# A Study on Economic Impact on the European Sardine Fishery due to Continued Global Warming

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Additional information is available at the end of the chapter

## 1. Introduction

The global warming is one of the biggest issues now facing humanity, including its repercussions on climate change. The climate change is directly or indirectly attributable to human activity and alters the composition of the atmosphere, along with the natural variability observed during comparable periods of time [1]. On a global level, human activity has generated a loss in biodiversity due, among other factors, to changes in the way we use the land, the pollution of soil and water, the diversion of water to intensively farmed ecosystems (intensive agricultural and livestock farming) and urban systems, the introduction of non-autochthonous species and the exhaustion of the ozone layer. In particular, the rate of biodiversity loss is currently greater than that of natural extinction [2]. In this context, climate change is contributing towards increasing this loss of biological biodiversity [3]. It is considered that the ongoing increase in the levels of greenhouse gases is one of the main causes, along with natural factors, of climate change [2]. The concentrations of greenhouse gases have been increased since the industrial age due fundamentally to the use of fossil fuels and to changes in soil use and cover; generating, among other effects, increases in land and sea surface temperatures, changes in precipitation (both spatial and seasonal), increases in sea levels and changes in the frequency and intensity of some climate phenomena (hurricanes, intensive precipitations, heat weaves). [4-5]

The scientific certainty that climate change is a reality [6] and, therefore, that it is necessary to live alongside it, leads us to take action aimed at reducing greenhouse gasses compatible with other action which aims to study the possibilities of adapting to these new environmental conditions that are going to characterise the planet in the coming decades. The new scenarios generated by this global phenomenon generate negative impacts on the majority of Spain's

ecosystems, and also on productive activities; but opportunities may also arise (for example, for tourism in northern Spain; [7]) and could be tapped into, if a certain level of scientific knowledge and prospective capacity with regard to the evolution of environmental conditions in the regions and their effects on natural systems over the next decades were reached.

In one of its latest reports, the Inter-governmental Panel on Climate Change (IPCC) estimates that, on a global level, the average temperature of the land surface could increase by between 1.4 and 5.8°C by the end of the 21st century (a greater increase in higher latitudes that in the tropics), that there will be an increase in the sea surface temperature, that terrestrial regions will undergo a higher increase than the oceans, that the sea will rise by between 0.09 and 0.88m, and that there will be an increase in the occurrence of extreme phenomena (heavy rainfall, hurricanes, etc.), although with regional differences (IPCC, 2013). Proximity to one or other extreme of the intervals will depend fundamentally on society's capacity to mitigate the effects of climate change.

The different scientific reports published by national [8-9] and international [6] bodies on global warming leave no doubt as to Spain's vulnerability to its effects. However, this knowledge is not sufficient to describe the behaviour of the various microclimates in different areas of Spain and their interaction with different ecosystems throughout the country. Northern Spain, to where the fishery that we are going to look at in this paper belongs, is located in medium latitudes, framed within an area of atmospheric circulation where western and northern winds prevail, and is the first point Atlantic perturbations reach with respect to the rest of Spain. However, at the same time, this zone is influenced by different air masses with very different thermodynamic characteristics. Specifically, masses of warm, humid air arrive, like tropical maritime masses, as well as masses of air which, as they come from higher latitudes, have the common characteristic of being cold, although with a different humidity content [10].

In the specific case of the oceans, one of their significant characteristics is that they store a much greater quantity of energy than the atmosphere, and thus the possible effects of global warming would have a greater impact on marine ecosystems than on land ecosystems [11-15]. Based on the last reports from the IPCC, the global warming will generate changes in the intensity and structure of oceanic currents, produce alterations in marine organisms and shoreline, among other effects. Such shocks on the oceans probably will have important repercussions on the fisheries [16-20]. The projected impacts of global warming on fisheries and aquaculture are negative on a global scale. These impacts of climate change and ocean acidification are generally exacerbated by other factors such as overfishing, habitat loss and pollution. This is contributing to an increase in the number of dead zones in the oceans, as well as to an increase in harmful algal blooms [6]. The fishing activity is conditioned by the natural characteristics of the marine environment. Therefore, this economic activity is located between the most affected by global warming, along with tourism and agriculture ([7], [21]-[25]). It is highly probable that global warming will generate impacts on the intensity and disposition of oceanic currents, and the effect of this, among others, will generate increasing in surface sea temperature, variations in acidification and salinity levels and variationson ([26], [6]-[7], [26]). The impacts will differ according to ecosystems and coastal or ocean zones, and will affect different

groups of organisms, from phytoplankton and zooplankton to fish and algae [9]. Among these organisms, small pelagic marine species will be among those most affected by the effects form the warmin gf seas and oceans, due to their high level of instability and sensitivity to environmental impacts [27-29]. Therefore, any sea surface temperature variation will have repercussions to a greater or lesser extent on the ecosystems and these species' reproduction levels [17], especially in warming scenarios, and so any significant modification in the biomass levels can affect fishermen's net profits.

In the northern Spain zone, an increase in the sea surface temperature of 0.2°C per decade over the last forty years has been observed [10]. An increase has also been observed in the sea level of between 2 and 2.5cm per decade, similar data to the global increase in the Atlantic Ocean, although it has accelerated in the last twenty years [10]. Furthermore, a decrease in the intensity and duration of upwelling due to changes in wind patterns has occurred (the duration of the period favourable for upwelling has decreased significantly, by 30%, and their intensity by 45% in the last forty years; [10]). For the northern zone overall, the IPCC foresees an rise in the sea level of between 0.5 and 1.4 metres, an increase of the sea surface temperature of between 1 and 3°C and a drop in the pH of around 0.35 units [6].

The small pelagic species are target species for the majority of the Spanish fleet, in general, and for the north-west in particular. The study case chosen is the sardine fishery in zones VIIIc and IXa delimited by the International Council for the Exploration of the Sea (ICES), due to it being a hugely important pelagic species for the European fisheries sector. The potential economic impacts of global warming on this fishery will be analysed. For it, the oceantemperature is introduced into the bio-economic management problem. The sea surface allows gathering evidence of the global warming and its effects on marine ecosystems, which are the bases of fish natural growth functions. Other variables, such as the frequency and intensity of rainfall, acidity, dissolved carbon and salinity, are also prone to experience environmental changes by the climate change. However there is a high level of correlation between all of these variables: greater frequency and intensity of rainfall, acidity, salinity and dissolved carbon when the sea surface is increasing.

In this chapter, the evolution of sardine biomass is showed, based on the changes of the stock's growth function with respect to variations in marine ecosystem characteristics through the sea surface temperature and using econometric techniques and the Theory of the Optimal Control. Correlations between the sea surface temperature and the sardine biomass are tested. The econometric techniques will allow define the significant parameters and variables that could be needed to include in the management problem. The Optimal Control Theory will allow solve the bio-economic management problem and obtain the values for the sardine biomass and catches according to the forecast scenarios for the surface sea temperature by the IPCC. In addition, we will analyse impacts on the economic yield of the fishery deriving from a possible change in the temperature conditions of the ecosystem. A strong statistical relation is showed between the sea surface temperature and the sardine biomass. In addition, the results show thatif the sea surface temperature trend in these fishing grounds continues to show warming (as it is expected), the European sardine biomass, the catches and the expected profits will drop over the medium- and long-term.

## 2. Material and method

The Ibero-atlantic sardine (*Sardina pilchardus*) fishery is a stock resource shared by Spain and Portugal, in the waters that surround the Iberian Peninsula between the Bay of Biscay and the Strait of Gibraltar. There are historical references to this fishery dating back to the 13th and 14th centuries, made by both Spain [30] and Portugal [31]. From its beginnings, this fishery has been significantly relevant for the fishery sectors of both countries as well as for the processing industry (salting and canning industries).

This stock is exploited majority by the purse seine gear (99% of landings [32]). The Spanish fleet using this gear in the Atlantic is composed by 491 vessels, of which 346 are involved in Cantabrian waters and the remaining 146 are fishing in the grounds of the Canary Islands and the Bay of Cadiz [33]. It is one of the more numerous fleets of the Spanish total, behind only of the artisanal fleet, and it targets small pelagic species, among which are the sardine, horse mackerel, mackerel and the anchovy ([7],[33]-[34]). The vessels involved in this fisheryare relatively homogenous vessels insofar as their technical characteristics are concerned, with an average fishing capacity of 34.2 GT, 151.8 Kw per vessel and 21m of length size. The average life of the fleet is 20 years, with a crew of 8 per vessel. The Spanish purse seine fleet in the North Atlantic grounds use nets made from synthetic materials, hydraulic haulers and electronic fish detectors. The Spanish fleet that operates in the purse seine fishery licensed to catch sardine in this fishery is 241 vessels in 2012 [35].

### 2.1. The sea surface temperature

The Ibero-atlantic sardine recruitment processes could be governed by localised oceanographic conditions, but also by climatic events of a global nature. The growing influence of subtropical climatic components, such as El Niño, would increase the sea surface temperature, while the frequency and intensity of the average coastal upwellings on the west coast of the Iberian Peninsula are reduced, probably meaning that such a combination would cause the fishery's productivity to decrease [36-37]. Therefore, in this paper, we are going to establish some of the relationships between environmental alterations that could be caused by global warming, through the sea surface temperature, and the sardine fishery. We will analyse a bio-economic model which will include alterations in the sea surface temperature, and we will estimate their effects on fish population dynamics.

With respect to the sea surface temperature (SST), the annual averages have been calculated using the monthly data provided by the Oceanography Department of the Spanish Institute of Marine Research (which belongs to the Council of Scientific Research, CSIC). Figure 1 shows the results for the different maritime locations of the fishing grounds. These maritime locations range from 35°N to 45°N and from 8°W to 12°W for the Atlantic Ocean; and from 43°N to 45°N with a horizontal movement from 2°W to 8°W, which covers the entire Cantabrian coast. The data has been gathered for each grid of 1° each side, both vertically and horizontally. In order to carry out an analysis of the evolution of possible local warming in the study area, we have divided it up into three zones according to the different average temperature values observed:

from the Gulf of Cadiz (in the south of Spain) to the coast of Porto, from Porto to the boundary with the Cantabrian sea in Galicia, and for the rest of the Cantabrian sea. As can be observed in Figure 1, the hottest zone is Cadiz-Porto, which exceeds the average temperature of Porto-Galicia by approximately 2°C and the Cantabrian coast by approximately 1.5°C.
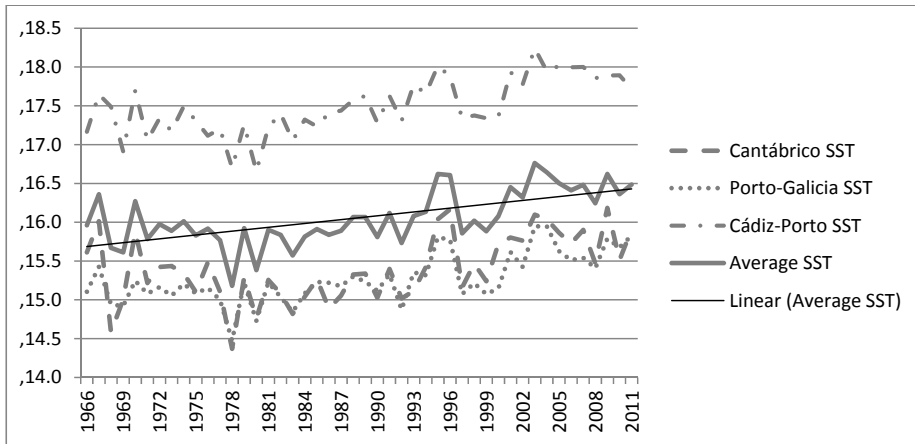


Source: Own compilation from Spanish Centre for Higher Scientific Research.

**Figure 1.** Sea surface temperature evolution (°C). 1987-2011

Although Figure 1 shows periods of average temperature increase (1968-1970, 1992-1996, 2000-2004) and periods where the temperature dropped (1975-1978, 1996-1998, 2003-2009), the overall trend shows an increase of the sea surface temperature for the period 1966-2011. On the other hand, in Table 1, some statistical measurements of the temperature series per maritime location are shown, this variable being highly disperse for the zone as a whole (0.35°C), greater in the Cantabrian zone (0.43°C). The minimum temperature value for the fishery overall was seen in 1978 (15.18°C), the maximum recorded in 2003 (16.76°C) And although the trend in the average temperature observed over the period 1966-2011 is upward, this increase was especially significant in the last thirty years of the period analysed: from the beginning of the decade of the 1980s. From that moment, the annual average sea surface temperature increased at a rate of 0.27°C per decade. Given that we do not know the foreseeable scenario with regard to warming for this fishing ground (the IPCC does not carry out forecasts at maritime zone level), this previous piece of data will be the one we use as a reference in the model applied, and we will assume that such a trend towards increases in SST will be maintained over the coming decades. In any case, we will devise an additional alternative scenario.

|  | Cantabrian zone SST | Porto-Galicia SST | Cádiz-Porto SST | Average SST |
|---|---|---|---|---|
| Standard deviation | 0.431 | 0.321 | 0.362 | 0.351 |
| Average | 15.410 | 15.270 | 17.490 | 16.060 |
| Variation coefficient | 0.028 | 0.021 | 0.021 | 0.022 |
| Minimum value | 14.370 | 14.480 | 16.660 | 15.180 |
| Maximum value | 16.180 | 15.950 | 18.240 | 16.760 |

Source: Own compilation from Spanish Centre for Higher Scientific Research.

**Table 1.** Statistical indicators for SST

## 2.2. The sardine stock

Similarly to most pelagic species, the sardine lives in relatively shallow water, in areas of high primary productivity (phytoplankton and zooplankton), generally situated on the edges of anti-cyclone areas and where intense upwelling phenomena that bring nutrients to the surface occur. International Council for Exploration of the Sea (ICES) scientists estimate that the northern and southern limits of sardine distribution could be related to the average water temperatures, as they need to be in waters with temperatures of between ten and twenty degrees centigrade. Therefore, it is a fishery which is particularly sensitive to the effects of climate change, and this could result in either a drop in productivity or the movement of the biomass to cooler waters. Since 1980, the ICES, as the institution in charge of evaluating the situation of the European sardine, considers the management unit to be the zone which lies between the French and Spanish maritime border and the Strait of Gibraltar. Most of the catches of these species take place in waters of the Ibero-atlantic continental platform, in the zone known as sardine stock distribution area in ICES divisions VIIIc and IXa.

The EU has regulated this fishery solely through the establishment of minimum catch sizes since 1999 (set at 11 cm). The Spanish government has limited catches per vessel and day (7,500 kg for sizes larger than 15cm and 500 for sizes of between 11 and 15cm), and has established a temporary ban during which it is not possible to fish (from February to March, inclusive, each year). For their part, various regional governments have established a weekly two-day ban in order to regulate the fishing effort in this fishery [38].

|  | Biomass | Landings |
|---|---|---|
|  | (tons) | (tons) |
| 1978 | 328000 | 145609 |
| 1979 | 358000 | 157241 |
| 1980 | 456000 | 194802 |
| 1981 | 554000 | 216517 |

| | Biomass | Landings |
|---|---|---|
| | (tons) | (tons) |
| 1982 | 583000 | 206946 |
| 1983 | 506000 | 183837 |
| 1984 | 624000 | 206005 |
| 1985 | 723000 | 208439 |
| 1986 | 629000 | 187363 |
| 1987 | 548000 | 177696 |
| 1988 | 514000 | 161531 |
| 1989 | 528000 | 140961 |
| 1990 | 481000 | 149429 |
| 1991 | 465000 | 132587 |
| 1992 | 699000 | 130250 |
| 1993 | 875000 | 142495 |
| 1994 | 797000 | 136582 |
| 1995 | 811000 | 125280 |
| 1996 | 548000 | 116736 |
| 1997 | 466000 | 115814 |
| 1998 | 383000 | 108924 |
| 1999 | 345000 | 94091 |
| 2000 | 296000 | 85785 |
| 2001 | 408000 | 101957 |
| 2002 | 462000 | 99673 |
| 2003 | 436000 | 97831 |
| 2004 | 417000 | 98020 |
| 2005 | 386000 | 87023 |
| 2006 | 518000 | 96469 |
| 2007 | 481000 | 101464 |
| 2008 | 364000 | 87740 |
| 2009 | 276000 | 89571 |
| 2010 | 228000 | 80403 |
| 2011 | 224000 | 54857 |

Source: Own compilation from [35].

**Table 2.** The sardine biomass and landings in ICES Zones VIIIc and IXa. 1978-2011
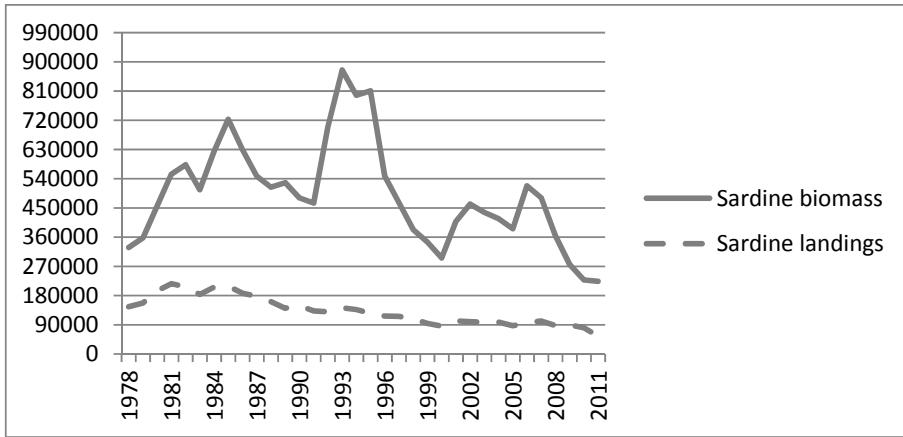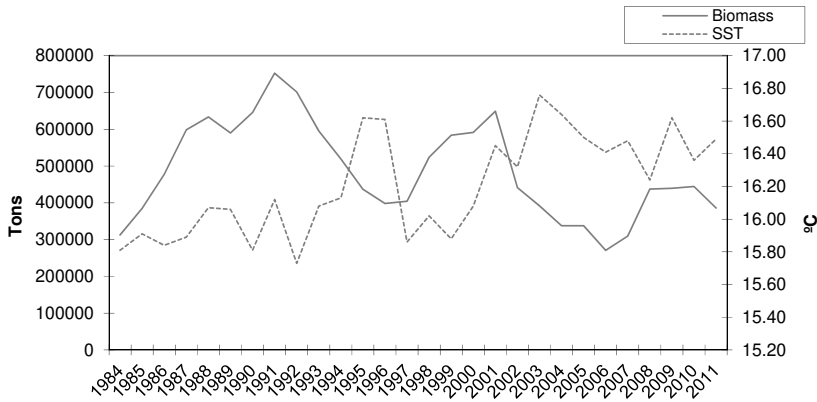
Source: Own compilation from [35].

**Figure 2.** The sardine biomass (tons) and landings (tons) trends. 1978-2011

Table 2 shows the sardine biomass and landings data for the period 1978-2011 on the basis of information provided by ICES. In Figure 1, the evolution of both variables over said period can be better observed. As shown in this figure, the Ibero-atlantic sardine spawning stock biomass underwent signification oscillations in said period, with a notable increase of sardine biomass in the period 1990-1992, to then undergo a significant reduction until the beginning of 2000.

These phases in biomass evolution do not seem to be reflected with the same rhythm and intensity in the total catches of this species landed. If in the second half of the decade of the 1980s the figure stood at around 150,000 tonnes, after that it continued to drop gradually, especially in the last years of the study period and in spite of the estimated increase for sardine biomass in some specific years. This could be related to the progressive drop in the number of vessels which have fished in the fishery since the beginning of the 1990s.

On the other hand, being a pelagic species, the sardine is extremely sensitive to environmental changes in general, and to increases in ocean temperature in particular. In Figure 3 we can see the evolution of the spawning stock biomass and the average temperature of the water on the Cantabrian-north-west coast over the period 1984-2011.

It can be seen how, in general, after periods of slight increases in the sea surface temperature there is a drop in sardine biomass. This is especially significant in the periods 1994-1996 and 2003-2007. However, after periods when there was a drop in temperatures (1990-1992 and 1997-2003), an increase in the level of sardine biomass was seen. This can be proved from a statistical point of view. Table 3 shows the statistical correlation data regarding sardine

Source: Own compilation from [35].

**Figure 3.** The sardine biomass (tons) and sea surface temperature (°C). 1984-2011

biomass and average sea temperature. The negative temperature sign denotes that when variations in this variable occurred, the signs for variations in biomass went in the opposite direction.

| | Sardine Biomass | Sardine biomass in t+1 | Temperature (SST) |
|---|---|---|---|
| Sardine Biomass | 1.0000 | | |
| Sardine biomass in t+1 | 0.86293 | 1.0000 | |
| Temperature (SST) | -0.51841 | -0.69284 | 1.0000 |

Source: Own compilation from Spanish Centre for Higher Scientific Research.

**Table 3.** Correlation matrix of variables

From all of the above, it can be deduced that oscillations in the sea temperature will impact on the natural productivity of this fish stock and, consequently, this will affect the generation of future economic yields through potential catches. On this basis, and in the face of an increase in the water temperature foreseeable for the northern hemisphere (as a consequence of global climate change; [6]), in this chapter we will make an estimation of its economic impact on the fishery. Prior to this, we will establish the zero scenario, our starting point, with which to make the comparison of possible future scenarios.

## 2.3. The economic data

Given that we do not have the economic data for the fleet whose target species is sardine as a whole, we are going to use a representative sample. The fleet sampled contributes around 18% of the total catches generated in the Ibero-atlantic sardine fishery in the period for which data

was gathered (2001-2011), although this level of representation rises to 25% in the last three years of said period. Table 4 shows the evolution of the sampled vessels' landings and the income generated by their sale at market for the period we have been able to compile data for (2001-2011).

|      | Landings | Income | Average price |
|------|----------|--------|---------------|
|      | (tons) | (euros 2011) | (euros/Kg) |
| 2001 | 19 303.04 | 11 581824.0 | 0.60 |
| 2002 | 8 548.63 | 5 214664.3 | 0.61 |
| 2003 | 6 474.87 | 4 014419.4 | 0.62 |
| 2004 | 5 930.54 | 4 210683.4 | 0.71 |
| 2005 | 14 546.12 | 12 493 800.2 | 0.86 |
| 2006 | 11 491.22 | 10 661 267.3 | 0.93 |
| 2007 | 13 237.87 | 9 632 988.3 | 0.73 |
| 2008 | 19 668.66 | 13 715 626.4 | 0.70 |
| 2009 | 21 511.70 | 11 969 763.4 | 0.56 |
| 2010 | 20 227.14 | 10 951 081.8 | 0.54 |
| 2011 | 16 714.95 | 10 741 674.3 | 0.64 |

Source: Own compilation from www.pescadegalicia.com.

**Table 4.** Economic data: Income

With regard to the sample vessels' landings a downward trend can be observed in the first years of the decade 2000-2010, coinciding with years of low biomass, after which time the trend recovered gradually, except in the final years of the series when a drop in landings was observed once again after a new reduction in sardine biomass. In general, income followed a similar trend to landings. On the basis of both variables, the average sale price for this species for each year the period comprises can be obtained. As can be seen in Table 4, the average price in 2011 constant monetary units, on the other hand, displayed an upward trend until the middle of the decade, at which time it began to fall progressively.

With respect to the exploitation costs of this fishing activity, from [39] and the vessels sampled which provided this data, we have the information relating to the cost structure of this fleet in relation with the annual value of sardine landings. As can be seen in Table 5, the largest proportion of fleet costs goes towards paying crews' wages and salaries (this cost represents just over 55% of the average for the period overall), followed by the Gross Operating Surplus/ Mixed Income-shipowner/vessel owner income – (they make up approximately 17%), and vessel costs –mainly repairs and maintenance of the vessels themselves as well as fishing gear – (representing around 14%). Furthermore, the gradual increase in fuel costs is notable, and is especially significant in the last year of the period for which data is available.

From the information shown in the last two Tables, the average unit price and cost for the overall period have been estimated, and are shown in Table 6. The price of 10-year public bonds has been used as the social discount rate for the period considered. Against this background, we are in a position to establish the bio-economic model that will be used to estimate the effects deriving from changes in the sea surface temperature on the net profits of the fishery as a whole. We will use a period of approximately fifteen years, up until 2030, as a temporary horizon, as is proposed in the Climate Change Adaptation Plan drawn up by the former Ministry for the Environment.

| % | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | Average 2006-11 |
|---|---|---|---|---|---|---|---|
| Value of landings | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 |
| Fuel costs | 5.70 | 7.14 | 7.96 | 7.14 | 5.00 | 7.47 | 6.74 |
| Other current costs | 5.37 | 6.43 | 6.23 | 9.09 | 7.22 | 10.33 | 7.44 |
| Vessel costs | 16.11 | 14.29 | 13.15 | 12.34 | 16.67 | 10.55 | 13.85 |
| Crew costs | 53.69 | 53.93 | 57.09 | 54.87 | 56.39 | 55.60 | 55.26 |
| Gross operating surplus/ Mixed income | 19.13 | 18.21 | 15.57 | 16.56 | 14.72 | 16.04 | 16.71 |
| Gross value added | 72.82 | 72.14 | 72.66 | 71.43 | 71.11 | 71.65 | 71.97 |

Source: Own compilation from [39] and sample.

**Table 5.** Economic data: Cost Structure (%).

| | Unit | Value of parameters |
|---|---|---|
| Unit Price of landings | €/ton | 681.82 |
| Unit cost of fishing | €/ton | 554.56 |
| Discount rate | % | 5.00 |

Source: Own compilation from www.pescadegalicia.com, [39] and sample.

**Table 6.** Economic data: Unit values

### 2.4. Methodology

Bio-economic modelling allows introducing natural, environmental and institutional varia-bles, in addition to the strictly economic, in one analytical body. For the specific case of fishing management problem, the aim is to control the stock of fish by limiting the catch (or effort) so that the stream of net benefits over time will be optimizedand tacking into account the dynamics of fishing stock. In this way, we can determine where society can invest (or divest) the marine resource and what should be the rate of abstraction allowing to maintain their sustainable exploitation.

The bio-economic problem is represented as follows:

$$Max_h \int_0^\infty \pi(X,h)e^{-\delta t}\, dt \tag{1}$$

$s.a.\ \dot{X} = \frac{dX}{dt} = F(X) - h\left(\dot{t}\right)$

where denotes the net economicbenefitsobtained from fishing activity in each instant $t$, Xrepresents the fish stock, $h$ denotes the harvest rate, $p$ the unit price of landings, cdenotes the unit cost of fishing, $\delta$ the social discount rate and $F(.)$ represents the natural growth of fishing stock (the stock dynamics without considering the harvest). The optimization problem for regulator [40] consists of determining the feasible control, $h(t)=h^*(t)$ with $t \geq 0$, which optimisesthe net benefit stream while satisfying the problem's conditions in aglobalwarming context.

Before solving the optimization problem (1), it is necessary to define previously the growth natural function $\dot{X}$. The stock dynamic isstatistically tested on the basis of the data that exists on biomass and catches showed in Table 4; in addition, the sea surface temperature is included in this study case. Ordinary Least Squares (OLS) will be used to obtaining the parameters values. The Gordon-Schaefer expression is the function commonly used in the bio-economic literature [41-42], which is as follows incorporating the sea surface temperature ($T$):

$$\dot{X} = \alpha X_t + \beta X_t^2 + \gamma T_t - h_t \tag{2}$$

|  | $X_{t+1} + h_t = \alpha X_t + \beta X_t^2 + \gamma T_t$ |
|---|---|
| $\alpha$ | 2.057 (0.076) |
| $\beta$ | -0.1048 E$^{-5}$ (0.357) |
| $\gamma$ | -6048.4 (0.712) |
| Jb | 0.5582 |
| Q-Stat | 4.6335 |
| LM (ARCH) | 0.171 |
| R$^2$ | 0.7528 |
| R$^2$ adjusted | 0.7250 |

Note: t-ratio between brackets. Jb is the Jarque-Bera statistic of the normality test; Q-Stat is the

Ljung-Box statistic used in the correlation test; LM (Lagrange multiplier) is the one used in the heteroscedasticity test.

**Table 7.** Econometric results for growth function of sardine stock

The equation (2) corresponds to the logistic model, where $\alpha$, $\beta$ and $\gamma$ are parameters containing biological information on sardine stock, and $T$ denotes the sea surface temperature. From data showed in Table 2, the results from the econometric estimation of (2) can be shown in Table 6 and so the stock dynamic is given by the following expression:

$$\dot{X} = 2.057\, X_t - 0.1048 E^{-5} X_t^2 - 6048.4\, T_t - h_t \tag{3}$$

In this way, the *Hamiltonian* function in usual terms (current moment $t$) associated with problem (1) is given by the following expression [43]:

$$H\ (X,\ h,\ t;\ \mu) = (p - c) h_t + \mu\left(\alpha X_t - \beta X_t^2 - \gamma T_t - h_t\right) \tag{4}$$

where $\mu$ denotes the shadow price of the marine resource in current terms.

The conditions necessary [43] to solve the optimization problem are given by the following mathematical expressions:

$$\frac{dH\ (X,\ h,\ t;\ \mu)}{dh} = 0 ==> (p - c) - \mu = 0 \tag{5}$$

$$\dot{\mu} - \delta\mu = - \frac{dH\ (X,\ h,\ t;\ \mu)}{dX} = -\mu(\alpha - 2\beta X) \tag{6}$$

$$\frac{dX}{dt} = 0 ==> \alpha X - \beta X^2 - \gamma T - h = 0 \tag{7}$$

The condition (5) represents the known condition of economic efficiency. The condition (6) expresses the compensation which should exist in the optimum trajectory between the profit rate on the resource minus the social cost of not exploiting it (left side) and the total productivity of the same. Note that the natural resource is productive in two different ways: for its contribution to obtaining profits and for its contribution in the function itself of the natural growth of fish stock. And the condition (7) describes the evolution of the sardine biomass over the time.

By using expressions (5)-(7) the biomass and catch levels are obtained, $X^*(t)$ and $h^*(t)$, which will depend on the level of sea surface temperature. Once these levels are known, the losses or profits associated with the global warming scenario in relation with the fishery's present situation can be obtained through the net economic benefit function for this stady case.

## 3. Findings

In order to obtain numerical results for the impact on profits and given that the biomass levels in our model are going to depend on the sea surface temperature in the years to come, we are going to assume three possible scenarios for this latter variable. In the first scenario, we will assume that the oceanic temperature will increase at the same rhythm as the increase observed in the last decades (0.027°C per year). In the second scenario, we will assume that global warming intensifies and that that will affect the oceanic temperature, increasing to a greater extent than what has been seen to date (we will be estimating increases of 5% above the trend in the past decades). And in the third scenario, on the other hand, but in a context of rising

temperatures, we will assume that global warming is being controlled to a greater extent (be it as a consequence of the current economic crisis or mitigation policies being carried out in the EU), and that this will give rise to a lower sea surface temperature in relation to that which would have occurred if the trend observed in the last decades continued (5% drop with regard to the past trend).

Table 8 summarises the three scenarios proposed. On the other hand, we will use up until the year 2030 as a temporary horizon, as is proposed in the Spanish government's Climate Change Adaptation Plan ([8-9]). In any case, we will extend it some years further in order to have a wider perspective of the evolution of the fishery's main indicators.

|  | Description | SST variation |
|---|---|---|
| Scenario 1 | Trends last few decades | Increase of 0.027ºC yearly |
| Scenario 2 | Acceleration in global warming and increasing in SST | Increase of 5% over trends last few decades |
| Scenario 3 | Mitigation of global warming and in variation of SST | Decrease of 5% over trends last few decades |

**Table 8.** Scenarios for trends in the sea surface temperature

Table 9 shows the scenarios forecast in relation with variations in sea surface temperatures. And the results obtained for the evolution of sardine biomass, catches and future profits the fleet could obtain are shown in Tables 10-12, respectively, for the different temperature variation scenarios contemplated.

|  | Scenario 1 | Scenario 2 | Scenario 3 |
|---|---|---|---|
| 2015 | 16.679 | 16.726 | 16.650 |
| 2016 | 16.706 | 16.754 | 16.677 |
| 2017 | 16.733 | 16.782 | 16.704 |
| 2018 | 16.76 | 16.811 | 16.731 |
| 2019 | 16.787 | 16.839 | 16.758 |
| 2020 | 16.814 | 16.868 | 16.785 |
| 2021 | 16.841 | 16.896 | 16.812 |
| 2022 | 16.868 | 16.924 | 16.839 |
| 2023 | 16.895 | 16.953 | 16.866 |
| 2024 | 16.922 | 16.981 | 16.893 |
| 2025 | 16.949 | 17.009 | 16.920 |
| 2026 | 16.976 | 17.038 | 16.947 |
| 2027 | 17.003 | 17.066 | 16.974 |

|      | Scenario 1 | Scenario 2 | Scenario 3 |
|------|-----------|-----------|-----------|
| 2028 | 17.030 | 17.094 | 17.001 |
| 2029 | 17.057 | 17.123 | 17.028 |
| 2030 | 17.084 | 17.151 | 17.055 |
| 2031 | 17.111 | 17.179 | 17.082 |
| 2032 | 17.138 | 17.208 | 17.109 |
| 2033 | 17.165 | 17.236 | 17.136 |
| 2034 | 17.192 | 17.264 | 17.163 |
| 2035 | 17.219 | 17.293 | 17.190 |
| 2036 | 17.246 | 17.321 | 17.217 |

Source: Own compilation.

**Table 9.** SST (°C) evolution under different scenarios

|      | Scenario 1 | Scenario 2 | Scenario 3 |
|------|-----------|-----------|-----------|
| 2015 | 223066.5 | 221837.425 | 224304.107 |
| 2016 | 217004.959 | 215510.916 | 218500.843 |
| 2017 | 205489.328 | 209431.150 | 212885.052 |
| 2018 | 205489.328 | 203543.027 | 207448.530 |
| 2019 | 200017.684 | 197880.085 | 202184.219 |
| 2020 | 194726.912 | 192393.630 | 197085.849 |
| 2021 | 189609.726 | 187114.034 | 192147.064 |
| 2022 | 184659.140 | 181996.034 | 187361.753 |
| 2023 | 179868.449 | 177070.778 | 182724.042 |
| 2024 | 175234.567 | 172292.792 | 178228.286 |
| 2025 | 170746.824 | 167690.392 | 173872.968 |
| 2026 | 166401.363 | 163224.606 | 169647.338 |
| 2027 | 162192.709 | 158920.764 | 165548.858 |
| 2028 | 158115.632 | 154742.593 | 161572.884 |
| 2029 | 155468.200 | 150713.953 | 157714.966 |
| 2030 | 150336.432 | 146801.044 | 153970.843 |
| 2031 | 146624.964 | 143026.362 | 150336.432 |
| 2032 | 143026.361 | 139358.379 | 146807.821 |
| 2033 | 139536.448 | 135818.318 | 143381.263 |
| 2034 | 136151.230 | 132376.743 | 140053.166 |

|      | Scenario 1  | Scenario 2  | Scenario 3  |
|------|-------------|-------------|-------------|
| 2035 | 132866.886  | 129053.689  | 136820.084  |
| 2036 | 129679.759  | 129680.000  | 133678.718  |

Source: Own compilation.

**Table 10.** Results for sardine biomass (tons) under different scenarios of SST

|      | Scenario 1  | Scenario 2  | Scenario 3  |
|------|-------------|-------------|-------------|
| 2015 | 136173.574  | 135682.327  | 136666.659  |
| 2016 | 133735.621  | 133134.565  | 134340.834  |
| 2017 | 131987.354  | 130633.823  | 132055.964  |
| 2018 | 128994.996  | 128184.904  | 129811.690  |
| 2019 | 126691.327  | 125782.099  | 127607.530  |
| 2020 | 124431.248  | 123429.341  | 125442.928  |
| 2021 | 122214.141  | 121121.508  | 123317.362  |
| 2022 | 120039.382  | 118862.051  | 121230.297  |
| 2023 | 117906.334  | 116645.972  | 119181.193  |
| 2024 | 115813.999  | 114476.667  | 117169.503  |
| 2025 | 113762.218  | 112349.624  | 115194.258  |
| 2026 | 111750.122  | 110267.480  | 113255.500  |
| 2027 | 109777.040  | 108226.212  | 111352.406  |
| 2028 | 107842.299  | 106228.127  | 109484.401  |
| 2029 | 105814.331  | 104269.509  | 107650.907  |
| 2030 | 104085.147  | 102352.38   | 105851.348  |
| 2031 | 102261.395  | 100473.302  | 104085.147  |
| 2032 | 100473.302  | 98634.044   | 102351.731  |
| 2033 | 98720.203   | 96831.428   | 100650.525  |
| 2034 | 97001.441   | 95067.000   | 98980.963   |
| 2035 | 95316.361   | 93337.816   | 97342.478   |
| 2036 | 93664.3171  | 91284.140   | 95734.509   |

Source: Own compilation.

**Table 11.** Results for the sardine catches (tons) under different scenarios of SST

|  | Scenario 1 | Scenario 2 | Scenario 3 |
|---|---|---|---|
| 2015 | 17329449.1 | 17266932.9 | 17392199.0 |
| 2016 | 17019195.1 | 16942704.8 | 17096214.5 |
| 2017 | 16796710.7 | 16624460.4 | 16805442.0 |
| 2018 | 16415903.1 | 16312810.9 | 16519835.6 |
| 2019 | 16122738.3 | 16007029.9 | 16239334.2 |
| 2020 | 15835120.6 | 15707617.9 | 15963867.1 |
| 2021 | 15552971.6 | 15413923.1 | 15693367.5 |
| 2022 | 15276211.7 | 15126384.6 | 15427767.6 |
| 2023 | 15004760.0 | 14844366.4 | 15166998.6 |
| 2024 | 14738489.5 | 14568300.6 | 14910990.9 |
| 2025 | 14477379.9 | 14297613.2 | 14659621.3 |
| 2026 | 14221320.6 | 14032639.5 | 14412895.0 |
| 2027 | 13970226.1 | 13772867.7 | 14170707.2 |
| 2028 | 13724010.9 | 13518591.4 | 13932984.9 |
| 2029 | 13465931.7 | 13269337.8 | 13699654.5 |
| 2030 | 13245875.9 | 13025363.8 | 13470642.6 |
| 2031 | 13013785.2 | 12786232.4 | 13245875.9 |
| 2032 | 12786232.4 | 12552168.5 | 13025281.2 |
| 2033 | 12563133.0 | 12322767.5 | 12808785.9 |
| 2034 | 12344403.3 | 12098226.4 | 12596317.3 |
| 2035 | 12129960.1 | 11878170.5 | 12387803.7 |
| 2036 | 11919721.0 | 11616819.7 | 12183173.6 |

Source: Own compilation.

**Table 12.** Results for the net profits (€) under different scenarios of SST

Starting with the evolution of sardine biomass (Table 10), as the sea surface temperature increases, the fish biomass decreases. The estimated biomass levels for the next twenty years are higher in the scenario of a lower increase than the one foreseen for temperature (scenario 3) and, on the other hand, they are lower in the temperature scenario with the greatest increase. This was to be expected, bearing in mind the relation observed between the sea temperature and the sardine biomass.

Along the same lines, the estimated catches evolve similarly to the fish biomass (Table 11). In particular, the fleet's potential catches dropped as the sea surface temperature rose over the

period as a whole. However, the estimated catches are greater in the scenario where temperature increases are lower (scenario 3) and lower when the temperatures are higher (scenario 2).

Lastly, and foreseeable given the forecast for the evolution of biomass and catches, the expected profits (Table 12) are higher in the scenario where the effects of climate change are mitigated (scenario 3), in which, with increasing sea surface temperatures, although lower than those proposed for the other scenarios, the profits would fall by 1.2% in the period (if the temperature were to drop 5% on the annual 0.027°C increase). In the remaining scenarios, the profits would fall more substantially: by approximately 1.25% (scenario 1) and 1.40% (scenario 2), approximately, in the period, as the annual sea surface temperature increases.

## 4. Conclusions

The scientific evidence available to date leaves no doubt that climate, the different ecosystems and the planet, as we know it now, will not be the same in the future. Knowing the possible impacts that such change will bring is fundamental if mankind is to mitigate its effects and adapt to new global warming scenarios.

In this chapter, we have estimated the economic effects of climate change on one of the most relevant socioeconomic fisheries for the Spanish fisheries sector as a whole. This has been based on the effects of global warming on the oceanic temperature and its impacts on the natural productivity of the marine species. It has been observed that after slight temperature increases, a decrease in spawning biomass occurs, and vice versa. Specifically, and after estimating the correlation between the spawning stock biomass of sardine and the sea surface temperature, it has been identified that the temperature explains around 30% of the uncertainty associated with this fishery.

With regard to the estimation of the future impact, three possible temperature evolution scenarios have been taken into account: where the observed annual trend of a 0.027°C increase in the sea surface temperature is maintained; where global warming intensifies and therefore there is a greater increase in the sea surface temperature (increases of 5% above the previous trend); and where global warming is controlled and mitigated, implying a lower increase in the sea surface temperature with respect to the trend observed in recent decades (5% decrease).

The results show that as the sea surface temperature of the Ibero-atlantic fishing grounds increases, lower levels of biomass and catches are obtained, while the economic yields would be reduced. In particular, if the current sea surface temperature increase trend is maintained, annual profits will fall by 1.3% over the period analysed (2015-2036). If global warming intensifies and this were to generate an even greater increase in the water temperature of the fishing grounds, profits would drop by around 1.4% on average in each year of the period analysed. However, if palliative measures tending towards reducing warming were introduced, giving rise to a lower increase in the sea surface temperature, which could also derive from the current economic crisis and subsequent drop in production activity, profits would fall at an annual rate of approximately 1.2%.

In short, the trends are toward higher sea surface temperatures in these zones and, as a consequence, lower levels of spawning stock biomass of sardine. It has a direct negative impact on the catches and net benefits for the fishermen involved in the fishery: the higher sea temperature, the less catches and profits will be obtained.

The results obtained in this analysis are not intended to be definitive, however they do show from a scientific point of view how global warming can impact upon a specific economic activity whose main input is a natural renewable resource. The results obtained herein make it possible to identify and quantify, under specific assumptions regarding economic parameters and climate scenarios, the direction of the economic effects of global warming on one of the fisheries most sensitive to environmental shocks, as are the pelagic fisheries. These results demonstrate, once again, the need to increase palliative action and design strategies as to how best to adapt to the possible climate scenario, at both global as well as national or local level. Better knowledge of the effects of global warming will affect future decisions on the sustainable management of marine resources and the foreseeable reduction of the pressure they are under.

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