

**Bioeconomic study of a two agent fishery with  
consideration on the valuation of goods and  
services by cold-water corals**

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**Abstract**

This thesis makes four contributions on the economic analysis of fisheries in cold-water corals contained waters.

The first contribution is the proposal of theoretical framework on the links among cold-water corals, fauna fish species, fisheries, and public. The interactions among these four parts are illustrated in the framework.

The second contribution is the identification and classification of goods and services by cold-water corals. The work of identification and classification helps greatly on the understanding of importance of cold-water corals to the public.

The third contribution is the bioeconomic models on the interactions among the four parties. Two types of coral-fish connections are assumed, i.e. corals are preferred habitat to fauna fish species, or corals are essential habitat. Our modeling results reveal the existence of optimum optimum values of the public.

The last contribution is the steady-state analysis of both new models and original models. From the state space diagrams, we find that the optimal equilibriums and the movements can be readily identified. Through comparison of the new models and the original models, we find two theorems. The first theorem is that the optimal coral stock level in the new model is always increased, while the fish stock level is always decreased. The second theorem is that in the new model, the optimum optimum PVNB (Present Value of Net Benefit) for the all parties is always increased, while the optimum optimum PVNB for the fishery is always decreased.

Our research work reveals the importance of identifying goods and services by marine habitat, and linking them into fishery management. Our findings highlight the improvement of social benefits by taking goods and services values into economic consideration of habitat management.

**Keywords:** cold-water coral; fishery management; bioeconomic modeling; steady-state analysis; goods and services; ecosystem approach.

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## 1 Introduction

This thesis presents bioeconomic models and analysis with specific considerations on the linkage of habitat, fishery, and public. The habitat is providing services to the fisheries in two scenarios, preferred and essential (Kahui & Armstrong 2008). When the habitat is preferred, fisheries benefit from higher catchability thus lower cost via fish concentrates nearby habitat; when the habitat is essential, fisheries benefit further from higher growth rate of fish stocks. Meanwhile, the habitat is providing a number of goods and services to public. Cold-water corals are used as the example habitat of this thesis. Two types of fleets are involved in the fishery, stationary gear fleets and non-stationary gear fleets. Non-stationary gears fleets, i.e. bottom trawlers, which are highly efficient, cause damage as by-product (Kahui & Armstrong 2008). If habitat is altered by fishery (the trawlers), its contribution to fisheries and public are reduced. Economics modeling and analysis on the trade-offs of habitat depletion, fishery harvest, and public benefits are thus needed for the resource managers, decision makers, scientific and policy advisors.

Cold water corals have been known since the 18<sup>th</sup> century (Roberts et al. 2003, 2006). Though we have known cold-water coral for more than two centuries, extensive research only started in last decade, with the aid of acoustic survey techniques and submersibles (Freiwald et al. 2004, Roberts et al. 2006). Cold-water corals have existed for many thousands to millions of years (Mortensen et al. 2001, Roberts et al. 2006). Some living cold-water coral banks and reefs were found to be up to 8000 years old (Freiwald et al. 2004). Living in the dark, cold-water corals have no light-dependent symbiotic algae; current-transported particulate organic matter and zooplankton are their food (Freiwald et al. 2004). Cold-water coral family contains cnidarians encompassing stony corals (Scleractinia), soft corals (Octocorollia), black corals (Antipatharia), and hydrocorals (Stylasteridae) (Roberts et al. 2006). Soft corals (Octocorollia) includes gorgonian sea fans and bamboo corals,

which are the so-called “precious” corals (Roberts et al. 2006).

Corals are able to form arguably the most three-dimensional complex habitats in the deep ocean, which could be up to 300m high and several kilometers in diameter in many thousands to millions of years (Roberts et al. 2006). Corals are also observed individually in small patch reefs several meters across (Roberts et al. 2006). Researchers have found unexpectedly widespread and diverse of cold-water corals in fjords, along the edge of the continental shelf, and around offshore submarine banks and seamounts, of almost all the world’s oceans and seas in 41 countries so far (Freiwald et al. 2004, Roberts et al. 2006). The azooxanthellate coral *Lophelia pertusa* (L.) is known to occur in the north-east Atlantic, north-west Atlantic, Pacific, Indian Ocean, and Mediterranean Sea (Roberts et al. 2003, from various sources).<sup>1</sup> Note that the graphical distribution of cold water corals does not fully reflect the real distribution of cold-water corals; rather, it reflects the geographically varied levels of research activities (Freiwald et al. 2004, Roberts et al. 2006). Technical difficulties are still constraining further research. We still do not know much on the functional relationships between species and cold-water coral reefs (Roberts et al. 2006). The exact importance of cold-water coral reefs remains unclear (Roberts et al. 2006). However, new discoveries are continued being made. For example, Kellogg et al. (2009) make the first contribution to the study of associated bacteria of cold-water coral *L. pertusa* in the Northeastern Gulf of Mexico. New findings of cold-water coral distribution, ecology, and biology are expected in the future.

Modern fisheries management has been practiced since the early 1940s, with primary focuses on fishing activity and fish resources (Garcia et al. 2003). In marine ecosystems, due to difficulty of direct intervention on the ecosystem, controlling human intervention (primarily fishing) has been the management strategy emphasis (Garcia et al. 2003). Ecosystem manage-

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<sup>1</sup> For an overview of the world distribution of cold-water corals, please see (Freiwald et al. 2004, pp. 7).



ment has been formally introduced as a concept since at least 1967 (Czech & Krausman 1997, Beaumont et al. 2007).<sup>2</sup> It is “*a management philosophy which focuses on desired states rather than system outputs and which recognizes the need to protect or restore critical ecological components, functions and structures in order to sustain resources in perpetuity*” (Cortner et al., 1994, cited by Garcia et al. 2003). United Nations (1992) defines Ecosystem Approach as “*Ecosystem and natural habitats management... to meet human requirements to use natural resources, whilst maintaining the biological richness and ecological processes necessary to sustain the composition, structure and function of the habitats or ecosystem concerned. Important within this process is the setting of explicit goals and practices, regularly updated in the light of the results of monitoring and research activities.*” The term Ecosystem Approach is usually used in the form of “ecosystem approach to ...” (Garcia et al. 2003), for example, the ecosystem approach to fisheries (EAF) in this thesis. EAF is “*an extension of conventional fisheries management recognizing more explicitly the interdependence between human well-being and ecosystem health and the need to maintain ecosystems productivity for present and future generations, e.g. conserving critical habitats, reducing pollution and degradation, minimizing waste, protecting endangered species*” (Ward et al., 2002, cited by Garcia et al. 2003).

Ecosystem can be viewed as capital assets (Daily et al. 2000). If they are properly managed, ecosystems can produce a flow of vital services (Daily et al. 2000). However, the importance of ecosystem services is often widely appreciated after their loss (Daily et al. 2000). Cold-water corals are not in the exception. A number of literature have contributed to the identification goods and services, e.g. by natural and semi-natural ecosystems (De Groot et al. 2002, Fischlin et al. 2007), by marine biodiversity (Beaumont et al. 2007), by mangrove forests (Ewel et al. 1998), by water resources (Jewitt

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<sup>2</sup> The idea of ecosystem management was expressed as “microcosm” as early as in 1887 (Schultz 1967).

2002). Moberg & Folke (1999) identify ecological goods and services by warm-water coral reef ecosystems, which is so far the only work on the identification of goods and services by (warm-water) coral ecosystems. Due to the apparent distinctions between cold-water corals and warm-water corals (Freiwald et al. 2004), it is necessary to carry out a study on the identification and classification of goods and services by cold-water corals.

This thesis first proposes a theoretical framework on the connections among cold-water corals, fauna fish species, fishery, and public. Then we adopt the classification scheme of goods and services by Beaumont et al. (2007), implement it with research into scientific literature (mainly biological and ecological literature from peer-reviewed journals), and identify and classify the goods and services by cold-water corals. In our work, 11 goods and services by cold-water corals are identified and classified. A note on the non-use values of cold-water corals is also given.

Kahui & Armstrong (2008) propose bioeconomic models and analysis on the cold-water corals, fauna species, and fishery interactions. Comparing with their methods, we realize that to model our theoretical framework, we need to first separate the indirect use value to fishery from other goods and services by cold-water corals, then add an extra valuation factor, which is a function of cold-water coral stock level, into the modeling. Our new models reveal the importance of taking goods and services values into consideration during the planning and management of a fishery in cold-water corals contained waters.

In the following chapters, we first propose the theoretical framework in Chapter 2. Then, we collect secondary data to identify and classify goods and services by cold-water corals in Chapter 3. Since the coral-fish connections are assumed in two types. Chapter 4 proposes our bioeconomic models under the preferred habitat scenario, which Chapter 5 proposes the bioeconomic models under the essential habitat scenario. Chapter 6 presents a detailed analysis and discussion on the new models; two new theorems are proposed

in this chapter. Finally, we present conclusions of our work and thoughts on further research work in Chapter 7.

## 2 Theoretical framework

Cold-water corals are long-lived but fragile deep-water sea-floor habitat (Freiwald et al. 2004). Global evidence has shown that bottom trawling for deep-water fish species has caused severe damage to cold water corals (Roberts et al. 2006, Freiwald et al. 2004). It is estimated that 30% to 50% of Norway's cold-water coral are lost (Fosså et al. 2002). At some sites, cold-water coral reefs have been completely wiped out (Fosså et al. 2002). Koslow et al. (2001 in Roberts et al. 2003) find that trawling has depleted seamount fauna off Tasmania. It is suggested that trawling has scarred the Atlantic Frontier region with marks (Hall-Spencer et al., 2002; Roberts et al., 2002; Bett, 2000b in Roberts et al. 2003). Roberts et al. (2003) also suggest that in the UK territorial waters, cold-water coral habitats have already been reduced by trawling activities substantially.

Gill-net and long-line gear users, a.k.a. the stationary gear users (Kahui & Armstrong 2008), have been laying their nets close to cold-water corals to have higher harvest (Mortensen et al. 2001). However, they do not place their gears direct over cold-water corals reefs, in order to avoid potential damage or lost to their equipments (Fosså et al. 2002). Thus stationary gear users have had minimal effects on cold-water coral reefs, though instances of coral harvest or damage occurred occasionally (Fosså et al. 2002, Kahui & Armstrong 2008).

Meanwhile, stationary gear users, i.e. trawlers in this thesis, are found to use their gear, wires, chain, and trawl doors to crush the cold-water corals to clear the area from fishing starts, as scientific research and anecdotal reports have suggested (Fosså et al. 2002, pp. 1), as quoted below:

*'Moderate damage probably occurred when the first small bottom trawls started, but the degree of impact probably changed dramatically with the development of larger vessels with powerful trawls, e.g. rockhopper gear, adapted to operate on rough stony bottoms*

*and coral reefs.'*

The goods and services by cold-water corals directly or indirectly contribute to the human society. Thus, while corals are depleted, the society will lose a certain amount of value. The reduction of cold water coral can be seen as externalities to those who have interests on corals, as quoted below:

*"... destructive harvesting by bottom trawls could then potentially reduce both non-use and use value, the former via loss of existence values, the latter by bottom trawling potentially reducing future harvests through destruction of essential or preferred habitat for commercial species or their prey, as well as through the reduction of fish stocks."* (Armstrong & Falk-Petersen 2008, pp. 3)

Cold-water corals grow at an annual rate of 0.5 to 2.5 cm (Freiwald et al. 1999). Because of its slow growth rates, cold-water corals are considered as non-renewable resource in a time-scale relevant content to commercial exploitation (Kahui & Armstrong 2008). For the already caused severe damages, it will take hundreds or thousands of years to fully recover (Roberts et al. 2006, Freiwald et al. 2004).

One consequence of the severe depletion of cold-water corals is the decrease of catches from previously cold-water corals contained waters (Fosså et al. 2002). In 1990s at Norway, long-line and gillnet fishermen contacted the Institute of Marine Research to express their concerns about the effects of trawling on cold-water corals reefs that catches in the areas, where previously covered cold water coral reefs had disappeared from trawling grounds, are lowered, and the potential function of the reefs as nursery areas for fish are gone (Fosså et al. 2002). Other consequence of cold-water coral depletion is the potential ecological effects, which may be substantial (Fosså et al. 2002).

Jackson et al. (2001 in Roberts et al. 2003) suggest that the effects of fishing activity have heavily biased our present day understanding of the marine environment. This quote expresses well biologists' concern on the lost of cold-water corals:

*“Given the paucity of baseline information and the difficulty and expense of wide-area survey in these environments, it is unlikely that the extent and significance of this damage will ever be fully appreciated.”* (Roberts et al. 2003, pp. 17)

It is urgent to raise long-term cold water coral management plans (Roberts et al. 2006). Several nations, including Canada, New Zealand, Norway, UK, and USA, have closed cold-water coral habitats to bottom fishing (Kahui & Armstrong 2008, Roberts et al. 2006). This quotation, from Elliot Morney, Minister for Environment and Agri-Environment, Defra, UK, well represents governments’ responses:

*‘Cold water corals are vitally important ecosystems, with immense biodiversity value; a treasure that must be preserved for future generations. The UK has secured a permanent ban on bottom trawling over Lophelia pertusa cold-water coral reefs in the Darwin Mounds through action at European Community level. However, further international cooperation is needed to conserve vulnerable marine ecosystems in areas beyond national jurisdiction.’*  
(Freiwald et al. 2004, pp. 4)

The other quotation, from Claude Martin, Director of General, WWF International, presents NGOs’ consideration on conservation of cold-water corals comparatively:

*‘At last, advanced science and world leaders recognize that the oceans’ resources are finite and now require thoughtful stewardship and intelligent management. We call upon government and industry leaders to take urgent action to conserve the spectacular and unique ecosystems of cold-water coral reefs.’* (Freiwald et al. 2004, pp. 4)

Another quotation, from two economists, presents their concerns on the point view of fishery management:

*'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.'* (Kahui & Armstrong 2008, pp. 5)

Therefore, we propose a framework on aggregating costs and benefits of cold-water corals to fishery and public (Figure 2.1). Point 4 and Point 6 demonstrate the consequences of damaging cold-water corals to the public and fisheries.

Note that Figure 2.1 itself is an extended model of Armstrong & Falk-Petersen (2008, pp. 2). For the “*missing link*” described in Armstrong & Falk-Petersen (2008), Kahui & Armstrong (2008) have developed new bioeconomic models to address the interactions among fisheries and cold-water corals explicitly.

Kahui & Armstrong (2008) apply bioeconomic models to evaluate effects of cold-water coral depletion to the fishery as endogenous factor. Their study reveals the externalities to non-stationary gear fishers and other compatriots' activities by non-stationary fishers' harmful fishing practices to cold-water corals (Armstrong & Falk-Petersen 2008). Because the exact biological and ecological roles of cold-water corals to fishery remains unclear (Roberts et al. 2006, Armstrong & Falk-Petersen 2008), Kahui & Armstrong (2008) assume two types of habitat interactions, preferred habitat and essential habitat. In the preferred habitat scenario, cold-water corals attract and aggregate commercially important fish species, such as redfish; while in the essential habitat scenario, cold-water corals not only attract and aggregate fish species and their fauna, but also affect their production and/or survival.

By simultaneously solving a system of differential equations and draws on the renewable resources by Clark & Munro (1975), the optimal extrac-

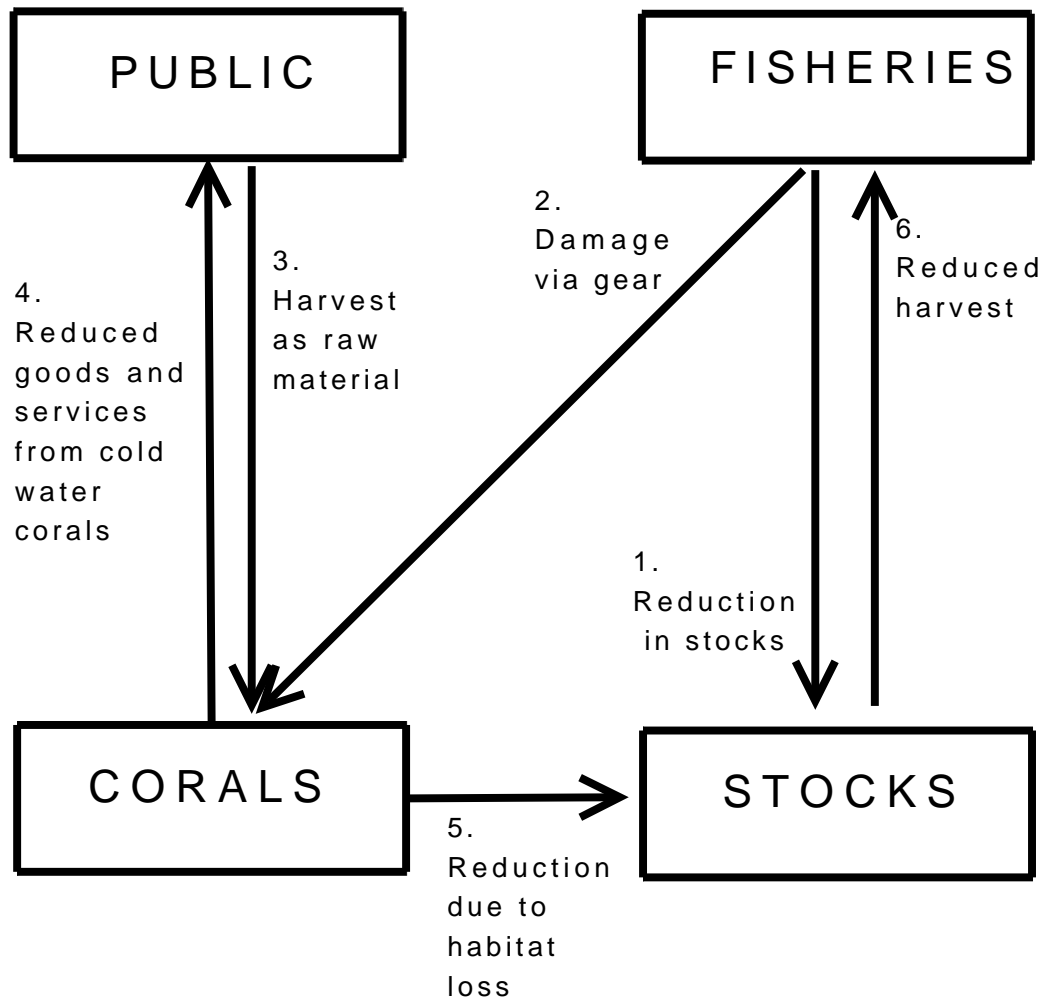


Fig. 2.1: Links among cold-water corals, fauna fish, fisheries, and public



tion path of non-renewable resources by Hotelling (1931) and Swallow (1990) analysis of interactions between a renewable and a non-renewable resource through the growth function of the renewable resource, the analyses carried out by Kahui & Armstrong (2008) show that when the habitat and fishery interact, optimal steady-state fish stock and habitat stock are interdependent, and *optimum optimum* values can be identified for the fish stock, the habitat stock, and the stationary gear harvest rate, for both preferred habitat and essential habitat scenarios (Kahui & Armstrong 2008). Their results indicate that though *optimum optimum* values of the fish stock, habitat stock, and stationary gear harvest rate can be found in both scenarios, the optimal steady-states will differ according to different assumptions of habitat interaction (Kahui & Armstrong 2008).

Kahui & Armstrong (2008) find that *optimum optimum* habitat level may not be the pristine level. Their finding suggests that for the maximization of resource rent, it may not be necessary for policy makers to close cold water corals at their pristine level, that bottom trawling may be optimal for a while in the beginning. When the optimal fish stock size and habitat stock size have been achieved, destructive gear fleets shall be ceased to preserve the habitat stock.

Before we start modeling the interactions among four parties, as shown in Fig. (2.1), it is essential to prove the importance of the goods and services by cold-water corals. Therefore, identification and classification on cold-water coral goods and services is needed.

## 3 Goods and services from cold-water corals

### 3.1 Introduction

Decisions from policy makers are often made after estimating net benefits of exploitation, degradation, or consumption of environmental goods are greater, while much evidence suggests that this may not always be the case (Barbier 1993). To ensure fishery decision making is sustainable, efficient, and equitable, it is essential that all social, economic, and environmental impacts, both short and long run, are identified and measured (Daily et al. 2000, Beaumont et al. 2007). We need to identify and define goods and services from cold-water corals (Daily et al. 2000). The utilization of concept of ecosystem goods and services is also required by the Ecosystem Approach, to ensure the integration of social, economic, and environmental demands and pressures (Beaumont et al. 2007). We need the assessment of ecological processes and resources of cold-water corals in monetary valuation to analyze the optimal management of fishery and cold-water corals.

We define goods and services from cold-water corals as “the direct and indirect benefits people obtain from cold-water corals”. This definition is derived from the definition of goods and services from marine ecosystem in Beaumont et al. (2007), which is “*the direct and indirect benefits people obtain from ecosystems*”. The purpose of the following study is to translate the complexity of cold-water coral ecosystem into series of functions, which can be better understood (Beaumont et al. 2007), and the enable a true understanding of exactly what is being gained and lost when exploitation takes place (Holmlund & Hammer 1999, Borgese 2000, Beaumont et al. 2007).

### 3.2 Background

Habitat preservation is important to biologists, ecologist, environmentalists, and even the public; this is reflected in the legislation of some countries (Bulte

& van Kooten 1999). Economists are also concerned about habitat conservation, but they're interested in making sure that economic efficiency is taken into account (Swallow 1990, Bulte & van Kooten 1999, Armstrong & Falk-Petersen 2008, Kahui & Armstrong 2008). The efficiency criterion requires that one knows not only the bio-ecological attributes of the habitat (e.g. biological function, ecological function, whether it is vital to its fauna), but also its monetary and non-monetary costs and benefits. The economic efficiency evaluation of habitat preservation is similar to the economic efficiency evaluation of species preservation (Bulte & van Kooten 1999). The service functions of these habitats indirectly to the support of economic activity and property may offer more benefits, e.g. flood control, storm prevention and groundwater recharge functions of wetlands (Barbier 1993). To achieve economic efficiency, both market (harvest) and non-market (use and non-use) values are required to be included, for the calculation of optimal stock levels and harvest levels (Bulte & van Kooten 1999). Goods and services approach provides a sound media for the measurement of both market and non-market values by ecosystems (Beaumont et al. 2008).

Ecosystem services can be difficult to understand (Lewan & Söderqvist 2002). It is explicit in Ecosystem Approach on the need of a holistic approach to identify and measure of all social, economic, and environmental impacts of a development (Daily et al. 2000, Beaumont et al. 2007). In 1992, during the Earth Summit in Rio, the term "Ecosystem Approach" was first adopted as an understanding concept of the Convention on Biological Diversity (Laffoley et al. 2004, Beaumont et al. 2007). The Ecosystem Approach now plays an important role in environmental policies (Laffoley et al. 2004, Beaumont et al. 2007). For example, the UK Government has accepted the Ecosystem Approach as a basis of its Marine Stewardship process; strong commitments of implementing Ecosystem Approach have been shown in the reformed Common Fisheries Policy of The European Union (Laffoley et al. 2004). One approach to ensure the integration of social, economics, and envi-

ronmental demands and pressures, as required by the Ecosystem Approach, is to apply the concept of ecosystem goods and services (Beaumont et al. 2007).

Beaumont et al. (2007) present goods and services by marine biodiversity in a concise fashion with user friendly definitions. In their research work, seven case studies were carried out. The classification scheme, which Beaumont et al. (2007) adopt, divides goods and services into four categories. A range of goods and services are identified in each category. Beaumont et al. (2007) aggregate option use values as one good or service. Option value is the value of currently unknown potential usages (Beaumont et al. 2007). Option value reflects the importance of more uses being discovered in the future. Weisbrod (1964) makes first contribution of “*suggesting that the set of values be expanded to a larger set than current users*” (Carson et al. 1999). He premises that an individual may be willing to pay for an asset to retain it for their future use, as “option value”, e.g. a park (Cummings & Harrison 1995). Weisbrod (1964) further suggests that an individual may be willing to pay for an asset, which he may not wish to use at all, e.g. hospital (Cummings & Harrison 1995). Note that the “option value” in Weisbrod (1964) is a use-related concept (Greenley et al. 1981, Cummings & Harrison 1995). Hence, Beaumont et al. (2007) include option value as use values.

Prior to the work of Beaumont et al. (2007), De Groot et al. (2002) identified and classified the functions, goods, and services of natural and semi-natural ecosystems.<sup>3</sup> A total of 23 functions are identified and classified. Each function is explained by its ecosystem processes and components. Goods and services of each function are given as examples. Note that all the 23 functions are classified in four categories: *i*) regulation functions; *ii*) habitat functions; *iii*) production functions; and *iv*) information functions.

Comparing with Table ??, we can see that the category “Regulation func-

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<sup>3</sup> The detailed results of their work can be found at pp. 396 – 397 in De Groot et al. (2002).

tions” and category “Production functions” are the same in both studies, while the “Culture services” in Beaumont et al. (2007) is one of the listed functions of “Information Functions” in De Groot et al. (2002) and the “habitat functions’ in De Groot et al. (2002) are labeled as “Over-arching support services” in the study of Beaumont et al. (2007). Note that, the “Option use value” was not included in the De Groot et al. (2002) study.

Now let’s see another study, which is the “Ecological goods and services of coral reef ecosystems” by Moberg & Folke (1999). Note that the “coral reef” in their study are referred to warm-water corals, which prefer temperatures from 20°C to 29°C and grow at depths from 0m to 100m (Freiwald et al. 2004).<sup>4</sup> Moberg & Folke (1999) adopt three levels of categorization to sort their findings.

Comparing with the results by Beaumont et al. (2007) and De Groot et al. (2002), we can see that

1. The results of goods and services will be more explicit, when analysis is carried out on a specific ecosystem;
2. The general analysis of goods and services of ecosystems, i.e. natural and semi-natural ecosystem by De Groot et al. (2002), marine biodiversity by Beaumont et al. (2007), have produced results of ecosystem goods and services, which can be used as guidance for specialized studies in for specific ecosystems.

Shall we expect the same explicitness of results from the research of goods and services by cold-water corals?

### 3.3 Methodology

Our research work attempts to refine previously defined approaches to goods and services (Moberg & Folke 1999, De Groot et al. 2002, Beaumont et al.

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<sup>4</sup> Detailed comparisons on cold-water corals and warm-water corals can be found at pp. 11 of Freiwald et al. (2004).

2007), to identify and define the goods and services provided specifically by cold-water corals. The results of this work is shown in Section 3.4.

All the information used in this part of research is secondary. We collect them from published scientific literature, mainly from biological and ecological literature on cold-water corals (e.g. Freiwald et al. 1999, Mortensen et al. 2001, Fosså et al. 2002, Grigg 2002, Roberts et al. 2003, Freiwald et al. 2004, Baco & Shank 2005, Roberts et al. 2006), with references of other studies or usages to support our findings (e.g. Barbier 1993, Bingham et al. 1995, Borgese 2000, Asafu-Adjaye & Tapsuwan 2008).

### 3.4 Results

Different methods for categorizing goods and services have been developed along the advancing of scientific research progress (Costanza et al. 1998, Ewel et al. 1998, Moberg & Folke 1999, Holmlund & Hammer 1999, De Groot et al. 2002, Beaumont et al. 2007). This thesis follows the over-arching classification by Beaumont et al. (2007, pp. 256) and divides goods and services into four categories: “*i) Production services are products obtained from the ecosystem; ii) Regulating services are the benefits obtained from the regulation of ecosystem processes; iii) Cultural services are the nonmaterial benefits people obtain from ecosystems; iv) Supporting services are those that are necessary for the production of all other ecosystem services, but do not yield direct benefits to humans.*” Table 3.1 shows the finding of our results upon goods and services by cold-water corals. Our results cover direct use values (e.g. the values derived from the direct use or interacting with cold-water corals’ resources and services), indirect use values (the direct support and service-provided to economic activity by cold-water corals’ natural functions), and non-use values (the values derived neither from current direct or indirect use of the cold water corals) (Williams 1990, Barbier 1993) of cold-water corals.

Tab. 3.1: Goods and services provided by cold-water corals

Category	Good or service
Production services	1 Food provision
	2 Biodiversity function
	3 Speciation function
	4 Function as paleoclimatic archive
	5 Biogeological function
	6 Raw material for jewelry
Regulation services	— —
Cultural services	7 Non-use value
Option use value	8 SCUBA diving destination
	9 Submarine tourism destination
Over-arching support services	10 Indirect use value for fishery
	11 Biogeographic function

### 3.4.1 Food provision

**Definition** The extraction of marine organisms for human consumption, as indirect benefits to the public via direct functions and services to the benthic fauna.

A number of commercially important fishes are observed on cold-water corals (Freiwald et al. 2004). Although “*we understand little of the functional relationships between species on cold-water coral reefs, and the reefs’ importance as a fish habitat is unclear*” (Roberts et al. 2006, pp. 545), we have reasons to assume that cold-water corals play important biological and ecological roles in the growth of these species (Freiwald et al. 2004, Fosså et al. 2002, Roberts et al. 2006, Armstrong & van den Hove 2008, Kahui & Armstrong 2008).<sup>5</sup>

<sup>5</sup> See (Freiwald et al. 2004, pp. 25) for a list of commercially important fish species, which are found near cold-water corals.

### 3.4.2 Biodiversity function

**Definition** Function provided by cold-water corals for the biodiversity of the benthic fauna.

Cold-water coral ecosystems are important biodiversity hot spots in the deep ocean (Freiwald et al. 1999, 2004). Cold-water corals provide niches for many species as arguably the most three dimensionally complex habitats in the deep ocean (Fosså et al. 2002, Roberts et al. 2006). More than 1300 species have been found living on *L. pertusa* reefs in the Northeast Atlantic (Roberts et al. 2006). In the Gulf of Mexico, *Lophelia* reefs are also found to provide an important complex habitat for a wide variety of fishes, crustaceans, and other invertebrates (Reed, Weaver, and Pomponi 2006 in Kellogg et al. 2009). It is clear that scattered *L. pertusa* habitats support many associated species, from scattered groups of colonies to vast reef complexes (Roberts et al. 2003). Roberts et al. (2006) suggest that the biodiversity of cold-water coral reefs may be comparable to that found on warm-water coral reefs.

### 3.4.3 Speciation function

**Definition** Speciation service provided by cold-water corals for the benthic fauna.

Evidence indicates that cold-water corals may be important speciation centers in the deep sea (Roberts et al. 2006). Species endemism in the studied seamounts have found to be high (Roberts et al. 2006). For example, about 34% of species on Southwest Pacific seamounts were newly discovered and potentially endemic (Roberts et al. 2006). Because cold-water corals are frequently found in seamounts, cold-water coral reefs may be major speciation centers (Roberts et al. 2006).



#### 3.4.4 Function as paleoclimatic archive

**Definition** The use value of cold-water coral skeletons as paleoclimatic archive.

Evidence has shown that cold-water corals have recorded oceanic shifts in their skeletons accurately (Roberts et al. 2006, Goldstein et al. 2001). Scandinavian cold-water coral reefs in northern Europe have ~10,000 to 14,000 years history, dating back to the Holocene after the retreat of Pleistocene ice sheet (Roberts et al. 2006). By using uranium-series and radiocarbon measurements, age of cold-water corals and age of the inorganic carbon in seawater can be estimated (Goldstein et al. 2001). Researchers have started using cold-water corals to study ventilation histories in North Atlantic (Adkins et al. 1998, Schröder-Ritzrau et al. 2003) and Southern Ocean (Goldstein et al. 2001).

#### 3.4.5 Biogeological function

**Definition** The biogeological use value of cold-water corals as information archives of the interactions between the Earth's biosphere and the lithosphere.

Please see Roberts et al. (2006, pp. 545) for an detailed presentation on the biogeological function of cold-water corals.

#### 3.4.6 Raw material for jewelry

**Definition** The use value of cold-water coral skeletons as raw material for jewelry.

Another direct use value of cold-water corals, though it may controversial to be listed as a value, it however reflects the other aspect of direct use value from cold-water corals. So-called 'precious corals', i.e. octocoral *Corallium secundum* and *Corallium lauense* of the Family Coralliidae, and hexacoral *Gerardia sp.* of the Family Gerardiidae, are being harvested for the jewelry

industry (Baco & Shank 2005). Among these three cold-water coral species, *C. lauense* or 'red coral' is the most valuable and may be sold at a price of US\$ 880 per kilogram (Grigg 2002, Baco & Shank 2005). The harvest of these cold-water coral species, are considered as a threat to the corals as well, making it potentially ambiguous assigned as one of direct use values of cold-water corals.

The reason of marking cold-water coral harvest by jewelry industry as direct use value is potentially controversial, is that the harvest activity has degraded and depleted coral stock, which is important part of benthic ecosystem (Roberts et al. 2006, Baco & Shank 2005, Grigg 2002).

#### 3.4.7 Non-use value

**Definition** Non-market, intangible values which people derive from preservation of cold-water corals (derived from Cummings & Harrison 1995, Oglethorpe & Miliadou 2000)

Armstrong & Falk-Petersen (2008, pp. 3) suggest that “*a charismatic habitat such as cold-water coral may give non-use or existence values, purely through the public valuation of these fascinating structures, although the general public may never actually observe the resources directly*”. And Cummings & Harrison (1995) suggest that for some individual users, non-use values surely exist. The only known valuation effort on the non-use values of cold-water corals was the mail survey in Ireland. Though 500 respondents of 5000 households were “*strongly in favour of protection, the average willingness to pay was 0 euro*” (Kahui & Armstrong 2008, pp. 9). However, if the reader notes that only 20% of these 500 respondents had heard about cold-water corals (The survey was conducted under the scheme of PROTECT, 2002–2006.), she/he may also wonder if the survey was conducted now, would there have been positive willingness to pay values? An additional note is given in Section 3.5.

### 3.4.8 SCUBA diving destination

**Definition** Optional use value of cold-water coral reefs as SCUBA diving destination.

Asafu-Adjaye & Tapsuwan (2008) have studied the use value of tropic coral reefs of Mu Ko Similan Marine National Park, Thailand as destinations of divers. Their work reveals that divers are willing to pay about US\$ 27.07 - 62.64 per person per annum on average (Asafu-Adjaye & Tapsuwan 2008). That is an aggregate benefits of between US\$ 932,940 to US\$ 2.1 million per annum (Asafu-Adjaye & Tapsuwan 2008). Though the tropical coral reefs, which are studied by Asafu-Adjaye & Tapsuwan (2008), are described as '*deep water corals*' in their text, growing at a 300m depth beneath the ocean surface; cold water corals are adapted to the lower temperature between 4textdegreeC to 12textdegreeC, at the depth between ~50m to 1000m at high latitudes, and at greatest depth (up to 4000 m) beneath warm water masses at low latitude (Roberts et al. 2006). Currently there isn't any use value of cold water corals as tourism destination. However, since there are some cold water SCUBA diving activities in lakes, at the depth of from 15.2 m to 44.8 m(Gerriets et al. 2000), cold-water corals at high latitudes may possess potential use value as tourism destination for divers.

### 3.4.9 Submarine tourism destination

**Definition** Optional use value of cold-water coral reefs as submarine tourism destination.

The other potential use value is the submarine tourism in cold-water coral contained water. A tourist, who enjoys submarine trips under water (Orams 1999, Rosenbaum & Spears 2005, Stolk et al. 2007), may in the future be longing to see cold-water corals in submarines as well. For example, in a research on the cross-cultural differences in services consumption among US, Japanese, Canadian, Chinese, South Korean, and Australian/New Zealand, Rosenbaum & Spears (2005) reveal that a significant portion of tourists in

Hawaii are interested in boat/submarine tours.

#### 3.4.10 Indirect use value for fishery

**Definition** The indirect use values of cold-water corals to fishery, through their direct biological and ecological functions to commercially important fish species.

Cold-water coral contained waters have traditionally been important fishing grounds (Fosså et al. 2002, Mortensen et al. 2001). Gil-netters and longliners have been seeking to position their gears close to the *L. pertusa* reefs to achieve higher catches off Mid-Norway for many years (Mortensen et al. 2001). Although it is not specified in their literature, Kahui & Armstrong (2008) has identified and interpreted the economic value of cold-water corals' indirect use value to fishery by bioeconomics models, while making their first contribution to bioeconomic literature by analyzing the endogenous habitat-fishery connection with the destructive fishing methods, where cold-water corals are considered as the example. The connection of habitat and fishery is made through the effects of cold-water coral habitats to commercially important fish species, in both preferred and essential scenario. These effects are part of the contributions of biological and ecological functions (Freiwald et al. 1999, Fosså et al. 2002, Freiwald et al. 2004, Roberts et al. 2006) of cold-water corals. Thus, besides its indirect value to fishery, attentions are needed for other values of habitat in fishery management (Eggert 1998).

#### 3.4.11 Biogeographic function

**Definition** The biogeographic function of cold-water corals to their fauna.

Henry & Roberts (2007, pp. 662 – 663) suggest “*that the widespread distribution of corals, reefs and mounds on the European continental shelf and slope could also have significant consequences for the biogeography of deep-water faunas with more dispersal*”. The contribution to biogeography

of the deep ocean (Taviani et al. 2005, Roberts et al. 2006) from cold-water corals need to be valued as well.

### 3.5 A note on non-use values of cold-water corals

We define the non-use values<sup>6</sup> by cold-water corals as “non-market, intangible values which people derive from preservation of cold-water corals”. (derived from Cummings & Harrison 1995, Oglethorpe & Miliadou 2000). Non-use values are motive-related values (Cummings & Harrison 1995). Because cold-water corals live at depths between ~50m to 1000m at high latitudes, and at greater depth (up to 4000 m) beneath warm water masses at low latitudes (Roberts et al. 2006), they are far away from people’s daily life. Note that researchers have found that users tend to offer higher valuation than non-users (e.g. (Greenley et al. 1981, Hanley et al. 1998); however, for cold-water corals, there aren’t many users currently. Hence, non-use values of cold-water corals are likely the more important non-market values than indirect use values (Bulte & van Kooten 1999).

Non-use values include existence value, bequest value, quasi option value, intrinsic value, and altruistic value. Existence value is derived from the satisfaction of knowing that cold-water corals are well preserved, even if people never experience or utilize cold-water corals (Beaumont et al. 2007, Loomis & White 1996). Krutilla (1967) was the first scholar to propose the existence value. He argues that non-users may place a value on the mere existence of some assets (Cummings & Harrison 1995). Bowers (1997) has also given a definition on the existence value. This quotation well presents how public raise their interests and receive benefits from the existence of cold-water corals:

“The considerable importance which the wider public attention to

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<sup>6</sup> Non-use values are sometimes referred as passive-use values (Carson et al. 1999). The term “Passive-use value” was adopted in the 1989 US Federal Court of Appeals decision in *Ohio v. US Department of Interior* (Carson et al. 1999).

maintaining diverse marine life is revealed through their interests in marine based media presentations, such as the ‘Blue Planet’. In addition, articles on cold water corals frequently appear in the media, despite the fact the majority of the general public will never see a cold water coral, they are interested in them and benefit from their existence.” (Beaumont et al. 2007, pp. 258)

Bequest value is what current generation receives from knowing preservation today cold-water corals to future generations (Loomis & White 1996). Krutilla (1967) also makes the first contribution of proposing bequest value. He suggests that non-users may possess “bequest” motivations on some assets (Cummings & Harrison 1995).<sup>7</sup> Other non-use values may also be included, e.g. quasi option value (Dixon & Sherman 1990), intrinsic value (Turner et al. 1994), and altruistic value (Bowers 1997).

Researchers have found significant non-use values in their studies. For example, by using choice experiments, Hanley et al. (1998, pp. 424) find non-users give positive valuations on landscape improvements. In their study of recreation and water quality, Greenley et al. (1981, pp. 667) find that about 20 percent of the households who do not utilize the river for recreational activities are *“willing to pay an average of \$25 annually for the knowlege of the existence of the natural aquatic ecosystem and \$17 annually to bequest clean water to future generations, for a total non-user value of \$42 annually”*. Oglethorpe & Miliadou (2000) find that a total non-use value of £3347 in their sample population, which turns out to be an estimated £28.3 million for the whole Macedonia, suggesting non-use values as a potential public funding for the sustainable management of the resource. Armstrong et al. (2008) convert the existence value of seabirds (exchange rate of January 2008) from the study of Green et al. (1994), and estimate an existence value of NOK 49.6 million for the seabirds in the Lofoten-Vesterålen area.

It is of importance to carry out more case studies on the non-use values

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<sup>7</sup> Turner & Brooke (1988) has also given their own definition of bequest value.

of cold-water coral, as the importance of non-use values have been realized in both scientific community and legitimacy in some countries. The 1980 Comprehensive Environmental Response, Compensation and Liability Act (CERCLA) and the 1990 Oil Pollution Act of the United States suggest that non-use values can be added in the determinations of damages that are compensable (Cummings & Harrison 1995). Weisbrod (1964 in Cummings & Harrison 1995) argues that the “optional value” should influence the decision making process. Oglethorpe & Miliadou (2000) suggest that in the case of wetlands, if non-use values are ignored, the total economic value can be severely undervalued; the consequence would be the inadequate resource management, inappropriate commercial exploitation, and thus environmental degradation.

Then, let’s go back to our question: if the survey (see Section 3.4.7) was conducted now, would there have been positive willingness to pay values? Let’s be more specific, that:

- Are people benefited from knowing existence of cold-water corals (the existence value)?
- Will people be willing to pay to retain of cold-water corals for future generations (the bequest value)?
- Are general public and decision makers aware of the loss of cold-water corals and the potential consequences, though we don’t currently know (the quasi option value)?
- Do people hope cold-water corals to be untouched (the intrinsic value)?
- Will some of the users (direct or indirect beneficiaries) of cold-water corals be willing to keep cold-water corals for the sake of others (the altruistic value)?

The answers are certainly yes to some people, as we have seen the rapid progress in the education and public advocacy on the cold-water corals (e.g.

Freiwald et al. 2004, Beaumont et al. 2007). To scientifically identify and quantify these non-use values, further research work is essential.



## 4 Bioeconomic modeling under preferred habitat scenario

To analyze the interacting processes among cold-water corals, fish stocks, fisheries, and public, we adopt bioeconomic modeling to derive optimal fish stock and harvest rates. Conventional bioeconomic literature (e.g. Clark & Munro 1975, Clark 1976, Munro 1979, Clark 1990, Munro 1992) assume a constant habitat quality, i.e. the fishing has no effect upon habitat at all.<sup>89</sup> However, as we have discussed in the prior text, that the practice of bottom trawling has caused irreversible damages to cold-water corals, resulting in significantly lowered catches in previous cold-water coral contained waters. It seems essential to plug the habitat-fish linkage into bioeconomic modeling of the links in Figure 2.1. Two types of coral-fish connections are assumed, preferred and essential (Kahui & Armstrong 2008).

In the preferred coral-fish connection scenario, no biological connection exists between cold-water corals and the fauna fish species; fishes tend to gather around corals, hence the harvest in coral contained waters is increased, resulting in a reduced harvest cost per unit catch. Since no biological connection exists, we adopt the standard Schaefer (1957) model in the preferred habitat scenario. The population dynamics are shown as below

$$\frac{dX}{dt} = F(X) - h_1 - h_2, \quad (4.1)$$

where  $h_1$ ,  $h_2$ , and  $x$  are the harvest rate and the population biomass at time

<sup>8</sup> There are some bioeconomic literature, which accounts habitat into modeling; for a selected review, see (Knowler 2002).

<sup>9</sup> Some bioeconomics literature have analyzed fishery under habitat constraints, while, however, the habitat does not interact, i.e. the environment itself doesn't alter or be altered. See Sanchirico & Wilen (1999) for example.

$t$ , and  $F(X)$  is the natural growth function of the *in situ* fish species, that

$$F(X) > 0 \quad (0 < X < K) \quad (4.2)$$

$$F(0) = F(K) = 0 \quad (4.3)$$

$$F_{XX} < 0 \quad (4.4)$$

$K$  is the carrying capacity. Note that we assume two types of fleets in the fishery, stationary and non-stationary fleets.<sup>10</sup> We adopt the notation used in Kahui & Armstrong (2008), where the harvest by non-stationary fleets is notated as  $h_1$  and the harvest by stationary fleets is notated as  $h_2$ . Total harvest at time  $t$  is then the summation of  $h_1$  and  $h_2$ , i.e.

$$h = h_1 + h_2, \quad (4.5)$$

$$0 \leq h_1 \leq h_{1max}, \quad (4.6)$$

$$0 \leq h_2 \leq h_{2max}. \quad (4.7)$$

We then use  $L$  to define cold-water corals. And, we have unit harvest costs  $c_1(X, L)$  and  $c_2(X, L)$  of non-stationary fleets and stationary fleets. Note that unit harvest costs are no longer independent of habitat, since cold-water corals have increased catchability of gears. Since bottom trawlers, i.e. the non-stationary fleets are more efficient than stationary fleets, we have

$$c_1(X, L) > c_2(X, L). \quad (4.8)$$

We assume that these two unit costs  $c_1(X, L)$  and  $c_2(X, L)$  are convex in fish stock  $X$  (Clark 1990, Kahui & Armstrong 2008), that the cost of one

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<sup>10</sup> It is common and useful to assume two competing groups in bioeconomic models. For examples, Kahui & Armstrong (2008), Armstrong (1999) assume two competing fishing groups in the same fishery; Flaaten (1991) assumes two competing fish species in the same fishery. A common two competing group assumption usually serves to reflect the intuition well. Assuming more groups in a bioeconomic model may approach closer to the reality, however, will increase the complexity of the models.

unit catch will be increasingly reduced as the fish stock  $X$  increases, i.e.

$$c_{1X} < 0, \quad (4.9)$$

$$c_{2X} < 0, \quad (4.10)$$

$$c_{1XX} > 0, \quad (4.11)$$

$$c_{2XX} > 0. \quad (4.12)$$

We further assume that unit costs are convex in cold-water coral stock  $L$  as well (Kahui & Armstrong 2008), that the increase in cold-water coral stock will increasingly decrease unit harvest costs  $c_1(X, L)$  and  $c_2(X, L)$ , i.e.

$$c_{1L} < 0, \quad (4.13)$$

$$c_{2L} < 0, \quad (4.14)$$

$$c_{1LL} > 0, \quad (4.15)$$

$$c_{2LL} > 0. \quad (4.16)$$

The price of fish is notated as  $p$ , which is a constant over time (Clark & Munro 1975, Kahui & Armstrong 2008). Remember the goods and services contributed by cold-water corals to the public, here we denote them as  $V(L)$ .  $V(L)$  is the aggregated values of these goods and services, except the contribution indirect to fisheries, which are taken into accounts as the cost reduction effects in  $c_1(X, L)$  and  $c_2(X, L)$ . It is hard to give explicit value on these goods and services by cold-water corals (Armstrong & Falk-Petersen 2008, Beaumont et al. 2008). We assure that  $V(L)$  will decreasingly increase as the cold-water coral stock increases, i.e.

$$V_L > 0, \quad (4.17)$$

$$V_{LL} < 0. \quad (4.18)$$

The present value of the net benefit (PVNB) is defined as

$$PVNB = \int_0^{\infty} e^{-\delta t} \{ [p - c_1(X, L)]h_1 + [p - c_2(X, L)]h_2 + V(L) \} dt, \quad (4.19)$$

where  $\delta$  is the social rate of discount. Now our goal is to maximize the *PVNB*. We adopt the same endogenous mechanism on the fishery-coral connection with Kahui & Armstrong (2008), that cold-water corals are depleted as by-product of bottom trawling

$$\frac{dL}{dt} = -\alpha h_1. \quad (4.20)$$

Note that the harvest on cold-water corals as raw material for jewelry industry is omitted in this model, because so-far only in Hawaiian waters cold-water corals are reported to be harvest directly for human use (Grigg 2002, Baco & Shank 2005). Comparing with the great distribution of cold-water corals (Freiwald et al. 2004, Roberts et al. 2006), the direct coral harvest in Hawaiian waters is very special and unique, thus it is not included in our model. We also omit the growth factor of cold-water corals, for its very slow growing rate (Roberts et al. 2006, Kahui & Armstrong 2008).

We have the initial conditions defined as below

$$X = X_0 \geq 0, \quad (4.21)$$

$$L = L_0 \geq 0. \quad (4.22)$$

The Hamiltonian of our problem is defined as

$$\begin{aligned} H = & e^{-\delta t} \{ [p - c_1(X, L)]h_1 + [p - c_2(X, L)]h_2 + V(L) \} \\ & + \mu_1 [F(X) - h_1 - h_2] + \mu_2 (-\alpha h_1). \end{aligned} \quad (4.23)$$

$h_1, h_2$  are the control variables; while  $\mu_1, \mu_2$  are the adjoint or costate

variables, which measure the shadow prices of the associated state variables  $X$  and  $L$  discounted back to  $t = 0$  (Clark & Munro 1975, Kahui & Armstrong 2008). We then can have two necessary conditions

$$\frac{\partial H}{\partial h_1} = e^{-\delta t}[p - c_1(X, L)] - \mu_1 - \alpha\mu_2 = 0, \quad (4.24)$$

$$\frac{\partial H}{\partial h_2} = e^{-\delta t}[p - c_2(X, L)] - \mu_1 = 0. \quad (4.25)$$

From Eq. (4.24) and Eq. (4.25) we can get

$$\mu_1 = e^{-\delta t}[p - c_2(X, L)], \quad (4.26)$$

$$\begin{aligned} \mu_2 &= \frac{1}{\alpha}\{e^{-\delta t}[p - c_1(X, L)] - \mu_1\} \\ &= \frac{e^{-\delta t}}{\alpha}[c_2(X, L) - c_1(X, L)]. \end{aligned} \quad (4.27)$$

Similarly, we can have two adjoint equations:

$$\begin{aligned} \frac{d\mu_1}{dt} = -\frac{\partial H}{\partial X} &= -[e^{-\delta t}(-c_{1X}h_1 - c_{2X}h_2) + \mu_1 F_X] \\ &= -e^{-\delta t}\{-(c_{1X}h_1 + c_{2X}h_2) + [p - c_2(X, L)]F_X\}, \end{aligned} \quad (4.28)$$

$$\frac{d\mu_2}{dt} = -\frac{\partial H}{\partial L} = -e^{-\delta t}[-(c_{1L}h_1 + c_{2L}h_2) + V_L]. \quad (4.29)$$

Now we have all the needed equation to solve for the optimal fish stock  $X^*$  conditional on cold-water coral stock  $L$ , as well as the optimal cold-water coral stock  $L^*$  conditional on fish stock  $X$ . One thing to note that, the Eq. (4.29) is now different from the Eq. (8a) in Kahui & Armstrong (2008, pp. 11). The extra term  $V_L$  in Eq. (4.29) now demonstrates the effect of marginal goods and services valuation.

## 4.1 Optimal fish stock $X^*$ conditional on coral stock $L$

By differentiating  $\mu_1$  of Eq. (4.26) with respect to time  $t$ , we have

$$\begin{aligned} \frac{d\mu_1}{dt} &= -e^{-\delta t} \{ \delta [p - c_2(X, L)] + c_{2X} F(X) \\ &\quad - (c_{2X} + \alpha c_{2L}) h_1 - c_{2X} h_2 \}. \end{aligned} \quad (4.30)$$

Now we have two expression on  $\frac{d\mu_1}{dt}$ . By equating the right part of Eq. (5.9) and the right part of (4.28), we have

$$\begin{aligned} &-e^{-\delta t} \{ -(c_{1X} h_1 + c_{2X} h_2) + [p - c_2(X, L)] F_X \} \\ &= -e^{-\delta t} \{ \delta [p - c_2(X, L)] + c_{2X} F(X) \\ &\quad - (c_{2X} + \alpha c_{2L}) h_1 - c_{2X} h_2 \}. \end{aligned} \quad (4.31)$$

Solve Eq. (4.31), with the appropriate transversality condition ( $X \geq 0$  and  $\lim_{t \rightarrow \infty} \{X(t)\mu_1(t)\} = 0$ ) (Kahui & Armstrong 2008), we have the expression of optimal fish stock  $X^*$  conditional on cold-water coral stock  $L$ , which is

$$\delta = F_X(X^*) + \frac{-c_{2X} F(X^*) + (-c_{1X} + c_{2X} + \alpha c_{2L}) h_1}{p - c_2(X^*, L)}. \quad (4.32)$$

Eq. 5.11 is the preferred coral-fish connection version of the Golden Rule equation by Clark & Munro (1975) (Kahui & Armstrong 2008). It indicates an optimal fish stock level  $X^*$  (Kahui & Armstrong 2008). At the optimal fish stock level, it becomes indifferent on whether investing in or consuming the stock (Kahui & Armstrong 2008).

The whole right part implies that the optimal fish stock  $X^*$  is earning the social discount rate  $\delta$  (Kahui & Armstrong 2008).  $F_X$  presents “*the instantaneous marginal physical product of the fish stock*” (Kahui & Armstrong 2008, pp. 11), while  $\frac{-c_{2X} F(X^*) + (-c_{1X} + c_{2X} + \alpha c_{2L}) h_1}{p - c_2(X^*, L)}$  demonstrates “*the marginal value of the fish stock relative to the marginal value of stationary gear user*”

*harvest*” (Kahui & Armstrong 2008, pp. 12).

The terms  $(-c_{1X} + c_{2X} + \alpha c_{2L})$  and  $p - c_2(X^*, L)$  in the right part of Eq. (5.11) shows that, when the coral-fish connection is taken into account, the optimal fish stock level  $X^*$  is no longer independent of its associated habitat level  $L$  (Kahui & Armstrong 2008). The involvement of the unit cost function and its partial derivatives indicate that the unit cost savings have to be adjust by the cold-water coral stock levels, due to the facts that  $\{c_{1XL} = c_{1LX}; c_{2XL} = c_{2LX}\} > 0$  and  $\{c_{1X}; c_{2X}\} < 0$  (Kahui & Armstrong 2008). Higher levels of stock  $L$  will then push  $c_{1X}$  and  $c_{2X}$  closer to zero, resulting lower returns from fish stock investments (Kahui & Armstrong 2008).

Now we totally differentiate Eq. (5.11), for the identification of optimal fish stock  $X^*$  corresponding to different levels of coral stock  $L$ . We get

$$\frac{dX^*}{dL} = -\frac{-c_{2L}F_X - c_{2XL}F(X^*) + \delta c_{2L}}{F_{XX}[p - c_2(X^*, L)] - 2c_{2X}F_X + \delta c_{2X} - c_{2XX}F(X^*)} \frac{+(-c_{1XL} + c_{2XL} + \alpha c_{2LL})h_1}{+(-c_{1XX} + c_{2XX} + \alpha c_{2XL})h_1}. \quad (4.33)$$

To make Eq. (4.33) easier to read, we set

$$a = -[-c_{2L}F_X - c_{2XL}F(X^*) + \delta c_{2L}], \quad (4.34)$$

$$b = -(-c_{1XL} + c_{2XL} + \alpha c_{2LL}), \quad (4.35)$$

$$j = F_{XX}[p - c_2(X^*, L)] - 2c_{2X}F_X + \delta c_{2X} - c_{2XX}F(X^*), \quad (4.36)$$

$$d = (-c_{1XX} + c_{2XX} + \alpha c_{2XL}). \quad (4.37)$$

Then, we can write Eq. (4.33) as

$$\frac{dX^*}{dL} = \frac{a + bh_1}{j + dh_1}. \quad (4.38)$$

Given the previously assumed conditions, we can have

$$\{a, b\} > 0, \quad (4.39)$$

$$\{b, e\} < 0. \quad (4.40)$$

Note that Eq. (4.33) is a rational function, by which we can identify the vertical/horizontal asymptotes and intercepts (Kahui & Armstrong 2008). For different levels of  $X^*$  and  $L$ , the parameters  $a$ ,  $b$ ,  $e$ , and  $d$  change, and thus  $\frac{dX^*}{dL}$  can be positive and negative for any  $h_1$  (Kahui & Armstrong 2008). We denote  $X^* : L$  to express conditional  $X^*$  on  $L$  (Kahui & Armstrong 2008, pp. 13). Because when the system reaches its equilibrium, the cold-water coral stock will be in a steady-state, the harvest from non-stationary fleets will be ceased. It indicates that any steady-state value for  $X^*$  along the curve  $X^* : L$  will be achieved for  $h_1^* = 0$ , and hence  $\frac{dX^*}{dL} = \frac{a}{e} < 0$  (Kahui & Armstrong 2008).

## 4.2 Optimal cold-water coral stock $L^*$ conditional on fish stock $X$

By differentiating  $\mu_2$  of Eq. (4.27) with respect to time  $t$ , we have

$$\begin{aligned} \frac{d\mu_2}{dt} &= -\frac{e^{-\delta t}}{\alpha} \{ \delta [c_2(X, L) - c_1(X, L)] + (c_{1X} - c_{2X})F(X) \\ &\quad - (c_{1X} - c_{2X} + \alpha c_{1L} - \alpha c_{2L})h_1 \\ &\quad - (c_{1X} - c_{2X})h_2 \}. \end{aligned} \quad (4.41)$$



From Eq. (4.29) and Eq. (4.41) we can get

$$\begin{aligned}
& -e^{-\delta t}[-(c_{1L}h_1 + c_{2L}h_2) + V_L] \\
& = -\frac{e^{-\delta t}}{\alpha}\{\delta[c_2(X, L) - c_1(X, L)] + (c_{1X} - c_{2X})F(X) \\
& \quad -(c_{1X} - c_{2X} + \alpha c_{1L} - \alpha c_{2L})h_1 \\
& \quad -(c_{1X} - c_{2X})h_2\}. \tag{4.42}
\end{aligned}$$

We solve Eq. (4.42) to obtain the expression of optimal cold-water coral stock  $L^*$  conditional on fish stock  $X$ , with the appropriate transversality conditions ( $L \geq 0$  and  $\lim_{t \rightarrow \infty} \{L(t)\mu_2(t)\} = 0$ ), which is

$$\delta = \frac{(c_{2X} - c_{1X})F(X) + (c_{1X} - c_{2X} - \alpha c_{2L})h + \alpha V_L}{c_2(X, L^*) - c_1(X, L^*)}. \tag{4.43}$$

Similar to Eq. (5.11), Eq. (4.43) shows us the optimal level of cold-water corals  $L^*$  conditional on fish stock level  $X$ . The optimal  $L^*$  is achieved when the social discount rate  $\delta$  is equal to the sum of the marginal cold-water coral stock effect (similar to the marginal fish stock effect in Eq. (5.11)) (Kahui & Armstrong 2008) and the marginal goods and services valuation effect. Note that due to the non-renewable characteristic of cold-water corals, no instantaneous marginal physical product is shown in Eq. (4.43) (Kahui & Armstrong 2008).

Note that Eq. (4.43) is not only different from the extraction path of exhaustible resource by Hotelling (1931), but also slightly different from the optimal cold-water coral stock  $L^*$  conditional on  $X$  by Kahui & Armstrong (2008). Eq. (4.43) is different from the extraction path by Hotelling (1931) is because cold-water coral, as a relative non-renewable resource, itself doesn't possess direct use values to the fishery, which depletes the corals as by-product of fishing (Kahui & Armstrong 2008). The marginal habitat stock effect is then interpreted by the marginal effects and unit differences in the differences of unit costs of the assumed two type fleets (Kahui & Armstrong

2008).

For the slight difference in the mathematical components of Eq. (4.43), comparing with Eq (11a) by Kahui & Armstrong (2008), it is because in our model, we explicitly take the valuation of goods and services by cold-water corals into consideration. The  $\frac{\alpha V_L}{c_2(X, L^*) - c_1(X, L^*)}$  demonstrates the additional consideration of our model. Note that though the mathematical form is only slightly changed, the final the steady-state and optimum optimum values may differ significantly, if  $\alpha V_L$  plays an significant portion.

Note that we have an negative factor in Eq. (4.43), that  $(c_{2X} - c_{1X})F(X) < 0$ . This indicates that the gains of marginal net cost savings to non-stationary fleets will affect the marginal indirect use values to fisheries by cold-water corals negatively (Kahui & Armstrong 2008), i.e. the activity of bottom trawling on cold-water corals is placing an externally to trawler itself as well as stationary gear users. Now let's look at  $(c_{1X} - c_{2X} - \alpha c_{2L})h$ . From our previous assumptions, we can get that  $(c_{1X} - c_{2X} - \alpha c_{2L})h > 0$ . This positive term indicates the effects of cold-water corals on marginal net harvesting costs (Kahui & Armstrong 2008). Kahui & Armstrong (2008, pp. 14) find that the optimal cold-water coral stock “ $L^* > 0$  is only true for  $h > 0$ ”, while specific functional forms for unit harvest costs and the growth function are assumed. The denominator part  $c_2(X, L^*) - c_1(X, L^*)$  indicates that the marginal value of coral depletion lies in the difference between the unit harvest costs of stationary and non-stationary fleets (Kahui & Armstrong 2008).

By the nature of Eq. (4.20), no singular solution of our optimal control problem Eq. (4.19) will exist. Given the nature of the bang-bang solution in the linear optimal control problem, we can only have the steady-state optimal cold-water coral stock  $L^*$ , when  $h_1 = 0$ , since the harvest by non-stationary fleets will be either  $h_1 = h_{1min} = 0$ , or  $h_1 = h_{1max}$ . Therefore, as we discussed in the previous subsection, it will be optimal to allow some periods of bottom trawling in the beginning to obtain the optimal cold-water coral stock  $L^*$ ,

then cease them totally (Kahui & Armstrong 2008).

Now, we totally differentiate Eq. (4.43), and we obtain

$$\frac{dL^*}{dX} = \frac{(c_{2X} - c_{1X})(F_X - \delta) + (c_{2_{XX}} - c_{1_{xx}})F(X)}{-(c_{2L} - c_{1L})\delta + (c_{2_{XL}} - c_{1_{XL}})F(X) + \alpha V_{LL}} + \frac{(c_{1_{XX}} - c_{2_{XX}} - \alpha c_{2_{XL}})h}{+(c_{1_{XL}} - c_{2_{XL}} - \alpha c_{2_{LL}})h}. \quad (4.44)$$

Now we define

$$m = -[(c_{2X} - c_{1X})(F_X - \delta) + (c_{2_{XX}} - c_{1_{xx}})F(X)], \quad (4.45)$$

$$i = -(c_{2L} - c_{1L})\delta + (c_{2_{XL}} - c_{1_{XL}})F(X) + \alpha V_{LL}. \quad (4.46)$$

Eq. (4.44) can then be written as

$$\frac{dL^*}{dX} = \frac{m + dh}{i + bh}. \quad (4.47)$$

We can see from our assumptions that  $m < 0$  (Kahui & Armstrong 2008). However, for  $i$ , we can not determine whether it is positive or negative, because  $[-(c_{2L} - c_{1L})\delta + (c_{2_{XL}} - c_{1_{XL}})F(X)] > 0$  (Kahui & Armstrong 2008) and  $\alpha V_{LL} < 0$ . Further, we can not determine whether the slope  $\frac{dL^*}{dX}$  is positive or negative, for any given  $h$  (Kahui & Armstrong 2008). Similar with the analysis on the  $X^* : X$  curve, we will only find positive steady-state value of  $L^*$  when  $h_1 = 0$  and  $h_2 > 0$  (Kahui & Armstrong 2008), i.e. the non-stationary fleets will be totally ceased and the harvest by stationary fleets will to sustained at the optimal level, when we reach the steady-state of the fishery.

Now we compare Eq. (4.44) with Eq. (12a) by Kahui & Armstrong (2008, pp. 15). We can see that when we take the valuation of goods and services by cold-water corals into consideration, we not only have the optimal cold-water coral stock  $L^*$  conditional on fish stock  $X$  (Eq. 4.43) altered, but also its slope (Eq. 4.44). That indicates that, when the valuation of goods and

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services by corals are accounted, we may have different optimal extraction path of cold-water corals, different steady-states of the fishery, as well as different optimum optimum values.

## 5 Bioeconomic modeling under essential habitat scenario

In the essential coral-fish connection scenario, a biological connection (Swallow 1990, Kahui & Armstrong 2008) is assumed as well the cost reduction effect. I.e. we assume that cold-water corals have direct effects on the growth of their fauna species. Thus the standard Schaefer (1957) model is now altered as

$$dX/dt = F(X, L), \quad (5.1)$$

and we have

$$F(0, L) = F(X, 0) = 0. \quad (5.2)$$

We further assume that  $F(X, L)$ , the growth of fauna fish, is concave in both  $X$  and  $L$  (Kahui & Armstrong 2008), which is

$$F_{XX} < 0, \quad (5.3)$$

$$F_{LL} < 0, \quad (5.4)$$

$$F_{XL} = F_{LX} \geq 0. \quad (5.5)$$

It is also known that  $K = K(L)$ , as  $F(K, L) = 0$  (Kahui & Armstrong 2008). When harvest involves, we have an altered version of Eq. (4.1), shown as below

$$dX/dt = F(X, L) - h_1 - h_2. \quad (5.6)$$

Note that in the essential habitat scenario, the PVNB (Eq. 4.19) and the depletion of coral (Eq. 4.20) do not change. Now we have our new Hamiltonian

$$\begin{aligned} H = e^{-\delta t} \{ & [p - c_1(X, L)]h_1 + [p - c_2(X, L)]h_2 + V(L) \} \\ & + \mu_1[F(X, L) - h_1 - h_2] + \mu_2(-\alpha h_1). \end{aligned} \quad (5.7)$$

From Eq. (5.7), we can obtain two necessary conditions and two adjoint equations. Note that the two necessary conditions are the same with the two necessary conditions from the Hamiltonian of the preferred habitat scenario (Eq. 4.23), i.e. Eq. (4.24) and Eq. (4.25). Thus we obtain the same set of  $\mu_1$  and  $\mu_2$ , i.e. Eq. (4.26) and Eq. (4.27). However, their differentiation with respect to time  $t$  will be altered, as  $\frac{dX}{dt}$  is now different. We'll present the changes of differentiations in Section 5.1 and Section (5.2).

Now let's look at the two adjoint equations. Note that the first adjoint equation is the same with the preferred habitat scenario, i.e. Eq. (4.28); while the second adjoint equation is altered, since  $F(X, L)$  is now a function of cold-water coral stock  $L$ .

$$\frac{d\mu_2}{dt} = -\frac{\partial H}{\partial L} = -e^{-\delta t} \{ -(c_{1L}h_1 + c_{2L}h_2) + V_L + [p - c_2(X, L)]F_L \} \quad (5.8)$$

## 5.1 Optimal fish stock $X^*$ conditional on coral stock $L$

Now we differentiate  $\mu_1$  with respect to time  $t$  again, with the new assumption of  $F(X, L)$ . We have

$$\begin{aligned} \frac{d\mu_1}{dt} &= -e^{-\delta t} \{ \delta [p - c_2(X, L)] + c_{2X}F(X, L) \\ &\quad - (c_{2X} + \alpha c_{2L})h_1 - c_{2X}h_2 \}. \end{aligned} \quad (5.9)$$

We can see that in Eq. (5.9), the term  $F(X, L)$  has replaced the term  $F(X)$  in Eq. (4.30).

From Eq. (4.28) and Eq. (5.9), we set

$$\begin{aligned} &-e^{-\delta t} \{ -(c_{1X}h_1 + c_{2X}h_2) + [p - c_2(X, L)]F_X \} \\ &= -e^{-\delta t} \{ \delta [p - c_2(X, L)] + c_{2X}F(X, L) \\ &\quad - (c_{2X} + \alpha c_{2L})h_1 - c_{2X}h_2 \}. \end{aligned} \quad (5.10)$$

By solving the above equation with the appropriate transversality condition,

we obtain the essential coral-fish connection version of the Golden Rule equation on the optimal fish stock  $X^*$  conditional on coral stock  $L$

$$\delta = F_X(X^*, L) + \frac{-c_{2_X}F(X^*, L) + (-c_{1_X} + c_{2_X} + \alpha c_{2_L})h_1}{p - c_2(X^*, L)}. \quad (5.11)$$

Comparing with the preferred habitat scenario, we find that the only difference is the replacement of  $F(X^*)$  by  $F(X^*, L)$ . It seems to be a minor change mathematically; however, a significant different analysis is actually suggested (Kahui & Armstrong 2008). We can see that when cold-water coral plays important role in fish's growth, it starts to affect the instantaneous marginal physical product of  $X^*$  (the  $F_X(X^*, L)$  part), resulting “*competing dynamics between the growth and the cost effect with respect to  $L$* ” (Kahui & Armstrong 2008, pp. 19).

Now we totally differentiate Eq. (5.11), we have

$$\begin{aligned} \frac{dX^*}{dL} = & -\frac{F_{XL}[p - c_2(X^*, L)] - c_{2_L}(F_X - \delta) - c_{2_{XL}}F(X^*, L) - c_{2_X}F_L}{F_{XX}[p - c_2(X^*, L)] - c_{2_X}(2F_X - \delta) - c_{2_{XX}}F(X^*, L)} \\ & \frac{+(-c_{1_{XL}} + c_{2_{XL}} + \alpha c_{2_{LL}})h_1}{+(-c_{1_{XX}} + c_{2_{XX}} + \alpha c_{2_{XL}})h_1}. \end{aligned} \quad (5.12)$$

By setting

$$\begin{aligned} A = & -\{F_{XL}[p - c_2(X^*, L)] - c_{2_L}(F_X - \delta) \\ & -c_{2_{XL}}F(X^*, L) - c_{2_X}F_L\}, \end{aligned} \quad (5.13)$$

we can rewrite Eq. (5.12) as

$$\frac{dX^*}{dL} = \frac{A + bh_1}{j + dh_1}. \quad (5.14)$$

Note that the only difference in the slope of optimal fish stock  $X^*$  conditional on  $L$  of the two scenarios is that in the essential habitat scenario, we have additional  $\{[p - c_2(X^*, L)]F_{XL} - c_{2_X}F_L\}$  in the parameter  $A$ , indicating

the positive habitat effect on the fish growth (Kahui & Armstrong 2008). However, it's uncertain whether  $A$  is positive (Kahui & Armstrong 2008).

## 5.2 Optimal cold-water coral stock $L^*$ conditional on fish stock $X$

By differentiating  $\mu_2$  (Eq. 4.27) with respect to time  $t$ , we have

$$\begin{aligned} \frac{d\mu_2}{dt} &= -\frac{e^{-\delta t}}{\alpha} \{ \delta [c_2(X, L) - c_1(X, L)] + (c_{1X} - c_{2X})F(X, L) \\ &\quad - (c_{1X} - c_{2X} + \alpha c_{1L} - \alpha c_{2L})h_1 - (c_{1X} - c_{2X})h_2 \}. \end{aligned} \quad (5.15)$$

From Eq. (5.8) and Eq. (5.15), we have

$$\begin{aligned} &-e^{-\delta t} \{ -(c_{1L}h_1 + c_{2L}h_2) + V_L + [p - c_2(X, L)]F_L \} \\ &= -\frac{e^{-\delta t}}{\alpha} \{ \delta [c_2(X, L) - c_1(X, L)] + (c_{1X} - c_{2X})F(X, L) \\ &\quad - (c_{1X} - c_{2X} + \alpha c_{1L} - \alpha c_{2L})h_1 - (c_{1X} - c_{2X})h_2 \}. \end{aligned} \quad (5.16)$$

By solving Eq. (5.16) with the appropriate transversality condition, we obtain the optimal cold-water coral stock  $L^*$  conditional on fish stock  $X$

$$\begin{aligned} \delta &= \frac{(c_{2X} - c_{1X})F(X, L^*) + \alpha[p - c_2(X, L^*)]F_L + \alpha V_L}{c_2(X, L^*)} \\ &\quad + \frac{(c_{1X} - c_{2X} - \alpha c_{2L})h}{-c_1(X, L^*)} \end{aligned} \quad (5.17)$$

We can first see that, the optimal cold-water coral stock  $L^*$  conditional on  $X$  of the essential habitat scenario also contains the marginal goods and services valuation effect  $\alpha V_L$ , comparing with the original result by Kahui & Armstrong (2008). If we compare Eq. (5.17) with Eq. (4.43), we can find that there is additional  $\alpha[p - c_2(X, L^*)]F_L$  in Eq. (5.17). Because  $\{\alpha[p - c_2(X, L^*)]F_L\} > 0$ , the additional factor indicates positive returns to fish reproduction by additional unit of cold-water corals (Kahui & Armstrong



2008).

Now we totally differentiate Eq. (5.17). We get

$$\frac{dL^*}{dX} = \frac{(c_{2_{XX}} - c_{1_{XX}})F(X, L^*) + (c_{2_X} - c_{1_X})(F_X - \delta)}{(c_{2_{XL}} - c_{1_{XL}})F(X, L^*) + (c_{2_X} - c_{1_X})F_L - (c_{2_L} - c_{1_L})\delta - \alpha c_{2_X} F_L + \alpha [p - c_2(X, L^*)] F_{XL}} \frac{-\alpha c_{2_L} F_L + \alpha [p - c_2(X, L^*)] F_{LL} + \alpha V_{LL}}{+(c_{1_{XX}} - c_{2_{XX}} - \alpha c_{2_{XL}})h} \cdot \frac{+(c_{1_{XL}} - c_{2_{XL}} - \alpha c_{2_{LL}})h}{+(c_{1_{XL}} - c_{2_{XL}} - \alpha c_{2_{LL}})h}. \quad (5.18)$$

By setting

$$M = -\{(c_{2_{XX}} - c_{1_{XX}})F(X, L^*) + (c_{2_X} - c_{1_X})(F_X - \delta) - \alpha c_{2_X} F_L + \alpha [p - c_2(X, L^*)] F_{XL}\}, \quad (5.19)$$

$$I = (c_{2_{XL}} - c_{1_{XL}})F(X, L^*) + (c_{2_X} - c_{1_X})F_L - (c_{2_L} - c_{1_L})\delta - \alpha c_{2_L} F_L + \alpha [p - c_2(X, L^*)] F_{LL} + \alpha V_{LL}, \quad (5.20)$$

we can rewrite Eq. (5.18) as

$$\frac{dL^*}{dX} = \frac{M + dh}{I + bh} \quad (5.21)$$

Comparing Eq. (5.18) with Eq. (4.44), we find two differences. The first difference is the term  $\{-\alpha c_{2_X} F_L + \alpha [p - c_2(X, L^*)]\}$  in  $M$ , while the second difference is the term  $\{(c_{2_X} - c_{1_X})F_L - \alpha c_{2_L} F_L + \alpha [p - c_2(X, L^*)] F_{LL}\}$  in  $I$ . From our previous assumptions, we see that  $M < 0$ ; however, the sign of  $I$  could be positive, or negative (Kahui & Armstrong 2008).

Comparing Eq. (5.18) with original result Eq. (12b) in Kahui & Armstrong (2008, pp. 20), our result has an extra  $\alpha V_{LL}$  in  $I$ , demonstrating the effects of marginal valuation on goods and services by corals.

## 6 Analysis and discussion

### 6.1 Steady-state analysis

#### 6.1.1 Preferred coral-fish connection

The state space diagram of  $X^* : L[1]$ <sup>11</sup> and  $L^* : X$  curves of preferred coral-fish connection scenario are shown in Figure (6.1). Points on curve  $X^* : L$  represents steady-state fish stock level  $X^*$  conditional on cold-water coral stock level  $L$  (where  $h_1^* = 0$  and  $h_2^* = F(X^*)$ ), while points on curve  $L^* : X$  represents steady-state cold-water coral stock level  $L^*$  conditional on fish stock level  $X$  (where  $h_1 = 0$  and  $h_2 > 0$ ) (Kahui & Armstrong 2008).

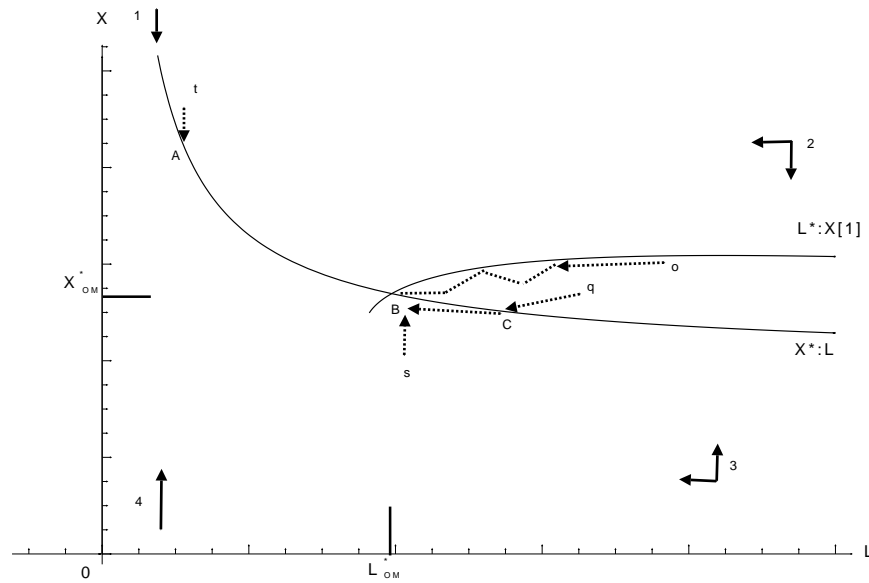


Fig. 6.1: Preferred habitat steady-state analysis

We can see from Fig. 6.1 that the Eq. (4.33) determines the slope of the  $X^* : L[1]$  curve, as  $\frac{dX^*}{dL} = \frac{a}{e}$ , when  $h_1^* = 0$  (Kahui & Armstrong 2008). Kahui

<sup>11</sup> The suffix [1] is added to  $X^* : L$  to distinguish different  $X^* : L$  curves by this thesis and by Kahui & Armstrong (2008). The  $X^* : L$  curves by Kahui & Armstrong (2008) are named with the [2] suffix.

& Armstrong (2008) further argued that the slope of the  $X^* : L$  curve is always negative, i.e.  $\{\frac{dX^*}{dL} = \frac{a}{e}\} < 0$ , no matter  $F_X$  is positive (for  $X^* < \frac{K}{2}$ ) or negative (for  $X^* > \frac{K}{2}$ ).

The  $L^* : X$  curve is determined by its slope, i.e. Eq. (4.44). We can see from the figure, that its slope is always positive. The intercept of the  $X^* : L$  curve and the  $L^* : X$  curve is marked as  $B$  in the figure. Point  $B$  is the optimal *equilibrium* steady-state value of harvest ( $h_2^* = F(X^*) = h_{2_{OM}}^*$ ), presenting an optimum optimum, where  $X^* = X_{OM}^*$  and  $L^* = L_{OM}^*$  (Kahui & Armstrong 2008).

Note that the  $L^* : X$  curve is illustrated under a constant  $h_2$  value, i.e. the optimal *equilibrium* harvest value at point  $B$ . It is known that if  $h_2$  is assumed to be greater than  $h_{2_{OM}}^*$ , the  $L^* : X$  curve will lie further to the right, and if it is assumed to be less than  $h_{2_{OM}}^*$ , the  $L^* : X$  curve will lie further to the left (Kahui & Armstrong 2008). Hereby, only one unique  $L^* : X$  will reach an equilibrium steady-state (Kahui & Armstrong 2008).

Stable equilibrium can only be found on point  $B$  and on  $X^* : L$  to the left of point  $B$ . In the area 1 and area 4,  $h_1 = 0$  will be applied, because cold-water coral stock  $L$  is below any of the optimal level, as shown by the curve  $L^* : X$ ; thus all non-stationary fleets are ceased. In the area 1, stationary fleets will first harvest at their maximum capacity, i.e.  $h_2 = h_{2_{max}}$ , to achieve optimal fish stock at the optimal level  $X_{OM}^*$ , the harvest at the optimal level  $h_2 = h_{2_{OM}}^*$ ; while in the area 2, stationary fleets will not have any harvest activity, i.e.  $h_2 = 0$ , to invest into the fish stock to the optimal level, then start harvesting at the optimal level  $h_2 = h_{2_{OM}}^*$ . The movement of trajectory  $t$  is the example.<sup>12</sup>

For areas on the right  $X^* : L$  part starting from point  $B$ , no stable equilibrium can be formed. In both area 3 and area 4, non-stationary fleets will harvest at their maximum capacity ( $h_1 = h_{1_{max}}$ ) to reduce cold-water

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<sup>12</sup> For detailed description on the movements of  $t$ ,  $s$ ,  $q$ , and  $o$ , please see Kahui & Armstrong (2008, pp. 17 – 18)

coral to the optimal stock level  $L_{OM}^*$ . In the area 2, the stationary fleets will also harvest at the maximum capacity ( $h_2 = h_{2_{max}}$ ) to obtain the optimal fish stock level  $X_{OM}^*$  in the shortest period, then start harvesting at the optimal level  $h_2 = h_{2_{OM}}^*$ ; while in the area 3, the stationary fleets will not harvest ( $h_2 = 0$ ), until the optimal fish stock level  $X_{OM}^*$  is reached, then start harvesting at the optimal level  $h_2 = h_{2_{OM}}^*$ . The movements of trajectory  $s$ ,  $q$ , and  $o$  are the examples.

From our previous analysis, we can conclude that

1. Fig. 6.1 presents the interdependency between optimal steady-state fish stock levels and cold-water coral levels;
2. The *optimum optimum* cold-water coral levels can be found between the pristine level and zero;
3. The optimal cold-water coral stock level can only be found in-between the *optimal optimum* coral level  $L_{OM}^*$  and zero;
4. Bottom trawling may be optimal for some periods as long as cold-water coral stock level is larger than the *optimal optimum* coral level, i.e.  $L > L_{OM}^*$ .

### 6.1.2 Essential coral-fish connection

Fig. 6.2 presents the state space diagram of the curve  $X^* : L$  and curve  $L^* : X$  in the essential habitat connection. Similarly with Fig. 6.1, the  $X^* : L$  curve indicates the steady-state optimal fish stock level  $X^*$  conditional on cold-water stock level  $L^*$  (where  $h_1^* = 0$  and  $h_2^* = F(X^*)$ ); while the  $L^* : X$  curve shows the steady-state optimal cold-water coral stock level  $L^*$  conditional on fish stock level  $X$  (where  $h_1 = 0$  and  $h_2 > 0$ ) (Kahui & Armstrong 2008).

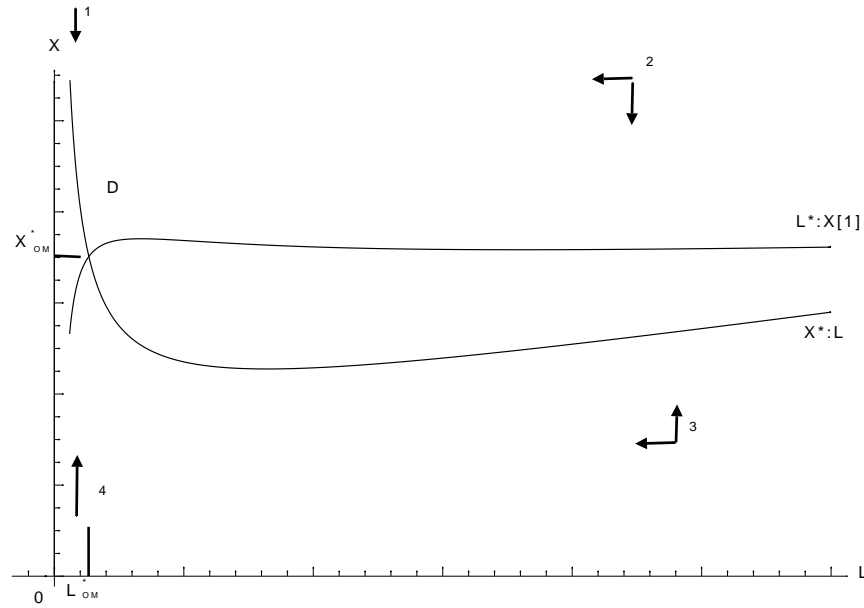


Fig. 6.2: Essential habitat steady-state analysis

The intercept of the  $X^* : L$  curve and the  $L^* : X$  curve is marked as  $D$  in the figure. Point  $D$  is the optimal *equilibrium* steady-state value of harvest ( $h_2^* = F(X^*) = h_{2_{OM}}^*$ ), presenting an optimum optimum, where  $X^* = X_{OM}^*$  and  $L^* = L_{OM}^*$

Comparing Fig. 6.1 and Fig. 6.2, we can see that it is complex to identify optimal stock levels and determining optimal fishing strategies (Kahui & Armstrong 2008). Further, the optimal stock levels of both fish and cold-water corals depend on the types of coral-fish connection, as well as the portion of goods and services value by cold-water corals.

## 6.2 Comparison with original models

### 6.2.1 Preferred coral-fish connection

Fig. 6.3 shows the state space diagrams of the  $X^* : L$  curves and the  $L^* : X$  curve of the models by this thesis and Kahui & Armstrong (2008), under the

*preferred* habitat connection scenario.  $X^* : L[1]$  presents the  $X^* : L$  curve of the model by this thesis; while  $X^* : L[2]$  presents the  $X^* : L$  curve of the model by Kahui & Armstrong (2008).

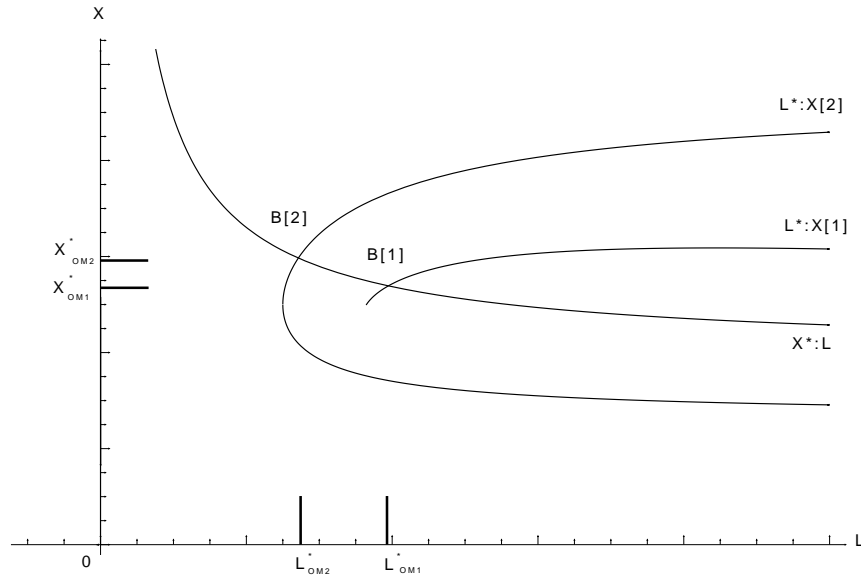


Fig. 6.3: Comparison on preferred habitat steady-state analysis

We mark the intercept of the  $X^* : L[1]$  curve and the  $L^* : X$  curve as  $B[1]$ , and the intercept of the  $X^* : L[2]$  curve and the  $L^* : X$  curve as  $B[2]$ . Point  $B[1]$  and point  $B[2]$  are the optimal *equilibrium* steady-state values of harvests, representing two *optimum optimorums*. The optimal *equilibrium* (i.e. point  $B[1]$ ) is reached when  $X^* = X^*_{OM1}$  and  $L^* = L^*_{OM1}$ , when the value of goods and services by cold-water corals is taken into account. However, if we do not take the goods and services value into consideration, optimal *equilibrium* (i.e. point  $B[2]$ ) is reached when  $X^* = X^*_{OM2}$  and  $L^* = L^*_{OM2}$ .

Now let's first compare the  $X^* : L[1]$  curve and the  $X^* : L[2]$  curve. It is clear from the figure that for any  $X > \frac{K}{2}$ , the optimal  $L^*_1$  is always greater than the optimal  $L^*_2$ . I.e. when the goods and services value is considered, the optimal cold-water coral stock level  $L^*$  will be larger. It

shows the importance of taking goods and services value into consideration for the preservation. The difference is the joint product of different  $L^* : X$  equations (Eq. (4.43) vs. Eq. (11a) in Kahui & Armstrong (2008, pp. 13)) as well as the slopes (Eq. (4.44) vs. Eq. (12a) in Kahui & Armstrong (2008, pp. 15)).

By comparing Eq. (4.43) with Eq. (11a) in Kahui & Armstrong (2008, pp. 13), we see that when the goods and services value by cold-water corals is accounted, we have an extra  $\frac{\alpha V_L}{c_2(X, L^*) - c_1(X, L^*)}$  in the optimal cold-water coral stock  $L^*$  conditional on  $X$  equation (Eq. (4.43)). That explains why the optimal cold-water coral stock level  $L^*$  will be larger, when the goods and services value is considered.

By comparing the slopes of Eq. (4.43) with Eq. (11a) in Kahui & Armstrong (2008, pp. 13) (i.e. Eq. (4.44) with Eq. (12a) in Kahui & Armstrong (2008, pp. 15)), we find that when the goods and services value by cold-water corals is accounted, the denominator is added with an extra  $\alpha V_{LL}$ . Note that as previously defined,  $V_{LL} < 0$ , hence

$$\frac{dL^*}{dX}[1] > \frac{dL^*}{dX}[2]. \quad (6.1)$$

Thus, the  $L_1^*$  will increase more dramatically than  $L_2^*$ , when the goods and services value is accounted, resulting in higher cold-water coral stock in equilibrium.

Now let's examine point  $B[1]$  and point  $B[2]$ . Since theory are the intercepts of  $X^* : L$  with  $L^* : X[1]$  and  $L^* : X[2]$ , both point  $B[1]$  and point  $B[2]$  are on the curve  $X^* : L$ . From the figure, we can read that the axes of both  $B[1]$  and point  $B[2]$ . It is clear that

$$X_{OM_1}^* < X_{OM_2}^*, \quad (6.2)$$

$$L_{OM_1}^* > L_{OM_2}^*. \quad (6.3)$$

Eq. (6.2) and Eq. (6.3) indicate that when the goods and services value

is accounted, in the *optimum optimum* points will be pushed to a lower  $X_{OM}^*$  with higher  $L_{OM}^*$ . How does this impact the fishery and the public? We will discuss them in detail in Section 6.3.

### 6.2.2 Essential coral-fish connection

Fig. 6.4 demonstrates the state space diagrams of the  $X^* : L$  curves and the  $L^* : X$  curve of the models by this thesis and Kahui & Armstrong (2008), under the *essential* habitat connection scenario.  $X^* : L[1]$  presents the  $X^* : L$  curve of the model by this thesis; while  $X^* : L[2]$  presents the  $X^* : L$  curve of the model by Kahui & Armstrong (2008).

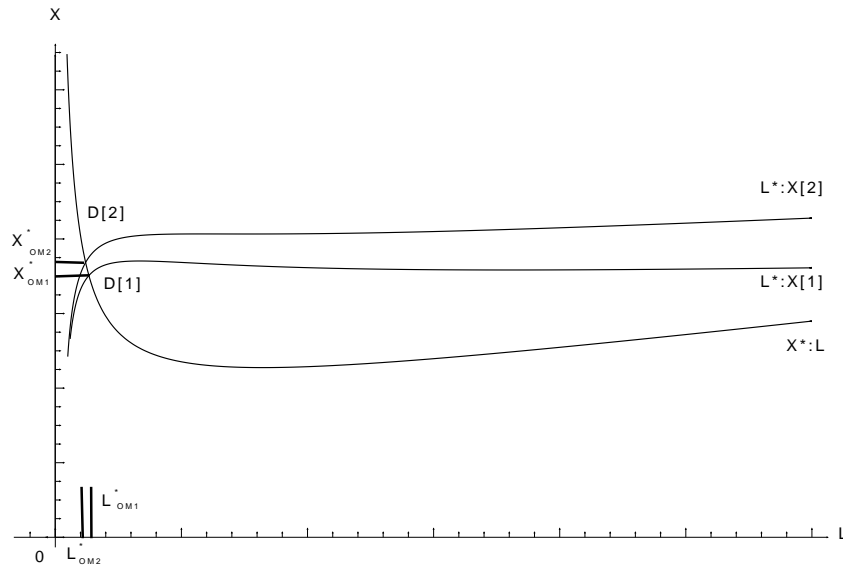


Fig. 6.4: Comparison on preferred habitat steady-state analysis

We mark the intercept of the  $X^* : L[1]$  curve and the  $L^* : X$  curve as  $D[1]$ , and the intercept of the  $X^* : L[2]$  curve and the  $L^* : X$  curve as  $D[2]$ . Point  $D[1]$  and point  $D[2]$  are the optimal *equilibrium* steady-state values of harvests, representing two *optimum optimums*. The optimal *equilibrium*



(i.e. point  $D[1]$ ) is reached when  $X^* = X_{OM_1}^*$  and  $L^* = L_{OM_1}^*$ , when the value of goods and services by cold-water corals is taken into account. However, if we do not take the goods and services value into consideration, optimal *equilibrium* (i.e. point  $D[2]$ ) is reached when  $X^* = X_{OM_2}^*$  and  $L^* = L_{OM_2}^*$ .

From Fig. 6.4, we find that similarly,

$$\frac{dL^*}{dX}[1] > \frac{dL^*}{dX}[2], \quad (6.4)$$

$$X_{OM_1}^* < X_{OM_2}^*, \quad (6.5)$$

$$L_{OM_1}^* > L_{OM_2}^*. \quad (6.6)$$

By comparing Eq. (5.17) with Eq. (11b) in Kahui & Armstrong (2008, pp. 20), we can see that the extra  $\frac{\alpha V_L}{c_2(X, L^*) - c_1(X, L^*)}$  in Eq. (5.17) has determined Eq. (6.6); and by comparing Eq. (5.18) with Eq. (12b) in Kahui & Armstrong (2008, pp. 20), we find that the extra  $\alpha V_{LL}$  in the denominator of Eq. (5.18) has determined Eq. (6.4).

## 6.3 New theorems

### 6.3.1 The change in $L^*$ and $X^*$

**Problem** When the goods and services value by cold-water corals is accounted, we have seen that

$$\frac{dL^*}{dX}[1] > \frac{dL^*}{dX}[2], \quad (6.7)$$

$$X_{OM_1}^* < X_{OM_2}^*, \quad (6.8)$$

$$L_{OM_1}^* > L_{OM_2}^*. \quad (6.9)$$

Are Eq. (6.7), Eq. (6.8), and (6.9) the general conclusions?

**Proof** For both preferred and essential habitat scenarios, we have found that, when the goods and services value is accounted as  $V(L)$ , there will be

an extra  $\frac{\alpha V_L}{c_2(X, L^*) - c_1(X, L^*)}$  in the formulas of optimal cold-water coral stock  $L^*$  conditional on fish stock  $X$  (e.g. Eq. (4.43) and Eq. (5.17)) and an extra  $\alpha V_{LL}$  in the denominator of the formulas of the slopes (e.g. Eq. (4.44) and Eq. (5.18)).

Because  $\alpha V_L > 0$  and  $[c_2(X, L^*) - c_1(X, L^*)] > 0$ ,  $\frac{\alpha V_L}{c_2(X, L^*) - c_1(X, L^*)} > 0$ . Thus  $L_{OM_1}^* > L_{OM_2}^*$ . Because  $L_{OM_1}^* > L_{OM_2}^*$ , we will never have  $B[1]$  and  $B[2]$  at the same position, nor  $D[1]$  and  $D[2]$  at the same position.

Because  $\alpha V_{LL} < 0$ , thus the denominators of Eq. (4.44) and Eq. (5.18) are reduced, therefore  $\frac{dL^*}{dX}[1] > \frac{dL^*}{dX}[2]$ . Thus  $X_{OM_1}^* < X_{OM_2}^*$ .

**Theorem 1.** *When the value of goods and services by cold-water corals is accounted, the optimal cold-water coral stock will be higher, while the optimal fish stock will be lower.*

### 6.3.2 The trade-off on PVNB

**Problem** When the value of goods and services by cold-water corals is accounted, who are the beneficiaries?

**Proof** First, when the value of goods and services by cold-water corals is accounted, the  $X^* : L$  curve is not altered, as we've shown in Eq. (4.32), Eq. (4.33), Eq. (5.11), and Eq. (5.12). Thus,  $B[1]$  and  $B[2]$  are on the same  $X^* : L$  curve of Fig. 6.3, while  $D[1]$  and  $D[2]$  are on the same  $X^* : L$  curve of Fig. 6.4.

We notate  $PVNB[1]$  as the optimal *Present Value of Net Benefits* when the value of goods and services by cold-water corals is accounted, and  $PVNB[2]$  as the optimal *Present Value of Net Benefits* when the value of goods and services by cold-water corals is *not* accounted.

Because  $B[1]$  is the intercept of the  $X^* : L$  curve with the  $L^* : X[1]$  curve, the  $PVNB[1]$  at point  $B[1]$  is the *optimum optimum PVNB[1]* point; thus  $PVNB[1]$  at point  $B[1]$  is greater than the  $PVNB[1]$  at point  $B[2]$ . That

is, when the value of goods and services by cold-water corals is accounted,

$$PVNB[1]_{B[1]} > PVNB[1]_{B[2]}. \quad (6.10)$$

Similarly, we will have

$$PVNB[1]_{D[1]} > PVNB[1]_{D[2]}. \quad (6.11)$$

From Eq. (6.12) and Eq. (6.13), we can conclude that when the value of goods and services by cold-water corals is accounted, the overall *optimum optimorum* net benefits will be larger than when it is not accounted.

Reversely, when the value of goods and services by cold-water corals is *not* accounted, because  $B[1]$  is the intercept of the  $X^* : L$  curve with the  $L^* : X[1]$  curve, the  $PVNB[2]$  at point  $B[2]$  is the *optimum optimorum*  $PVNB[2]$  point; thus the  $PVNB[2]$  at point  $B[1]$  is less than the  $PVNB[2]$  at point  $B[2]$ . I.e.

$$PVNB[2]_{B[1]} < PVNB[2]_{B[2]}, \quad (6.12)$$

$$PVNB[2]_{D[1]} < PVNB[2]_{D[2]}. \quad (6.13)$$

Therefore, when the value of goods and services by cold-water corals is accounted, and the fishery management strategy is followed by the *optimum optimorum* extraction path, the overall  $PVNB$  will be increase, while the  $PVNB$  of fishery will be reduced.

**Theorem 2.** *When the value of goods and services by cold-water corals is accounted, the total optimum optimorum  $PVNB$  is increased, i.e. larger than when it is not accounted; however, to fishery, its optimum optimorum  $PVNB$  is reduced, i.e. less than when it is not accounted.*

## 7 Conclusions

For the concerns on the economic efficiency of cold-water coral preservation, we propose a theoretical framework to analyze the interactions among cold-water coral, fish, fishery, and public. We find that: 1) the fishery benefits from cold-water corals indirectly, via the services of corals to commercially important species; 2) the public benefits from cold-water corals both directly and indirectly, via goods and services from cold-water corals; 3) both fishery and public may have affected cold-water corals negatively; 4) the depletion of cold-water corals affects both fishery and public negatively.

Before we start modeling on the links and interactions among cold-water coral, fish, fishery, and public, we collect secondary data from peer-reviewed journal to identify and classify the goods and services by cold-water corals. We totally identified 11 types of goods and services by cold-water corals, and classified them into 4 categories. They 11 goods and services from cold-water corals are: 1) food provision; 2) biodiversity function; 3) speciation function; 4) function as paleoclimatic archive; 5) biogeological function; 6) raw material for jewelry; 7) non-use value; 8) SCUBA diving destination; 9) submarine tourism destination; 10) indirect use value for fishery; and 11) biogeographic function.

We then develop bioeconomic models to analyze our problem. Our work on the modeling is based on the work done by Kahui & Armstrong 2008. We separated the No. 10 good and service (i.e. Indirect use value for fishery) from other goods and services in our modeling. Two types of coral-fish connections are assumed: 1) the preferred habitat scenario; and 2) the essential habitat scenario. Our new models reveal that, once the value of goods and services by cold-water corals is accounted, *optimum optimorum* values of the fishery and public can be identified.

To understand new models better, we adopt steady-state analysis on both new models and original models by Kahui & Armstrong 2008. Our steady-state analysis on the new models show that with the accounted goods and

services value, new steady-states can be readily identified and therefore new optimum optimum values can be estimated as well.

Comparing the steady-states of new models and original models, we find that optimum optimum equilibrium is altered, when goods and services value is accounted. We realize that in the new equilibrium, the optimum optimum cold-water coral stock level is increase, while the optimum optimum fish stock level is decreased.

We further raise two questions on the effects of taking goods and services value into consideration, and begin to analyze them. By solving the two questions, we raise two theorems.

The first theorem is *when the value of goods and services by cold-water corals is accounted, the optimal cold-water coral stock will be higher, while the optimal fish stock will be lower*; while the second theorem is *when the value of goods and services by cold-water corals is accounted, the total optimum optimum PVNB is increased, i.e. larger than when it is not accounted; however, to fishery, its optimum optimum PVNB is reduced, i.e. less than when it is not accounted*.

The proposal on the theoretical framework of cold-water coral, fish, fishery, and public covers the links among these four parties. The identification and classification of goods and services by cold-water corals suggest the importance of taking these values into management consideration in cold-water coral contained waters. The new models provide quantitative tools for the assessment of optimal management. The analysis illustrates the optimum optimum equilibrium of the fishery management. The new theorem indicates the trade-offs on the fishery and public, when goods and services value is accounted.

Further work is needed on the more specific identification and modeling of the goods and services values, as well as the coral-fish connection. A more specific work may also be carried out on the values of one or several goods and services by cold-water corals, e.g. the non-use value. Cold-water corals

are also facing two other threats, *1*) hydrocarbon and mineral exploration and production (Freiwald et al. 2004, Roberts et al. 2006); and *2*) ocean acidification (Roberts et al. 2006). It may also be of interests to include these two threats into the modeling and analysis.

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