Fishing on cold water coral reefs: A bioeconomic model of habitat-fishery connections

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Abstract

This paper applies a bioeconomic model in order to study different interactions between a harvested renewable resource and a non-renewable resource without commercial value that is negatively affected by the harvesting activity. This enables the analysis of for instance cold water coral habitats and their importance to commercial fish species. The fish is harvested either in a manner that does not damage coral, such as stationary gear, or in a destructive fashion, such as bottom trawling. We find that when coral is a *preferred* or *essential* habitat, the optimal steady-state fish stock is no longer independent of the habitat level, i.e. *optimum optimorum* values determine the optimal stationary gear harvest rate and how much habitat should optimally be preserved. Such *optimum optimorum* values will vary according to the type of habitat-fishery connection, and some bottom trawling may be optimal for some periods of time. Our findings extend upon the underlying assumption of a constant habitat quality of bioeconomic models when destructive fishing methods are involved and a habitat-fishery connection exists.

Keywords: bioeconomic analysis; interaction renewable non-renewable resource; destructive fishing method; cold water coral; essential and preferred habitat-fishery connection; steady-state analysis;

JEL codes: Q22, Q30

1. Introduction

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). An amendment of the Magnuson-Stevens Fishery Conservation and Management Act in 1996 soon followed mandating regional fishery management Councils to identify, assess and conserve essential fish habitat defined as *"those waters and substrate necessary to fish for spawning, breeding, feeding or growth to maturity."* On the other side of the Atlantic, a reform of the European Union Common Fisheries Policy in 2003 similarly reflected a fundamental shift in the approach to fisheries management away from the narrow focus on single fish stock assessments to a holistic ecosystem approach, which embeds the issue of sustainable fisheries management into the much wider context of marine ecosystem diversity (Pope and Symes 2006).

Such a change in the approach to fisheries management is not surprising considering wide scale failure in managing fish stocks, both regionally and globally. With more than 70% of the world's commercially important fish stocks in decline (FAO 2000), it seems vital to reconsider standard single stock assessment and bioeconomic models deriving optimal harvest paths against the backdrop of habitat-fishery interactions. Conventional bioeconomic analysis assumes the environmental quality of productive fishing grounds remains constant and unaffected by harvesting activities (e.g. Clark 1990; Clark and Munro 1975). There is some bioeconomic modelling that takes explicit account of the interaction between fisheries and marine habitats (see Knowler 2002; Upton and Sutinen 2003 for overviews). Most of these models treat environmental effects as an exogenous variable (see for example Bell 1972 and Smith 2007). Little

research, however, is done on endogenous environmental effects, i.e. little attention is paid to the fact that fishing effort, the primary control variable in many policy situations, and the choice of policy will affect the use of gear types and has thus a direct impact on habitat quality. Most notably, bottom trawling and dredging are primary fishing practices that continue to attract international attention because of their wide-scale effects on fragile seafloor habitats (Ocean Studies Board 2002).

This article makes a first contribution to the bioeconomic literature by analysing the endogenous effects of destructive fishing practices given potential types of habitat-fishery connections where we consider cold water corals as an example of a deepwater seafloor habitat. Cold water corals represent a structurally complex system in depths of 50 to 2000 metres (Cairns 1994), a preferred temperature range of 6-8 °C (Fossa, Mortensen and Furevik 2002) and with many habitat niches that produce high levels of biodiversity (Costello et al. 2005). With estimated growth rates between 4.1 to 25 mm per year (Freiwald 1998), they are considered non-renewable on a time-scale relevant to commercial exploitation. Cold water corals are associated with some of the most productive fishing grounds and are found in the North Atlantic, the Mediterranean, the Indian Ocean and the Pacific Ocean (Husebo et al. 2002). Pristine levels can readily be identified since natural decay of such reefs is easily distinguished from harvest induced destruction, i.e. from bottom trawling, by visual inspection[1] (Costello et al. 2005; Fossa, Mortensen and Furevik 2002; Freiwald et al. 2004).

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[1] Evidence of trawling can be seen by barren landscapes with crushed remains of cold water coral skeleton spread over the area indicating a severely disturbed bottom substrate (Fossa, Mortensen and Furevik 2002).

In Norway, cold water coral reefs have been important fishing grounds for stationary gear users, such as gill-netters and long-liners, who position their nets near the reefs to yield higher catch rates (Mortensen et al. 2001). Despite instances of coral harvest or damage, harvesting by such stationary gears has had a minimal effect upon the reefs in the past (Fosså et al. 2002). In the past bottom trawlers avoided cold water coral reefs for fear of damage to nets making them de facto refuges. However, since the 1980s larger vessels with rock hopper gear (large rubber discs or steel bobbins) have been encroaching on previously inaccessible areas targeting the same species as stationary gear users (Fosså et al. 2002). Stationary gear users have increasingly been voicing their concern about the effects of bottom trawling on their decreasing catch rates. Following the airing of research footage on the Norwegian national news in 1998 of previously pristine cold water coral areas that had been reduced to coral rubble by bottom trawling activity, the government acted swiftly and closed a number of areas of cold water coral reefs off the Norwegian coast to all fishing activities involving gear that touches the ocean floor (Armstrong and Hove 2008). Bans on bottom trawling are also in existence in other areas, such as on the Oculina deepwater reef off the coast of Florida, in areas off Alaska's Aleutian Islands and in New Zealand's Exclusive Economic Zone. As more and more cold water coral reefs are discovered and non-governmental agencies are increasingly putting pressure on governments to protect these areas, it is natural to ask how exactly bottom trawling impacts upon optimal catch rates of other gear users fishing in the same area and whether it is always optimal from a fisheries management point of view to protect the whole area of any given coral stock.

The impacts of bottom trawling on deep water corals have been little explored in the literature (Freiwald et al. 2004) and the exact ecological role deep water corals

play as habitat remains poorly understood, but fish species such as saithe, redfish and tusk are commonly observed on or near such reefs in Norwegian waters (Mortensen et al. 2001)[2]. Fosså et al. (2000) and Mortensen (2000) provide possible explanations for the fact that fish seem to be attracted to the reefs; (1) for enhanced feeding; (2) as a refuge; and (3) as a nursery area. Based on the premise that exact habitat-fishery connections are only vaguely identified, we consider two types of possible connections. The first type presupposes the scenario when a defined area containing cold water corals is a *preferred* place of aggregation for a commercially important deepwater species such as redfish, while the second scenario assumes the corals are *essential* to the species' reproduction and/or survival.

By employing dynamic optimization methods for a two-fleet model (bottom trawlers and stationary gear users) targeting the same commercial fish stock, but with only one gear type (bottom trawl) affecting cold water coral, we characterise optimal paths and steady-state values for two control variables (harvest rates of bottom trawlers and stationary gear users) and two state variables (fish and cold water coral habitat stock). The analysis involves simultaneously solving a system of differential equations and draws on the work of renewable resources by Clark and Munro (1975), the optimal extraction path of non-renewable resources by Hotelling (1931) and Swallow's (1990) analysis of interactions between a

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[2] Furevik et al. (1999) find that long-line catches can be six times higher for redfish, and two to three times higher for ling and tusk above or next to the reefs compared to non-reef areas. Similarly, Husebø et al. (2002) observe the average catch to be 5.7 redfish per long-line around cold water coral reefs compared to 0.8 redfish per long-line in non-coral areas. They also report larger modal sizes of redfish, tusk and ling on reef habitat.

renewable and a non-renewable resource through the growth function of the renewable resource.

We show that when a habitat-fisheries connection exists, optimal steady-state fish stock and habitat levels are interdependent. *Optimum optimorum* values can be found for the fish stock, the stationary gear harvest rate and the habitat stock when the non-renewable habitat is *preferred* and has a positive effect on the cost of harvest. For fisheries managers this implies the optimal stationary gear harvest rate will be directly dependent on the level of habitat. For policy makers with habitat conservation goals in mind it is of interest that the *optimum optimorum* habitat level is not necessarily found at its pristine level, i.e. bottom trawling may be optimal for some periods of time. In the case of an *essential* habitat-fishery connection where habitat has a positive effect on the cost of harvest as well as on the biological growth of the renewable resource, the *optimum optimorum* will differ from the scenario when a habitat is *preferred*, and again some bottom trawling may be optimal for some periods of time depending on the starting position of the industry in terms of given habitat and stock levels.

Our results highlight the importance of identifying habitat-fisheries connections when contemplating spatial closures as new cold water coral reefs are discovered. When no habitat-fisheries connections exists, it will be optimal to continue harvest by the most efficient method, such as trawling, since the optimal cold water coral stock to preserve is zero. If, however, a habitat-fisheries connection exists, the result is different. Once the optimal level of cold water coral and fish stock are attained, destructive fishing methods should cease in favour of non-destructive methods to preserve the optimal habitat stock.

2. Preferred habitat-fishery connection

Anecdotal information suggests that bottom trawlers often 'mow' or 'skirt' the edges of cold water coral reefs leaving behind barren landscapes with crushed remains of coral skeleton spread over the area ('coral rubble') (Costello et al. 2005; Fossa, Mortensen and Furevik 2002; Freiwald et al. 2004). This process has an irreversible impact on the habitat for the benefit of expanding the area of harvest available to the bottom trawler. The nature of this particular problem implies that bottom trawlers skirt consecutive patches within a defined area of pristine reefs leading to *successively lower levels* of cold water coral reefs *L* (denoting *Lophelia pertusa*, one of the most common cold water corals) i.e. the problem lends itself well to analysing *L* in terms of its overall stock level rather than in terms of its spatial dimension. The degradation of *L* is thus understood as a reduction in its quantity rather than in its quality.

Bioeconomic modelling is used to derive optimal fish stock and harvest rates, generally based on the underlying assumption of a constant habitat quality. Assuming a resource manager aims to maximise profits of harvest from a destructive but also highly efficient fishing sector such as bottom trawling without taking the effects on the non-renewable habitat into account leads to Clark and Munro's (1975) familiar Golden Rule equation where optimum harvest rates and profits are completely independent of the habitat level, i.e. the optimal amount of cold water coral to be preserved will be zero. This scenario reflects the highly destructive results of current deep sea fishing practices where cold water coral have no perceived value.

If, however, habitat attracts larger concentrations of the commercial species, thereby reducing harvesting costs, but this has no biological effect, the analysis

will be different. We define cold water corals L to play the role of a *preferred* habitat when the commercial catch of a renewable deepwater species X is affected through the cost of harvest but not through reproductive parameters for a given non-renewable habitat level. The underlying intuition is that the fish species might use the habitat for enhanced feeding, shelter or refuge from predators at times, which could increase their chances of survival and arguably have a biological effect. However, we assume this effect is negligible in this scenario, i.e. the habitat has more of an "amenity" value to the species rather than a survival value.

We assume a resource manager aims to maximise profits of harvest h_1 from a destructive but also highly efficient fishing sector such as bottom trawling, as well the profits of non-destructive harvest h_2 by stationary gear users such as gill-netters and long-liners, both of which target the same renewable fish stock X in a defined area of non-renewable habitat L^3. Bottom trawlers and stationary gear users harvest at a unit cost $c_1(X,L)$ and $c_2(X,L)$, respectively, while receiving an exogenous constant price of fish, p. The present value of the net benefit (PVNB) function is defined as

$$PVNB = \int_0^\infty e^{-\delta t} \left[(p - c_1(X,L))h_1 + (p - c_2(X,L))h_2 \right] dt \qquad (1)$$

where δ represents the social rate of discount. We assume bottom trawlers face a lower unit cost of harvest than stationary gear users, i.e. $c_1(X,L) < c_2(X,L)$. The unit costs $c_1(X,L)$ and $c_2(X,L)$ are convex in X, i.e. the cost of catching one unit of

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[3] The formulation of the problem assumes society places no value on the non-use value of cold water corals. In a yet unpublished mail survey to 5000 households in Ireland only 20% of the 500 respondents had heard about cold water corals before, and while most respondents were strongly in favour of protection, the average willingness to pay was 0 euro (PROTECT, project co-funded by the European Commission within the Sixth Framework Programme, 2002-2006).

fish decreases as the general abundance of the fish population increases ($c_{1X} < 0$; $c_{2X} < 0$; $c_{1XX} > 0$ and $c_{2XX} > 0$) (Clark 1990). Unit costs are also convex in L, i.e. fish are observed to congregate around cold water corals, and higher levels of L will increase the number of aggregations of X on and around reefs thereby lowering unit harvesting costs ($c_{1L} < 0$; $c_{2L} < 0$; $c_{1LL} > 0$; $c_{2LL} > 0$; $c_{1XL} = c_{1LX} > 0$; $c_{2XL} = c_{2LX} > 0$; $c_{1XX}c_{1L\ L} > c_1{}^2{}_{XL}$ and $c_{2XX}c_{2L\ L} > c_2{}^2{}_{XL}$). Higher levels of L may constrain bottom trawlers in their movement across space thus increasing gear loss. However, most bottom trawlers nowadays are equipped with computer interfaced multipurpose fishfinders combining GPS technology, digital chart-plotting and radar, which provide accurate displays of bottom structures allowing boats to minimize gear loss and damage.

The change in the renewable fish stock over time is described by the difference between the natural rate of growth, $F(X)$, and the harvest rates h_1 and h_2 (where $0 \leq h_1 \leq h_{1max}$ and $0 \leq h_2 \leq h_{2max}$).

$$\frac{dX}{dt} = F(X) - h_1 - h_2 \tag{2a}$$

Assuming a standard Pearl-Verhulst logistic model, the growth function $F(X)$ satisfies the assumptions $F(X) > 0$ for $0 < X < K$, $F(0) = F(K) = 0$ and $F_{XX} < 0$, where K denotes the environmental carrying capacity. Pristine reefs are assumed to be depleted as a by-product of bottom trawling activity h_1 at a constant rate α according to the equation

$$\frac{dL}{dt} = -\alpha h_1 \tag{3}$$

$X = X_0 \geq 0$ and $L = L_0 \geq 0$ define the initial conditions. The Hamiltonian can be defined as

$$H = e^{-\delta t}\left[(p - c_1(X,L))h_1 + (p - c_2(X,L))h_2\right] + \mu_1\left[F(X) - h_1 - h_2\right] + \mu_2\left[-\alpha h_1\right] \tag{4a}$$

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where h_1 and h_2 are the control variables and μ_1 and μ_2 are the adjoint variables measuring the shadow prices of the associated state variables X and L. The linear control problem leads to the familiar bang-bang control where singular paths for the control and state variables are derived by simultaneously solving the system of differential equations. The necessary conditions and adjoint equations are

$$\frac{\partial H}{\partial h_1} = e^{-\delta t}(p - c_1(X,L)) - \mu_1 - \alpha\mu_2 = 0 \tag{5}$$

$$\frac{\partial H}{\partial h_2} = e^{-\delta t}(p - c_2(X,L)) - \mu_1 = 0 \tag{6}$$

$$\frac{d\mu_1}{dt} = -\frac{\partial H}{\partial X} = -\left(e^{-\delta t}[-c_{1X}h_1 - c_{2X}h_2] + \mu_1 F_X\right) = \left(e^{-rt}[c_{1X}h_1 + c_{2x}h_2 - (p - c_2(X,L))F_X]\right) \tag{7}$$

$$\frac{d\mu_2}{dt} = -\frac{\partial H}{\partial L} = -\left(e^{-\delta t}[-c_{1L}h_1 - c_{2L}h_2]\right) \tag{8a}$$

In the first step we solve for the optimal fish stock value X^* *conditional* on levels of L, and in the second step for the optimal cold water coral stock L^* *conditional* on levels of X.

2.1 The optimal fish stock X* conditional on L

Given the appropriate transversality condition ($X \geq 0$ and $lim_{t\to\infty}\{X(t)\,\mu_1(t)\} = 0$), the preferred habitat-fishery connection version of the Golden Rule equation by Clark and Munro's (1975) is derived as

$$\delta = F_X(X^*) + \frac{-c_{2X}F(X^*) + (c_{2X} - c_{1X} + \alpha c_{2L})h_1}{(p - c_2(X^*,L))} \tag{9a}$$

Equation (9a) implies an optimal fish stock level X^* where the resource manager is indifferent to further investment in the fish stock and further consumption of it because X^* earns the discount rate δ. The first term on the right hand side describes the instantaneous marginal physical product of the fish stock while the

latter term represents the marginal fish stock effect. This stock effect measures the marginal value of the fish stock relative to the marginal value of stationary gear user harvest.

With habitat explicitly being ascribed a value in terms of its effect on unit harvest costs, the optimal fish stock level X^* is no longer independent of the level of L[4]. This is reflected by the term $(c_{2X} - c_{1X} + \alpha c_{2L})h_1$ in the numerator of the marginal fish stock effect and by the effect of $c_2(X,L)$ in the denominator, i.e. unit cost savings from harvest on a larger *in situ* fish stock now also have to be adjusted by the given habitat stock level (since $\{c_{1XL} = c_{1LX}; c_{2XL} = c_{2LX}\} > 0$ and $\{c_{1X}; c_{2X}\} < 0$). Pristine or higher levels of L push $\{c_{1X}; c_{2X}\}$ closer to zero thus lowering the return on investment in the *in situ* fish stock, which implies a lower X^*. To identify X^* values corresponding to different levels of L we totally differentiate equation (9a) to obtain

$$\frac{dX^*}{dL} = \frac{-\left[-c_{2L}F_X - c_{2XL}F(X^*) + \delta c_{2L} + (c_{2XL} - c_{1XL} + \alpha c_{2LL})h_1\right]}{(p - c_2(X^*,L))F_{XX} - 2c_{2X}F_X - c_{2XX}F(X^*) + \delta c_{2X} + (c_{2XX} - c_{1XX} + \alpha c_{2LX})h_1} = \frac{a + bh_1}{e + dh_1}$$

(10a)

where

$$a = -\left[-c_{2L}F_X - c_{2XL}F(X^*) + \delta c_{2L}\right]$$

$$b = -\left[c_{2XL} - c_{1XL} + \alpha c_{2LL}\right]$$

$$e = (p - c_2(X^*,L))F_{XX} - 2c_{2X}F_X - c_{2XX}F(X^*) + \delta c_{2X}$$

$$d = c_{2XX} - c_{1XX} + \alpha c_{2LX}$$

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[4] Escapa & Prellezo (2003) derive the Golden Rule equation for two countries sharing harvest of the same species but using different fishing gears. Similarly, they find that the optimal stock is not independent of the harvest quota allocation when the natural growth of the resource is altered by the fishing technology.

Analysis of the signs of each term contained in a, b, e and d according to the assumptions about the derivatives implies $\{a, d\} > 0$ and $\{b, e\} < 0$[5]. Equation (10a) is a rational function and the vertical/horizontal asymptotes and intercepts can be identified. However, since the parameters a, b, e and d themselves change magnitude for different levels of X^*, and thus L, the slope dX^*/dL can both be positive and negative for any given h_1 depending on the magnitude of the parameters. Any *steady-state value* for X^* along a curve $X^*:L$ (denoted in this manner to indicate conditionality on L) is achieved when $h_1^* = 0$ where $dX^*/dL = a/e < 0$. This is because according to equation (3) any $h_1^* > 0$ implies a continuous reduction in L leading to the continuous adjustment of X^*.

2.2 The optimal habitat stock L* conditional on X

We derive the optimal level of stock of the non-renewable habitat, L^*, by differentiating equation (5) and setting it equal to the adjoint equation (8a) with the appropriate transversality condition ($L \geq 0$ and $lim_{t \to \infty} \{L(t) \; \mu_2(t)\} = 0$) to obtain

$$\delta = \frac{(c_{2X} - c_{1X})F(X) + (c_{1X} - c_{2X} - \alpha c_{2L})h}{(c_2(X, L^*) - c_1(X, L^*))} \quad \text{for } h = h_1 + h_2 \qquad (11a)$$

Equation (11a) shows that the optimal level of L^* is found when the discount rate on alternative assets in the capital market is equal to the 'marginal habitat stock effect' (akin to marginal fish stock effect in equation (9a)). There is no instantaneous marginal physical product since the habitat is a non-renewable resource.

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[5] This is the case for both $F_X > 0$ and $F_X < 0$. See further discussion under the section 'Steady-state analysis'.

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Note equation (11a) is very different from the exhaustible resource path of extraction identified by Hotelling (1931) in that the habitat stock is depleted as a by-product of the profitable extraction of a renewable resource and has no value other than in terms of its positive effect on harvesting costs. The marginal habitat stock effect is thus characterized by the effect of marginal and unit differences in the cost efficiency between the two fleets.

The numerator of the marginal habitat stock effect contains the negative term $(c_{2X} - c_{1X})F(X)$, i.e. as we would expect the marginal net cost savings gained from bottom trawling activity affect the marginal value of the habitat stock negatively. The term $(c_{1X} - c_{2X} - \alpha c_{2L})h$ is positive and represents the effect of habitat on marginal net harvesting costs. When assuming specific functional forms for unit harvest costs and the growth function and solving for $L*$ analytically we find $L* > 0$ is only true for $h > 0$, i.e. because the value of the habitat stock is expressed solely by its effect on the cost of harvest, a positive optimal habitat stock is only desirable when harvesting occurs. The denominator shows that the marginal value of the 'harvest of L' (i.e. the 'benefit' of depleting L as a by-product of h_l) lies in the difference between the unit costs of stationary gear and bottom trawler harvest.

Equation (3) implies that there is no singular solution and a steady-state $L*$ identified by equation (11a) occurs only when $h_l = 0$, i.e. given the bang-bang nature of the linear optimal control problem bottom trawler harvest is either $h_l = 0$ or $h_l = h_{lmax}$. Therefore $L*$ represents a threshold to bottom trawler harvest, upon which it is optimal for the resource manager to cease all destructive bottom trawling activities in the defined area containing cold water corals. Totally differentiating equation (11a) we find

$$\frac{dL*}{dX} = \frac{-\left[\left(c_{2X}-c_{1X}\right)F_X + \left(c_{2XX}-c_{1XX}\right)F(X) - \left(c_{2X}-c_{1X}\right)\delta + \left(c_{1XX}-c_{2XX}-\alpha c_{2LX}\right)h\right]}{\left(c_{2XL}-c_{1XL}\right)F(X) - \left(c_{2L}-c_{1L}\right)\delta + \left(c_{1XL}-c_{2XL}-\alpha c_{2LL}\right)h} = \frac{m+dh}{i+bh}$$

(12a)

where

$$m = -\left[\left(c_{2X}-c_{1X}\right)F_X + \left(c_{2XX}-c_{1XX}\right)F(X) - \left(c_{2X}-c_{1X}\right)\delta\right]$$

$$i = \left(c_{2XL}-c_{1XL}\right)F(X) - \left(c_{2L}-c_{1L}\right)\delta$$

The parameters *b* and *d* are as previously defined in equation (10a). Analysis of the signs of each term contained in the parameters *m* and *i* according to our assumption about the derivatives implies $i > 0$ and $m < 0$[6]. Again, these parameters change in magnitude depending on the level of *L**, and thus *X*. That is, for any given *h* the slope *dL*/dX* can be positive or negative. Any positive *steady-state value* for *L** along a curve *L*:X* (denoted in this manner to indicate conditionality on *X*) is achieved when $h_1 = 0$ and $h_2 > 0$. This is so because according to equations (3) and (11a) a steady-state optimal habitat level requires zero bottom trawling but a positive level of sustainable harvest.

2.3 Steady-state analysis

Figure 1 shows a state space diagram depicting the *X*:L* and *L*:X* curves for a *preferred* habitat-fishery connection. Any point on the *X*:L* curve represents a steady-state fish stock level *X** at different levels of *L* (where $h_1* = 0$ and $h_2* = F(X*)$). Similarly, any point on the *L*:X* curve represents a steady-state habitat stock level *L** at different levels of *X* (where $h_1 = 0$ and $h_2 > 0$).

[Insert figure 1]

The shape of the *X*:L* curve is determined by its slope identified in equation (10a), i.e. *dX*/dL = a/e* for $h_1* = 0$. Both the parameters *a* and *e* contain the term

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[6] This is the case for both $F_X > 0$ and $F_X < 0$. See further discussion under the section 'Steady-state analysis'.

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F_X, which can be positive or negative depending on the size of the optimal stock. When $X^* > K/2$, $F_X < 0$ and the slope dX^*/dL is unambiguously negative ($dX^*/dL = a/e < 0$ and $dX^{*2}/d^2L > 0$). When $X^* < K/2$, $F_X > 0$ but the effect is always outweighed by large values for the term $F(X^*)$ in a and e so that dX^*/dL remains negative for all X^*.

The C-shape[7] of the $L^*:X$ curve is determined by its inverted slope identified in equation (12a). In this case, dL^*/dX can be both positive and negative depending on the level of X. This result is driven by the term F_X contained in the parameter m of the numerator in combination with the magnitude of the assumed h_2.

For any given $h_2 > 0$ and X the denominator of equation (12a) is negative because $|i| < |bh_2|$ (where $i > 0$ and $b < 0$), i.e. a positive stationary harvest rate h_2 gives disproportionate weight to the parameter b. The numerator, however, is sensitive to levels of X, i.e. at high levels of X, $F_X < 0$, $|m| > |dh_2|$ (where $m < 0$ and $d > 0$), the numerator becomes negative and $dL^*/dX > 0$ is the case. At some low X the term F_X becomes sufficiently positive so that $|m| < |dh_2|$, the numerator becomes positive and thus $dL^*/dX < 0$ is the case[8].

Note the $L^*:X$ curve is drawn for a constant h_2 value, which corresponds to the optimal *equilibrium* steady-state value of harvest ($h_2^* = F(X^*) = h_{2OM}^*$) identified by the $X^*:L$ curve at the point of intersection with $L^*:X$ (point B). This point represents an *optimum optimorum* where $X^* = X_{OM}^*$ and $L^* = L_{OM}^*$. Assuming any h_2 other than h_{2OM}^* implies the $L^*:X$ curve will lie either further to the right

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[7] As a matter of fact the $L^*:X$ curve represents 2 out of 3 solutions (the third solution is in the negative domain). Amalgamating the two solution curves, which meet at the minimum point of L^*, yields the same final results and is done here for convenience of illustration.

[8] Numerical simulations for a wide range of parameter values support this result.

(for $h_2 > h_{2OM}*$)[9] or further to the left (for $h_2 < h_{2OM}*$). The assumed stationary gear harvest rate will then not be equal to the optimal stationary gear harvest rate where the $X*:L$ and $L*:X$ curves intersect ($h_2 \neq h_{2OM}*$ at B). It follows there is only one unique $L*:X$ curve that allows an equilibrium steady-state to be reached.

To the left of $L*:X$ (i.e. in areas 1 and 4) the resource manager applies $h_1 = 0$ because L is below any of the optimal habitat stock levels determined by the habitat depletion threshold boundary $L*:X$ where all bottom trawling activity ceases (movement to the right towards the threshold boundary is not possible because the habitat is non-renewable). To the right of $L*:X$ (i.e. areas 2 and 3) $h_1 = h_{1max}$ applies. Anywhere above $X*:L$ (i.e. areas 1 and 2) $h_2 = h_{2max}$ applies because the fish stock level is above the optimal level $X*$ while anywhere below (i.e. areas 3 and 4) $h_2 = 0$ applies.

Trajectory t thus represents a downwards movement in the state space diagram and a steady-state fish stock level is achieved at A without further movement, i.e. A is a stable equilibrium. Trajectory o may lead to an equilibrium steady-state at the *optimum optimorum* B. At the start of this trajectory the manager applies $h_1 = h_{1max}$ and $h_2 = h_{2max}$ until the threshold boundary of habitat depletion is reached where $h_1 = 0$ and $h_2 = h_{2max}$ apply. However, any downward movement into area 2 is instantaneously adjusted by adopting $h_1 = h_{1max}$ again in order to return to the threshold boundary. The equilibrium at B is thus reached in a step-wise fashion. Trajectory s describes a similar path, i.e. first $h_1 = 0$ and $h_2 = 0$ apply, however, as soon as we are to the right of $L*:X$ the most rapid approach implies $h_1 = h_{1max}$ until $L*:X$ is reached again.

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[9] A higher level of harvest appreciates the habitat stock and thus implies higher levels of $L*$ at each X (see equation (11a)).

Stable equilibria are only found on $X^*{:}L$ to the left of B. For example, along trajectory q oscillations below C lead to a movement towards the habitat depletion boundary $L^*{:}X$ with $h_1 = h_{1max}$ and $h_2 = 0$, eventually settling on B or to the left of B on $X^*{:}L$.

Figure 1 highlights the interdependency between optimal steady-state fish stock levels and habitat levels. The optimal stationary gear harvest rate along $X^*{:}L$ generally increases with higher habitat levels (since the implied optimal fish stock level X^* is lower) as long as $X^* > K/2$. The *optimum optimorum* habitat level can be found anywhere between its pristine level and zero depending on the identified *optimum optimorum* stationary gear harvest level. Bottom trawling may be optimal for some periods of time whenever the fishery starts to the right of the habitat depletion boundary (i.e. to the right of the minimum L^* identified by $L^*{:}X$).

3. Essential habitat-fishery connection

Cold water corals as an *essential* habitat are assumed to affect the commercial catch of the species both through the cost of harvest *and* through the growth function[10] $F(X,L)$ where $F(0,L) = F(X,0) = 0$, F is concave in both X and L ($F_{XX} < 0$, $F_{LL} < 0$, $F_{XX}F_{LL} - F^2_{XL} > 0$) and the carrying capacity K is an increasing function of L ($F_L > 0$, $F_{XL} = F_{LX} \geq 0$, $K = K(L)$ because $F(K,L) = 0$). In this scenario we account for the possibility of the habitat having a biological effect. Equation (2a) can then be restated as

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[10] Swallow (1990) has incorporated the effect of irreversible coastal zone development on a renewable resource in terms of its carrying capacity but not in the terms of the cost of harvest. We extend on Swallow's results by considering the case when commercial catch is affected both through the growth function *and* the cost of harvest.

$$\frac{dX}{dt} = F(X,L) - h_1 - h_2 \tag{2b}$$

Based on equations (1), (2b) and (3) the Hamiltonian is defined as

$$H = e^{-\delta t}\left[(p - c_1(X,L))h_1 + (p - c_2(X,L))h_2\right] + \mu_1\left[F(X,L) - h_1 - h_2\right] + \mu_2\left[-\alpha h_1\right] \tag{4b}$$

The necessary conditions and adjoint equations are the same as in equations (5), (6) and (7) but the adjoint equation (8a) is now

$$\frac{d\mu_2}{dt} = -\frac{\partial H}{\partial L} = -\left(e^{-\delta t}\left[-c_{1L}h_1 - c_{2L}h_2 + (p - c_2(X,L))F_L\right]\right) \tag{8b}$$

3.1 The optimal fish stock X* conditional on L

The essential habitat-fishery connection version of the Golden Rule equation is derived as

$$\delta = F_X(X^*,L) + \frac{-c_{2X}F(X^*,L) + (c_{2X} - c_{1X} + \alpha c_{2L})h_1}{(p - c_2(X^*,L))} \tag{9b}$$

Comparison to equation (9a) shows that the term *F(X*)* is simply replaced by *F(X*,L)*. This, however, implies a significantly different analysis. Equation (9b) shows that in addition to the effect *L* has on the marginal fish stock effect, *L* now also affects the instantaneous marginal physical product of *X**, i.e. *L* enters the growth function through the carrying capacity (*K = K(L)*). The result is that there are competing dynamics between the growth and the cost effect with respect to *L*. Totally differentiating equation (9b) we obtain

$$\frac{dX^*}{dL} = \frac{-\left[(p - c_2(X^*,L))F_{XL} - c_{2X}F_L - c_{2L}F_X - c_{2XL}F(X^*L) + \delta c_{2L} + (c_{2XL} - c_{1XL} + \alpha c_{2LL})h_1\right]}{(p - c_2(X^*,L))F_{XX} - 2c_{2X}F_X - c_{2XX}F(X^*,L) + \delta c_{2X} + (c_{2XX} - c_{1XX} + \alpha c_{2LX})h_1} = \frac{A+b}{e+d} \tag{10b}$$

where

$$A = -\left[(p - c_2(X^*,L))F_{XL} - c_{2X}F_L - c_{2L}F_X - c_{2XL}F(X^*,L) + \delta c_{2L}\right]$$

Equation (10b) differs from equation (10a) by the terms $(p - c_2(X^*, L))F_{XL} - c_{2X}F_L$ contained in the parameter A. These reflect the positive effect of habitat levels on the growth of the fish stock. The terms b, e and d are as previously defined, but the sign of A is now uncertain.

3.2 The optimal habitat stock L* conditional on X

Equations (5) and (8b) together with the appropriate transversality condition characterise the optimal level of cold water coral stock.

$$\delta = \frac{(c_{2X} - c_{1X})F(X, L^*) + (p - c_2(X, L^*))\alpha F_L + (c_{1X} - c_{2X} - \alpha c_{2L})h}{(c_2(X, L^*) - c_1(X, L^*))}$$

for $\quad h = h_1 + h_2$ (11b)

Comparing equations (11b) and (11a) we see that the numerator of the marginal habitat stock effect is augmented by the term $[(p - c_2(X, L^*))\alpha F_L > 0]$. This represents the positive return from an additional unit of L to renewable resource production. Totally differentiating equation (11b) we find[11]

$$\frac{dL^*}{dX} = \frac{M + dh}{I + bh}$$ (12b)

where

$$M = -[(p - c_2(X, L^*))\alpha F_{LX} - c_{2X}\alpha F_L + (c_{2X} - c_{1X})F_X + (c_{2XX} - c_{1XX})F(X, L^*) - (c_{2X} - c_{1X})\delta]$$

$$I = [(c_{2X} - c_{1X})F_L + (p - c_2(X, L^*))\alpha F_{LL} - c_{2L}\alpha F_L + (c_{2XL} - c_{1XL})F(X, L^*) - (c_{2L} - c_{1L})\delta]$$

Equation (12b) differs from equation (12a) by the terms $(p - c_2(X, L^*))\alpha F_{LX} - c_{2X}\alpha F_L$ in the parameter M and by the terms $(c_{2X} - c_{1X})F_L + (p - c_2(X, L^*))\alpha F_{LL} - c_{2L}\alpha F_L$ in I. The parameters b and d are as

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[11] The full display of dL^*/dX containing all its elements does not fit physically on the page.

previously defined. Based on our assumptions of the derivatives the sign of M remains negative while the sign of I is uncertain.

3.3 Steady-state analysis

Figure 2 shows a state space diagram depicting the $X^*{:}L$ and $L^*{:}X$ curves for an *essential* habitat-fishery connection. As before, any point on the $X^*{:}L$ curve represents a steady-state fish stock level X^* at different levels of L (where $h_1^* = 0$ and $h_2^* = F(X^*)$) while any point on the $L^*{:}X$ curve represents a steady-state habitat stock level L^* at different levels of X (where $h_1 = 0$ and $h_2 > 0$).

[Insert figure 2]

With the sign of the parameter A in equation (10b) uncertain, the slope of the $X^*{:}L$ curve can now be both positive and negative depending on the level of L. At low levels of L the cost effect outweighs the growth effect and A is positive, as is the case for a *preferred* habitat-fishery connection (i.e. $dX^*/dL < 0$). However, as L increases the growth effect becomes more dominant and A becomes negative implying $dX^*/dL > 0$. The intuitive explanation is that at low habitat levels the effect of having a higher fish stock level is more important in order to compensate for rising harvesting costs, while at higher habitat levels the positive impact on the carrying capacity of the fish stock is more pronounced.

The shape of the $L^*{:}X$ curve is similar to that of the *preferred* habitat-fishery connection and the same reasoning applies despite the new terms in the parameters M and I. The added terms change the magnitude, i.e. the relative position of the $L^*{:}X$ curve, but not the qualitative results. For example, the added negative terms in M imply the stock level X now has to be lower to produce a sufficiently positive F_X in order for $dL^*/dX < 0$ to be the case.

The same forces apply as in figure 1. One clear difference to the *preferred* habitat-fishery connection is that the optimal stationary gear harvest rate along $X^*:L$ will continuously increase for higher levels of habitat after its turning point (i.e. when $dX^*/dL > 0$) because the effect of habitat on increasing the carrying capacity of the fish stock dominates. Figure 2 also shows that the *optimum optimorum* at D will be different to the one found for the preferred habitat-fishery connection.

Figures 1 and 2 highlight the growing complexities in identifying optimal stock levels and determining optimal fishing strategies when fish stock levels are interdependent with habitat levels due to cost efficiency gains and biological connections. Optimal stock levels for both the commercial stock and the habitat stock will depend on the type of fisheries connection.

4. Discussion

In November 2006 countries seeking to ban bottom trawling in unregulated international waters failed to get the United Nations' support. Still, the effort to establish networks of marine protected areas (MPAs) to conserve and sustain fisheries and maintain healthy marine ecosystems around the world is gaining momentum, for example the United States and the European Community envisage the establishment of a network of MPAs to reduce the impact of fishing on marine ecosystems. Cold water corals have been identified as prime candidates for protection through MPAs since they are sessile organisms and their primary threat, bottom trawling, can be controlled spatially (Grass 2003). Complete bans on bottom trawling are already in existence in some areas around the world but closures of additional areas of cold water coral reefs nationally and internationally will inevitably raise the question as to how exactly bottom trawling impacts upon optimal stock and catch rates of other gear users and how much of any given cold

water coral stock should be protected to safeguard its functional role as a habitat to commercially important fish species.

Our dynamic bioeconomic analysis addresses the endogenous impact of bottom trawling when considering two types of linkages between a non-renewable habitat such as cold water corals and a commercially important renewable resource, i.e. we consider the scenario of when habitat is *preferred* and when it is *essential*. Bottom trawling is usually an efficient way of harvesting and we explicitly account for this fact by assuming a lower unit harvest cost for bottom trawling than for stationary gear users. By solving a system of differential equations we deduce a number of findings that may have important implications for optimal fisheries management.

Firstly, when a non-renewable habitat is *preferred* and has a positive effect on the cost of harvest, any optimal steady-state fish stock identified by Clark and Munro's (1975) Golden Rule equation is no longer independent of the level of habitat. In fact, a high level of cold water coral abundance lowers the return on investment in the *in situ* fish stock implying a lower optimal fish stock compared to one at a depleted habitat level. Similarly, the identified optimal steady-state habitat level is dependent on the level of fish stock and represents a threshold boundary of habitat depletion beyond which it is optimal to cease all bottom trawling. *Optimum optimorum* values for the fish stock, the stationary gear harvest rate and the habitat stock can be identified at the point where both curves intersect. Depending on the starting position some bottom trawling may be optimal for some periods of time, i.e. the *optimum optimorum* habitat stock level is not necessarily found at a pristine level but depends largely on the identified *optimum optimorum* stationary gear harvest level.

Secondly, when a non-renewable habitat is *essential* and has a positive effect on the cost of harvest as well as on the biological growth of the renewable resource, the *optimum optimorum* will differ from the one implied by a *preferred* habitat. The shape of the curve identifying the optimal fish stock shows that a high level of cold water coral abundance may now imply a higher optimal steady-state fish stock level compared to one at a more depleted level. However, at a certain point the relationship is reversed, i.e. given the competing cost and growth effects the optimal steady-state fish stock level may increase or decrease for higher levels of habitat. The shape of the threshold boundary of habitat depletion, however, remains qualitatively the same as for the preferred habitat-fishery connection.

Our findings highlight the importance of identifying the exact habitat-fisheries connections of any commercial fishery as input to the debate of any future spatial closures. *Optimum optimorum* stock, stationary gear and habitat levels will vary according to the type of habitat-fishery connection (if there is one) and some bottom trawling may be optimal depending on the starting position of the industry. This information may provide guidance to the question as to what extent destructive fishing methods affect profits of other gear users in the same industry and how much of a given cold water coral stock should be protected if intrinsic values are not considered a priority. More importantly, we extend upon the results of bioeconomic models when destructive fishing methods, such as bottom trawling, violate the assumption of a constant environmental habitat that is non-renewable.

Further analysis should include aspects of the public value of cold water corals as people become increasingly aware of them, which will affect some of the findings in this study. It may also be more realistic to include a probabilistic function to

model the impact of bottom trawling on habitat depletion rather than assuming a constant deterministic effect. Undoubtedly, the complexities involved in the modelling of habitat-fishery interactions soon become analytically difficult to handle as more variables are added. However, our study shows that incorporating the endogenous effects of destructive fishing activity can have important implications for fisheries management.
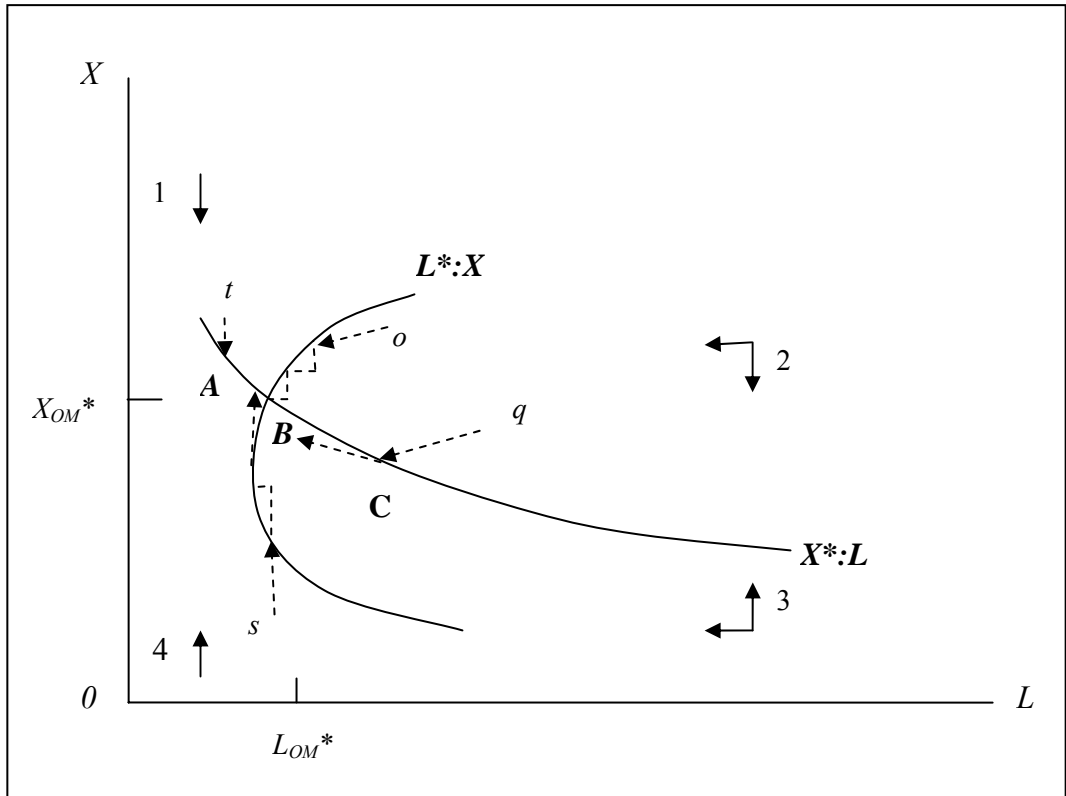
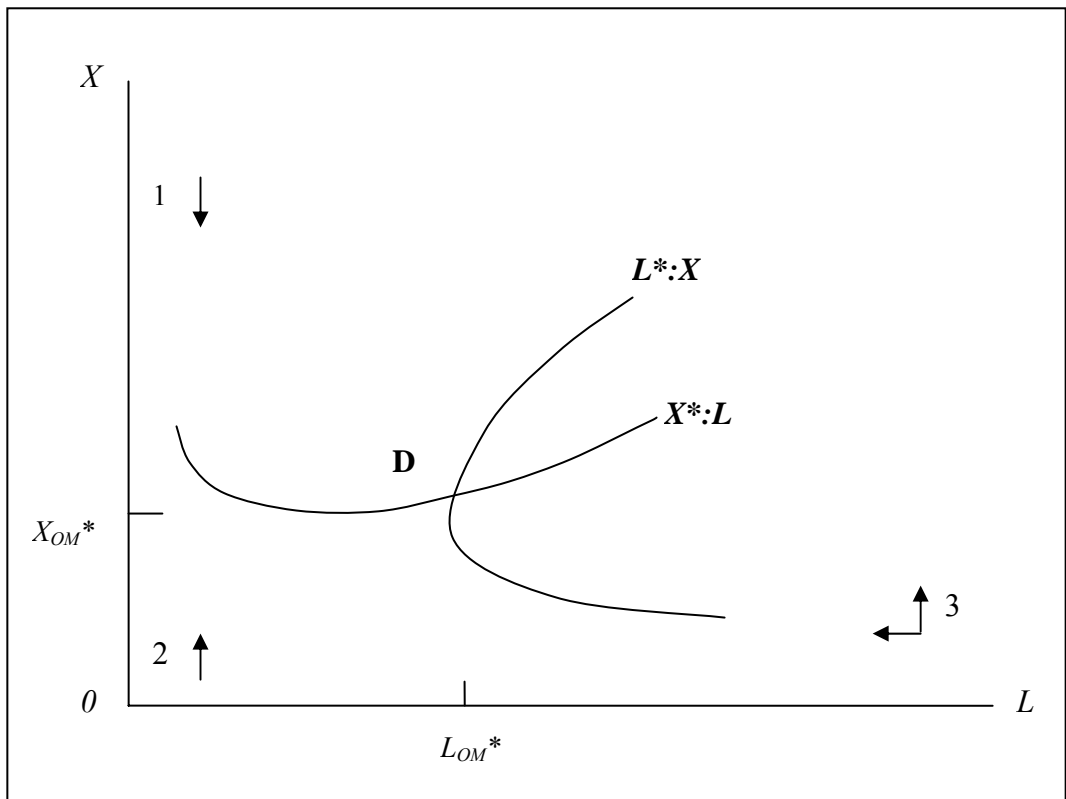Figure 1. Preferred habitat: steady-state analysis.

Figure 2. Essential habitat: steady-state analysis.

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