

# JOURNAL OF NATURAL RESOURCES AND DEVELOPMENT

## The effects of global warming on fisheries: Simulation estimates

Carlos A. Medel

School of Economics, University of Nottingham, United Kingdom  
carlos\_medel@yahoo.com

### Article history

Received: 24/03/2015  
Accepted: 15/01/2016  
Published: 20/04/2016

### Keywords

Fisheries  
Fisheries economics  
Global warming  
Climate change

### Abstract

This paper develops two fisheries models in order to estimate the effect of global warming (GW) on firm value. GW is defined as an increase in the average temperature of the Earth's surface as a result of CO<sub>2</sub> emissions. It is assumed that (i) GW exists, and (ii) higher temperatures negatively affect biomass. The literature on biology and GW supporting these two crucial assumptions is reviewed. The main argument presented is that temperature increase has two effects on biomass, both of which have an impact on firm value. First, higher temperatures cause biomass to oscillate. To measure the effect of biomass oscillation on firm value the model in [1] is modified to include water temperature as a variable. The results indicate that a 1 to 20% variation in biomass causes firm value to fall from 6 to 44%, respectively. Second, higher temperatures reduce biomass, and a modification of the model in [2] reveals that an increase in temperature anomaly between +1 and +8°C causes fishing firm value to decrease by 8 to 10%.

JEL Classification: Q21, Q22, Q54, Q56, Q57.

### 1. Introduction

The aim of this paper is to estimate the impact of global warming (GW) on fisheries<sup>1</sup>. For the purpose of this paper, fishing is understood to be industrial deep-sea extraction and subsequent sale of marine resources that takes place outside the Exclusive Economic Zone where there is international competition for these resources. Artisan fishing cannot be included in this study since the variables that affect productivity are different to those observed in a mass-investment scale industry player. It should be noted, however, that fish farming could also be addressed as an extension of this article, since it may also be subject to the same uncontrolled input, e.g. water temperature<sup>2</sup>.

Although GW is an issue of growing interest in many fields, this study only includes those aspects applicable to the field of marine biology, where efforts to understand the relationship between biomass and temperature changes have been on the rise, especially after the 2008 El Niño phenomenon (*El-Niño-Southern-Oscillation*, or ENSO).

This study considers two of the effects, oscillation and reduction, which GW has on biomass<sup>3</sup>. When GW causes biomass to oscillate, a firm that uses technology designed for non-oscillating biomass will be put at risk, since it has to increase efforts to remain competitive (which can be costly). Random oscillations are used when modelling this effect to reflect that resource availability is not always completely known. It is also assumed that fisheries participate in a competitive market.

The main aim of this paper is to estimate the economic impact on fisheries of biomass oscillation and reduction due to GW, *i.e.* a more reliable method to estimate fisheries' profits. To do this, two models from the existing literature on fisheries economics are modified. First, for the case of stochastic biomass, the model in [1] is adapted to include water temperature at a given depth (deep-sea level) as an explicit variable in biomass and an implicit variable in the profit function, in order to measure the economic cost faced by firms trying to reach an optimum extraction level. In order to understand how biomass reduction affects firm value, the model in [2] is modified to include water temperature as a variable in biomass and in the firm's profit function. Both models are developed under two non-economic assumptions: *the average temperature of the Earth's (marine) surface is rising* and *global warming affects biomass*. The data and literature concerning these two assumptions are reviewed. Although the two models were developed decades ago, it is worth mentioning that both of them are still used currently with several improvements. However, the inclusion of the two aforementioned assumptions is made in the "root" models, to specifically isolate the effect of temperature on fisheries' value.

The following section (Section 2) presents the arguments supporting the aforementioned assumptions and reviews the pertinent literature on biology and GW. Based on the existing literature it can be concluded that although temperature time series are still too short to indicate structural change on ecosystems, the Earth's temperature has been on the rise.<sup>4</sup> Methodologically different studies concerning, for example, the consequences of ENSO in the Pacific Ocean and the warming of the sea floor, are also cited as indicators that the Earth's surface temperature is rising. Several specific case studies that demonstrate the effect of elevated water temperature on biomass at deep-sea level are analysed; and the literature on ENSO, its impact on oceans in the southern hemisphere and other similar phenomena occurring in the northern hemisphere is presented. This section also includes a literature review on the three issues that intersect in this paper: fisheries economics, GW, and marine biology. The first fisheries economics models and the changes that have been made to these over time are explained in detail, as is the current literature on GW, much of which is still in the early stages of development and lacks precision.

Section 3 presents the model for stochastic biomass based on [1]. Stochastic differential equations are used to model biomass and classic firm theory is used to represent the fishery. The model includes an equation that illustrates how firms react to biomass shocks (that

is, how much is spent understanding and mitigating the problem). This equation is intended to create a deeper understanding of how firms react to stochastic biomass, whether they face it by increasing spending or simply enduring a higher number of shocks, both costly options.

In Section 4, the model in [2] is adjusted to fit the purpose of this study. This model is used because the comparative static analysis that it provides simplifies situations where temperatures continue to rise as firms attempt to maximize profit. This model is also used to thoroughly analyse the effects of water temperature on biomass. Note that both models implicitly assume that the water is warming at a level in which biomass is present. Although the literature on GW often focuses on the land surface of certain areas, specific articles are reviewed supporting evidence of warming either the ocean surface or bottom. To have a clear counterfactual of a firm under GW risk, the models assume that the same technology is able to extract resources at different depths, but at a higher cost when extracting at higher water temperature. Hence, a higher temperature implies an increase of cost due to a higher effort rather than the adoption of a new technology for different depths.

In Section 5, both models are calibrated and the relevant numerical results indicate that stochastic biomass variations of 1 to 20% cause firm value to drop by 6 to 44%. On the other hand, if a firm extracts resources from a biomass where temperatures have risen between +1 and +9°C, its annual value decreases by between 8 and 10%. The deterministic model also provides the optimal investment dynamic, showing that capital invested increases until the temperature anomaly has increased by +4.3°C, after which it falls and stabilises at a negative value. In other words, it is economically advisable to withdraw capital from a firm if the temperature anomaly of the biomass has increased by +4.3°C; a less plausible scenario according to current research. This corresponds to the "many boats-few fish" problem that makes investing in the fishing industry a less attractive option.

Section 6 describes the theoretical difficulties in fusing the two models into one and discusses using stochastic components in static models. The analysis presented in this section also justifies separating oscillation and reduction in biomass, since isolating them allows for a direct estimation of their impact on firm value, although the literature suggests (or at least does not reject that) they occur together.

Finally, Section 7 presents the principal conclusions gathered from these models.

<sup>1</sup> GW is understood as the increase in the Earth's average temperature due to CO<sub>2</sub> emissions that prevent solar radiation absorbed by the Earth from completely returning to the atmosphere.

<sup>2</sup> It is worth mentioning that there must be made some extra assumptions for this case, as well as those considered in the baseline models. This is because competition for the resources does not occur only at sea, as farming could be more prone to monopolistic competition. Additionally, fish farming does not necessarily rely on the same technology adopted by a mass-investment scale industry player fishing outside the Exclusive Economic Zone.

<sup>3</sup> Biomass is understood as the abbreviation for *biological mass*, the living material produced in a determined area of land or water.

<sup>4</sup> An important discussion in this matter is provided in [3] where the authors find that the increasing pace in temperature is not monotone. Hence, the non-monotonic increase makes it difficult to identify a clear rising trend in temperature, showing the difficulty of using a finite sample for the statistical identification of an unobserved component, *i.e.* a trend. Note, however, that the models are developed assuming a rise in ocean temperature that produces damaging effects to biomass. This fact is noticeable, at least, in some specific areas despite the temperature sample span.

## 2. Literature review: fisheries economics, global warming, and marine biology

Initially, biology and economics were developed as separate sciences. Starting in the 1960s, research began to acknowledge the connection between the economic problems of fisheries (for example, fleet investment and optimal harvest levels) and biological issues, such as biomass sustainability and diseases in fish populations. Fisheries economics began with the work of [4], which tackles a number of topics relevant to fisheries, for example, how continual international competition, technological advances, and the growing global demand for marine resources create a divergence between economic objectives and resource sustainability, and how fisheries can be regulated to assure resource renewability. Resource renewability is also the cornerstone of the work of [5], which argues that the sole owner of a resource will exploit that resource in a sustainable way, based on monopolistic theory, as opposed to the theory of maximum extraction that is assumed in a competitive market. The focus adopted by [4] is slightly more complicated because it assumes that firms function in a competitive market and are subject to international regulations. This paper is developed under the same assumption. In other words, for the purposes of this paper, the fishing industry is understood as the collection of firms, either domestic or foreign, that produce goods using *common*<sup>5</sup> marine resources or transform these goods into another product (a process known as "reduction"). Only deep-sea fishing, known for being highly technological and industrialised, is considered; rudimentary, artisan fishing operations are not included.

It is worth noting that the level of harvest proposed by the static theoretical model in [4], which by definition does not capture the contingent problems of biomass, actually threatened biodiversity. In fact, the regulations based on static theoretical models exacerbate the ecological damage of exceeding sustainable harvest quotas. Despite this problem, similar models such as those of [6] and [7] are used as a basis for more advanced models.

Since the 1970s, models have been incorporating mathematical elements that significantly improve both fishing efficiency and regulations. However, these improved models have not always been taken into account by firms and governments facing the pressures of competition and demand, leading to major losses of biodiversity. The work of [8], for example, revealed that excessive fishing in tropical regions had reduced predator populations and caused permanent damage to biodiversity. Most recently [9] updated a survey on fisheries economics carried out by [10].

### 2.1. Fisheries economics: static models

Since GW is a relatively new line of research, the 1970s fisheries economics research only considered the relationship between biological models and classical theory of the firm. Some of the most important works from this period are [6], [7], [11], and later, [2] and [12], who picked up the earlier research, added aspects of the theory of the firm and expanded the analysis to other natural resources.<sup>6</sup> The approach of these models is presented below (based on [10]). The analysis focuses on fishable biomass, that is to say the biomass that supports fish populations that can be industrially extracted. It is assumed that biomasses do not interact with each other, and their movement is affected by (i.) recruitment (new species entering the biomass), (ii.) individual growth, (iii.) natural mortality, and (iv.) fishing mortality (extraction). According to [7], if  $x$  is fishable biomass:

$$\dot{x} = z(x) + g(x) - m(x) - f(x, E), \quad (2.1)$$

where  $z(x)$ ,  $g(x)$ ,  $m(x)$  and  $f(x, E)$  represent recruitment, individual growth, natural mortality and fishing mortality, with  $x' \equiv dx/dt$ . Fishing mortality is dependent on  $E$ , the 'fishing effort,' commonly measured in terms of boat-days per unit of time. These kinds of models are typically simplified due to the fact that it is impossible to know the exact functional form of the right side of equation 2.1. As such, it is assumed that:

$$\dot{x} = b(x, A) = b(x), \quad (2.2)$$

where  $A$  is a constant that represents the aquatic environment. In general, when talking about fish as opposed to other resources it is crucial to specify  $b(x)$  in an inverted U-shaped curve in the plane  $(x, x')$ . The logistic model has been widely used for fisheries, because of the insight it provides. In effect:

$$b(x) = rx \left(1 - x / W\right) \quad (2.3)$$

where  $r$  is the intrinsic population growth rate (constant), which incorporates recruitment and mortality, and  $W$  denotes the biomass's maximum support capacity. The connection between the firm and the biomass is expressed by harvest. Therefore, according to [7], the extraction function  $f(x, E)$  in (2.1) can be expressed as:<sup>7</sup>

$$h(E, x) = qE^\alpha x^\beta, \quad (2.4)$$

where  $q$ ,  $\alpha$  and  $\beta$  are constants. In general, it is assumed that  $\alpha = \beta = 1$  and  $q \in [0, 1]$ . Under this assumption, biomass takes the form.

<sup>5</sup> When a good is *common* the use of this good by a consumer lowers the consumption of another good (*rival*) and it is impossible to stop other consumers from using this good (*non-excludable*). On the other hand, when a consumer uses a *public* good it does not reduce the consumption of another good (*non-rival*) and does not stop other consumers from using it (*non-excludable*).

<sup>6</sup> While the main emphasis in [6] and [7] is a deep exploration of the mechanics behind the model developed in this article, [11] addresses the issue of whether it could be applied to other natural resources such as petroleum production, hunting, trapping, etc. Although the main focus in [11] is always the fishery, some important annotations of the modelling consequences to other resources are described. A concise version of the model of [6] and [7] is considered in [2] and it is also direct in the mathematical derivation of the key dynamic equations. [12] analyses the cases of an industry with externalities, sole ownership versus right access to a fishery, centralised recovery, and regulation.

<sup>7</sup> Although they are not identical, the terms harvesting and extraction will not be differentiated in this paper. This does not affect the relevant results.

$$\dot{x} = b(x) - h(E, x). \tag{2.5}$$

The steady-state solution ( $\dot{x}=0$ ) occurs when extraction is positive, or  $b(x^*)=h(E,x^*)>0$  with  $0<x^*<W$ . Given the solution  $x^*$ , effort and extraction can be written as a function of  $x$ , which in the function  $b(x)$  gives sustainable yield ( $Y_s$ ), since  $\dot{x}=0$ . This is shown graphically in **Figure 1**, where  $Y_s^*$  corresponds to the maximum sustainable extraction.

Provided that  $h(\dots)$  is a function of  $E$ , sustainable yield can therefore also be written as a function of  $E$ , and is a variable decision of the firm. Therefore, sustainable yield is given by:

$$Y_s = \eta E - \theta E^2, \tag{2.6}$$

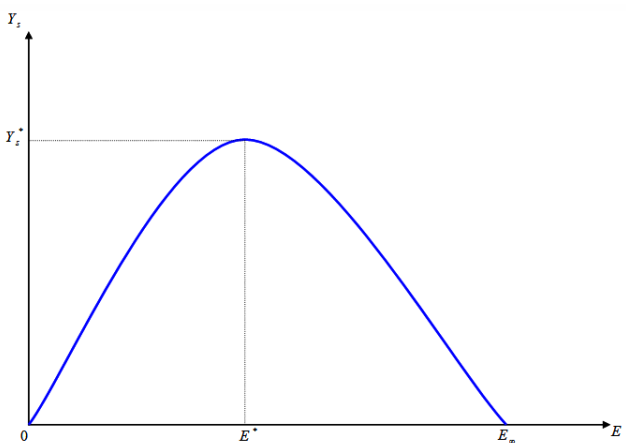
with  $\eta=qWy$   $\theta=q^2W/r$ , conserving the inverted-U shape. Equation 2.6 is the core of the static theory and can be used to find the optimal effort level which allows for the maximum degree of sustainable extraction. The introduction of the cost function to this scenario is direct,  $C(E)=\gamma E$  with  $\gamma>0$ . Thus, the firm's maximisation occurs when:

$$\max_{\{E\}} [TI(E_0) - C(E)] \geq 0, \tag{2.7}$$

where  $TI(\dots)$  corresponds to total income and  $E=E_0$  represents the optimal level of effort obtained from (2.6). The firm's static problem is shown graphically in **Figure 2**. The solution  $E=E_\infty$  corresponds to a situation of perfect competition, where profits have been completely dissipated and there is biological and economical equilibrium.

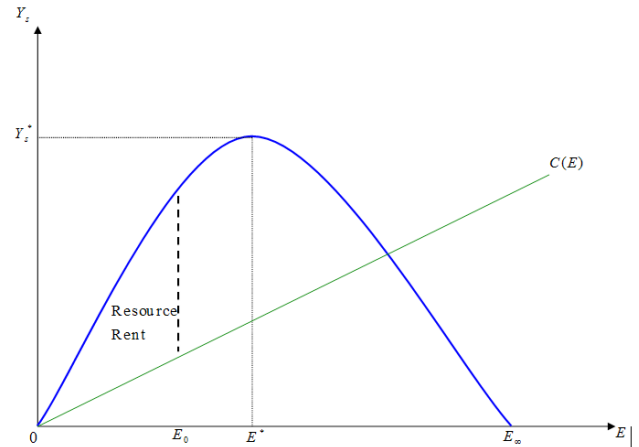
The first chapters of [13] are dedicated to the derivation of this result. An additional microeconomic analysis is included to better compare a competitive situation and a monopoly. However, throughout this paper a competitive market is assumed.

**Figure 1: Sustainable Extraction as a Function of Fishing Effort**



Source: Own elaboration.

**Figure 2: Sustainable Income and Total Cost of Fishing Effort**



Source: Own elaboration.

**2.2. Fisheries economics: dynamic models**

The referential work for advanced models is [14], which proposes a complete dynamic theory of the fishing process and includes a comprehensive review of the existing models at that time, and then introduces the theory of optimal control to calculate the appropriate level of extraction. The improvements to the static approach are presented below. The firm maintains its goal, though now in terms of present value. In effect:

$$\max PV = \int_0^\infty e^{-\delta t} \pi(x_t, h_t) dt, \tag{2.8}$$

where  $\delta$  is the social discount rate. The profit function corresponds to:

$$\pi(x_t, h_t) = \{p - c(x)\}h_t, \quad \forall t, \tag{2.9}$$

where  $p$  is the unit price and  $c(x)$  is the unit cost. The biomass is still represented by the equation 2.5. The corresponding Hamiltonian is:

$$H = e^{-\delta t} \{p - c(x)\}h_t + \lambda_t \{b(x) - h_t\}, \tag{2.10}$$

where  $\lambda_t$  is the dynamic Lagrange multiplier, which is interpreted as the resource's shadow price. This formulation emphasises the temporary trade-off firms face between the level of investment to be made per period and the profits obtained in that period.

The solution is the *fundamental equation of the use of natural resources*, set out (for example) in [15] and presented below,

$$b_x + \left. \frac{\partial \pi / \partial x}{\partial \pi / \partial h} \right|_{h=b(x^*)} = \delta. \tag{2.11}$$

Equation 2.11 is interpreted as an investment decision rule: the marginal return on an investment in a resource should be equal to the social discount rate. The first term on the left side is the impact of one additional unit of stock on the resource's return, while the second term reflects the fact that the level of stock has a different impact on extraction cost. [16], [17], and [18] present different methods of deriving this result; which are brought together in this paper. Any differences are due only to the fact that the formulation of the prior equations is focused on particular situations. The extensions of this result are diverse. It is used in [19] to better understand the effect of irreversible investment on the optimal extraction level, finding that at least in the short-term, irreversibility is a relevant assumption forcing firms to increase fishing effort. [17] analysed the herring in Canada in 1977, where a ban on herring fishing narrowly avoided the extinction of this species in the area. Other applications include the bio-economic modelling of Atlantic Ocean harp seals ([20]), of sharks in the waters south of Australia ([21]) and of tiger prawns (a crustacean similar to the lobster) in Australia's Exmouth Gulf ([22]). In addition to temporary decisions, the dynamic models also tend to be associated with the inclusion of random variables. In [2], a stochastic component dependent on biomass level is included. In that study, the biomass formulation is:

$$dx = \{b(x) - h_t\}dt + \sigma(x)dz, \quad (2.12)$$

where  $z = \varepsilon_t \sqrt{dt}$  is a Wiener process, or alternatively,  $\varepsilon_t$  is a Brownian process. The variable  $\sigma(x)$  indicates biomass variability and is specified in such a way that the resource is always non-negative. The representative biomass described by equation 2.12 has been applied to various problems. [23] propose a model for the capture of eels on the coasts of Italy. In [24], the result of 2.12 is extended to include contingencies that can affect biomass growth. The specified function for biomass in that study takes the following form:

$$dx = \{b(x)s(x) - h_t\}dt + \sigma(x)dz, \quad (2.13)$$

where the function  $s(x)$  captures the effect of disaster that reduces biomass.

In [25], a different approach is taken, using an advanced and complex mathematical analysis. The study's perspective better incorporates the time variable, allowing the model to be used to determine the optimum moment for extraction. A similar methodology is used in [26] to develop a model for fishing in rivers. The dynamic approach has also been refined by including rational expectations ([27]), game theory, and incomplete information ([28], [29], [30], and [31]).

The present study adds to these already sophisticated models by including a recent and unprecedented problem, about which little is known and which could affect the performance of fisheries: the warming of the Earth's marine and land surfaces. This problem is considered recent because the trend of rising temperatures is present as recently as 2007, as can be seen in **Figure 3**, and is unprecedented

because this trend was not observed before 1990.<sup>8</sup>

### 2.3. On the existence of global warming

This section reviews the interpretation and scope of Assumption 1: *The average temperature of the Earth's (marine) surface is rising.* GW is the increase in the Earth's average temperature due to CO<sub>2</sub> emissions that prevent solar radiation absorbed by the Earth from completely returning to the atmosphere. The effect of GW is exacerbated by the emission of greenhouse gases like methane, ozone, nitrogen oxide and others into the atmosphere.<sup>9</sup> The Carbon Dioxide Information Analysis Center (<http://cdiac.ornl.gov/>, reprinted in [34]) provides a graphic representation of CO<sub>2</sub> emissions per continent from the year 1800 to 2000 and the relationship between temperature and CO<sub>2</sub> emissions for the years 1000 to 2000, affirming that this relationship is not a cyclical phenomenon, and that GW is indeed a novel phenomenon. This definition does not explicitly differentiate between the causes of GW, since the increase in CO<sub>2</sub> emissions can be the result of anthropogenic factors, natural factors (like forest fires) or a combination of both.

Methodologically speaking, the time series confirms that temperatures are rising. However, biologically speaking this data should be interpreted with caution since longer time series than those currently available are needed to confirm structural change in ecosystems. Time series are reviewed here only for the purpose of illustration. Studies from specific geographic zones better validate Assumption 1. **Figure 3** displays the *Global Land-Ocean Temperature Anomaly Index* from January 1979 to April 2008 provided by Goddard Institute for Space Studies (GISS) of the US National Aeronautics and Space Administration (NASA). The anomaly appears to have been on the rise since 1993, having increased at the peak of each cycle (3-5 years) between +0.02 and +0.08°C per cycle.

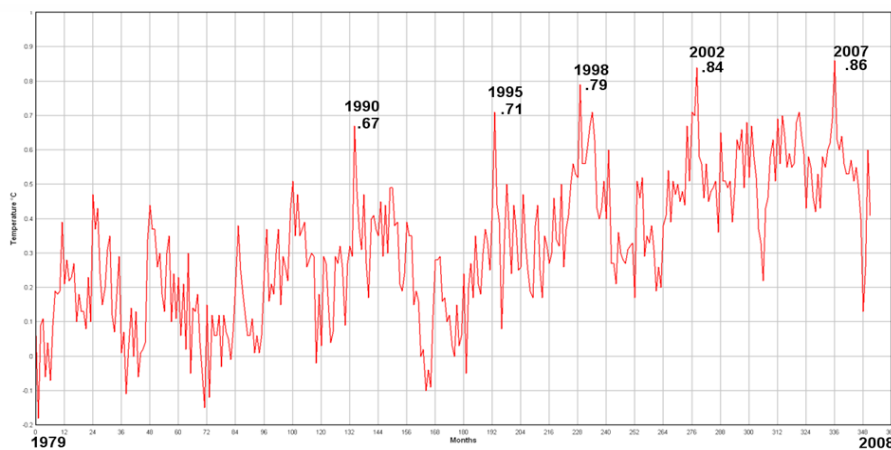
In [35], the GISS series from 1880 to 2005 are thoroughly analysed, finding that from the beginning of the last century to 1975, the temperature anomaly was around +0.2°C per decade. However, between 1975 and the turn of the century the anomaly increased to +0.7°C. After reaching this point, the authors estimate that it returned to a level of +0.2°C per decade. As far as rising water temperatures go, there is a great deal of data and specific studies that confirm this trend in many particular regions and oceans across the world. It is indicated in [36] that climate change more severely impacts ecosystems located in low-temperature areas, or in other words the polar circles.

[35] provides confident data of the global oceanic anomalies from 1880 to 2005. Although in comparison with land anomaly series the increase in temperature is less, ocean temperatures have also been on the rise since 1993. It was found in [37] that the temperature of Signey Island, located among the South Orkney Islands in the Antarctic Ocean, has increased by +0.8°C in the last 50 years. 1998's ENSO phenomenon is also a relevant case study for GW research,

<sup>8</sup> See, for instance, [32].

<sup>9</sup> [33] provides the times series of greenhouse gas emissions on a global level

Figure 3: Global Land-Ocean Temperature Anomaly Index, 1979-2008.1Q.



Source: Goddard Institute for Space Studies, <http://data.giss.nasa.gov>.

since as [38] indicated, long and short-term changes affect ecosystems and ENSO was a sudden, short-term change with long-term consequences. [39] found that ENSO increased the temperature of the South Orkney archipelago by  $+2.0^{\circ}\text{C}$ . Some of the consequences of this phenomenon were also documented in [40], finding that the frequency of typhoons in the Asian-Pacific Ocean increased due to ENSO. In [36], it is argued that since the Antarctic, Pacific, Atlantic and Indian Oceans are connected, the effects of higher temperatures will be felt throughout the entire southern hemisphere, from the arctic poles to the tropical zones, and will permanently affect the ecosystems of all these oceans.

In an important study, [41] collected temperature data from the Pacific Ocean floor and found that seafloor temperatures, like surface temperatures, are also on the rise but at a lower rate. [42] suggests that the rise in ocean surface temperature has also reach the abyssal level in the central Pacific, western Atlantic and eastern Indian oceans, with decreasing patterns in the northern regions of each zone. The results in [43] support the findings of [42] by analysing the rise in temperature from 1958 to 2009 in search of an explanation to the upper-ocean-warming hiatus. In particular, authors suggest that while there was a pause in the pace at which the ocean surface is warming, this is due to absorption at deeper ocean levels. As such, the main finding attributes 30% of ocean warming to the warming below 700 m since 2004 to the present.

Particularly for the case of Pacific Ocean, [44] analyses the ENSO phenomena in a bigger perspective considering the second round impact that an increase in temperature has. This contributes to an awakening of trade winds, changes in mean climate of the tropical Pacific region, and a warmer tropical zone, particularly in the equator. Nevertheless, a "net effect" of ENSO on the Pacific Ocean in the long-term is still an on-going research subject.

The situation in the northern hemisphere appears to be quite similar. Note that the key issue for the purposes of this article is that an

increase in temperature makes fisheries more unstable due to the greater effort needed to extract the resources. Although temperature may directly affect the resource, it may also affect its food chain, particularly plankton. This is the case addressed in [45] for the North Sea, in which it is suggested that temperature influences cod recruitment, though only weak relationships were found previously. A similar situation is reported in [46], documenting how sea-surface temperature and climate change affect ecosystems in the North Atlantic Ocean. This analysis in [46] is important since it suggests that temperature not only affects phytoplankton and zooplankton but also the fish directly; thereby affecting a firm's value.

[35] compares the temperature anomaly series from both hemispheres and reveals that as of 1987 the average anomalies in the northern hemisphere are increasingly higher than those in the southern hemisphere. In 2005 the temperature anomaly in the northern hemisphere was approximately  $+0.75^{\circ}\text{C}$ , while in the south it was around half this ( $+0.36^{\circ}\text{C}$ ). This behaviour is also observed [35], presenting the anomaly series from between  $90$  and  $23.6^{\circ}\text{N}$  (the most arctic two thirds of the northern hemisphere) and finding that the anomaly in this zone increased by around  $+1.0^{\circ}\text{C}$  in 2005.

At middepths and in the deep layer within the gyre there is also evidence of warming. [47] reports higher temperatures in the Weddell Sea between 1990-8, whilst [48], [49], and [50] report the same for the Ross Sea.

On a global scale, a study in [51] looks at temperature change by dividing the earth into 21 oceanic zones and finds that since 1980 temperatures have been on the rise in all zones, including interior oceans. The report in [52] forecasts future GW in order to assess its impact and work on political policies concerning elevated temperatures. The panel's report presents their projections up to the year 2100. The forecast in [52] is of an increase of between  $+1.0$  and  $+6.0^{\circ}\text{C}$ , which is used as the basis for the estimates found in the section on numerical findings (Section 5).

#### 2.4. Literature review: global warming and its economic impact

The research on GW applied to economic phenomena is still being developed. One of the most significant problems researchers face is that the inter-sectoral consequences of GW are relatively unknown. This is known as the aggregation problem ([53]). The fact that GW has only recently been recognised as a problem also contributes to the uncertainty surrounding its consequences.

A good introduction to the literature is a survey in [54] which discusses recent discoveries concerning the economic consequences of GW. However, the studies reviewed in [54] are multidisciplinary and there are no concrete principles used across the models, leading to diverging estimates. In [55], for example, predictions are given of the economic consequences of rising sea levels in coastal zones due to the melting of ice masses on land.<sup>10</sup> The estimates show that rising sea levels will create an economic loss, but establishing policies and protective technology to prevent these losses would create even more losses. The losses are asymmetric, and although the agricultural and livestock sectors in an economy could benefit from higher temperatures, the fishing sector could be seriously damaged. In other words, one sector's gain is the other's loss.

An exhaustive annotated list of references on the economic impact of global warming is given in [56]. The list contains more than 135 papers covering the many impacts of global warming on different economic activities, including fisheries. Another sector typically associated with negative effects due to global warming is tourism. [57] offer a survey on this issue, including both a literature review and review of recent developments in tourism flow modelling.

[58] considers the economic effects on places typically visited by UK tourists around the world. The results calculate a rise of 0.3-0.4°C per decade in the regions in question, which is estimated to reduce the demand for tourism. This would make certain colder regions located within the UK more attractive, and the Eastern Mediterranean zone, plus some Brazilian and Australian natural environments less attractive. Moreover, [59] analyses the case in some Caribbean countries finding a reduction in tourism demand leading to losses under different scenarios ranging from USD 43.9 to 46.3 billion by the end of 2100.

Estimates that can be made at an aggregate level are easier to compute rather than some particular sectors. For example, [60] adapts the Ramsey-Caas-Koopmans growth model to learn more about the macroeconomic effects of GW and concludes that it reduces savings and lowers capital accumulation. [61] assumes growth with a GW adaptation strategy that consists of protecting capital. The authors show that its early implementation would have negligible effects on annual consumption, with losses of 0.44% per year in the worst case and 0.00005% in the best case. [62] develops a deterministic model, calibrated for Germany, which finds that productivity falls

and generates yearly gross domestic product (GDP) losses between 0.1% and 0.5%. However, not all the results are categorical. [63] calculates how an average temperature increase of +1°C affects GDP, resulting in +2, -3 and 0%, depending on the aggregation method. A comprehensive study, the Stern Review ([64]), attempts to provide a basis for a standard analysis of GW, but for the purpose of the present paper it represents a generalisation and does not provide the necessary depth.

At the present, there are few studies directly related to the effect of GW on the fishing industry that use elements of fisheries economics. [65] assumes that temperature, which is considered an input in the production function, is a Brownian process that directly impacts the firm. The present paper, on the other hand, takes an additional intermediary step, considering first the effect of temperatures on biomass and only then, how changes in biomass affect firm value. This paper only considers the increase in temperature.

The model in [65] makes its empirical estimate using the Solow decomposition method. According to this method, any change that cannot be attributed to another factor is said to be caused by temperature. This could include changes in technology and temporary changes in the fishing efficiency, among other factors. The model is calibrated for Greenland and Iceland and the results are similar to what is found in the present paper, although they cannot be directly compared since this involves data from different geographical zones.

The present paper and [65] also differ in that the former provides a more detailed model of how higher temperature is transferred onto firm value, and separates the two effects of temperature on biomass (oscillation and reduction). That said, [65] is the best benchmark from the current literature.

#### 2.5. Literature review: the effects of global warming on biomass

This subsection reviews the literature on Assumption 2: *Global warming affects biomass*. This is not intended to be an exhaustive review because it is not needed for the purposes of this article; rather it is a way of orientating and refining how Assumption 2 is interpreted. [66] develops an economic model under a similar assumption in an effort to learn more about how species migration due to rising water temperatures affects firms, and finds that it is possible to quickly reach a level of extraction that is not economically viable. In finding that species migrate faster than firms can withdraw capital, which creates a very risky situation for the industry, this work is relevant to this paper. While the fact that biomass is always changing due to natural causes is an important consideration, [8] shows that in the tropics the biggest biomass fluctuations are a result of anthropogenic factors, that is to say, human activity. Likewise, [67] estimates that since 1960 the biomass of pelagic fish species on the African coast has fallen by as much as 13 times due to a number of factors, including temperature.

<sup>10</sup> The melting of ice already in the water does not cause changes in sea level.

It is important to reiterate that the present paper only refers to those changes in biomass caused by increasing temperature, and only reviews the pertinent literature. For example, [68] analyses the movements of ENSO toward the southern Pacific Ocean, in particular focusing on the biomass of a commercially important species: tuna. One of the important conclusions from this study is that the reduction in tuna biomass exceeds recovery 3 to 1. In other words, the biomass lost in one period is recovered over the following three periods. In a study of the northern Pacific, [69] finds that ENSO was associated with the loss of 200 million tons of pelagic species.

Another way of proving the effect of temperature on biomass is by studying the behaviour of predators in a set geographic area ([38]). This is the technique used by [70] in a study of krill, the main food source of predators in the Antarctic Ocean, in which the close relationship between temperature and the abundance of Antarctic krill is shown. This is consistent with the research of [71], which documents how variations in the krill stock due to ENSO caused species that depend on krill to survive to migrate, thus lowering biomass. [72] documents how the inter and intra-annual variations in krill affected the biomass in sectors near the South Georgia Islands in the Antarctic Ocean. [73] estimates that an increase of  $+1.0^{\circ}\text{C}$  in the Scotia Sea (also in the Antarctic Ocean) over 100 years would reduce the biomass and abundance of krill by 95%.

In a study focusing on the coastal areas surrounding Tampa Bay in the US, [74] finds that higher temperatures incubate sicknesses and negatively affect biomass due to *acidification*.<sup>11</sup>

In the polar zones in the Northern hemisphere, ice-thaws have also been studied as one of ways that GW affects biomass. Ice-thaws influence water density and effect thermohaline circulation.<sup>12</sup> [78] shows that changes in this circulation cause a significant reduction in the stock of cod and capulin in the Barents Sea, to the north of the Scandinavian Peninsula.<sup>13</sup>

[79] finds that the marine temperature on the coasts of Greenland has increased by  $+2.0^{\circ}\text{C}$ , damaging the stock of cod and pollock, two species with very high commercial value.

The literature on fisheries economics also includes studies on how anthropogenic factors affect nature. For example, [24] develops a model that incorporates possible disasters caused by excessively high quotas, higher fishing efficiency and government subsidies. Industrial contamination is also a factor. Other works that include relevant biomass issues are cited in subsection 2.2.; i.e. [45] and [46].

Other fisheries economics studies, like [67], include temperature as

part of their models, but only as a proxy for water salinity, an indicator of biomass quality. In [80], the effects of ocean acidification and *hypercapnia*, i.e. the abnormal retention of  $\text{CO}_2$  in blood, are analysed on a global scale. Two major strengths of the article are worth mentioning: a thorough critical review of the literature concerning plausible scenarios and forecasting ocean temperature plus a detailed transmission mechanism of  $\text{CO}_2$  to species' metabolism. Particularly for the case of the south-eastern Australian marine ecosystem, in [81] the adverse effects due to fishing, ocean warming and acidification are analysed jointly. Interestingly, the interaction of these factors exacerbates damages to biomass, but when considered separately, only acidification has a negative effect on total biomass. Finally, [82] also treats ocean acidification as the main threat to marine ecosystems and fisheries in the Northeast Pacific. The authors first describe the ecosystem with current available data to then stress it with scenarios prone to acidification, including a temperature rise. The results show that acidification may have profound implications for ecosystems. It also has indirect negative impacts on finfish through changes at lower trophic levels and in fish habitats.

This review is meant to contextualize the two assumptions and also to serve as an introduction to fisheries economics. Based on the literature, it can be concluded that higher temperature (i) causes biomass oscillation and (ii) reduces biomass. Although some articles may find that for a specific region the climate could be cooling, the majority of the literature emphasised that the Earth surface—including oceans at different levels—on average is warming up. Most relevantly, this is happening in zones where biomass contains massive resources to be exploited, for example, seas close to polar circles plus zones close to the tropics ([35]-[37], [45]-[49]).

The present study models and quantifies the economic impacts that both oscillation and reduction in biomass have on fishing firms. In the case of oscillation, the model in [1] is modified to better isolate biomass shocks. The second effect, reduction of biomass, can be measured by contrasting high temperature situations. The model in [2] is updated for this purpose.

### 3. Stochastic biomass model: global warming shocks

This section develops a model for a fishery that extracts resources from a stochastic biomass. It is modelled in such a way that temperature, an exogenous factor, is the cause of biomass oscillation. The model is inspired by [1], but differs in the sense that temperature is relevant to firm value. Although this study complements [65], the approach developed here is different. [62] assumes a Brownian motion of temperature of the form:

<sup>11</sup> Among the damaging effects of a rise in ocean water temperature is the propagation of the phenomena known as *acidification*, which is fully analysed in [75]. In particular, an increase of the  $\text{CO}_2$  present in the water, which also causes global warming, negatively affects the mortality rate of some commercial species ([76]), thus affecting the fishery, and particularly in the Southern Ocean. Another channel, in which warmer temperature may affect biomass, is through *hypoxia*, which consists of lower levels of oxygen in the water. The effects of global warming on biomass through hypoxia plus some risk-managing recommendations are thoroughly analysed in [77].

<sup>12</sup> Thermohaline circulation is the name for the convective circulation that affects oceanic bodies of water on a global scale. Global circulation can be described as relatively superficial flow of water, which is heated in the tropical zones of the Pacific, Indian, and Atlantic Oceans, before dropping to the depths of the northern Atlantic Ocean.

<sup>13</sup> Both species are of high commercial value for the zone.



$$dT_t = \mu_t dt + \sigma_t dz, \quad (3.1)$$

and includes the variable  $T$ , temperature, as a fishing firm input to carry out a Solow decomposition. Thus, the impact of temperature change on the firm's value is understood. As mentioned, this study is different in that it assumes that temperature is always increasing ( $dT/dt > 0$ ), and therefore analyses the effect of stochastic biomass, not stochastic temperature, on the fishery's value.

### 3.1. Assumptions

It is assumed that there is perfect competition on the fishing market for the final product, which means one firm cannot influence the market price. The fishing industry is understood as the collection of firms that produce goods using marine resources or transform them into another product. Based on these two assumptions, temperature increases that affect biomass are assumed to exist. Resources are extracted directly from the ocean, and species are treated as *public* goods, not *common* goods (which they really are).<sup>14</sup> Hence, the firm's cost function is  $c(x,j)=c(x)$ , with  $j \in Y = \{1, \dots, J\}$ , where  $Y$  is the collection of firms that participate in the industry.

The  $T$  variable, temperature, is the first difference between this study and [1], and has only been included in [65], as mentioned above. Although temperature is included in other models as an explanatory variable,<sup>15</sup> in these cases it is only used as a proxy for water salinity, since this determines a biomass's maximum capacity. Temperature movements in this context do not necessarily involve biomass oscillations.

In the present study, the  $T$  variable causes biomass variations. It is measured in traditional units ( $^{\circ}\text{C}$ ,  $^{\circ}\text{F}$  or  $^{\circ}\text{K}$ ), and can be defined as a continuous, increasing function of effective temperature ( $TE$ ), i.e.  $T = v(TE)$ , with  $v_{TE} > 0$ . An alternative specification, which is useful for model calibration, is to define the variable in terms of categories or groups according to the GW projections specified by [52].  $T: TE \rightarrow R^+$  is assumed only because of its simplicity.

The social interest rate is  $\delta$ , which reflects the alternative cost of any investment in the economy. Capital is assumed to be homogenous, which is consistent with the assumption that there are no entry or exit barriers in a perfectly competitive market. Despite the fact that there are no barriers, there is incomplete information concerning when a shock occurs. In other words, the firm cannot know when a negative shock will occur, although it can know the variance of the biomass. This lack of information can potentially lead to short-term losses. However, the firm's reaction does not perpetuate negative results since, as proposed by [61], firms have strategies for accommodating biomass shocks. This also goes along with the conclusions of [19] regarding the high cost of adjusting capital investment, showing that in the short-term a firm will face financial stress, but in the long-term it will return to its competitive position.

<sup>14</sup> See footnote 6.

<sup>15</sup> Such as [67].

<sup>16</sup> This follows the work described in [83].

Two elements are considered in the response to GW: spending per period on mitigating the problem and the direct economic impact of biomass variability. The reaction can be interpreted as a costly adjustment to new technology, since a fleet designed to extract from a biomass with a given oscillation must increase effort to compensate for lower production due to increasing oscillation. A firm can adjust either by facing a higher number of unfavourable events until completing the learning process or by spending more on adjusting to the problem. Both solutions are expensive.

### 3.2. Model

The model can be divided into two parts: biological (biomass) and economic (firm).

#### 3.2.1. Biomass

According to [1] and [24], the stochastic biomass responds to unanticipated movements in the components of equation 2.1 and its synthesized version (3.2). The model assumes that variability is a function of temperature,  $\sigma = \sigma(T)$ , which has two precautions with respect to the traditional formulation  $\sigma = \sigma(x)$ . First, that  $\sigma(T)$  can be found by specifying an equation for how temperature affects fish metabolism and second, that  $T$  is a variable that cannot be controlled. Even with these considerations, it is biologically complex to establish the exact form of these functions. For this reason, biomass is given by equation 3.2:

$$dx = \{b(x) - h_t\}dt + \sigma(T)x dz, \quad (3.2)$$

conserving the notation from the previous sections.

#### 3.2.2. Firm

When temperature increases biomass variability, firm harvest is lower due to the fact that firm technology is not designed for the more difficult extraction that greater biomass variability entails. In this context,  $i$  can be defined as the cost incurred by the firm to carry out an extraction plan that allows it to maintain its competitive position. That is to say that  $i$  is defined as the firm's expenditure exclusively due to greater stock volatility. For simplicity, it is assumed that the transfer is direct, of the form:<sup>16</sup>

$$dT = i dt. \quad (3.3)$$

On the other hand, a fishery's reaction to GW occurs in the context of profit maximisation and the consequent knowledge attained about how to deal with a biomass with greater oscillation. This gives:

$$G(i) = \frac{\sqrt{i}}{g}, \quad (3.4)$$

the function for the firm's total expenditure for GW. Generically, it is required that  $G_i > 0$  and  $G_{ii} < 0$ . Firms could respond in different ways, but because of the depth of the effect on the ocean, stand-alone solutions are not considered.<sup>17</sup>

From equation 3.4, it is possible to state that knowledge is attained ( $G(i)$  falls) as  $i$  increases because  $G(i)$  is concave in  $i$  and also directly as a result of increases in  $g$ . Note that if  $g=0$  then  $G(i)=\infty^+$  and the firm leaves the markets.

The profit function is given by:

$$\pi(x, h, i) = \int_0^h \{p(h) - c(x)\} dh - G(i), \quad (3.5)$$

where  $p(h)$  is the demand function. The function  $c(x)$  represents the marginal cost per unit and is decreasing in  $x$ . Note that:

$$\lim_{i \rightarrow \infty} \frac{\partial G(i)}{\partial i} = \lim_{g \rightarrow \infty} \frac{dG(i)}{dg} = 0. \quad (3.6)$$

Increases in  $i$  as well as  $g$  signify a proactive adaptation strategy where short-term losses are expected in order to gain biomass risk reduction *know-how*. This also allows for the possibility of acquiring and/or maintaining a competitive position, at least in the short-term.

This function incorporates the effect of GW on profit, abstracting it from the effect on harvest.<sup>18</sup> In effect:

$$h(E, x) = qE^\alpha x^\beta. \quad (3.7)$$

For simplicity, it is assumed that  $E, \alpha, \beta = 1$  and  $q = 0.10$ .

### 3.3.3. Equilibrium and model dynamic

This subsection closely follows the derivation of [83], which presents the problem of extracting from a stochastic biomass where variability is reduced by research. The problem of maximisation on an infinite horizon means repeating the maximisation infinite times. Since the formulation is similar each time, one period can be optimised to find the solution for the infinite horizon. This is the *Bellman equation*, which for the firm corresponds to the maximisation of equation 3.8 subject to equation 3.2:

$$\delta V(x, T) = \max_{\{h, i\}} \left\{ \pi(x, h, i) + \frac{d}{dt} E_i V(x, T) \right\}. \quad (3.8)$$

This expression is equivalent to equation 9, p. 293, in [1], except that there the univariate case is presented. The first term on the right side corresponds to the current profit, while the second term on the right represents the expected appreciation.  $h$  and  $i$  are the decision variables and  $x$  and  $T$  are the state variables. To find the solution, the first-order conditions (FOC) are derived, noting that the second term on the right side is a *diffusion process* whose stochastic differential can be found using Itô's Lemma:

$$dV = \frac{dV}{dt} + V_x dx + V_T dT + \frac{1}{2} \{V_{xx}(dx^2) + V_{TT}(dT^2)\} + V_{xT}. \quad (3.9)$$

Since the problem is time-independent,  $dV/dt=0$ . Substituting in the equations for  $dx$  and  $dT$ , and applying Itô's Lemma:

$$dV = \frac{dV}{dt} + V_x dx + V_T dT + \frac{1}{2} \{V_{xx}(dx^2) + V_{TT}(dT^2)\} + V_{xT}. \quad (3.10)$$

Considering  $E_t dz_t = 0$ , since  $z_t$  is a Wiener process with mean zero, and substituting equations 3.5 and 3.10 into equation 3.8 gives:

$$\delta V(x, T) = \max_{\{h, i\}} \left[ \int_0^h \{p(h) - c(x)\} dh - G(i) + V_x \{b(x) - h\} + iV_T + \frac{1}{2} V_{xx} \sigma^2 x^2 \right] \quad (3.11)$$

The FOC are:

$$\delta \frac{\partial V(x, T)}{\partial h} = \{p(h) - c(x)\} - V_x = 0 \Rightarrow \{p(h) - c(x)\} = V_x, \quad (3.12)$$

$$\delta \frac{\partial V(x, T)}{\partial i} = -G_i(i) + V_T = 0 \Rightarrow G_i(i) = V_T. \quad (3.13)$$

Both FOC represent partial results of the economic effects of GW. The direct effects of GW on the fishing industry in terms of social well-being can then be derived. The first FOC represents the standard condition of optimality for  $h$ . The marginal extraction value is equal to the shadow price of one additional extracted unit. The second FOC represents firm transfer when faced with a shock, and may be different for each firm. It is interpreted as the marginal expense incurred by the firm, which is equivalent to the change in firm value because of an increase in temperature. In summary, this FOC can be used to find the optimal firm response when faced with temperature shocks.

The value of  $V_T$  will be less as  $G_i$  falls. This occurs with increases of  $i$  and/or  $g$ , that is to say, when the impact is perceived as high, and spending on mitigating GW increasing. The firm is completely isolated from temperature when  $g \rightarrow \infty$  and/or  $i \rightarrow \infty$ .

To determine how the industry is affected, the optimal values for  $h^*$  and  $i^*$  are substituted into equation 3.8 and the first derivative with respect to  $x$  is found. In effect,

$$\delta V_x = \{p(h^*) - c(x) - V_x\} \frac{dh^*}{dx} - c_x h^* + b_x V_x + \sigma^2(T) x V_{xx} + \{b(x) - h^*\} V_{xx} + i V_{Tx} + \frac{1}{2} \sigma^2(T) x^2 V_{xxx}. \quad (3.14)$$

Differentiating the result of  $dV$  with respect to  $x$  (equation 3.10) gives an expression that contains the last three terms on the right side of

<sup>17</sup> As opposed to fish farming, where temperature can be controlled.

<sup>18</sup> However, the decision is affected in a tangential way by temperature, since movements of  $x$  are caused only by this decision.

equation 3.14,

$$\frac{d}{dt}E_t V_x = \{b(x) - h^*\}V_{xx} + iV_{Tx} + \frac{1}{2}\sigma^2(T)x^2V_{xxx}, \quad (3.15)$$

and from the FOC 3.12 it follows that this expression is equivalent to:

$$\frac{d}{dt}E_t V_x = \frac{d}{dt}\{p(h^*) - c(x)\}. \quad (3.16)$$

Substituting this result into equation 3.14 and considering that the first term is zero (due to the CPO 3.12) gives:

$$\delta V_x = -c_x h^* + b_x V_x + \sigma^2(T)xV_{xx} + \frac{d}{dt}\{p(h^*) - c(x)\}. \quad (3.17)$$

Combining similar terms, simplifying and solving gives a modified version of the *fundamental equation of the use of natural resources*, similar to equation 18 in [1], p. 294:

$$\delta + \sigma^2(T)xARA(x,x) = b_x + \left[ \frac{d\{p(h^*) - c(x)\}/dt}{p(h^*) - c(x)} - \frac{c_x h^*}{p(h^*) - c(x)} \right], \quad (3.18)$$

where  $ARA(x,x) = -V_{xx}/V_x$  is the coefficient of absolute risk aversion ([84]). The left side of the equation shows that the opportunity cost increases when biomass oscillates.

The right side shows that the profit *in-situ* fish unit breaks down into the profit conferred by greater biomass availability ( $b_x$ ), plus the economic change divided into (i) earnings due to higher margins, and (ii.) reduction of the marginal cost.

This equation can be used to assess the economic effect of *biomass oscillation* on the fishing industry. The opportunity cost increases because  $\sigma(T) \neq 0$ ,  $\sigma_T > 0$ ,  $x > 0$  and  $ARA(x,x) > 0$ . This result is an algebraic representation of the harmful effect of GW on the industry. The traditional proposal for the extraction of natural resources is returned to in the event that the resource is completely controlled.

The same methodology is used to determine the increase in opportunity cost caused by a rise in temperature. Differentiating equation 3.14 with respect to  $T$  gives,

$$\delta V_T = \{p(h^*) - c(x) - V_x\} \frac{dh^*}{dT} + \sigma_T \sigma(T)x^2V_{xx} + \{b(x) - h^*\}V_{xT} + iV_{TT} + \frac{1}{2}\sigma^2(T)x^2V_{xxxT}, \quad (3.19)$$

On the other hand, the derivative of  $dV$  (equation 3.10) with respect to  $T$  equals:

$$\frac{d}{dt}E_t V_T = \{b(x) - h^*\}V_{xT} + iV_{TT} + \frac{1}{2}\sigma^2(T)x^2V_{xxxT}. \quad (3.20)$$

Substituting into equation 3.19, simplifying, dividing by  $V_T$  and noting that the first term is zero (because of FOC 3.12), gives:

$$\delta + \sigma_T \sigma(T)x^2ARA(x,T) = \frac{d}{dt} \frac{E_t V_T}{V_T}, \quad (3.21)$$

where  $ARA(x,T) = -V_{xx}/V_T$  is an indicator of the coefficient of absolute risk aversion. On the left side an increase in firm opportunity cost due to biomass variability and the fact that  $\sigma(T) > 0$ ,  $\sigma_T > 0$  and  $ARA(x,T) > 0$  can be observed. Optimally, higher opportunity cost is equal to the expected change in firm value due to temperature increase (in percentile units).

The result gives the coefficient for the transfer of higher temperature onto the fishery's opportunity cost. From FOC 3.13 it is inferred that:

$$\frac{d}{dt} \frac{E_t V_T}{V_T} = \frac{d}{dt} \frac{G_i}{G_i}. \quad (3.22)$$

That is to say, once knowledge has been attained and/or adaptation is complete, spending on this costs the same as any other investment in the economy. Thus, equation 3.22 summarises the economic disincentive caused by biomass oscillation.

#### 4. Deterministic biomass model: the direct effect of global warming

This section studies the other effects of GW from a different perspective than that of the previous section. Note that the effects are complementary and occur simultaneously. Later in the paper the theoretical difficulties in joining these two models will be explained.

A modification to the *fundamental equation of the use of natural resources* is proposed in this model due to the introduction of  $T$ .

The harvesting path that maximises firm value is derived from the dynamic models. This section models how GW-induced temperature increase damages harvesting path, and thus, firm value. The introduction of  $T$  is associated to a decrease in biomass and the consequent rise in funding cost and risk.

Assuming the biomass and profit function are dependent on  $T$ , the discount rate therefore includes an element of risk when it is influenced by an exogenous circumstance, as described in equation 4.1:

$$b_x(x,T) + \frac{\partial \pi(T, \dots) / \partial x^*}{\partial \pi(T, \dots) / \partial h} \Big|_{h=b(x^*,T)} = \delta(T), \quad (4.1)$$

with  $\delta_T > 0$ . Comparative statics are used because of the simplified view of the impact of less biomass on the firm that they provide. If the model is dependent on  $x$  and  $T$ , then the long-term movements (when  $\dot{x} = 0$ ) are exclusively due to increases in  $T$ , through a function of mortality and/or species migration.

Unlike the previous model, all of the equations are deterministic. For simplicity, the work is mainly framed around the model in [2]. However, this study is an advancement of this model not only because it incorporates GW but also because it calibrates the model specifically for fishing firms.

#### 4.1. Assumptions

The model is developed for a fishing firm that participates in a competitive environment. The social discount rate is  $\delta(T)$  with  $\delta_T > 0$ , and can be asymmetrical depending on the sign of  $\pi(\dots)$ . In effect:

$$\delta(T) = \begin{cases} \delta_1(T) & \text{si } \pi \geq 0 \\ \delta_2(T) & \text{si } \pi < 0. \end{cases} \quad (4.2)$$

This rate is assumed to be exogenous to the firm but endogenous to the industry. Investment adjustments are assumed to be instantaneous, as are capital increases and reductions.

#### 4.2. Model

The model is divided into two parts: biological (biomass) and economic (firm).

#### 4.3. Biomass

As Smith's work shows, the biomass is the natural resource's "technological restriction": a population that exceeds the biomass's capacity cannot survive. As such, within that environment, the climatic variable is introduced in a manner similar to the methodology in [24] for the effect of illness, in the sense that a disturbance is added that modifies the deep parameters of recruitment, growth, and mortality. In effect, if  $M(T)$  is a function of mortality and/or migration caused exclusively by higher temperature, then the biomass corresponds to

$$\dot{x} = b(x)M(T), \quad (4.3)$$

where  $b_x > 0$  if  $x \in \{x_m, x_e\}$ ,  $b_x < 0$  if  $x \in \{x_e, x_p\}$  and  $M_T < 0$ .<sup>19</sup> All of the variables are time-dependent and each one is represented by a differential equation.

The previous assumptions regarding the measurement of  $T$  are maintained despite the fact that in this model it makes more sense to define the effect of  $T$  by categories, and thus analyse the static comparative of moving from one category to another. This specification also allows nonlinearities of the effect of warming the water on the population to be captured. Based on this argument,

$M(T)$  can represent mortality levels (*severe*→*mild*), depending on the temperature range being measured. Formally it corresponds to a function  $M(T)$  that collapses the effective temperature into some category, which numerically defines the effect on the population:

$$M(T) : \mathbb{R}_T^+ \rightarrow M(\omega_i) \rightarrow \mathbb{R}_\tau^+, \quad (4.4)$$

As such, each  $T$  has a correspondent in the set,  $\tau$ :

$$T : \mathbb{R}_T^+ \rightarrow \tau, \quad (4.5)$$

The set  $\tau$  is a finite union that excludes subsets  $\omega_i$ :

$$\tau = \bigcup_{i=1}^{\infty} \omega_i ; \bigcap_{i=1}^{\infty} \omega_i = \emptyset, \quad (4.6)$$

$$\omega_i = [T_{i-j}, T_i] ; i, j \in \mathbb{R}^{++} ; i > j, \quad (4.7)$$

In this way, the temperature interval  $\omega_i$  produces a lower rate of biomass mortality than  $\omega_{i-j}$  with  $i > j$ . There is unambiguity on the effect caused by temperature  $T = T_0$  on the mortality  $M(T_0) = M_0$  but not if that mortality  $M_0$  is due only to temperature  $T_0$ .

#### 4.4. Firm

The firm's decisions are synthesised in the dynamics of the invested capital. The reason for this is that the firm always extracts the maximum amount permitted by the biomass subject to its capital restriction, and thus, the optimal extraction decision is subordinate to the investment decision.

Investment is  $K$  (i.e. boats). There is an immediate capital adjustment, and thus if  $K$  corresponds to an acquired boat, all are assumed as equal and an active secondary market is also assumed. The cost function of the representative firm is:

$$C(h, x, K, T) = \varphi(h, x, K) + G(h, T, M(T)), \quad (4.8)$$

This equation resembles equation 3.2 in [2], p. 413. Harvest corresponds to  $h \in [x_m, x_p]$ , where  $x$  is still fishable biomass.

Based on an argument similar to that presented in the previous section, the function  $G(h, T, M(T))$  represents the firm's response to temperature increases. It is assumed that  $G_h > 0$ ,  $G_T > 0$  and  $G_{M(T)} < 0$ . On the other hand, and following [2], the function  $\varphi$  is characterized by  $\varphi_h > 0$ ,  $\varphi_x \leq 0$  and  $\varphi_K \geq 0$ .

The term  $\varphi_x < 0$ , called *stock externality*, implies that improvements in biomass quality are interpreted as a less costly harvest. The term  $\varphi_K > 0$ , called *crowding externality*, appears when the amount of boats is above the optimal level, causing congestion in resource extraction. Under this condition, fish cease to be *public* goods and become *rival* goods. Consequently, this serves as the capital adjustment

<sup>19</sup> The fact that  $M_T < 0$  indicates that mortality is high when temperature levels are low, and later decreases as temperature increases. The reason for this is that when temperature increases the mortality of less adaptable species increases, later stabilising for species that are more resistant that mortality depends on the size-shape relation of species.

mechanism: above average profits create incentives for new competitors to enter, which in turn generates *crowding externalities* that increase the cost of extraction until profits return to their normal level. The industry's competitive environment is constructed by applying the same logic to *stock externalities*.

Each boat allows for a maximum extraction level  $h$ , where the firm's total extraction is  $Kh$ . With this intervention, biomass takes the form:

$$\dot{x} = b(x)M(T) - Kh. \quad (4.9)$$

The firm's total income depends on the level of extraction and the level of capital invested  $\rho(Kh)$ , therefore the profit is:

$$\pi(h, x, K, T) = \frac{\rho(Kh)}{K} - C(h, x, K, T), \quad (4.10)$$

where  $\rho(Kh)/K$  is the income obtained by extraction  $h$ . The industry's price level, then, is  $\rho(Kh)/Kh$ . In a perfect competition environment, it holds that:

$$\frac{\rho(Kh)}{Kh} = \varphi_h + G_h, \quad (4.11)$$

This is equivalent to equation 4.2 in [2], p. 414. New firms enter the market when they observe  $\pi > 0$ , and firms that are already participating in the market leave when  $\pi < 0$ . This decision is in line with the amount of capital invested, and therefore the dynamic equation corresponds to:

$$\dot{K} = \delta(T) \left[ \frac{\rho(Kh)}{K} - C(h, x, K, T) \right], \quad (4.12)$$

with:

$$\frac{\partial \dot{K}}{\partial T} = \delta_T \left[ \frac{\rho(Kh)}{K} - C(h, x, K, T) \right] - \delta(T) C_T. \quad (4.13)$$

When equation 4.13 is positive the firm remains in the industry, although it requires more capital in order to compensate for losses due to GW. Nevertheless, this capital is invested with a lower rate of return, since the opportunity cost is greater ( $\delta_T > 0$ ). This partial result provides a picture of the mechanism through which higher temperature affects investment dynamics, making the industry less attractive.

From a dynamic perspective, for there to be investment, profits must continue to increase in order to compensate for the cost  $\delta(T)C_T$  (increasing in  $T$ ), even though returns are still smaller.

#### 4.5. Development and model equilibrium

The model is summarised by the following system of equations:

$$\dot{x} = b(x)M(T) - Kh, \quad (4.14)$$

$$p = \varphi_h + G_h, \quad (4.15)$$

$$\dot{K} = \delta(T)[ph - C(h, x, K, T)], \quad (4.16)$$

because price is equal to marginal cost all the time, equation 4.15 is solved instantaneously, and  $h$  is exogenously determined. Therefore, the dynamic system to solve is:

$$\dot{x} = F(x, K, T) \quad (4.17)$$

$$\dot{K} = I(x, K, T) \quad (4.18)$$

with initial conditions  $x(0) = x_0$  and  $K(0) = K_0 > 0$ . Should price movements cause the margin per unit to fluctuate, the form of  $I(x, K, T)$  will be nonlinear. On the other hand, if the price is constant, then the form is a horizontal line in the plane  $(x, K)$ .

Figure 4 presents the model's solution in a phase diagram, i.e. when  $x^* = K^* = 0$ .  $F(x^*, K^*, T) = 0$  corresponds to a point of biological and economic equilibrium  $(x^*, K^*)$ , which represents *equilibrium between resource mass and its environment*.  $I(x^*, K^*, T) = 0$  represents *equilibrium between the resource exploiting firm and any investment made in the economy*. The phase diagram indicates how quickly equilibrium can be reached from any point in the plane, starting from initial conditions. Superimposing both equations divides the first quadrant into five regions. Each region contains the direction from a point towards the steady-state equilibrium. Without the firm's intervention the equilibrium is  $x = x_m$ . With the firm's introduction, there are two equilibriums,  $P^I$  and  $P^{II}$ , both of which are unstable. As indicated in Figure 4, the firm rests on point  $P^{II}$ , which corresponds to the equilibrium reached once  $x_m$  has been abandoned.

However, the phase diagram shows equilibrium in a steady-state. Assuming that temperature is non-stationary, its increase moves the curves in the direction shown in Figure 5.<sup>20</sup> In such a situation, and following the previous logic, the new equilibrium occurs at point  $P^{III}$ , with lower capital levels extracting fewer resources. The move from  $P^{II}$  to  $P^{III}$  implies firms leaving the industry and lower biomass capacity. If the firms continue to operate with the same technology, the result of the exercise is predictable: the temperature increase moves the equilibrium to a point  $(0, K_t^* > 0)$ , similar to  $P^{IV}$  in Figure 6. In this scenario  $h^* = 0$  since  $h < x_m$ , coinciding with a capital investment level with a return rate of  $-\infty$  if  $\lim_{h \rightarrow 0} C(h, x, K, T) = \infty$ , with  $K_0 > 0$ . In other words, for a positive level of initial capital, the firm that doesn't extract resources gets a return rate of  $-\infty$  for that capital. The definition of the firm's value considered in this model is expressed as:<sup>21</sup>

$$V = [ph - C(h, x, K, T)] - \dot{K}[\delta(T)]. \quad (4.19)$$

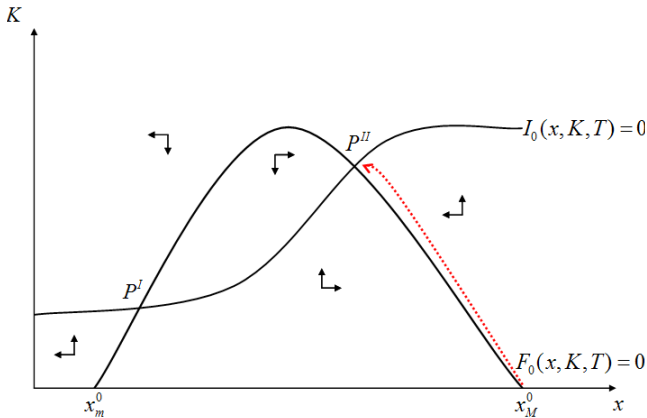
From this equation it can be concluded that while  $ph$  increases by increments of  $h$  ( $p$  is constant), the cost function  $C(h, x, K, T)$  increases through  $h$  and  $T$ , reducing the firm's value. In the same way, the effect of greater investment is added through  $K^*$ , since it is expected to

<sup>20</sup> It is clear that biomass capacity, measured as the area under the  $x^*$  curve, is reduced. However, this does not necessarily modify  $x_m$  and/or  $x_m$ .

<sup>21</sup> Similar to that used in [86].

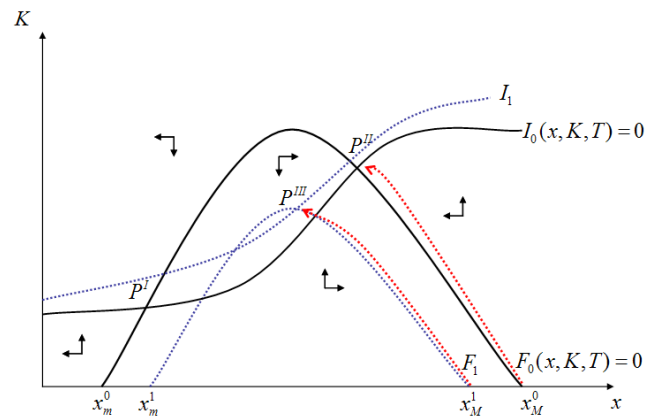
increase up to an economically sustainable level and then decline as a result of the “many boats-few fish” effect, accompanied by a return that makes investment less and less attractive. This argument proves that the non-stationary nature of temperature has harmful effects on the industry, even in the long-term.

**Figure 4: Initial phase diagram**



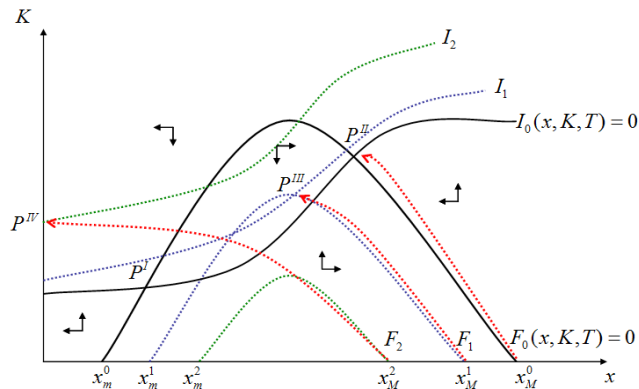
Source: Own elaboration.

**Figure 5: Intermediate phase diagram**



Source: Own elaboration.

**Figure 6: Final phase diagram**



Source: Own elaboration.

## 5. Numerical findings

This section presents some of the numeric results from both models, calibrated according to the studies presented in Section 2.

### 5.1. Stochastic biomass model

The analytical form of the model is similar to that presented in [87], [86], [24], [88], [89], and [1]. These studies use equations similar to the equations 5.2, 5.3, 5.4 and 5.6 shown in Table 1. The parameters used are taken from [27], [88], and [23], despite being responses to different situations from those presented in this paper. Nevertheless, these parameters are used because they provide a convenient description of a mid to large-sized fishing firm that does not affect industry price levels.

Since it is difficult to know the exact analytical form of a biomass variation function, the function  $\sigma(T)$  takes on different values in the biomass equation (3.2),

$$dx = \{b(x) - h_t\}dt + \sigma(T)x dz, \quad (3.2)$$

The values are considered reasonable in light of a review of [73], [79], [36], [69], [68], and [67]. In practice, seven situations are considered for  $\sigma(T)$ :

$$\sigma(T) \in \Sigma, \\ \Sigma = \{1\%, 2\%, 3\%, 4\%, 5\%, 10\%, 20\%\}$$

Figure A1 of Annex A shows equation 3.2 with the  $\Sigma$  values. Unlikely cases (10 and 20%) are included to see how robust the results are. The estimation corresponds to the annual value of a firm that extracts resources from a biomass with different volatilities. The definition of value is the result of annual profit maximisation, subject to the availability provided by the biomass. The estimate is given by equation 5.1:

$$\delta V(x, T) = \int_{\alpha}^{h^*} p(h) - c(x)h_t^* - G_i(i) + V_x \{b(x) - h_t^*\} + i^*V_T + \frac{1}{2}V_{xx}\sigma^2x^2 \quad (5.1)$$

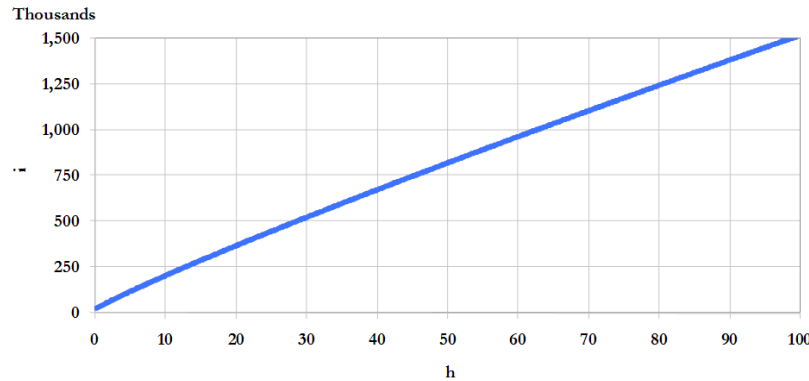
To normalise the units of account, the results are a benchmark for the case  $\sigma(T)=0$ . Other partial results are not included in order to focus the analysis exclusively on the impact on value.

#### 5.1.1. Calibration

The calibration of the equations is presented in Table 1. The values of equation 5.2 are measured in thousands of metric tons and the values of equations 5.4 and 5.5 are measured in monetary units (i.e. millions of dollars). The  $a_2$  parameter in equation 5.2 is used as an adjustment parameter for units of measurement. A firm's spending on GW is assumed to increase as biomass variability rises, according to Table 2. An extraction of  $h \in [0, 100]$  (thousands of tons) is assumed, obtained from 1000 observations. The firm's response series is presented in

Figure 7, this is obtained assuming a temperature transfer equation of  $197,894.63T^{0.9}$ , with  $T \in [0, 10]$  distributed across 1000 observations.

Figure 7: Response series for simulated firm



Source: Own elaboration.

### 5.1.2. Results

The results are displayed in Table 3. The "Average Biomass" row provides the average firm value with respect to the benchmark for the firm's fishable biomass, calculated using equation 5.7:

$$\text{Average Biomass} = \frac{1}{h^{MAX}} \sum_{h=0}^{h^{MAX}} \frac{V_h |_{\sigma(T) \in \Sigma}}{V_h |_{\sigma(T)=0}} \quad (5.7)$$

This calculation is repeated for all elements of  $\Sigma$ . The value of  $h^{MAX}$  corresponds to the maximum value of the firm's extraction, which is assumed to be proportional to the total biomass, and  $V_h$  is the annual value of the firm that sells  $h$  amount of tons. Figure 8 graphs the percentage change in value per biomass unit as the firm extracts larger and larger quantities of resources. As expected, value falls as biomass variability increases, from -6.4% loss when  $\sigma=1\%$ , to -44.6% when  $\sigma=20\%$ .

Table 1: Calibration of stochastic biomass model.

Equation	Function	Analytical Form	Parameters
(5.2)	Biomass Function	$b(x) = a_1x + a_2x(1 - x/a_3)$	$a_1=0.40$ $a_2=0.14$ $a_3=320$
(5.3)	Demand Function	$p(h) = b_1 - b_2h$	$b_1=20000$ $b_2=-0.09$
(5.4)	Marginal Cost Function	$c(x) = c_1x^{-c_2}$	$c_1=15000$ $c_2=-0.05$
(5.5)	Spending Function due to GW	$G(i) = \frac{\sqrt{i}}{g_i}$	$g_k = \{100; 500; 7000; 10000\}$
(5.6)	Extraction Function	$h = qE^{\alpha}x^{\beta}$	$q=0.10$ $E=\alpha=\beta=1.00$

Source: Own elaboration based on [87], [86], [24], [88], [89], and [1].

Table 2:  $g_k$  values for different  $\sigma(T)$  values

Value of $\sigma(T)$	Value of $g$
0, 1, 2, 3%	$g_1=100$
4, 5%	$g_2=500$
10%	$g_3=7000$
20%	$g_4=10000$

Source: Own elaboration.

Table 3: Change in firm value due to stochastic biomass (base:  $\sigma(T)=0\%$ ).

$\sigma(T)$	1%	2%	3%	4%	5%	10%	20%
Average Biomass	-6.42%	-10.81%	-14.37%	-17.51%	-20.35%	-31.11%	-44.87%
Standard Deviation	0.10	0.13	0.15	0.16	0.17	0.19	0.20
Time Trend	-0.01%	-0.02%	-0.03%	-0.04%	-0.04%	-0.06%	-0.08%
S.D. of Residuals	0.09	0.10	0.11	0.11	0.11	0.10	0.10
R <sup>2</sup>	30.66%	43.17%	51.03%	57.54%	62.66%	76.02%	73.50%

Source: Own elaboration.

The harmful effects of biomass variation on firms can also be calculated by assuming that a firm decides to extract resources from a biomass with a known variation of  $\Sigma$ . Each marginal unit extracted causes exposure to temperature shocks. Exposure is then calculated by estimating the noise around a trend, which is understood to be the expected value of each extraction.

In Table 3 the "Trend" row shows the estimation given by equation 5.8:

$$\frac{V_h |_{\sigma(T) \in \Sigma}}{V_h |_{\sigma(T)=0}} = \mu_h h + \varepsilon_h, \quad (5.8)$$

where  $\mu_h h$  is the trend and  $\varepsilon_h$  is white noise. The coefficient  $\mu_h$  is the percentage change in firm value (dependent variable) as harvesting increases (independent variable).

Since the variance of the stochastic term stabilises around 10%, the  $\mu_h$  values for all  $\Sigma$  elements can be compared to judge, with a certain amount of confidence, the loss of value as more resources are extracted. The coefficient of this trend (value loss as extraction increases) increases (in absolute terms) as  $\sigma$  grows. When  $\sigma=1\%$ , firm value is reduced by -0.014% for each marginal unit extracted, and

when  $\sigma=20\%$ , exposure causes a -0.081% reduction per marginal unit extracted, confirming the detrimental effects of stochastic biomass on fisheries.

## 5.2. Deterministic biomass model

This model is calibrated based on studies in [88], [23], [10], [20], [2], and [12]. Although these studies have different focuses and use different processes, they are still useful for the bio-economic purposes of the present research.

In [49], forecasts are used for the temperature anomaly. The present paper presents the results considering 12 points from a series described by equation 5.9:

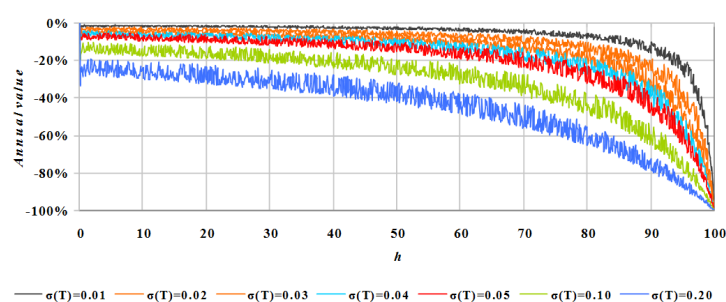
$$T_t = 0.3 + 0.8 \cdot (t - 1). \quad (5.9)$$

with  $t \in [1, 12]$ . Figure A2 from Annex A provides a graphic illustration of the biomass equation (4.4):

$$\dot{x} = b(x)M(T), \quad (4.4)$$

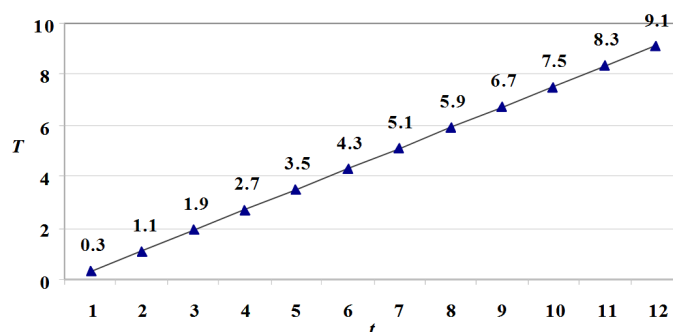
for different values of  $T \in \Theta$  measured in degrees Celsius and presented in Figure 9.

Figure 8: Changes in firm value per different biomass volatility



Source: Own elaboration.

Figure 9: T values used in estimations



Source: Own elaboration.



In this model the estimate focuses on firm value and the dynamics of invested capital. Applied value is defined as:

$$V = [ph - C(h, x, K, T)] - \dot{K}[\delta(T)]. \quad (4.19)$$

As with the previous case, these results are a benchmark for the case of a temperature anomaly of +0.3°C, in order to standardise the unit of measurement.

### 5.2.1. Calibration

The calibration is presented in **Table 4**. The values of equations 5.10 and 5.15 are measured in thousands of metric tons, the values for equations 5.11 and 5.12 are measured as percentages, and finally the values of equations 5.13 and 5.14 are measured in monetary units (*i.e.* millions of dollars). The parameter  $k_2$  from equation 5.10 is used as an adjustment parameter for units of measurements. An extraction of  $h \in [0, 100]$  (thousands of tons), obtained with 1000 observations, is assumed for the estimate.

when it is +9.1°C.

The methodology from the previous section provides another way of investigating how temperature influences value. It is assumed that a firm extracts resources from a biomass with a given temperature, expressed by  $\Theta$ . Marginally increasing the level of extraction over time exposes the firm to a reduction in biomass that could affect the economic yield of the harvest. This exposure is quantified in terms of a noise around a trend, which is understood to be each extraction's expected value. The results are presented in the "Trend" row in **Table 5**, and correspond to the estimate provided by equation 5.17:

$$\frac{V_h|_{T \in \Theta}}{V_h|_{T=0.3^\circ\text{C}}} = \mu_h h + \varepsilon_h, \quad (5.17)$$

where  $\mu_h h$  is the trend and  $\varepsilon_h$  is white noise. The coefficient  $\mu_h$  indicates the percentage change in firm value (dependent

**Table 4: Deterministic biomass model calibration**

Equation	Function	Analytical Form	Parameters
(5.10)	Partial Biomass Function	$b(x) = k_1 x + k_2 x (1 - x / k_3)$	$k_1 = 0.40$ $k_2 = 0.50$ $k_3 = 166.33$
(5.11)	Mortality and/or Migration Function	$M(T) = l_1 T^{-l_2}$	$l_1 = 1.00$ $l_2 = -0.30$
(5.12)	Interest Rate	$\delta(T) = m_1 T^{-m_2}$	$m_1 = 0.09$ $m_2 = -0.20$
(5.13)	Function for firm reaction to GW	$G(h, T, M(T)) = n_1 h M(T)^{n_2}$	$n_1 = 1.00$ $n_2 = -0.50$
(5.14)	Partial Cost Function	$\phi(h, x, K) = r_1 h + r_2 x + r_3 K$	$r_1 = 2.00$ $r_2 = -2.00$ $r_3 = 0.01$
(5.15)	Extraction Function	$h = qE^{\alpha} x^{\beta}$	$q = 0.10$ $E, \alpha, \beta = 1.00$

Source: Own elaboration based on [88], [23], [10], [20], [2], and [12].

### 5.2.2. Results

The results for firm value are presented in **Table 5**. The "Average Biomass" row provides changes (%) in value with regard to the benchmark from the results of equation 5.16,

$$\text{Average Biomass} = \frac{1}{h^{MAX}} \sum_{h=0}^{h^{MAX}} \frac{V_h|_{T \in \Theta}}{V_h|_{T=0.3^\circ\text{C}}}. \quad (5.16)$$

The calculation is repeated for all  $\Theta$  elements.  $h^{MAX}$  is the firm's maximum extraction level, which is assumed to be proportional to total biomass, and  $V_h$  is the annual value of a firm that sells  $h$  tons.

This confirms that when temperature increases, value falls due to less fishable biomass, from -8.68% when the anomaly is +1.1°C to -9.98%

variable) as harvest (independent variable) increases.

On average, the biomass trend and the cyclical component are stable as temperature increases. Consequently, the anomaly does not substantially disturb the firm's risk profile, although it does hurt its rate of return because of lower annual profit.

An analysis of the amount of capital invested, which is related to the movement of the discount rate and annual profits, contributes to the understanding of this phenomenon by indicating the direction of capital contributions or withdrawals both in transitory and steady-state. Once a steady-state has been reached, capital only moves because of increases in temperature. In effect, fishing firms increase (lower) capital as  $\delta(T)$  increases (lowers) and/or the profits are positive (negative), as equation 4.16 indicates. Measuring capital levels is understood to be a measurement of how attractive the industry is.

Table 5: Change in firm value due to biomass reduction (base:  $T=0.3^{\circ}\text{C}$ ).

Temperature	1.1	1.9	2.7	3.5	4.3
Average Biomass	-8.69%	-9.00%	-9.21%	-9.37%	-9.49%
Standard deviation	0.02	0.02	0.02	0.02	0.02
Time Trend	-0.14%	-0.15%	-0.15%	-0.15%	-0.16%
S.D. of Residuals	0.03	0.03	0.03	0.03	0.04
Temperature	5.9	6.7	7.5	8.3	9.1
Average Biomass	-9.24%	-9.78%	-9.86%	-9.93%	-9.99%
Standard deviation	0.02	0.01	0.01	0.01	0.01
Time Trend	-0.15%	-0.16%	-0.16%	-0.16%	-0.16%
S.D. of Residuals	0.03	0.04	0.04	0.04	0.04

Source: Own elaboration.

Table 6: Investment per biomass unit.

Temperature	1.1	1.9	2.7	3.5	4.3
Average Biomass	1.38%	1.68%	1.90%	2.11%	2.27%
Standard deviation	5.76	7.02	7.96	8.74	9.42
Time Trend	-0.15%	-0.19%	-0.21%	-0.26%	-0.25%
S.D. of Residuals	5.76	7.01	7.96	9.27	9.41
Temperature	5.9	6.7	7.5	8.3	9.1
Average Biomass	-19.50%	-20.51%	-20.56%	-20.60%	-20.63%
Standard deviation	30.83	32.59	32.84	33.07	33.28
Time Trend	-1.16%	-1.23%	-1.24%	-1.24%	-1.25%
S.D. of Residuals	30.82	32.58	32.83	33.06	33.27

Source: Own elaboration.

The results are presented in Table 6. The "Average Investment" row provides the average capital per biomass unit for the different temperature anomalies, provided by equation 5.18:

$$\text{Average Investment} = \frac{1}{h^{MAX}} \sum_{h=0}^{h^{MAX}} \frac{\dot{K}_h |_{T \in \Theta}}{b(x)M(T)_h |_{T \in \Theta}}. \quad (5.18)$$

Capital appears to grow as the anomaly grows until reaching around  $+4.3^{\circ}\text{C}$ . Before reaching this temperature investment is around 0.015 monetary unites per biomass unit (*i.e.* millions of dollars per metric ton). After passing this temperature, however, capital falls and stabilises in negative terms for higher temperature values. This trajectory can be interpreted in a similar way to how fleets adapt to resource availability. In fact, temperatures lower than  $+4.3^{\circ}\text{C}$  indicate that the investment flow should be positive, which suggests that—economically speaking—higher extraction capacity is required. After this point, temperature reduces biomass to levels where it is more convenient to extract from the biomass at a less than maximum capacity. The result suggests capital withdrawal each time the anomaly surpasses  $+4.3^{\circ}\text{C}$ , in which case a reduction of 0.2 monetary units per biomass unit is expected. This is the very circumstance that creates the "many boats, few fish" problem.

## 6. Discussion

This section looks at the problems found when the two models are joined in order to discuss the shared effects of GW. The equation for biomass (6.1) indicates that the joint model does not allow both effects to coexist and thus, it is impossible to calculate numerical results.

$$dx = \{f(x, T) - h_t\}dt + \sigma(T)xdz. \quad (6.1)$$

For the purposes of the arguments presented in this paper, it is worth mentioning some similarities between both models.  $f(x, T)=b(x)$  and  $dx \neq 0$  represent the stochastic model. When  $dx=0$  and  $\sigma(T)=0$ , this represents the deterministic model. Equation 6.1, when  $dx=0$ ,  $f(x, T)=b(x)$  and  $\sigma(T) \neq 0$ , is graphed in the phase diagram in Figure 10,<sup>22</sup> showing that the expected biomass is within the confidence interval from the stochastic term  $\sigma(T)xdz$  of equation 6.1. In a steady-state, when  $dx=0$ , equilibrium is  $P''$ .

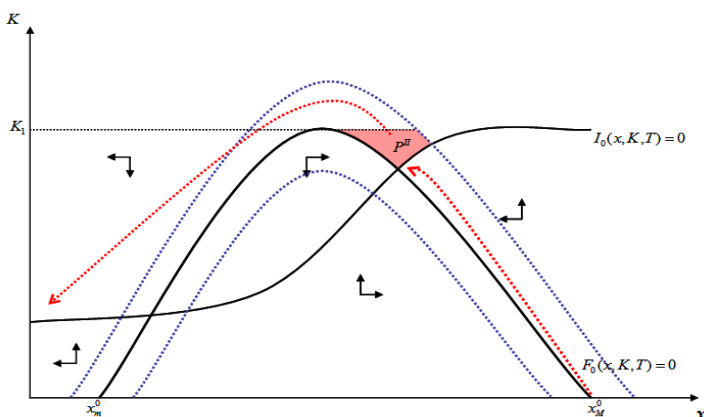
The problem with doing this is that it makes the initial equilibrium unstable. At the equilibrium point, the functions of the derived probabilities are degenerate: with a probability equal to one the

system lands on  $(0, K_t)$ , as is shown in **Figure 10**. In effect, around equilibrium there is an area that has been divided in four quadrants because of biomass variation that does not disappear in the long term. Supposing that  $\sigma(T) > 0$ , an increase in temperature will move equilibrium to the upper quadrant, even when  $\sigma(T)$  is small. The phase diagram indicates when equilibrium is located around this area, when  $K > K_t$ , the systems moves towards  $(0, K_t)$ , which makes it impossible to model the effect with biomass oscillations in a steady state. There is also a more direct way to verify this argument. Assuming that  $\sigma(T) \neq 0$ ,  $dx = 0$  and  $f(x, T) = b(x)$ , equation 6.1 is graphed in **Figure 11**. The initial equilibrium is  $P^{II}$ . If a temperature shock reduces biomass<sup>23</sup> this can either move the system to a point like A or to point B. In both cases some firms abandon the market.

If the impact moves equilibrium to quadrant A then the system continues in initial equilibrium. If a stronger shock moves the equilibrium to a point such as B not only do firms leave from the market, but harvest will also be close to the biomass's minimum capacity. This is the equivalent of some firms closing, at least temporarily, until the remaining stock generates enough population to be sustainable. The more biomass variability, the higher the possibility of equilibrium being located at  $(0, K_t)$ . As such, the conclusion is that separating both models allows for a more direct estimate.

All these difficulties contribute to a scarce number of research papers to compare the results of this article. [65] explicitly includes water temperature as an explanatory variable in a model similar to the one analysed in this article, and closely following [1]. The focus is the climate change effect on the Gross Domestic Product (GDP) of Iceland and Greenland, where fisheries contribute in a substantial way. A key difference with this article is that [65] consider a generalised Wiener process in discrete time for temperature, allowing for a positive as well as negative and an oscillatory behaviour to temperature. The mechanism in which temperature affects fisheries is similar. Under similar scenarios of rising temperatures (1.5–6°C by 2100) the effect on GDP is estimated through a reduction of fish stock of 0.2% yearly, achieving a reduction close to 1% in the 50<sup>th</sup> year after the shock.

**Figure 10: Joint model**

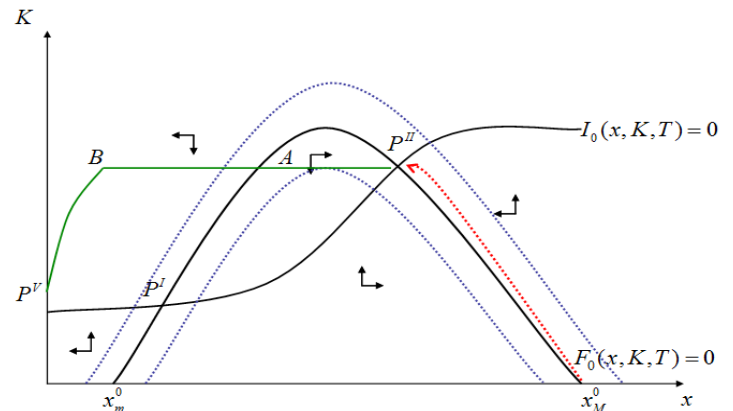


Source: Own elaboration.

<sup>22</sup> Capital dynamic (equation 4.16) is also graphed, identical to the figure in Section 4.

<sup>23</sup> The shock is necessarily a product of temperature since it is the only variable that does not behave in a stationary manner in the long term.

**Figure 11: Shocks in the deterministic model**



Source: Own elaboration.

Some other studies analysing the impact of GW on fisheries are [90] and [91]. In [90] the GW issue is analysed for the case of European sardine fishery making use of a bio-economic stochastic model. An interesting feature is the inclusion of a forward-looking solution to include the expectations of sea-surface temperature, which will no longer be constant. The baseline results, considering different warming scenarios, show that in the first five years of warming, the biomass levels actually increase firm's value, but in the long run the firm is hurt due to lower productivity.

In [91], a narrative framework is presented, suggesting the analysis of the effects of GW on fisheries. In line with this paper, [91] offers a wide review of evidence on GW first, and of the effects on biomass later. It is suggested that for the period covering 1997-2008 capture production has decreased by close to 5%, accompanied by a global temperature rising close to e.g. 2-3°C in the North Sea. It is argued that ENSO plays a key role in biomass determination, and that the expected biomass reductions could reach from 3% in the Canadian Grand Bank to 50% in Iceland, reflecting the difficulty of making a numerical statement on the effects of GW on biomass with certainty. Finally, some recommendations are provided in order to reduce the transfer of biomass cut-off on to a firms' value.

## 7. Conclusions

While GW is an issue of growing interest among diverse disciplines, this paper focuses on the biological side of GW in order to uncover its economic consequences on the fishing industry.

As a starting point, the paper argues that higher temperature anomalies cause oscillation and reduction in biomass and it then discusses how these affect fishing firm value.

Two important assumptions are included in the model: *the average temperature of the Earth's marine surface is increasing* and *GW affects biomass*. These assumptions are reviewed and time series and studies from specific geographic zones are highlighted to validate the assumptions.

The literature on fisheries economics is also reviewed, and it is found that although the subject has made considerable advances over the past several decades, only on rare occasions has GW been considered as one of the problems of administering a fishing firm. This study contributes to the literature by providing estimates of the economic consequences of a biomass that has been affected by GW.

The model in [1], which includes current elements from fisheries economics, is adapted to investigate the effect of biomass oscillation on fisheries. The model in [2], which is used because it simplifies comparative statics, is adapted to analyse the consequences of biomass reduction on firm value. Therefore, the arguments for separating oscillation and reduction even though these occur together are discussed.

The results indicate that if there is a 1% variation in biomass, annual firm value drops by around 6%, while a 20% variation means values could fall by as much as 44%.

Reduced biomass, which is assumed to be the result of increased mortality and/or fishing, forces firms to increase extraction levels, which also requires more capital. The results indicate that if the temperature anomaly increases between +1 and +8°C, annual value will fall between 8 and 10%. This calculation also provides optimal capital investment trajectories: investment is positive until the increase in temperature hits +4.3°C, after which point it is advisable to withdraw capital, creating the problem of "many boats and few fish". The results of both models demonstrate the negative effect of GW on the fishing industry.

Further research could include the derivation of an econometric-statistical model that encompasses the two models presented here in a reduced form. Despite the time span considered, this kind of estimation provides the flexibility to embed different GW scenarios, and instantaneously consider the impact on a fisheries' value. Accurate time series from both biological and economic variables would be of special interest for this area of study.

A calibrated merged version of the two models still could be possible for a particular region which allows small-size shocks and a moderate temperature rise. However, a theoretically feasible merged model will provide robustness to the present results, which is left for further research.

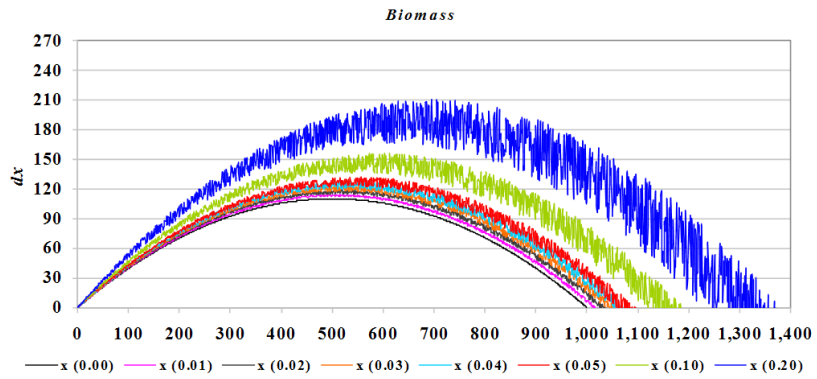
## 8. Acknowledgements

I thank to Mauricio Calani, Augusto Castillo, José Antonio Carrasco, Rodrigo Caputo, Gabriela Contreras, Gonzalo Edwards, Rodrigo Harrison, Hugo Salgado, Diego Schmidt-Hebbel, Klaus Schmidt-Hebbel, and two anonymous referees for their comments and suggestions. Also, to seminar assistants at the Central Bank of Chile, Alberto Hurtado University, and the 2009 SECHI Annual Meeting. I would also like to thank Marcelo Saavedra for his assistance on the biological aspects of this paper, and Carla Fucito for her support. This work is dedicated to the memory of the late Diego Schmidt-Hebbel.

## Annex A

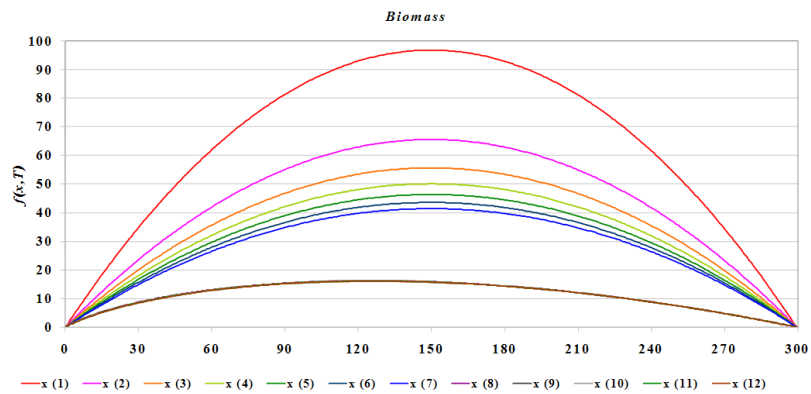
### Basic equation estimates

Figure A1: Stochastic biomass dependent on T.



Source: Own elaboration.

Figure A2: Deterministic biomass dependent on



Source: Own elaboration.

## 9. References

- [1] R. PINDYCK, "Uncertainty in the Theory of Renewable Resource Markets," *Review of Econ. Stud.*, vol. 51, no. 2, pp. 289-303, 1984. Doi: <http://dx.doi.org/10.2307/2297693>
- [2] V. SMITH, "Economics of Production from Natural Resources," *Amer. Econ. Review*, vol. 58, no. 3, pp. 409-431, 1968. Available: <http://www.jstor.org/stable/1813767>
- [3] D. R. EASTERLING and M. F. WEHNER, "Is the Climate Warming or Cooling?" *Geophysical Research Lett.*, vol. 36, L08706, 2009. Doi: <http://dx.doi.org/10.1029/2009gl037810>
- [4] F. CHRISTY and A. SCOTT, *The Common Wealth in Ocean Fisheries. Some Problems of Growth and Economic Allocation*, The Johns Hopkins University Press, Baltimore and London, USA, 1965. Doi: <http://dx.doi.org/10.2307/143296>
- [5] A. SCOTT, "The Fishery: The Objectives of Sole Ownership," *J. of Political Economy*, vol. 63, pp. 116-124, 1965. Doi: <http://dx.doi.org/10.1086/257653>
- [6] R. J. H. BEVERTON and S. HOLT, "On the Dynamics of Exploited Fish Populations," Ministry of Agriculture, Fisheries and Food, Fishery Investigations, ser. II, vol. XIX, London, 1957. Available: <http://journals.cambridge.org/action/displayAbstract?fromPage=online&aid=4367888>
- [7] M. B. SCHAEFER and R. J. H. BEVERTON, *Fishery Dynamics—Their Analysis and Interpretation*, in M. N. HILL (editor), *The Sea*, vol. 2, Interscience, New York, USA, 1963.
- [8] D. PAULY, V. CHRISTENSEN, J. DALSGAARD, R. FROESE, and F. TORRES, "Fishing Down Marine Food Webs", *Sci.*, vol. 279, pp. 860-863, 1998. Doi: <http://dx.doi.org/10.1126/science.279.5352.860>
- [9] T. BJØRNDAL, D. GORDON, R. ARNASON and R. SUMAILA (editors), *Advances in Economic Fisheries*, Blackwell Publishing, USA, 2007. Doi: <http://dx.doi.org/10.1002/9780470751589>
- [10] T. BJØRNDAL and G. MUNRO, *The Economics of Fisheries Management: A Survey*, in T. TIETENBERG and H. FOLMER (editors), *The International Yearbook of Environmental and Resource Economics 1998/1999: A Survey of Current Issues*, Cheltenham, Edward Elgar, pp. 153-188, 1998.
- [11] H. GORDON, "The Economic Theory of a Common Property: The Fishery," *J. of Political Economy*, vol. 62, no. 2, pp. 124-142, 1954. Doi: <http://dx.doi.org/10.1086/257497>
- [12] V. SMITH, "On Models of Commercial Fishing," *J. of Political Economy*, vol. 77, pp. 181-198, 1969. Doi: <http://dx.doi.org/10.1086/259925>
- [13] L. G. ANDERSON, *The Economics of Fisheries Management*, The Johns Hopkins University Press, Baltimore and London, USA, 1977.
- [14] C. W. CLARK, *Mathematical Bioeconomics: The Optimal Management of Renewable Resources*, First Edition, Wiley-Interscience, New York, USA, 1976. Doi: <http://dx.doi.org/10.2307/2532591>
- [15] D. W. PEARCE and R. K. TURNER, *The Economics of Natural Resources and the Environment*, The Johns Hopkins University Press, Baltimore, USA, 1990.
- [16] C. W. CLARK and G. R. MUNRO, *The Economics of Fishing and Modern Capital Theory: A Simplified Approach*, in L. J. MIRMAN and D. F. SPULBER (editors), *Essays in the Economics of Renewable Resources*, North-Holland, Amsterdam, Netherlands, pp. 31-54, 1982. Doi: [http://dx.doi.org/10.1016/0095-0696\(75\)90002-9](http://dx.doi.org/10.1016/0095-0696(75)90002-9)
- [17] T. BJØRNDAL, "Production Economics and the Optimal Stock Size in a North Atlantic Fishery," *Scandinavian J. of Econ.*, vol. 89, no. 2, pp. 145-162, 1987. Doi: <http://dx.doi.org/10.2307/3440061>
- [18] C. W. CLARK, *Mathematical Bioeconomics*, Wiley & Sons, New York, USA, 1990. Doi: [http://dx.doi.org/10.1007/978-3-642-45455-4\\_3](http://dx.doi.org/10.1007/978-3-642-45455-4_3)
- [19] C. W. CLARK, F. H. CLARKE, and G. MUNRO, "The Optimal Exploitation of Renewable Resource Stocks: Problems of Irreversible Investment," *Econometrica*, vol. 47, no. 1, pp. 25-47, 1979. Doi: <http://dx.doi.org/10.2307/1912344>
- [20] J. CONRAD and T. BJØRNDAL, "A Bioeconomic Model of the Harp Seal in the Northwest Atlantic," *Land Econ.*, vol. 67, pp. 158-171, 1991. Doi: <http://dx.doi.org/10.2307/3146408>
- [21] S. PASCOE, T. BATTAGLENE, and D. CAMPBELL, "A Bioeconomic Model of the Southern Shark Fishery," ABARE Research Report 92.1, 1992. Available: <http://catalogue.nla.gov.au/Record/604389>
- [22] Y. YE, N. LONERAGAN, D. J. DIE, R. WATSON, and B. HARCH, "Bioeconomic Modelling and Risk Assessment of Tiger Prawn (*Penaeus Esculentus*) Stock Enhancement in Exmouth Gulf, Australia," *Fisheries Research*, vol. 73, pp. 231-249, 2005. Doi: <http://dx.doi.org/10.1016/j.fishres.2004.12.004>
- [23] G. A. DE LEO and M. GATTO, "A Stochastic Bioeconomic Analysis of Silver Eel Fisheries," *Ecological Applicat.*, vol. 11, no. 1, pp. 281-294, 2001. Doi: [http://dx.doi.org/10.1890/1051-0761\(2001\)011\[0281:asbaos\]2.0.co;2](http://dx.doi.org/10.1890/1051-0761(2001)011[0281:asbaos]2.0.co;2)
- [24] J. K. LEVY, D. M. KILGOUR, and K. W. HIPEL, "Reducing the Risk of Fishery Resource Disasters: A Bioeconomic Approach to Sustainable Resource Management," *J. of the Amer. Water Resources Assoc.*, vol. 42, no. 6, pp. 1451-1463, 2006. Doi: <http://dx.doi.org/10.1111/j.1752-1688.2006.tb06013.x>
- [25] O. A. G. CHONG, D. IGLESIAS, and G. DINIZ, "Modelo Cuadrático para Simular el Crecimiento de una Población de Peces," *Biomatemática*, no. 16, pp. 117-129, 2006. Available: [http://www.ime.unicamp.br/~biomat/bio16\\_art9.pdf](http://www.ime.unicamp.br/~biomat/bio16_art9.pdf)
- [26] O. A. G. CHONG, G. L. DINIZ, and F. R. VILLATORO, "Dispersal of Fish Populations in Dams: Modelling and Simulation," *Ecological Modelling*, vol. 186, pp. 290-298, 2005. Doi: <http://dx.doi.org/10.1016/j.ecolmodel.2004.11.025>
- [27] C. W. CLARK, *Rational Expectations and Fisheries Management*, in T. BJØRNDAL, D. GORDON, R. ARNASON, and R. SUMAILA (editors), *Advances in Economic Fisheries*, Blackwell Publishing, USA, 2007. Doi: <http://dx.doi.org/10.1002/9780470751589>
- [28] R. HANNESSON, *Incentive Compatibility of Fish-Sharing Agreements*, in T. BJØRNDAL, D. GORDON, R. ARNASON, and R. SUMAILA (editors), *Advances in Economic Fisheries*, Blackwell Publishing, USA, 2007. Doi: <http://dx.doi.org/10.1002/9780470751589>
- [29] S. KOBAYASHI, *A Dynamic Game of Renewable Natural Resource Exploitation and Markov Perfect Equilibrium*, in T. BJØRNDAL, D. GORDON, R. ARNASON, and R. SUMAILA (editors), *Advances in Economic Fisheries*, Blackwell Publishing, USA, 2007. Doi: <http://dx.doi.org/10.1002/9780470751589>
- [30] M. LINDROOS, V. KAITALA, and L. G. KRONBAK, *Coalition Games in Fisheries Economics*, in T. BJØRNDAL, D. GORDON, R. ARNASON, and R. SUMAILA (editors), *Advances in Economic Fisheries*, Blackwell Publishing, USA, 2007. Doi: <http://dx.doi.org/10.1002/9780470751589>
- [31] R. MCKELVEY, P. V. GOLUBTSOV, G. CRIPE, and K. MILLER, *The Incomplete Information Stochastic Split-Stream Model: An Overview*, in T. BJØRNDAL, D. GORDON, R. ARNASON, and R. SUMAILA (editors), *Advances in Economic Fisheries*, Blackwell Publishing, USA, 2007. Doi: <http://dx.doi.org/10.1002/9780470751589>
- [32] D.M. ETHERIDGE, L.P. STEELE, R.J. FRANCEY, and R.L. LANGENFELDS, "Atmospheric Methane between 1000 A.D. and Present: Evidence of Anthropogenic Emissions and Climatic Variability," *J. of Geophysical Research*, vol. 103, no. D13, pp. 15979-15993, Jul. 1998. Doi: <http://dx.doi.org/10.1029/98jd00923>
- [33] C. KEMFERT, "The Economic Costs of Climate Change," *German Inst. for Econ. Research*, vol. 1, no. 2, pp. 43-49, 2005. Doi: [http://dx.doi.org/10.1007/978-0-387-30440-3\\_71](http://dx.doi.org/10.1007/978-0-387-30440-3_71)
- [34] C. A. MEDEL, "The Effects of Global Warming on Fisheries," MPRA Paper 28373, 2011. Available: [http://mpra.ub.uni-muenchen.de/28373/1/MPRA\\_paper\\_28373.pdf](http://mpra.ub.uni-muenchen.de/28373/1/MPRA_paper_28373.pdf)

- [35] J. HANSEN, M. SATO, R. RUEDY, K. LO, D. W. LEA, and M. MEDINA-ELIZADE, "Global Temperature Change," *Proc. of the Nat. Academy of Sci.*, vol. 103, pp. 14288-14293, 2006. Doi: <http://dx.doi.org/10.1073/pnas.0606291103>
- [36] W. C. QUAYLE, L. S. PECK, H. PEAT, J. C. ELLIS-EVANS, and P. R. HARRIGAN, "Extreme Responses to Climate Change in Antarctic Lakes," *Science*, vol. 295, p. 645, 2002. Doi: <http://dx.doi.org/10.1126/science.1064074>
- [37] P. N. TRATHAN, J. FORCADA, and E. MURPHY, "Environmental Forcing and Southern Ocean Marine Predator Populations: Effects of Climate Change and Variability," *Philosophical Transactions of the Royal Society B*, vol. 362, pp. 2351-2365, 2007. <http://dx.doi.org/10.1098/rstb.2006.1953>
- [38] P. M. THOMPSON and J. C. OLLASON, "Lagged Effects of Ocean Climate Change on Fulmar Populations Dynamics," *Nature*, vol. 413, pp. 417-420, 2001. [http://www.abdn.ac.uk/lighthouse/documents/pdf/thompson\\_ollason\\_2001.pdf](http://www.abdn.ac.uk/lighthouse/documents/pdf/thompson_ollason_2001.pdf)
- [39] J. FORCADA, P. N. TRATHAN, K. REID, E. J. MURPHY, and J. P. CROXALL, "Contrasting Population Changes in Sympatric Penguin Species in Association with Climate Warming," *Global Change Biology*, vol. 12, pp. 411-423, 2006. Doi: <http://dx.doi.org/10.1111/j.1365-2486.2006.01108.x>
- [40] J. C. CHAN and K. S. LIU, "Typhoon Intensity in a Warming World," *Bulletin Amer. Meteorological Soc.*, vol. 85, pp. 660-661, 2004.
- [41] G. C. JOHNSON, S. MECKING, B. M. SLOYAN, and S. E. WIJFFELS, "Recent Bottom Water Warming in the Pacific Ocean," *J. of Climate*, vol. 20, no. 21, pp. 5365-5375, 2007. Doi: <http://dx.doi.org/10.1175/2007jcli1879.1>
- [42] S. G. PURKEY and G. C. JOHNSON, "Warming of Global Abyssal and Deep Southern Ocean Waters between the 1990s and 2000: Contributions to Global Heat and Sea Level Rise Budgets," *J. of Climate*, vol. 23, pp. 6336-6351, 2010. Doi: <http://dx.doi.org/10.1175/2010jcli3682.1>
- [43] M. A. BALMASEDA, K. E. TRENBERTH, and E. KÄLLÉN, "Distinctive Climate Signals in Reanalysis of Global Ocean Heat Content," *Geophysical Research Lett.*, vol. 40, no. 9, pp. 1754-1759, 2013. Doi: <http://dx.doi.org/10.1002/grl.50382>
- [44] M. COLLINS, S.-I. AN, W. CAI, A. GANACHAUD, E. GUILYARDI, F.-F. JIN, M. JOCHUM, M. LENGAIGNE, S. POWER, A. TIMMERMANN, G. VECCHI, and A. WITTENBERG, "The Impact of Global Warming on the Tropical Pacific Ocean and El Niño," *Nature Geosci.*, vol. 3, pp. 391-397, 2010. Doi: <http://dx.doi.org/10.1038/ngeo868>
- [45] G. BEAUGRAND, K. M. BRANDER, J. A. LINDLEY, S. SOUSSI, and P. C. REID, "Plankton Effect on Cod Recruitment in the North Sea," *Nature*, vol. 426, pp. 661-664, 2003. Doi: <http://dx.doi.org/10.1038/nature02164>
- [46] G. BEAUGRAND, "Decadal Changes in Climate and Ecosystems in the North Atlantic Ocean and Adjacent Seas," *Deep-Sea Res. II*, vol. 56, pp. 656-673. Doi: <http://dx.doi.org/10.1016/j.dsr2.2008.12.022>
- [47] E. FAHRBACH, M. HOPPEMA, G. ROHARDT, M. SCHROEDER, AND A. WISOTZKI, "Decadal-scale Variations of Water Mass Properties in the Deep Weddell Sea," *Ocean Dyn.*, vol. 54, pp. 77-91, 2004. Doi: <http://dx.doi.org/10.1007/s10236-003-0082-3>
- [48] S. S. JACOBS, C. F. GIULIVI, AND P. A. MELE, "Freshening of the Ross Sea during the late 20th Century," *Sci.*, vol. 297, pp. 386-389, 2002. Doi: <http://dx.doi.org/10.1126/science.1069574>
- [49] H. OZAKI, H. OBATA, M. NAGANOBU, AND T. GAMO, "Long-term Bottom Water Warming in the North Ross Sea," *J. Oceanogr.*, vol. 65, pp. 235-244, 2009. Doi: <http://dx.doi.org/10.1007/s10872-009-0022-z>
- [50] S. S. JACOBS and C. F. GIULIVI, "Large Multidecadal Salinity Trends Near the Pacific-Antarctic Continental Margin," *J. of Climate*, vol. 23, pp. 4508-4524, 2002. Doi: <http://dx.doi.org/10.1175/2010jcli3284.1>
- [51] T. GOREAU, R. HAYES, and D. McALLISTER, "Regional Patterns of Sea Surface Temperature Rise: Implications for Global Ocean Circulation Change and the Future of Coral Reefs and Fisheries," *World Resource Review*, vol. 17, pp. 350-374, 2005. Available: [http://www.globalcoral.org/\\_oldgcra/WRR%20Goreau%20Hayes%20&%20McAllister%20.pdf](http://www.globalcoral.org/_oldgcra/WRR%20Goreau%20Hayes%20&%20McAllister%20.pdf)
- [52] INTERGOVERNMENTAL PANEL OF CLIMATE CHANGE (IPCC), *Climate Change 2001: Third Assessment Report, Synthesis Report*, Cambridge, UK, 2001. Available: [https://www.ipcc.ch/pdf/assessment-report/ar4/wg2/ar4\\_wg2\\_full\\_report.pdf](https://www.ipcc.ch/pdf/assessment-report/ar4/wg2/ar4_wg2_full_report.pdf)
- [53] S. FANKHAUSER, R. S. J. TOL, and D. W. PEARCE, "The Aggregation of Climate Change Damages: A Welfare Theoretic Approach," *Environmental and Resource Econ.*, vol. 10, pp. 249-266, 1997. Doi: <http://dx.doi.org/10.1023/a:1026420425961>
- [54] S. PETERSON, "Uncertainty and Economic Analysis of Climate Change: A Survey of Approaches and Findings," *Environmental Modeling and Assessment*, vol. 11, no. 1, pp. 1-17, Feb. 2006. Doi: <http://dx.doi.org/10.1007/s10666-005-9014-6>
- [55] F. BOSELLO, R. ROSON, and R. S. J. TOL, "Economy-wide Estimates of the Implications of Climate Change: Sea Level Rise," *Environmental and Resource Econ.*, vol. 37, no. 3, pp. 549-571, Jan. 2007. Doi: <http://dx.doi.org/10.1007/s10640-006-9048-5>
- [56] A. L. SHRIVER, Y. B. HONG, T. K. ONN, M. GARCÍA, and M. AHMED, "Annotated Bibliography on the Economic Effects of Global Climate Change on Fisheries," Working Paper, The WorldFish Center, 2005. Available: [http://worldfish.catalog.cgiar.org/Naga/WF\\_527.pdf](http://worldfish.catalog.cgiar.org/Naga/WF_527.pdf)
- [57] J. M. HAMILTON and R. S. J. TOL, "The Impact of Climate Change on Tourism and Recreation," Working Paper, Research Unit Sustainability and Global Change, Hamburg University, 2004. Available: <http://www.fnu.zmaw.de/fileadmin/fnu-files/publication/working-papers/tourlitrev.pdf>
- [58] D. VINER and M. AGNEW, "Climate Change and Its Impacts on Tourism," *Climate Research Unit, University of East Anglia, UK*, 1999. Available: [http://www.wwf.org.uk/filelibrary/pdf/tourism\\_and\\_cc\\_full.pdf](http://www.wwf.org.uk/filelibrary/pdf/tourism_and_cc_full.pdf)
- [59] S. SOOKRAM, "The Impact of Climate Change on the Tourism Sector in Selected Caribbean Countries," *Caribbean Development Report, Volume 2, ECLAC – Project Documents Collection*, 2009. Available: <http://www.cepal.org/publicaciones/xml/3/38253/lcarl.245part4.pdf>
- [60] S. FANKHAUSER and R. S. J. TOL, "On Climate Change and Economic Growth," *Resource and Energy Econ.*, vol. 27, no. 1, pp. 1-17, 2005. Doi: <http://dx.doi.org/10.1016/j.reseneeco.2004.03.003>
- [61] P. DUMAS and M. HA-DUONG, "Optimal Growth with Adaptation to Climate Change," *Climatic Change*, vol. 117, no. 4, pp. 691-710, 2012. Doi: <http://dx.doi.org/10.1007/s10584-012-0601-7>
- [62] M. HÜBLER, G. KLEPPER, and S. PETERSON, "Costs of Climate Change – The Effects of Rising Temperatures on Health and Productivity in Germany," *Ecological Econ.*, vol. 68, nos. 1-2, pp. 381-393, Dec. 2008. Doi: <http://dx.doi.org/10.1016/j.ecolecon.2008.04.010>
- [63] R. S. J. TOL, "Estimates of the Damage Costs of Climate Change, Part I: Benchmark Estimates," *Environmental and Resource Econ.*, vol. 21, no. 1, pp. 47-73, 2002. Doi: <http://dx.doi.org/10.1023/a:1014500930521>
- [64] N. STERN, *The Economics of Climate Change: The Stern Review*, Cambridge University Press, Cambridge, UK, 2007. Available: [http://mudancasclimaticas.cptec.inpe.br/~rmlima/pdfs/destaques/sternreview\\_report\\_complete.pdf](http://mudancasclimaticas.cptec.inpe.br/~rmlima/pdfs/destaques/sternreview_report_complete.pdf)
- [65] R. ARNASON, "Climate Change and Fisheries: Assessing the Economic Impact in Iceland and Greenland," *Natural Resource Modelling*, vol. 20, no. 2, pp. 163-197, 2007. Doi: <http://dx.doi.org/10.1111/j.1939-7445.2007.tb00205.x>
- [66] R. HANNESSON, "Global Warming and Fish Migrations," *Natural Resource Modelling*, vol. 20, no. 2, pp. 301-319, 2007. Doi: <http://dx.doi.org/10.1111/j.1939-7445.2007.tb00209.x>

- [67] V. CHRISTENSEN, P. AMORIM, I. DIALLO, T. DIOUF, S. GUÉNETTE, J. J. HEYMANS, A. N. MENDY, T. MAHFOUDH SIDI, M. L. D. PALOMARES, B. SAMB, K. STOBBERUP, J. M. VAKILY, M. VASCONCELLOS, R. WATSON, and D. PAULY, Trends in Fish Biomass Off Northwest Africa, 1960–2000, in M. L. D. PALOMARES and D. PAULY (editors), West African Marine Ecosystems: Models and Fisheries Impacts, Fisheries Centre Research Reports, vol. 12, no. 7, pp. 215–220, Fisheries Centre, UBC, Vancouver, 2004.
- [68] J. SUÁREZ, W. RITTER, C. GAY, and J. TORRES, “ENSO–Tuna Relations in the Eastern Pacific Ocean and its Prediction as a Non-Linear Dynamic System,” *Atmosfera*, pp. 245–258, 2004. Available: <http://www.revistascca.unam.mx/atm/index.php/atm/article/view/8532/8002>
- [69] B. HERNÁNDEZ, G. GAXIOLA-CASTRO, and S. NÁJERA MARTÍNEZ, “Efectos del ENSO en la Producción Primaria frente a Baja California,” *Ciencias Marinas*, vol. 30, no. 3, pp. 427–441, 2004. Available: <http://www.redalyc.org/articulo.oa?id=48030305>
- [70] P. N. TRATHAN, A. S. BRIERLEY, M. A. BRANDON, D. G. BONE, C. GOSS, S. A. GRANT, E. J. MURPHY, J. L. WATKINS, “Oceanographic Variability and Changes in Antarctic Krill (*Euphausia Superba*) Abundance at South Georgia,” *Fisheries Oceanography*, vol. 12, pp. 569–583, 2003. Doi: <http://dx.doi.org/10.1046/j.1365-2419.2003.00268.x>
- [71] P. N. TRATHAN, E. J. MURPHY, J. FORCADA, J. P. CROXALL, K. REID, and S. E. THORPE, Physical Forcing in the Southwest Atlantic: Ecosystem Control, in I. L. BOYD, S. WANLESS, and C. J. CAMPHUYSEN (editors), *Top Predators in Marine Ecosystems*, Cambridge University Press, 2006.
- [72] S. BRIERLEY, J. L. WATKINS, C. GOSS, M. WILKINSON and I. EVERSON, “Acoustic Estimates of Krill Density at South Georgia, 1981 to 1998,” *CCAMLR Sci.*, vol. 6, pp. 47–57, 1999. Available: [http://www.ccamlr.org/en/system/files/science\\_journal\\_papers/04brierley-et-al.pdf](http://www.ccamlr.org/en/system/files/science_journal_papers/04brierley-et-al.pdf)
- [73] E. MURPHY, P. TRATHAN, J. WATKINS, K. REID, M. MEREDITH, J. FORCADA, S. THORPE, N. JOHNSTON, and P. ROTHERY, “Climatically Driven Fluctuations in Southern Ocean Ecosystems,” *Philosoph. Trans. of The Roy. Soc. B*, vol. 274, pp. 3057–3067, 2007. Doi: <http://dx.doi.org/10.1098/rspb.2007.1180>
- [74] E. LIPP, N. SCHMIDT, M. LUTHER, and J. ROSE, “Determining the Effects of El Niño–Southern Oscillation Events on Coastal Water Quality,” *Estuaries*, vol. 24, no. 4, pp. 491–497, 2001. Doi: <http://dx.doi.org/10.2307/1353251>
- [75] E. POLOCZANSKA, G. ABELL, B. FULTON, S. GRIFFITH, A. HOBDAV, M. LOUREY, K. PATERSON, S. ROBERT, P. THOMPSON, B. TILBORK, and R. THRESHER, “Ocean Acidification,” Working Paper, Commonwealth Scientific and Industrial Research Organization, 2011. Available: [ftp://ftp.marine.csiro.au/pub/bax/OA\\_Report\\_28\\_Nov\\_11\\_FINAL.pdf](ftp://ftp.marine.csiro.au/pub/bax/OA_Report_28_Nov_11_FINAL.pdf)
- [76] A. H. ALTIERI and K. B. GEDAN, “Climate Change and Dead Zones,” *Global Change Biology*, vol. 21, no. 4, pp. 1395–1406, 2014. Doi: <http://dx.doi.org/10.1111/gcb.12754>
- [77] G. P. GRIFFITH, E. A. FULTON, and A. J. RICHARDSON, “Effects of Fishing and Acidification-related Benthic Mortality on the Southeast Australian Marine Ecosystem,” *Global Change Biology*, vol. 17, pp. 3058–3074, 2011. Doi: <http://dx.doi.org/10.1111/j.1365-2486.2011.02453.x>
- [78] P. M. LINK and R. S. J. TOL, “Economic Impacts on Key Barents Sea Fisheries Arising from Changes in the Strength of the Atlantic Thermohaline Circulation,” *Global Environmental Change*, vol. 19, no. 4, pp. 422–433, 2009. Doi: <http://dx.doi.org/10.1016/j.gloenvcha.2009.07.007>
- [79] M. STEIN, “Warming Periods off Greenland during 1800–2005. Their Potential Influence on the Abundance of Cod (*Gadus morhua*) and Haddock (*Melanogrammus aeglefinus*) in Greenlandic Waters,” *J. of Northwestern Atlantic Fishery Sci.*, vol. 39, pp. 1–20, 2007. Doi: <http://dx.doi.org/10.2960/j.v39.m580>
- [80] H.-O. PÖRTNER, “Ecosystem Effects of Ocean Acidification in Times of Ocean Warming: A Physiologist’s View,” *Mar. Ecol. Prog. Ser.*, vol. 373, pp. 203–217, 2008. Doi: <http://dx.doi.org/10.3354/meps07768>
- [81] G. P. GRIFFITH, E. A. FULTON, R. GORTON, and A. J. RICHARDSON, “Predicting Interactions among Fishing, Ocean Warming, and Ocean Acidification in a Marine System with Whole-Ecosystem Models,” *Conservation Biology*, vol. 26, no. 6, pp. 1145–1152, 2012. Doi: <http://dx.doi.org/10.1111/j.1523-1739.2012.01937.x>
- [82] R. HAIGH, D. IANSON, C. A. HOLT, H. E. NEATE, A. M. EDWARDS, “Effects of Ocean Acidification on Temperate Coastal Marine Ecosystems and Fisheries in the Northeast Pacific,” *PLoS ONE*, vol. 10, num. 2, pp. 1–46, 2015. Doi: <http://dx.doi.org/10.1371/journal.pone.0117533>
- [83] D. JIN and G. E. HERRERA, “A Stochastic Bioeconomic Model with Research,” *Marine Resource Econ.*, vol. 20, pp. 249–261, 2005. Available: [http://www.jstor.org/stable/42629474?seq=1#page\\_scan\\_tab\\_contents](http://www.jstor.org/stable/42629474?seq=1#page_scan_tab_contents).
- [84] J. PRATT, “Risk Aversion in the Small and the Large,” *Econometrica*, vol. 32, pp. 122–136, 1964. Doi: <http://dx.doi.org/10.2307/1913738>
- [85] K. LORENZEN, “Allometry of Natural Mortality as a Basis for Assessing Optimal Release Size in Fish–Stocking Programmes,” *Canadian J. of Fisheries and Aquatic Sci.*, vol. 57, pp. 2374–2381, 2000. Doi: <http://dx.doi.org/10.1139/f00-215>
- [86] M. DOYLE, R. SINGH, and Q. WENINGER, Fisheries Management with Stock Uncertainty and Costly Capital Adjustment, in T. BJØRNDAL, D. GORDON, R. ARNASON, and R. SUMAILA (editors), *Advances in Economic Fisheries*, Blackwell Publishing, USA, 2007. Doi: <http://dx.doi.org/10.1002/9780470751589>
- [87] A. CHARLES, Linking Natural Capital and Physical Capital: A Review of Natural Resource Investment Models, in T. BJØRNDAL, D. GORDON, R. ARNASON and R. SUMAILA (editors), *Advances in Economic Fisheries*, Blackwell Publishing, USA, 2007. Doi: <http://dx.doi.org/10.1002/9780470751589>
- [88] A. McDONALD, L. K. SANDAL, and S. I. STEINSHAMN, “Implications of a Nested Stochastic/Deterministic Bio-Economic Model for a Pelagic Fishery,” *Ecological Modelling*, vol. 149, pp. 193–201, 2002. Doi: [http://dx.doi.org/10.1016/s0304-3800\(01\)00523-3](http://dx.doi.org/10.1016/s0304-3800(01)00523-3)
- [89] G. MUNRO, “Mathematical Bioeconomics and the Evolution of Modern Fisheries Economics,” *Bulletin of Math. Biology*, vol. 54, pp. 163–184, 1992. Doi: <http://dx.doi.org/10.1007/bf02464828>
- [90] J. M. DA ROCHA, M.-J. GUTIÉRREZ, and S. VILLASANTE, “Coping with Global Warming Under Stock Growth Uncertainty in Marine Social-Ecological Systems: The European Sardine Fishery,” Discussion Paper 238, The Beijer Institute of Ecological Economics, 2012. Available: [http://www.beijer.kva.se/pubinfo.php?pub\\_id=655](http://www.beijer.kva.se/pubinfo.php?pub_id=655)
- [91] K. BRANDER, “Impacts of Climate Change on Fisheries,” *J. of Marine Systems*, vol. 79, pp. 389–402, 2010. Doi: <http://dx.doi.org/10.1016/j.jmarsys.2008.12.015>