral habitat compared to the latter. Common cold water coral species in New Zealand's waters, such as Madrepora oculata, have been aged between 200 and 6000 years (Consalvey et al. 2006), and seamounts are literally stripped bare by trawling (Roberts 2002).

The Chatham Rise fishery is New Zealand's largest and most-established fishery and biophysical studies point to a pattern of serial depletion of seamount complexes (e.g. Smith 2001). The fishery expanded during the 1980s with peak catches of over 50,000 tonnes in 1988/89 but subsequently contracted along with incremental quota reductions. Orange roughy stocks have seen rapid biomass declines because maturation and reproduction rates had been repeatedly overestimated leading to unsustainably high catch limits (Francis 1992). Initially, most catch was taken from relatively flat bottom on the Chatham Rise in the Pacific Ocean to the east of New Zealand and on the Challenger Plateau in the Tasman Sea to the west of New Zealand during predictable times of the year when orange roughy congregated for spawning (Clark 1999; Ministry of Fisheries 2011b). However, during the 1990s major changes in the redistribution of effort saw over 60% of catch being taken from seamounts where orange roughy form sporadic non-spawning aggregations all year round (O'Driscoll and Clark 2005). The development of the fishery from relatively long tows on flat ground to very short and precisely targeted tows near the tops of pinnacles was enabled by technical advancements such as GPS navigation, net monitoring and swathe mapping (Smith 2001; Francis and Clark 2005). Seamount features were actively sought out by the fishing industry during what Clark and O'Driscoll (2003) call the 'discovery phase' and by 2000 about 80% of known seamounts at suitable depths for deepwater fisheries (>1000 m) had been fished[4].

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[4] An important aspect pertains to the definition of seamounts. Smith (2001) notes that strict definitions describe seamounts as features with an elevation greater than 1000 m, leading the fishing industry in New Zealand to assert that 'virtually no fishing is undertaken on seamounts' (SeaFIC 2007). However, in practice seamounts covered by cold water corals include any topographic "hill" and "knoll" features (including pinnacles) with

In summary, fishers seek out seamount topographies that yield high catch rates, thereby depleting associated for all purposes non-renewable stony coral habitats, followed by a rapid decline in catch rates, and move on to find new seamounts. This bottom trawl externality remains unaddressed under New Zealand's single species management and presents the focus of the ensuing analysis.

DESCRIPTIVE STATISTICS

Despite known patterns of seamount depletion, there is no comprehensive record on the amount, change and spatial occurrence of pristine seamount habitat over time[5] and the catch and effort data collected by the Ministry of Fisheries lack information on the bathymetry of harvesting locations[6]. We provide descriptive statistics of the Ministry's data on catch, effort and location between 2001 and 2010, which examine associations between high catch rates and pristine seamounts. The analysis informs the bioeconomic model in the next section which formalises the expected gains of unit cost reductions from bottom trawling on pristine seamounts.

Fishing for orange roughy on the Chatham Rise, New Zealand's largest fishery, was initially confined to the northern slopes of the Rise, but gradually moved to the south, east and northwestern parts of the Rise as catches declined, focusing on knoll and hill features (Ministry of Fisheries 2011b). The overall unstandardised annual catch rate[7] on the Chatham Rise has dropped from 8 tonnes/tow in

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peaks up to 1000 m that contrast with the surrounding flat bottom. The difference is semantic and for ease of discussion we adopt the practical definition.

[5] Some physical data on seamounts is held by the National Institute of Water and Atmospheric Research (NIWA), the New Zealand Hydrographic Office and the Royal New Zelaand Navy, but records are not comprehensive.

[6] In principle, it should be possible for researchers to overlay locations of known catches with bathymetric maps assuming enough spatial detail is available. This likely involves more sophisticated spatial analysis and software, which is beyond the scope of this study and left for further research.

[7] Data on catch and effort display variations in tow time and vessel characteristics. Standardised catch rates have recently been estimated for selected datasets (see e.g. Mormede 2009) but involve the application of econometric analysis.

1979/80 to 6 tonnes/tow in 1992/93 and even further to recent levels of 3-4 tonnes/tow. Since the early 1990s new fishing grounds have developed south of the Chatham Rise on the Puysegur, followed by other grounds such as the Arrow Plateau and the Sub-Antarctic (Ministry of Fisheries 2011b) (see Figure 2 for a detailed map).

[Insert Figure 2 here]

The majority of catches continues to come from the Chatham Rise, which is divided into the Northwest, the East and the South Chatham Rise. Out of those three areas, the East Rise constitutes the main fishing grounds, predominantly because of large spawning aggregations inside what is known as the 'Spawning Box' between June and early August every year. Catches within the remainder of the Chatham Rise have increased in the 1990s with highly variable catch rates, sustained largely by the discovery of new seamount complexes such as the Andes, Smith City, Graveyard, etc. (Ministry of Fisheries 2011b). The Ministry of Fisheries reports a decline in the (unstandardised) annual catch rate for all of these complexes since their discovery.

We obtained data on catch, effort and location on the Chatham Rise and the Sub-Antarctic fishing grounds between 2001 and 2010 from the Ministry of Fisheries[8]. A standard fishing year in New Zealand runs from October to September, and some preliminary analysis of data from the East Chatham Rise[9] shows that the average *monthly* catch rate (tonnes/tow) remains fairly low during the start of the fishing year in October but rises dramatically between June and August, when orange roughy spawn (see Figure 3) (the notation has been chosen such that the fishing year "2001", for instance, represents fishing activity from October 2000 to September 2001). The majority of the TACC is harvested during this time, but harvesting also occurs at other times during the fishing year (see Figure 4).

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[8] 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, vessel characteristics, etc.

[9] The area of the East Chatham Rise is defined by the points -42.2/182, -42.2/186.3, -46/182 and -46/186.3 decimal degrees (Ministry of Fisheries 2007).

[Insert Figures 3 and 4 here]

The harvest pattern on the East Chatham Rise, as shown by Figures 3 and 4, makes it difficult to disentangle the effect of seamount discovery from the overriding spatial contraction of the fishery during the spawning period, and therefore we focus on an area to the south of the Chatham Rise where orange roughy do not spawn (but may aggregate on topgraphic features such as seamounts for other purposes).

The Sub-Antarctic includes areas such as the Auckland Islands, Priceless, Pukaki, Bounty and the Antipodes (see Figure 2). In 1995 large catches of over 3000 tonnes were derived from the southeast Pukaki Rise. Catches soon declined rapidly, and new fisheries were developed on the northeast Pukaki Rise, which includes areas such as the Priceless. The catch limit for the Sub-Antarctic has risen from 1,300 tonnes in 2001 to 1,850 tonnes in 2006 but recently dropped to a mere 500 tonnes since 2010. Until then, a limit of 500 tonnes applied to individual seamount complexes within the Sub-Antarctic (Ministry of Fisheries 2007). Figures 5 and 6 show the average monthly catch rates and monthly catches in the Sub-Antarctic[10] between 2001 and 2010.

[Insert Figures 5 and 6 here]

In absence of any large spawning aggregations, average catch rates and monthly catch appear sporadic and non-predictable during the fishing year. A particularly high average catch rate of nearly 30 tonnes/tow occurs in 2007 and coincides with the reported discovery of a new fishing ground to the south of the Priceless (Ministry of Fisheries 2007). We plot catch rates within the Sub-Antarctic ocean space between 2001 and 2011 to visualise spatial harvesting patterns. The harvesting locations are represented by the latitude/longitude axes (in decimal degrees) while the vertical axis shows the maximum monthly catch rate for each location during the given time frame.

[Insert Figure 7 here]

Figure 7 shows tight groupings of catch locations in selected areas while the vast majority of the ocean space remains unfished. This provides visual support to the argument that high catch rates are associated with areas that exhibit distinct topographical features. Time tags are attached to some of

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[10] The area of the Sub-Antarctic excludes the Puysegur and contains as all waters below -47.5 decimal degrees.

the major peaks to indicate the observed trend of serial depletion in the data; any given high catch rate associated with a given location declines rapidly upon ‘discovery’ and new locations are sought out.

BIOECONOMIC MODEL

Management

This section explores the current management of orange roughy in New Zealand, which informs the maximisation constraint under which fishers operate. The orange roughy fishery is managed under New Zealand’s QMS, which was implemented as the result of a comprehensive management vision to address dwindling coastal fish stocks in the 1980s. Each year the Ministry of Fisheries sets a total allowable commercial catch (TACC) for orange roughy in a specific quota management area (QMA), and Individual Transferable Quotas (ITQs) represent well defined rights to harvest a percentage share of this TACC. Figure 8 shows the boundaries for the 8 QMAs which cover the whole of New Zealand’s waters.

[Insert Figure 8 here]

ITQ owners can buy (sell) parts of their ITQ holdings in order to increase (reduce) their landings. To enhance flexibility of the system, ITQ owners may lease part or all of their quotas to other fishers. The result is that anyone may enter the industry by buying or leasing ITQs at any time and New Zealand’s QMS is considered to be a potentially effective instrument for efficient fisheries management (Newell et al. 2005).

For the Chatham Rise, which lies within ORH 3B (see Figure 8), deepwater interests since 2005 are combined in a single management company called the Deepwater Group Ltd. (from here on referred to as the ‘Group’), representing approximately 96% of the ORH 3B quota owners (Ministry of Fisheries 2011b). Shareholders agree to and fund an annual business plan based on their ITQ holdings, which ensures proportionate representation in decision-making and governance. The 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. For example, a range of sub-QMA catch limits in ORH 3B are managed under a voluntary agreement between the Ministry of Fisheries and the Group since the early 1990s (Ministry of Fisheries 2011b). The overall aim of the

Group is to achieve efficient management, but vessels may still compete for catch rates on the water. However, operational procedures and catch reporting requirements are in place to coordinate efforts and enforce sub-QMA catch limits, e.g. vessels have to notify the Group of their intention to fish within proclaimed areas prior to sailing, have to have an independent observer on board and are required to report catches on a daily or weekly basis, depending on the area (Deepwater Group 2007).

Model

The bioeconomic model presents a theoretical treatment of the cost savings gained from bottom trawling on seamount complexes where catch rates are high. We start with the assumption that, in the case of the orange roughy fishery, the fishers' management problem is best described as the optimisation problem of a private, sole owner fishery (represented by the Group) under the constraints of a yearly total allowable catch limit and declining pristine seamount habitat. The maximization problem is solved for the time period of a fishing year to reflect the constraint of an annual catch limit, but the solution can be extended seamlessly to an infinite sequence of fishing years[11]. The approach is adapted and extended from the economics of exhaustible resources, where the owner of a non-renewable resource faces a constraint of a total stock of exhaustible resources.

It is assumed that $h_j(t)$ represents the rate of bottom trawling and $S(t)$ the number of seamounts in a defined area such as ORH 3B. The subscript $j = 0$ indicates bottom trawling occurs on pristine seamounts (h_0) while $j = 1$ implies bottom trawling occurs either along known tracks on destroyed (non-pristine) seamounts or on the flat bottom (h_1). The export price of orange roughy is assumed constant[12] and denoted by p while the unit cost function of harvest $c(X)$ is assumed convex

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[11] Unlike in the forestry problem of infinite rotations which has to consider the opportunity cost of occupied land.

[12] The New Zealand Seafood Industry Council provided a monthly export price series for orange roughy between 2001 and 2010, which we adjusted for inflation (constant NZ$2006). The price series is relatively stable during the fishing year (overall average of 14.28 NZ$/kg and st.dev. 0.75), i.e. there are no pronounced seasonal effects.

in the orange roughy fish stock $X(t)$ implying the cost of catching one unit of fish decreases as the general abundance of the fish population increases ($c_X < 0$ and $c_{XX} > 0$) (Clark 2005).

In the following model the fish stock $\bar{X}$ is assumed constant *during the time period of a fishing year* (i.e. the time period of maximisation). The New Zealand Fisheries Act 1996 S13 (2) requires that the Minister of Fisheries sets a yearly TACC that maintains the stock at or above a biomass level that can produce the maximum sustainable yield, or moves it towards or above such a level, implying the industry operates under the harvest constraint of a predetermined fish stock level during any given fishing year. The unit cost of fishing $c(\bar{X})$ is therefore independent of X during the period of maximisation and the parameter $\bar{X}$ is dropped from the following notation.

However, dense aggregations of orange roughy on or near pristine seamounts at any given time increase catchability and lower unit harvesting costs, and we capture the difference in costs between fishing on and off seamounts by the binary subscript j $[c_0 < c_1]$ (where c_0 represents the unit cost of fishing on pristine seamounts and c_1 the cost of fishing on known tracks/flat bottom[13]). There are also search costs $\tilde{c}(S_0(t))$ associated with the discovery of pristine seamounts $S_0(t)$, which are a decreasing function of undiscovered seamounts ($\tilde{c}_{S_0} < 0$). Finally, the probability of finding pristine seamounts $\tilde{\rho}\big(S_0(t)\big)$ in a given area is assumed to be an increasing function of undiscovered seamounts ($\tilde{\rho}_{S_0} > 0$).

The Group's problem is to maximise the present value PV of the weighted net revenue during a fishing year (discounted at an instantaneous annual rate of interest δ) for given a predetermined stock level according to

$$PV = \int_0^T e^{-\delta t}[\tilde{\rho}\big(S_0(t)\big)\Big(p - c_0 - \tilde{c}\big(S_0(t)\big)\Big)h_0(t) + (1 - \tilde{\rho}\,(S_0(t)))\Big(p - c_1 - \tilde{c}\big(S_0(t)\big)\Big)h_0(t) + (p - c_1)h_1]dt \tag{1}$$

subject to

$$\int_0^T (h_0(t) + h_1(t))dt \leq TACC \tag{2}$$

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[13] Based on Samples and Sproul (1985) who represent differences in the average cost per unit of standardized effort in Fish Aggregating Devices (FAD) and non-FAD fisheries in this way.

and subject to changes in habitat by a fraction α when bottom trawling occurs on pristine seamounts

$$\int_0^T \frac{dS_0}{dt} = \dot{S}_0 = -\alpha h_0(t) \tag{3}$$

The objective function in (1) is set up to reflect the choice of the Group of how to allocate their total allowable catch between searching for (and destroying) seamounts and fishing on known tracks/flat bottoms. The probabilities represent the weight of harvest from pristine seamounts. When the search is successful, $\tilde{\rho}\big(S_0(t)\big)$ represents the harvest from pristine seamounts at a low unit cost c_0, while an unsuccessful search determines the share of harvest $(1 - \tilde{\rho}\,(S_0(t)))$ from flat bottoms at a higher unit cost c_1. This weighted average is augmented by trawling on known tracks/flat bottom $(p - c_1)h_1$to meet the TACC.

The linear control problem in (1) subject to (2) and (3) is a dynamic continuous optimization problem with $h_j(t)$ as a control variable, $S_0(t)$ as a state variable, a finite horizon T (the end of the fishing year) and a free terminal state (there are no boundary conditions). The isoperimetric constraint in (2) implies the solution value of the corresponding multiplier $\bar{\mu}_1$ is constant (Chiang 1992). For ease of exposition the argument t is suppressed in the following equations. The Hamiltonian is defined as

$$\begin{aligned} H = e^{-\delta t}\big[\tilde{\rho}(S_0)\big(p - c_0 - \tilde{c}(S_0)\big)h_0 + (1 - \tilde{\rho}(S_0))\big(p - c_1 - \tilde{c}(S_0)\big)h_0 + (p - c_1)h_1\big] - \\ \bar{\mu}_1(h_0 + h_1) - \mu_2 \alpha h_0 \end{aligned} \tag{4}$$

The necessary conditions and adjoint equation are

$$\frac{\partial H}{\partial h_0} = e^{-\delta t}\big[\tilde{\rho}(S_0)\big(p - c_0 - \tilde{c}(S_0)\big) + (1 - \tilde{\rho}(S_0))\big(p - c_1 - \tilde{c}(S_0)\big)\big] - \bar{\mu}_1 - \mu_2 \alpha \tag{5}$$

$$\frac{\partial H}{\partial h_1} = e^{-\delta t}[(p - c_1)] - \bar{\mu}_1 \tag{6}$$

$$\begin{aligned} \frac{d\mu_2}{dt} = -\frac{\partial H}{\partial S_0} = -e^{-\delta t}[\tilde{\rho}_{S_0}\big(p - c_0 - \tilde{c}(S_0)\big)h_0 - \tilde{\rho}(S_0)\tilde{c}_{S_0}h_0 - \tilde{\rho}_{S_0}\big(p - c_1 - \tilde{c}(S_0)\big)h_0 - (1 - \\ \tilde{\rho}(S_0))\tilde{c}_{S_0}h_0] \end{aligned} \tag{7}$$

The first order conditions in (5) and (6) can be rearranged and solved for μ_2

$$\mu_2 = e^{-\delta t}[\tilde{\rho}(S_0)(c_1 - c_0) - \tilde{c}(S_0)]\,\frac{1}{\alpha} \tag{8}$$

The adjoint variable μ_2 in equation (8) measures the shadow price of S_0 in terms of the difference in expected unit cost reduction from harvest on pristine seamounts. Equation (8) formalizes the observation that the search for seamounts is driven by the difference in unit harvest costs. Cost savings from bottom trawling on seamount complexes where catch rates are high yield a superior marginal rent, however, as pristine seamounts are irreversibly affected from fishing and the probability of finding them decreases, μ_2 decreases over time. Equations (7) and (8) can be used to derive the singular case where $\mu_2(t)$ vanishes identically over time.

$$\tilde{\rho}(S_0)(c_1 - c_0) = \tilde{c}(S_0) \tag{9}$$

Equation (9) shows that all bottom trawling activity on pristine seamounts ceases when the expected reduction in harvest costs is equal to the search cost per unit of harvest. Thereafter, all orange roughy harvest occurs on known tracks/flat bottoms at a harvest cost c_1.

POLICY DISCUSSION

This section discusses the measures that have been adopted to protect seamounts, and how our analysis can be utilised to inform policy making. To date, the Ministry of Fisheries has responded to the effects of bottom trawling on fragile benthic invertebrate communities and localised depletions of orange roughy in a number of ways. In September 2000, 19 seamounts were closed to all bottom trawling, 10 of which lie within ORH 3B (Ministry of Fisheries 2011a). A further 17 areas are closed to bottom trawling by regulation as a result of industry-initiated Benthic Protection Areas (BPAs), 11 of which lie within or across ORH 3B. The Ministry of Fisheries (2011a) estimates that these closures protect 15% of areas of recognised orange roughy occurrence.

The Ministry of Fisheries has also over the years gradually reduced the TACC in ORH 3B from a high of 38 300 tonnes in 1988 to an all-time low of 4 610 tonnes in 2010. Such overall reductions went hand in hand with continuous realignments of sub-stock management borders and something known as ‘catch spreading’ arrangements between the Ministry of Fisheries and the industry[14], e.g.

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[14] ORH 3B comprises five individual sub-stocks, for each of which voluntary sub-QMA catch limits had been agreed to by the industry.

the ORH 3B TACC of 7 950 tonnes in 2009 was divided into a catch limit of 750 tonnes on the Northwest Rise, 5 100 tonnes on the East Rise and 1 850 tonnes for the Sub-Antarctic (Ministry of Fisheries 2011b). Attempts by the Ministry to yield catch limits at an even finer scale singling out individual hill complexes within the East Chatham Rise were opposed by the Group and eventually rejected (Ministry of Fisheries 2007). The Group argued that localised depletions of orange roughy should be considered as an economic issue affecting catch rates rather than sustainability at a broader scale and that management becomes prohibitively difficult and costly at finer scale.

The World Wide Fund for Nature (WWF) and Environment and Conservation Organisations in New Zealand (ECO) argue that regulations to date have failed to arrest the continuing decline in orange roughy biomass and the fishery should be completely closed to allow recovery. The Group, on the other hand, argues the current catch limits should remain in place until further information becomes available (Ministry of Fisheries 2011a).

A possible key to understanding declining biomass levels on the Chatham Rise as well as other distinct areas within ORH 3B lies in the benefits and costs of pristine seamount depletion. The benefits are short-term and are solely appropriated by the Group in terms of reduced unit harvest cost. The costs, however, are external to the Group’s yearly maximisation problem and may include the loss of existence and habitat values. If, for example, pristine seamount habitat plays an essential role in orange roughy’s life cycle, then its depletion will affect biomass levels negatively in the long term.

To date, the effectiveness of seamount closures and TACC reductions has been thwarted. Fishers dislike the closure of highly productive areas, reflected by the fact that closed seamounts are a small proportion of known seamounts (19 out of approximately 800). The industry-led initiative of closing 32% of New Zealand’s waters to bottom trawling in 2007 known as BPAs has been criticised by environmental agencies as having low conservation values serving to deflect environmental controls on fishing (ECO 2006). Many scientists consider seamount closures by the government as ‘too little too late’ (Smith 2001), essentially because they are reactionary measures that are taken after seamounts are discovered and destructive fishing is already underway.

The bioeconomic model can inform and improve policy making. The policies to date do not address the spatial determinants of rent appropriation, i.e. equation (9) shows that the search for pristine seamounts will only cease when the expected reduction in harvest costs is equal to the search cost per unit of harvest. The imposition of a 'seamount' fee $\theta(t)$ levied on the Group's harvest activities may provide a way to internalise the cost of seamount destruction more effectively.

$$\tilde{\rho}(S_0)(c_1 - c_0 - \theta) = \tilde{c}(S_0) \qquad (10)$$

where

$$\theta = c_1 - c_0 - \frac{\tilde{c}(S_0)}{\tilde{\rho}(S_0)}$$

The elimination of differences in unit harvest costs from bottom trawling on pristine seamounts removes the incentive for search and discovery. The fee θ is a price instrument that ties the impacts of destructive fishing to orange roughy catch and can be imposed by the Ministry of Fisheries when vessels are known to trawl in new areas. Bottom trawling on known tracks/flat bottom or alternatively, if the Group can prove that fishing in pristine areas occurs in such a manner that it has a reduced or no impact on the benthic habitat, will carry reduced or no fees.

Such a policy would have a number of advantages, discussed in more detail below; 1) it addresses the spatial dimension of the Group's behaviour; 2) it targets individual vessel behaviour, 3) it internalises the effects on cold water corals by making it part of the Group's economic problem, thus providing an impetus for fishers to develop and adopt selective fishing practices; 4) implementation is feasible and, finally, 5) it is forward looking.

The first point is important because a seamount fee policy addresses the spatial determinants of rent appropriation. The Group maintains its flexibility of harvesting activity during the fishing year to maximize returns whilst internalising the cost of seamount destruction. Secondly, despite the Group's collusion to maximise economic returns, vessels still compete for catch rates on the water[15] and effective policies have to target individual vessel behaviour. By making the fee contingent on fishing location, vessels and quota holders are directly accountable.

The third point resonates with Kennelly and Broadhurst's (2002) who strongly advocate innovative gear-based and operational solutions to ameliorate issues of by-catch and impacts of

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[15] Personal communication with the industry, 5 December 2011.

fishing on entire ecosystems. They argue that effective regulation has to provide incentives for the industry to develop new technologies that reduce the impacts of bottom trawling on seamounts. Carr and Milliken (1998) explore changes to ground-chains, footropes, sweeps and trawl doors as promising ideas to reduce disturbances. Technological changes in gear and other equipment have been made successfully in response to concerns over by-catch of charismatic species (such as Turtle-Excluder Devices on trawlers) and it is the emphasis on such innovative fishing technology that a 'seamount' fee policy would promote. If the Group can prove reduced or no impacts of newly developed fishing technology on pristine seamount habitat ($\alpha = 0$), fishers can benefit from increased catch rates without incurring a fee. This provides a strong incentive to engage in the uptake of innovative non-destructive technology.

Fourthly, implementation is feasible because New Zealand's fishery management is familiar with the application of fees. Primarily, the ITQ system is a quantity instrument to maximise economic value from fishing, however, a landing-fee approach known as the deemed-value system is also employed. Newell 2004 (p. 29) notes that 'the New Zealand QMS has evolved into a hybrid system that employs both quantity and price instruments in controlling catch'. Deemed values rates are a type of fee levied on additional units of catch above what is covered by fishers' quota and encourages fishers to cover any fish by-catch with quota in a multi-species fishery. As such, New Zealand's fishery management has experience with the implementation of fees. The Ministry of Fisheries also devotes substantial resources to monitoring and enforcement and maintains a sophisticated database with a public user face[16]. The reporting of cold water coral by-catch has been made a requirement since October 2008 and all commercial vessels targeting orange roughy have to report starting and finishing locations of tows. It should be possible for the Ministry of Fisheries to match incoming data with previous reported locations and calculate corresponding 'seamount' fees based on spatial differences in catch rates and prevailing price and cost parameters

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

And finally, the policy can be applied to any given area, irrespective of the level of explored seamounts. Putting a ‘price’ on the bottom trawl externality is forward looking because it does not rely on knowledge about occurrence and geographical position of pristine seamounts, but rather targets the use of the fishing method on a spatial dimension.

The challenges of the proposed policy will likely focus on determining the correct ‘seamount’ fee according to equation (10). Collaboration with the Group and data analysis of past catch rates associated with pristine seamount habitat will be pivotal to arrive at accurate values and to achieve the desired incentives of seamount preservation. Further research and more detailed policy analysis will be required.

CONCLUSION

The approach in this paper reflects the importance of understanding the underlying economic incentives governing fisher behaviour that are generated by prevailing regulation before efficient fish and habitat management can be devised. We analyse the externality of bottom trawling and advocate a ‘seamount’ fee approach that internalises the effects on benthic habitat by making it part of the Group’s economic problem. Such an approach addresses the spatial determinants of rent appropriation and is also forward looking. It promotes the development of selective fishing practices by penalizing the method of fishing and can be extended to address other forms of destructive fishing gears. The scientific community generally advocates spatial closures as the panacea to managing destructive fishing practices but to put it in Kenelly and Broadhurst’s (2002, p. 352) words, “if fishing technology does not develop to an almost ‘utopian’ point of perfect selectivity, the fisheries of the world will continue to decline at its current (or a faster) rate.”

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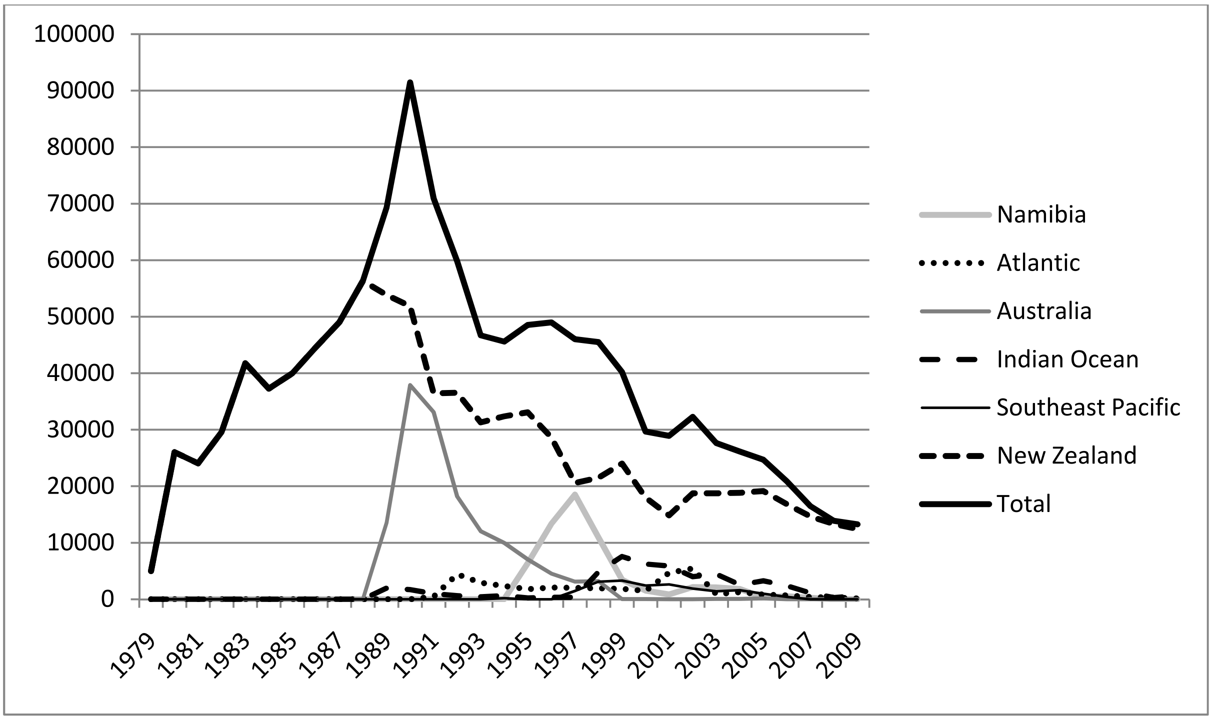
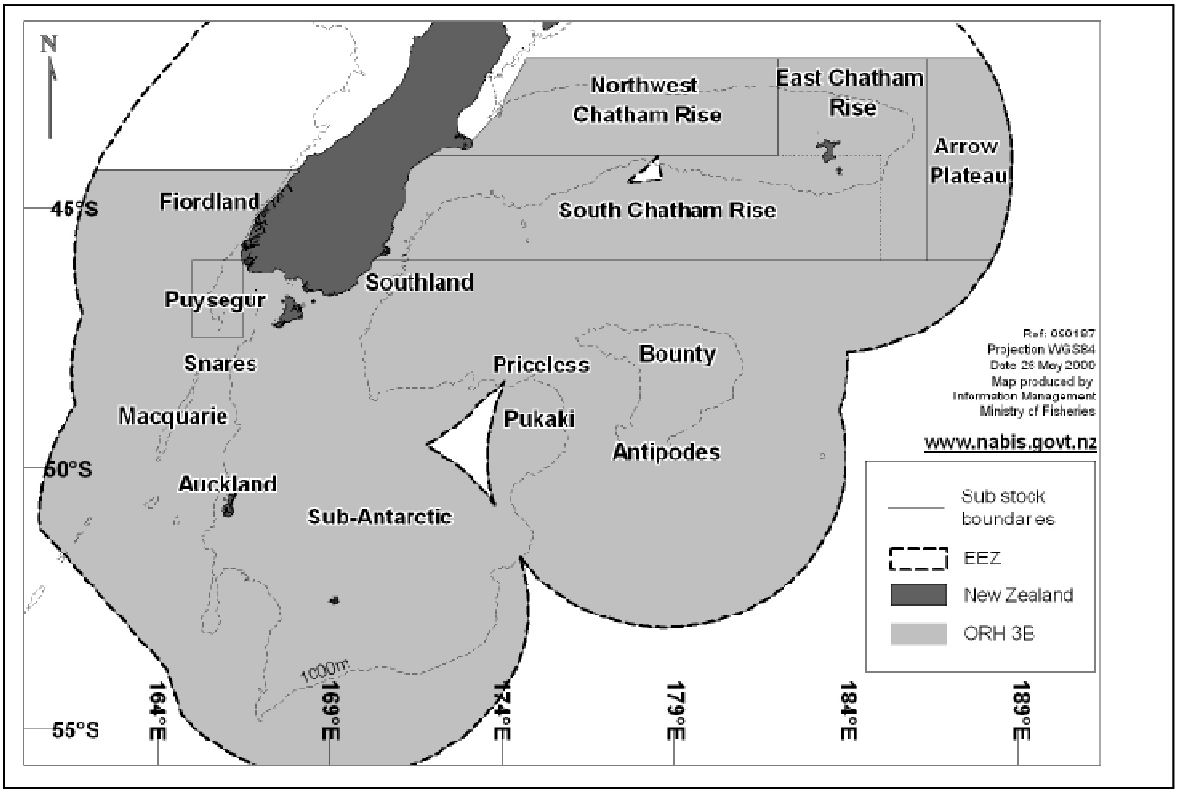
Figure 1. Annual world catches (tonnes) of orange roughy by region.



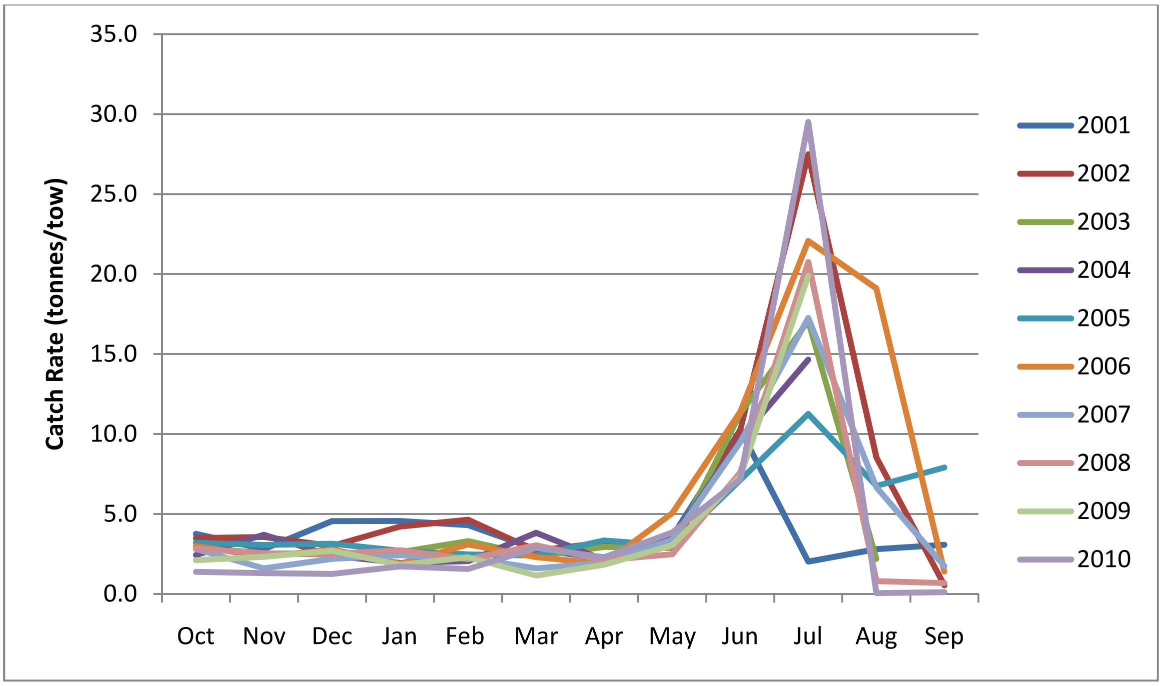
Source: produced from FAO data using FishStatJ (free software from http://www.fao.org/fishery/statistics/en).

Figure 2. Map of Chatham Rise and Sub-Antarctic fishing grounds.



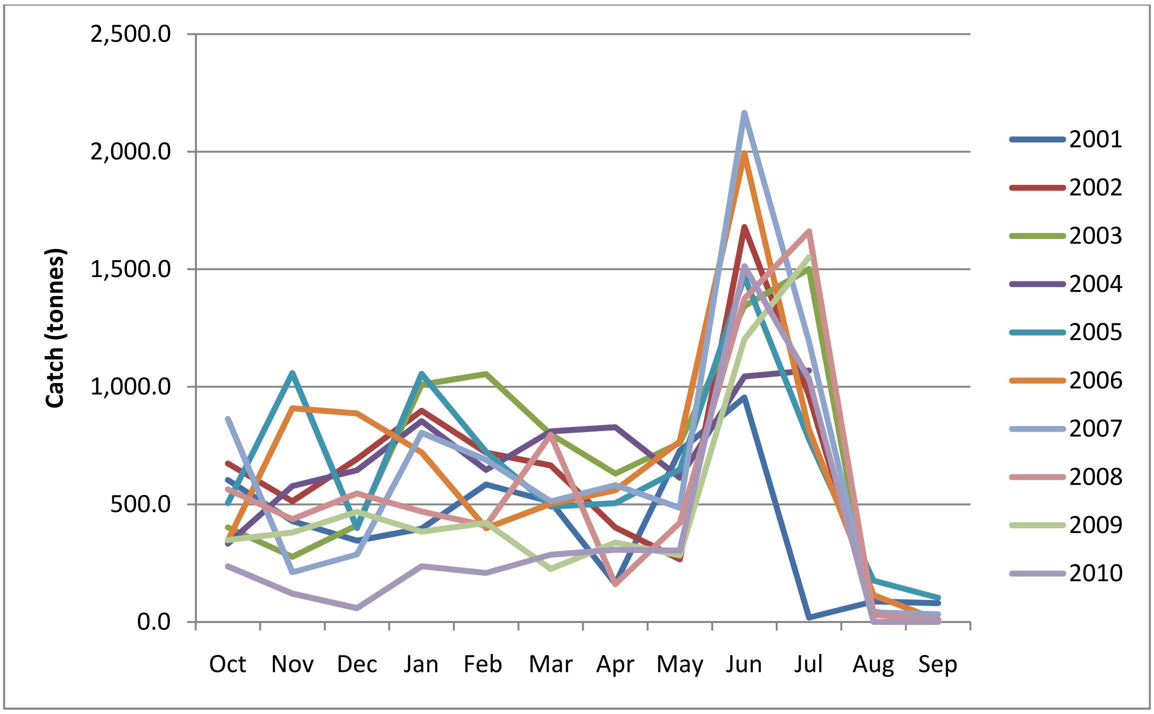
Source: reproduced from Ministry of Fisheries (2011b), p. 536, Figure 1.

Figure 3. Average monthly catch rate on the East Chatham Rise between 2001 and 2010.



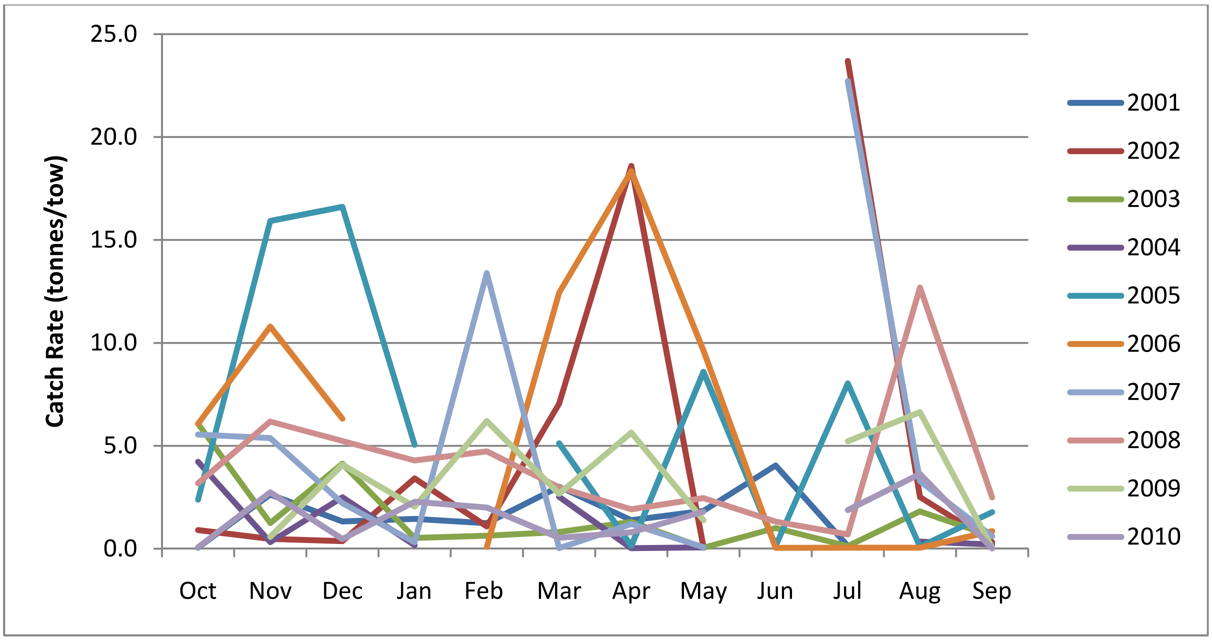
Source: produced from ORH 3B catch and effort data provided by the Ministry of Fisheries.

Figure 4. Monthly catch on the East Chatham Rise between 2001 and 2010.



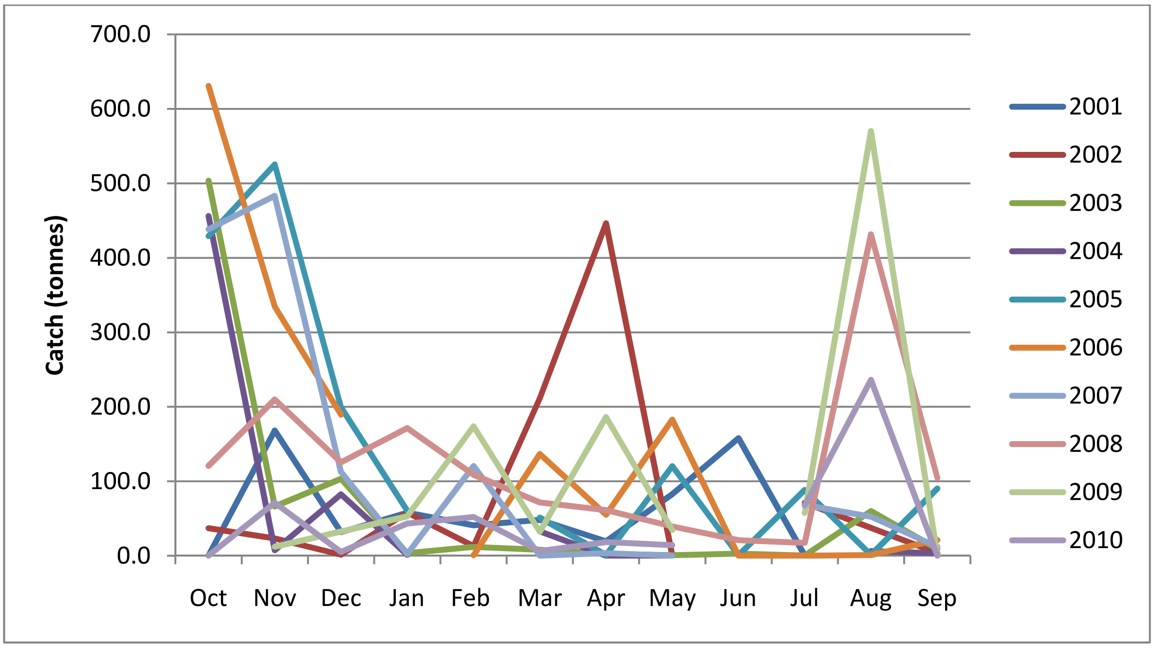
Source: produced from ORH 3B catch and effort data provided by the Ministry of Fisheries.

Figure 5. Average monthly catch rate in the Sub-Antarctic between 2001 and 2010.



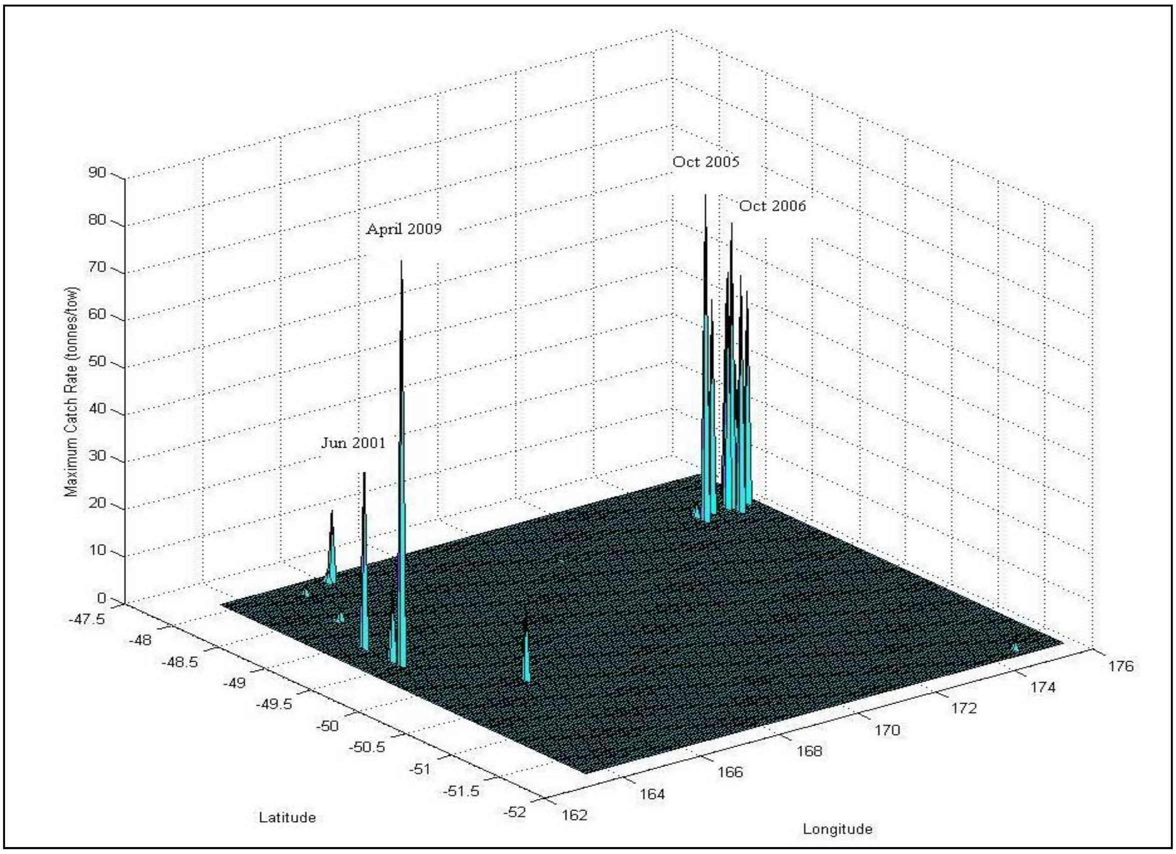
Source: produced from ORH 3B catch and effort data provided by the Ministry of Fisheries.

Figure 6. Monthly catch in the Sub-Antarctic between 2001 and 2010.



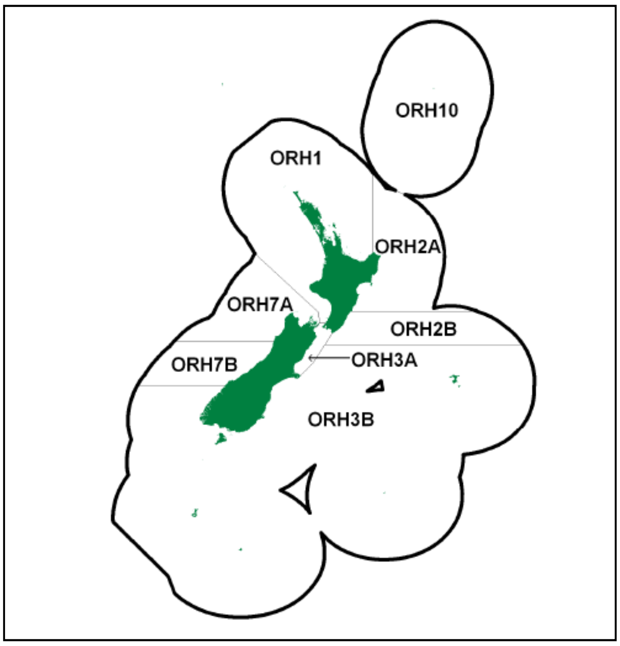
Source: produced from ORH 3B catch and effort data provided by the Ministry of Fisheries.

Figure 7. Maximum monthly catch rate in the Sub-Antarctic between 2000 and 2010.



Source: produced from ORH 3B catch and effort data provided by the Ministry of Fisheries.

Figure 8. QMA boundaries for orange roughy.



Source: reproduced from Ministry of Fisheries (2011b), p. 502.