

# Factor input constraints in resource dynamics

Inaugural-Dissertation

zur Erlangung des akademischen Grades eines Doktors  
der Wirtschafts- und Sozialwissenschaften  
der Wirtschafts- und Sozialwissenschaftlichen Fakultät  
der Christian-Albrechts-Universität zu Kiel

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aus Hamburg

Kiel, 2018

Gedruckt mit Genehmigung der  
der Wirtschafts- und Sozialwissenschaftlichen Fakultät  
der Christian-Albrechts-Universität zu Kiel

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Tag der Abgabe der Arbeit:	27.08.2018
Tag der mündlichen Prüfung:	06.12.2018

## Acknowledgements

While working on this dissertation, I had the great privilege to enjoy the support of Prof. Martin Quaas, my main supervisor. I am deeply thankful for the steady and valuable support, from my early resource economics lectures until the final chapter of this dissertation. I perceived this direct contact to my supervisor as a great luxury. I am truly glad for the opportunity to continue my research and work in his working group. I would also like to thank Prof. Till Requate, for invaluable comments and for kindly agreeing to serve as second referee.

I am glad that I had the chance to work on the chapters of this thesis in co-authorship with Prof. Martin Quaas, Dr. Lorena Fricke, Dr. Jörn Schmidt, Anna Deppenmeier and Dr. Teferi Demissie. Along the way, I had the opportunity to learn a lot about not only my own field of research, but also about related questions in biology and climate research.

The time as a PhD student would not have been as stimulating, fun and successful without my colleagues, both within my working group and within the projects that I contributed to during the last years. I would like to thank all of you for your support, feedback, and wonderful times at our yearly retreats. Furthermore, I was given the chance to attend several international conferences during my time as a PHD student. The comments and discussions provided valuable input to the papers presented, that are now part of this dissertation. I would like to thank the organizers for providing such stellar possibilities to exchange ideas.

I gratefully acknowledge data provision by the Centre of Oceanographic Research of Dakar-Thiaroye (CRODT), the Direction des pêches maritimes (DPM), the National Agency of Statistics and Demography (ANSD) and the European Centre for Medium-Range Weather Forecasts (ECMWF). Fur-

thermore, the hydro-acoustic surveys done by the research vessel R/V Dr FRIDTJOF NANSEN enabled our studies to include harvest independent stock assessment data. The studies benefited also from biomass distribution data provided by T. Brochier, and although said data was not used in the end, I am thankful for the chance to work with it.

My dearest thanks go to my family and friends for support in hours of distress and frustration and for keeping me company throughout the rest.

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# 1 Introduction

My motivation to conduct research in economics derives from the aim to contribute to improved living conditions for the people on this planet. One important question to achieve this addresses the extraction of natural resources over time. For many products, natural resources constitute a necessary production input. Moreover, their extraction now may affect the ability of future generations to meet their own needs. Even renewable resources are usually exhaustible, such that extraction paths exist that would leave the resource fully exhausted in finite time. Optimal resource management takes such inter-temporal effects into account. However, the determination of optimal extraction paths is often complicated.

First, it is important to assess the welfare society derives from a natural resource in the current state and to see how the availability of other factors of production impacts these benefits. As will be shown in chapter 1, a fishery can generate rents even under open access, if production factors are supplied locally. Second, this assessment should include future benefits' development given environmental and economic changes (chapter 2). Chapters 3 and 4 show that the inter-temporal aspect increases in complexity when factors of production are not flexibly adaptable over time, or when learning-by-doing occurs, such that today's production affects productivity in the future. In summary, numerous constraints affect resource use and production now and in the future. This dissertation addresses some of these constraints in order to help to improve resource management. It contributes to different strands of literature, in particular resource, development and energy economics.

This cumulative doctoral thesis consists of four individual research articles. The first chapter, titled “**Empirical bio-economic modeling of artisanal fisheries' food security contribution: A new approach and**

**application to the Senegalese purse-seine fishery**” is joint work with Lorena Fricke and Jörn Schmidt. It will be presented at the Annual Science Conference (ASC) of the International Council for the Exploration of the Sea (ICES) in Hamburg coming September 2018. Currently, this paper is under review at “Food policy”.

Fish is an important source of protein, especially in many developing countries. Artisanal fisheries provide livelihoods for millions of people. However, local markets provide significant non-linear links between quantities and prices, and data is often scarce and of poor quality. Due to that, problems of endogeneity complicate the assessment of welfare derived from these fisheries as well as the estimation of environmental effects. This paper develops a bio-economic model and presents a two-step estimation procedure to overcome these difficulties. Local factor inputs and local demand lead to rent generation. In an application to the Senegalese purse-seine fishery, we find that total rents account for 2% of per capita yearly food expenditures for the coastal inhabitants. Yet, we also find environmental impacts that may affect this rent in the future. Our estimates can be used for robust prediction beyond the currently observed environmental state.

I have substantially contributed to this paper during all major stages of research. The model builds on previous work in Lorena Fricke’ dissertation (Fricke, 2016) and by Quaas et al. (2017). With support from Lorena Fricke and feedback from my co-authors and supervisor, I took the lead concerning model adaptation to the Senegalese fishing sector, data preparation and analysis as well as estimation and writing.

The second chapter, **“Climate change adaptation and the role of fuel subsidies: An empirical bio-economic modeling study for an artisanal open- access fishery”** is joint work with two colleagues from

climate sciences – Anna Deppenmeier and Teferi Demissie – as well as Jörn Schmidt, who has a background in marine biology. This paper has been submitted to “PLOS ONE”. Therefore, the paper is written as to suit readers outside the economic research community.

This paper builds on the first chapter and studies how climate change can impact open-access artisanal fisheries and their role for food security. The paper extends the model from chapter 1 to include biological dynamics affected by climate impacts. In addition, we introduce fuel as a production input. The model is estimated and results are used for a simulation of the fisheries development under four different climate projections and two policy scenarios concerning fuel subsidy reform. We find that the regions’ catch potential increases with climate change. However, this escalates over-fishing which outruns the incipiently favorable climate change effects under three of four climate projections. If fuel subsidies are abolished, ecological sustainability as well as fisheries’ welfare contribution increase regardless of the climate projection.

I have substantially contributed to this paper during all major stages of the research process. All co-authors developed the research question. I developed the biological part of the model with advice from Jörn Schmidt. The economic model builds on the previous chapter, which I extended to account for the effect of fuel as a production input. The empirical part and the simulations were carried out by myself. Martin Quaas recommended the stochastic runs to better assess climate variability effects. Anna Deppenmeier and Teferi Demissie contributed the climate projections used in the simulation.

Chapter 3 is entitled “**Over-capitalization in fisheries with irreversible investment and factor substitution**”. I presented this paper

at the international conference organized by the International Institute of Fisheries Economics & Trade (IIFET) in 2017.

While previous chapters assumed that production inputs such as capital, labor and fuel can be flexibly adapted, inter-temporal resource management is even more complex when production inputs have to be optimized inter-temporally as well. Investment into fisheries is often irreversible. For fisheries, this can complicate the problem of over-capitalization. This paper extends the previous literature, that typically assumes capital and effort to enter harvest production as perfect complements, as my model allows for the substitution of imperfectly malleable capital with flexibly adaptable inputs. By means of Hamiltonian derivation and numerical analysis, qualitative and quantitative consequences of substitutability are highlighted. Successful fisheries management needs to take the level of potential factor substitution in the respective fishery into account.

This is a single-authored paper, although it benefited from extensive discussions with Martin Quaas.

Chapter 4, titled “**Increasing marginal costs and the efficiency of differentiated feed-in tariffs**” is joint work with my supervisor Martin Quaas. This paper was presented at the Ulvön Conference on Environmental Economics 2014 and the international conference of the European Association of Environmental and Resource Economists (EAERE), as well as at the Cologne International Energy Summer School (CIES), in 2015. It has been submitted for publication at “Energy Economics”.

Another way in which a resource may shape inter-temporal production is learning by doing. The paper studies optimal subsidies for renewable energy generation. In our model, the policy-maker intervenes because learning-by-doing spillovers constitute a positive externality. Sites for renewable energy

generation are in limited supply, such that marginal costs increase at the industry level. Scarcity of sites means that the resource constrains another input inter-temporally, namely learning. We use an analytical modeling approach to study optimal subsidy differentiation between technologies and to derive a condition under which less efficient technologies should receive higher support, as common in actual policy-making. We underline the importance of site scarcity for this condition.

I have substantially contributed to this paper during all major stages of the research process. The research idea and model were jointly developed with my co-author Martin Quaas, who also contributed the proofs in the Appendix. We shared writing the paper. My contribution to this paper includes furthermore the literature review and the numerical example that links our findings to empirical estimations of learning rates.

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# Empirical bio-economic modeling of artisanal fisheries' food security contribution: A new approach and application to the Senegalese purse-seine fishery

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**Abstract** Artisanal open access fisheries are an important source of protein in many developing regions and provide livelihoods for millions of people. They are challenged by changing environmental and local market conditions. Quantitative bio-economic models are needed that comprehensively assess artisanal fisheries contribution to food security. The empirical estimation of model parameters faces issues of endogeneity, as local markets constitute strong links between quantities and prices. Data is often scarce.

Our bio-economic model, based on standard resource economics assumptions, is able to explain impacts of environmental variations on output and prices. We present an estimation approach that efficiently utilizes scarce data, as it estimates dynamic model equations directly. It averts endogeneity bias by means of a two-step estimation procedure. Our estimates can be used for robust prediction beyond the currently observed state. The application to the Senegalese purse-seine fishery illustrates the link between environmental impacts, economic outcomes and consequences for food security.

**JEL Classification:** Q22, Q21, C32, Q54

**Keywords:** artisanal fisheries, open-access, food security, livelihoods, endogeneity, climate change

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# 1 Introduction

In recent years, artisanal fisheries received substantial scientific attention, especially concerning their implications for food security (e.g. Belhabib et al., 2015; Failler, 2014; Kawarazuka and Béné, 2010). Fish constitutes the cheapest and quantitatively most important source of protein in many countries where food security is an issue (World Bank, 2007). Worldwide, around 90% of fishers belong to the artisanal sector (FAO, 2005; World Bank, 2008), that thus serves as a safety net for thousands. Because 90–95% of their landings are humanly consumed, their contribution to food security is invaluable.

While economic welfare analysis is a standard endeavor for industrial fisheries (Arnason et al., 2004; Costello et al., 2016; Quaas et al., 2017; Willmann and Kelleher, 2009), studies on artisanal fisheries have been criticized to focus on profit, marginalizing labor buffer and food security benefits (Béné et al., 2010; Andrew et al., 2007; Schuhbauer and Sumaila, 2016). Welfare impacts are often given in qualitative terms or as proxy indicators like employment. Dynamic equilibrium changes are disregarded (e.g. Adeogun et al., 2009; Failler, 2014; Lam et al., 2012). These studies are convincing as to the current status. However, with changing climatic and economic conditions, the equilibrium of fish quantity and price changes. To enable meaningful simulations of future impacts and to assess the actual vulnerability to relevant drivers, a dynamic equilibrium analysis is required. We identify two main reasons for this imbalance: Firstly, welfare analysis needs a methodology to disentangle simultaneous changes in prices and quantities. Secondly, data scarcity inhibits welfare analysis (Schuhbauer and Sumaila, 2016).

The separate analysis of supply and demand systems is still standard. The majority of demand analyses (e.g. Asche et al., 1997; Gallet, 2009) uses the almost ideal demand system, which does not embed productivity changes.

Supply estimation either directly estimates cost functions (Cheilari et al., 2013; Daurès et al., 2013; Quaas et al., 2017) or assumes perfectly elastic demand, where one fishery is too small to impact the world market price (Arnason et al., 2004; Kronbak, 2004; del Valle et al., 2001). Only two studies in fisheries economics use a simultaneous equations approach: Tsoa et al. (1982) use a semi-reduced form that incompletely alleviates endogeneity bias, because they lack the biologic data. Angrist et al. (2000) use stormy weather as instrument, arguing that this shifts supply but not demand. However, they do not embed this instrument into a full welfare analysis.

The standard single-equation approach is not readily applicable for small-scale artisanal fisheries. They are typically characterized by fishing under open-access conditions, localized markets for labor and landed fish, and a large number of actors involved (Guyader et al., 2013; Willmann and Kelleher, 2009). These characteristics translate into scientific challenges: First, output is determined by economic behavior of fishers in an open access fishery. It can not be assumed exogenous as is possible in a managed fishery. Localized markets lead to a pronounced inter-dependency of factor and fish prices and quantities. The analysis of either the production or the demand side alone is flawed due to endogeneity. On the other hand, in food security studies that assume constant prices (Cissé et al., 2015; Hardy et al., 2017; Lam et al., 2012), demand is implicitly assumed perfectly elastic such that consumer welfare does not depend on harvest. A second endogeneity issue arises from the high number of actors, that makes it difficult to obtain exact effort measurements. Days at sea, though inaccurate with respect to duration and distance, is often the best measure available. However, it is likely that actors adapt their effort *per day at sea* to environmental factors, such as the proximity of biomass. An empirical strategy is needed that can deal

with this twofold endogeneity.

We propose a theoretical bio-economic model to explain the impact of variations in catchability or biomass on output and prices. We include biomass changes, seasonality and weather impacts as productivity drivers. Artisanal fisheries are particularly prone to these, as their movement is limited by safety and freshness considerations. Market development, consumer dependence on the fish and the sectors relevance to factor markets all impact the resulting equilibrium. We are therefore able to determine the relative importance of main drivers and the particular vulnerability of different regions to these drivers. Based on this, we present an estimation approach that efficiently utilizes scarce data by directly estimating dynamic model equations. It averts endogeneity bias by means of a two-step estimation procedure and can control for unobserved effort heterogeneity. Hence, the results from our model can be used to predict effects of climate change. By contrast, an uncorrected catchability might no longer hold once markets or the environment change. We apply our model and empirical approach to the Senegalese small pelagic purse seine fishery targeting *Sardinella aurita*.

The paper is structured as follows: The model is developed in section 2. Section 3 describes the data and the estimation approach. Empirical results are presented in section 4. We analyze the ensuing consequences for fisheries livelihoods and food security in section 5, followed by conclusions on food policy in 6.

## 2 Model

In the following, we explain the theoretical model that is partly based on the model by Quaas et al. (2017). The general time period  $t$  is one month. Part

of the data is only available per year, denoted by subscript  $y$ . In addition, we account for dependence on the month using subscript  $m$ . We use regions, denoted by subscript  $i$ , to distinguish fleets and markets. Thus, we assume that fleet locations and their corresponding markets are congruous.

In region  $i$  at time step  $t$ , fishers harvest amount  $h_{it}$  by use of factor inputs effort  $E_{it}$  and Biomass  $x_y$ . Biomass  $x_y$  is an exogenous production factor, its stock elasticity or schooling parameter (Clark, 1990)  $\chi > 0$  is expected to be positive. As is usual for an open access setting, they take biomass as given, and do not take into account their impact on future stock levels. Fishing effort  $E_{it}$  can be thought of as an intermediate product that is produced by means of labor  $l_{it}$  and capital  $k_{it}$ . We follow estimation results by Comitini and Huang (1967) and Squires (1987) and assume a Cobb-Douglas production function. This implies an elasticity of substitution – moderate substitutability – between the production factors. For example, capital can substitute labor by use of motors instead of rowing or by use of fish locating devices instead of visual spotting of fish. Harvesting is described by the generalized Gordon-Schäfer production function (1).

$$h_{it} = q_i(m, W_{it}) x_y^\chi E_{it} (1 + \tau_{qi})^{\Delta t}, \quad (1)$$

Catchability  $q_i(m, W_{it})$  of the fish species depends on an exponential function of linear additive monthly impacts  $\delta_m$  and environmental factors  $W_{it}$ . The latter exert a monotone convex impact on the respective monthly baseline value. Catchability is assumed to be of the following form:

$$q_i(m, W_{it}) = q_{i9} \exp \left( \sum_{m=1, m \neq 9}^{12} \delta_m D_m + f(W_{it}) \right) \geq 0, \quad (2)$$

where  $q_{i9}$  is the reference baseline catchability in September. This ref-

erence month is chosen for interpretational ease: According to our data, catchability is lowest in September. However,  $q_i(m, W_{it})$  varies throughout the year, following Eide et al. (2003) and Pech et al. (2001). We interpret this as a variability of the accessibility of the resource to fishers, for example due to migrations of the stock. This limited accessibility is a matter of technology, for example the depth that the gear reaches, the speed a boat can use to fish fast-going fish or the distance to shore a canoe can travel. In particular, boats are confined to fishing within the limits of their respective port regions, considering that they have to land the fish in fresh condition. This frontier is exogenous and can not be extended by inputting more of any factor of production. Monthly dummies are used to control for seasonally recurring effects, such as cyclical bio-dynamics. We assume that these are homogeneous across regions, but relax this restriction in the robustness checks. We include climate shocks to let regional seasonality differ and to control for environmental impacts that were not captured by monthly dummies. These explicit environmental impacts  $f(W_{it})$  are specified as a linear sum of weather influences, e.g. sea surface temperature, precipitation, and wind. These factors may affect the location of the fish in the fishing area or technical aspects, e.g. weather conditions that reduce visibility or cause currents. Weather effects are used as controls and as examples for endogeneity bias. For these purposes, it suffices to use shock terms, i.e. deviations from the monthly average normalized by the standard deviation. In addition, this strategy helps to avoid multi-collinearity issues.

A region-specific time trend  $\tau_{qi}$  is introduced in harvest production (1), given as a percentage progress rate per month. The trends is subject to elapsed months  $\Delta t$  since the start of the study period (January 2001). It accounts for an unobserved dynamic development in productivity. This may

have different reasons, in particular the following two. The first is exogenous progress in production technology. The other perceivable channel is a continuous consolidation process, where less productive boats leave the sector. This measurement error would show up in terms of a positive time trend on catchability.

In each period, fishers minimize their costs subject to factor supply. Individual fishers are price takers with respect to labor and capital prices, but inverse supply functions of both inputs are assumed to be iso-elastic, upward sloping functions of factor use in the fishery (Quaas et al., 2017). The assumption behind upward sloping inverse supply functions is that factors are supplied on local markets and neither capital nor labor used in the fishery is perfectly flexible (Clark et al., 2005). The assumption of local capital markets is not uncommon for in fisheries (Banerjee and Duflo, 2010; Riekhof, 2016), where issues of asymmetric information, trust and verifiability prevent fishers from benefiting from the formal capital markets. Once invested, capital does not move easily out of the market, the scrap value for canoes is typically low. In a situation with low capital demand, already invested capital is used first and will be supplied at a low price. Barriers to labor mobility are for example needed fishing skills and social affiliations. A limited labor mobility into and out of the fishery is the result, which was for example found for the Maldives case by Ghosh and Siddique (1998).

Fishers face a constant returns to scale technology, such that their factor demand function is linear in effort. However, upward sloping inverse supply functions entail that factor prices are not independent from harvest and stock levels. This leads to non-linear costs in the equilibrium between factor

markets and the fishery. Then, the fisher's equilibrium cost function reads<sup>2</sup>:

$$C_{it}(h_{it}, x_y) = c_i (1 + \tau_{ci})^{\Delta t} \left( \frac{h_{it}}{q_i(m, W_{it}) x_y^\chi (1 + \tau_{qi})^{\Delta t}} \right)^{1+e}, \quad (3)$$

with the region-specific scaling parameter  $c_i > 0$ . The size of  $e$  controls the extent of effort expansion as a reaction to increases in marginal revenues. If  $e > 0$ , costs are increasing and convex in harvest and actual effort  $E_{it}$ . The time trend  $\tau_{ci}$  for this equation incorporates unobserved trends in factor prices as well as size of effort units.

We assume an iso-elastic inverse demand function,

$$p_{it}(h_{it}) = \bar{p}_i h_{it}^{-\nu(B_{iy})}, \quad (4)$$

where  $0 \leq \nu(B_{iy}) < 1$  is the inverse price elasticity of demand. As  $\nu < 1$ , revenues  $p_{it} h_{it}$  increase with harvest. Note that  $\nu(B_{iy}) + e > 0$  has to hold in the strict sense, since otherwise, the profit maximum is not well defined. The constant  $\bar{p}_i$  is different for each region if base price levels differ<sup>3</sup>. Differences could be due to a lack in transport and cooling possibilities to take advantage of price differences. Even if means are available, transported fish is not as fresh, and fresh fish of other species may constitute a closer substitute.

A particular concern is the correct estimation of the inverse price elasticity function  $\nu(B_{iy})$ . Market size could be a major determinant of inter-regional differences. A region with a higher population density  $B_{iy}$  is likely to produce or attract more substitutes, such that consumer behavior is more price elas-

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<sup>2</sup>See Appendix A.2 for the derivation of the cost function.

<sup>3</sup>A trend to capture unobserved trends in income was omitted since it was found to be not significant in estimation.

tic<sup>4</sup>. We expect a convex negative relationship between population density and inverse demand elasticity  $\nu(B_{iy})$ . The following structure is assumed:

$$\nu(B_{iy}) = \exp(\nu_0 + \eta B_{iy}) \quad (5)$$

To control for an effect of outside opportunities linked to other fishing activities on cost elasticity parameter  $e$ , we run a robustness check concerning specialization with respect to species (see A.3). However, this leads to a reduction in usable observations and the gain in explanatory power is low, such that we use a constant  $e$  in the main model.

We consider an open access situation, where fishers enter the fishery when profits are positive and leave the fishery when profits are negative. The individual fisher takes factor prices as given. Marginal cost equals average cost in the supply decision. Using the zero profit condition,  $p_{it}(h_{it}) = \frac{C_{it}(h_{it}, x_y)}{h_{it}}$ , with Eq. (3) and Eq. (4), we obtain the open access harvest function (6). This is the static equilibrium quantity between fishers behavior, factor market supply and fish demand. It changes from period to period with changing environmental impacts and stock size.

$$h_{it}^{oa} = \left( \frac{\bar{p}_i}{c_i (1 + \tau_{ci})^{\Delta t}} (q_i(m, W_{it}) x_y^\chi (1 + \tau_{qi})^{\Delta t})^{e+1} \right)^{\frac{1}{\nu(B_{iy})+e}} \quad (6)$$

Using (6) in (4), we derive the open access price level (7).

$$p_{it}^{oa} = \bar{p}_i^{\frac{e}{e+\nu(B_{iy})}} \left( \frac{(q_i(m, W_{it}) x_y^\chi (1 + \tau_{qi})^{\Delta t})^{e+1}}{c_i (1 + \tau_{ci})^{\Delta t}} \right)^{\frac{-\nu(B_{iy})}{\nu(B_{iy})+e}}. \quad (7)$$

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<sup>4</sup>One might use population mass to represent market size. We prefer to use density, in order to account for the differences in market size.

Open access harvest and open access price are constant elasticity functions of biomass. The stock elasticity of open access harvest,  $\frac{\chi(e+1)}{\nu(B_{iy})+e}$  and of the open access price,  $-\nu(B_{iy}) \frac{\chi(e+1)}{\nu(B_{iy})+e}$ , allows us to assess to what extent producers and consumers bear the consequences of over-fishing and climate change.

The net trend on open access harvest is given by

$$\tau_{hoa} = \left( \frac{1 + \tau_{ci}}{(1 + \tau_{qi})^{e+1}} \right)^{\frac{-1}{e+\nu}} - 1 \quad (8)$$

If it is positive, fishing pressure, all else constant, increases over time. We interpret it as trend in sector competitiveness and expect  $\tau_{hoa} > 0$ . The net trend on the open access price is given by (9).

$$\tau_{paa} = (1 + \tau_{hoa})^{-\nu} - 1 \quad (9)$$

Producer and consumer rents are incurred, even though profits are zero. Consumer surplus (CS) (10) is the amount to which consumers' willingness to pay exceeds the equilibrium price. All individuals but the marginal one would rather pay more for *Sardinella aurita* than substitute it with another good. A higher consumer surplus signals a greater relevance of the fish as food resource. It can be compared to producer surplus, the rents to capital owners and workers. We interpret the sum of these rents as fishers' surplus (FS) (11). Fishers do not have equal willingness to accept a certain labor and capital price. The marginal individual would exit were his or her income only a bit lower. For him or her, the sub-sector does not hold any value above other opportunities to work or invest. The rent calculated is the income to fishers who do not represent the marginal individual in excess of what they would have earned had they been the marginal individual. The contribution

of the sub-sector to food security thus consists of a livelihood aspect and a direct consumption aspect. They constitute the food security benefit that would not exist without the fishery and that could not easily be achieved by other sectors or food substitutes.

$$CS_i = \frac{\nu(B_{iy})}{1 - \nu(B_{iy})} \bar{P}_i h_{oait}^{1-\nu(B_{iy})} \quad (10)$$

$$FS_i = \frac{e}{1+e} c_i (1 + \tau_{ci})^{\Delta t} \left( \frac{h_{oait}}{q_i(m, W_{it}) x_y^x (1 + \tau_{qi})^{\Delta t}} \right)^{e+1} \quad (11)$$

### 3 Empirical approach: Estimation model

#### 3.1 Case study and data resources

Small pelagic fish are the main target of the Senegalese artisanal fishery with catches of 284,000 tons per year on average between 2002 – 2006, that account for more than 70% of the total landings (Thiaw et al., 2017). The most important species for the Senegalese fishery is *Sardinella aurita*. It is caught by purse seiners (Dème et al., 2012; Diankha et al., 2017).

Due to data availability, this study considers landings between 2001 – 2009 in four areas (see Figure 1), namely Fleuve, Thiès Sud, the Dakar area called Cap Vert and Thiès Nord. Data on effort (fishing days at sea, DAS) and catch (tons) per fleet, species, and region on a monthly time scale is available from the extensive database provided by the Centre of Oceanographic Research of Dakar-Thiaroye (CRODT) of the Senegalese Institute of Agricultural Research (ISRA), as described in Thiao (2009). Our data-set used for estimation is described in Table 5 in the Appendix, section A.1. Effort is recorded in terms of DAS on a daily basis. The technician notes

down the number of boats not onshore at the same time of the day, and record one DAS for each canoe missing. No discrimination is made between longer or shorter days, days with longer or shorter journey or days with a larger or smaller crew. However, some of this variation may be the result as the fisher composes the optimal effort, for example when the resource is farther from or closer to the shore. This problem has been mentioned by Thiaw et al. (2017) and Diankha et al. (2018). Catch per day at sea (CPUE) are randomly sampled and multiplied by the total number of fishing days to compute total catch<sup>5</sup>. Catch is dominated by *Sardinella aurita*. Over the study period, its share in total purse seine landings is above 80% for all regions but Thiès Sud. For the latter, it is still the vast majority with 57%.

Atlantic *Sardinella aurita* are a migratory schooling species (Thiaw et al., 2017). Catches are highly variable throughout the year: Catch per day at sea is lowest in February and October/ November for most regions. It peaks in June and in December. Annual biomass data is available from 1995 until 2006 from the R/V Dr FRIDTJOF NANSEN project (hydroacoustic and trawl surveys) (Toresen et al., 2001, 2002; Krakstad et al., 2003, 2004, 2005, 2006). The time series is complemented by estimates from national trawl surveys for 2007-2009 (FAO, 2008, 2011a,b), that were inter-calibrated with the Nansen surveys. This combined time series was used in yearly FAO stock assessments for 1995-2009<sup>6</sup>. The surveys were carried out in the fourth quarter of each year, usually in November. We focus on the part of the stock that was found in the Senegalese and Gambian coastal areas, which fluctuates around 200,000 tons.

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<sup>5</sup>CRODT does not distinguish landings and catch. Discards are assumed to be very small.

<sup>6</sup>The working group partly used regression models to account for regional gaps.

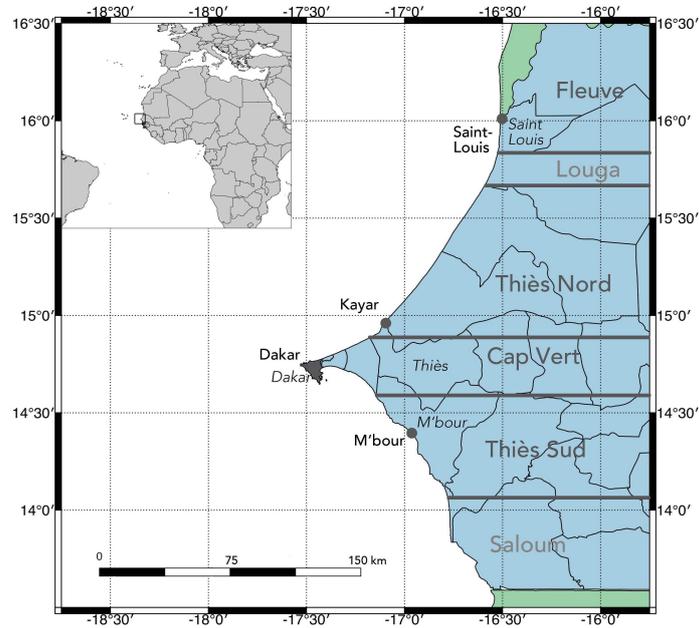


Figure 1: Major Senegalese landing areas

The species is climate sensitive (Thiaw et al., 2017; Tiedemann et al., 2017; Zeeberg et al., 2008). Its abundance has been linked to changes in sea surface temperature (SST). Diankha et al. (2015) find an optimal temperature of 22.7°C, and a generally high abundance between 20°C and 24°C for Senegalese waters. SST in Senegalese waters fluctuates between 18.85 – 28.6°Celsius (2001 – 2009) around a mean of 23.3 – 24.5°Celsius, depending on the region. To control for inter-annual weather impacts on the biomass and impacts on fishing behavior, we use monthly reanalysis data from the European Centre for Medium-Range Weather Forecasts (ECMWF, 2012). The data-set we use is the ECMWF Interim reanalysis product. Weather data is used in terms of deviations from a long-term mean, to control for irregular events and regional differences (we provide a data summary in the

supplementary material B.1).

Small pelagic fish is sold mainly on local markets (Ba et al., 2017; Dème et al., 2012). Roughly 100,000 tons (40%) of the artisanal *Sardinella* landings supply the local market for fresh fish, and the remainder is processed locally (Failler, 2014). The closest substitute to *Sardinella aurita*, in terms of price correlation, markets and nutrient content, is *Sardinella maderensis* (Ba et al., 2017; Failler, 2014).

Price data is available on a monthly time scale for *Sardinella aurita* from CRODT. We use ex-vessel prices for good quality fresh fish to generate mean monthly prices per region. For all regions but Fleuve, this approach leads to a data-set with only few and non-systematic gaps. Where the gap concerns only *Sardinella aurita*, we substitute its price by the price for *Sardinella maderensis* (6% of observations). Fleuve is the region farthest from the capital and therefore suffers from more frequent gaps. We complete the data-set substituting missing observations with prices from the neighboring region, Thiès Nord. Correlation between the two regions' logged prices is at 81%. The regions share similar catch conditions due to the geographic proximity, such that we consider this a sound solution. We use yearly consumer price index data from the World Development Indicator database (The World Bank, 2017) for deflation. Prices are used in units of 2010-level of the Senegalese currency Franc de la Communauté Financière d'Afrique (FCFA) per kg.

Figure 2 depicts price seasonality across regions. In terms of the overall price level, *Sardinella aurita* is cheapest in Thiès Sud with prices around 70 FCFA/kg, while prices lie rather around 100 FCFA/kg in the other locations. We conclude that inter-regional arbitrage likely plays only a small role. Seasonal variation is lowest in Thiès Sud as well. For Fleuve and Thiès Nord, a depression in prices occurs during May/June, in the high productiv-

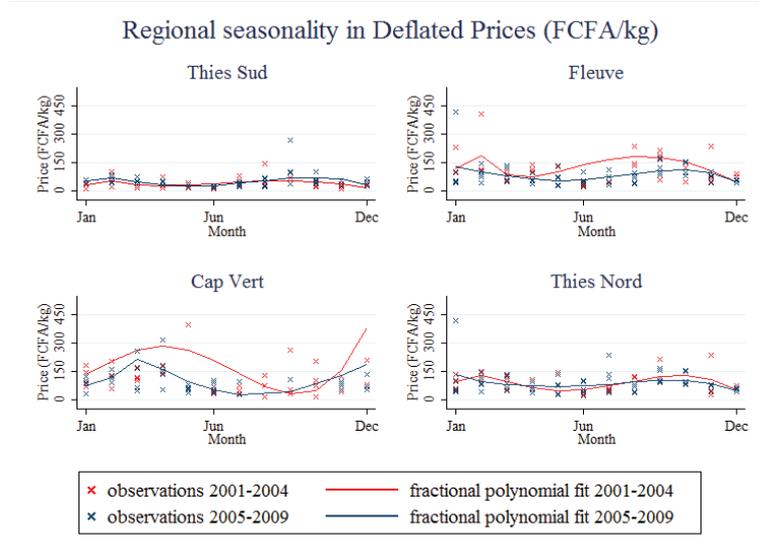


Figure 2: Regional seasonality in Prices (based on data provided by the provided by the Centre of Oceanographic Research of Dakar-Thiaroye (CRODT)).

ity season. Prices here are highest in February. Overall, the price variation runs counter to the productivity variation, which points toward an own price effect. By contrast, prices in Cap Vert seem to have little relationship with catch per day at sea. This is the main area of agglomeration in Senegal with around 23% of the total Senegalese population. Yearly data on population density per administrative department is obtained from the National Agency of Statistics and Demography (ANSD) in Senegal (Agence Nationale de la Statistique et de la Démographie, 2015b).<sup>7</sup> Mean density is highest for Dakar, i.e. the Cap Vert region, with over 12,000 inhabitants/km<sup>2</sup>.

<sup>7</sup>We choose the department of Dakar for Cap Vert, St. Louis for Fleuve, Mbour for Thiès Sud and Thiès for Thiès Nord

### 3.2 Estimation strategy

We estimate the simultaneous equations system of market demand and supply jointly via its reduced form, as specified in (6) and (7), adding error terms. The reduced form can be estimated consistently using least squares (Greene, 2003). The two equations impose restrictions on each other. The log reduced form of the regression model with catchability  $q_i(m, W_{it})$  as given by (2) and  $\nu_B = \nu(B_{iy})$  as specified in (5), reads:

$$\begin{aligned} \ln h_{it} = & \frac{1}{\nu_B + e} \left( \ln \bar{p}_i - \ln c_i - \Delta t \ln(1 + \tau_{ci}) \right. \\ & \left. + (1 + e) (\ln q_i(m, W_{it}) + \chi \ln x_y + \Delta t \ln(1 + \tau_{qi})) \right) + \epsilon_{ht} \quad (12a) \end{aligned}$$

$$\begin{aligned} \ln p_{it} = & \frac{\nu_B}{\nu_B + e} \left( \ln c_i + \Delta t \ln(1 + \tau_{ci}) + \frac{e}{\nu} \ln \bar{p}_i \right. \\ & \left. - (1 + e) (\ln q_i(m, W_{it}) + \chi \ln x_y + \Delta t \ln(1 + \tau_{qi})) \right) + \epsilon_{pt} \quad (12b) \end{aligned}$$

Note that this estimation step does not achieve differentiation of  $c_i$  and  $q_{i9}$  and cannot identify the two different time trends  $\tau_{ci}$  and  $\tau_{qi}$ . For this identification, we could additionally use the  $CPUE_{it}$  data and estimate (13). But as discussed above, the effort measure is inaccurate. An endogeneity problem could result from unobserved heterogeneity. We expect that catchabilities are negatively correlated with the resources' distance from shore. This might be approximated by sea surface temperature  $SST_{it}$ : The true catch per unit of effort is expected to be positively correlated to  $SST_{it}$ . However, in the actually observed  $CPUE_{it}$  measure this effect may be partially masked by the inaccurate measure in terms of days at sea. If fishers choose shorter

DAS when the resource resides farther inshore, the positive effect of  $SST_{it}$  would for example be underestimated.

$$\ln CPU E_{it} = \ln q_i(m, W_{it}) + \chi \ln x_y + \Delta t \ln(1 + \tau_{qi}) + \epsilon_{ct} \quad (13)$$

In equations (12a) and (12b), we would see zero effect, because actual catch does not change. No DAS measurement is used or relied upon. We assume that a longer day at sea leads to an increase in costs, just as additional hours on a separate day would. The term  $q_i(m, W_{it}) x_y^\chi (1 + \tau_{qi})^{\Delta t}$  only accounts for exogenous effects on catch productivity. Thus, if we are interested in whether environmental impacts change actual harvest and prices and unsure whether the error in effort measurement correlates with environmental variables, we should use these equations only.

To solve the identification problem, we estimate (12a) and (12b) with a net time trend on reference baseline catchability in September  $q_{i9}$  and competitiveness parameter  $g_i$  that compounds cost baseline catchability. The estimation equations in the first step read:

$$\ln h_{it} = \frac{1}{\nu + e} (\ln \bar{p}_i + (1 + e) (\ln g_i + \ln q_i(m_{-9}, W_{it}) + \chi \ln x_y + \Delta t \ln(1 + \tau_{ni}))) + \epsilon_{ht} \quad (14a)$$

$$\ln p_{it} = \frac{\nu}{\nu + e} \left( \frac{e}{\nu} \ln \bar{p}_i - (1 + e) (\ln g_i + \ln q_i(m_{-9}, W_{it}) + \chi \ln x_y + \Delta t \ln(1 + \tau_{ni})) \right) + \epsilon_{pt} \quad (14b)$$

with  $q_i(m_{-9}, W_{it})$  defined as the catchability excluding reference baseline

catchability in September, catchability net cost defined as

$$\ln g_i = \ln q_{i9} - \frac{1}{1+e} \ln c_i$$

and

$$\ln(1 + \tau_{ni}) = \ln(1 + \tau_{qi}) - \frac{1}{1+e} \ln(1 + \tau_{ci})$$

The second step serves to identify the missing parameters. We use estimator  $I$  with fixed coefficient equal to 1 to correct observed  $CPUE$ . In this step, we add the time trend  $\tau_{si}$  and estimate constant  $q_{i9}$ . Note that  $\tau_{si}$  can be consistently estimated, if effort endogeneity does not include a time trend other than the net trend that we already control for. The second step equation reads:

$$\ln CPUE_{it} = \ln q_{i9} + I + \Delta t \ln(1 + \tau_{si}) \epsilon_{ct} \quad (14c)$$

with

$$I = \ln q_i(m_{-9}, W_{it}) + \chi \ln x_y + \Delta t \ln(1 + \tau_{ni})$$

and

$$\tau_{si} = (1 + \tau_{ci})^{\frac{1}{e+1}} - 1$$

Results from this two-step model on seasonality, environmental impacts and stock elasticity are exogenous, they can be used for robust prediction beyond the currently observed environmental state. By contrast, the uncorrected catchability as estimated when using effort data might no longer

hold. We estimate by means of the two-step feasible generalized least squares (FGLS) provided by Stata’s `nlshr` command. The first step uses ordinary least squares (OLS) regression to estimate the unknown covariance matrix of disturbances. The second step estimates model coefficients by generalized least squares, using the estimated covariance matrix. We iterate to improve accuracy<sup>8</sup>

A model of relatively low complexity is preferable due to asymptotic characteristic and because it lowers the data requirements. Several weather controls were tested. We choose among these models using a significance level of 20% and the Bayesian information criterion (BIC). In our preferred model, SST and precipitation lagged by one month are included as weather controls. We consider alternative specifications in section (A.3).

To account for potential heteroscedasticity, we use robust standard errors in the first step. We do not use clustered standard errors, as four clusters, corresponding to the four regions, would be very few compared to the number of observations per cluster, and therefore suffer from over-rejection (Cameron and Miller, 2015). Because  $I$  is a generated regressor, we employ bootstrapped standard errors in the second step. Visual inspection and variance inflation factors did not point towards multi-collinearity issues in the data.

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<sup>8</sup>A seemingly unrelated regressions (SUR) model could be asymptotically more efficient than OLS, but this gain is only achieved if the regressor matrices are not identical and they are not a subset of each other (Greene, 2003), such that we expect no efficiency gains of SUR over OLS.

## 4 Results and discussion

### 4.1 Estimation results: Seasonality and environmental impacts

Table 1 shows regression results and statistics for the first and second step estimation, and a separate estimation of the CPUE equation for comparison (see section B.3 for a more detailed comparison of the full two step results and results from the separate model). The effect of SST is marked by  $sw_t$  and the precipitation effect by  $sw_{p1}$ . We can make use of 374 observations in the first step and 423 observations in the second step. BIC (2,025 and 1,262) and  $R^2$ -values (0.37 and 0.38 for the first step and 0.41 for the second step) are high enough to trust the explanatory power of the model.

The estimated stock-elasticity of catch, sometimes also referred to as ‘schooling’ parameter,  $\hat{\chi}$  of *Sardinella aurita* lies at 0.207 ( $p = .045$ ). Catchability is highest for Thiès Sud. The second step estimation results (column 2) reveal that this ranking is primarily due to differences in the catchability baseline parameter  $\hat{q}_{i0}$ . The other regions are quite similar. Their reference scale parameters  $\ln \hat{g}_i$  are insignificant ( $p = .0158, p = .164, p = .167, p = .476$  in order of table appearance), however. In Fleuve, the catch technology seems to differ from the rest of the sample. A high catchability is associated with a higher cost scale parameter, leading to a similar catchability net cost  $g_i$  as in the other regions. The specific role of Thiès Sud can be explained by differences in the fishing area with its proximity to one main spawning area and lower prices. Bycatch may be responsible for the high uncertainty in Thiès Sud. Catchability underlies a positive and significant trend  $\tau_{in}$  in Fleuve (1.5%,  $p < .001$ ) and Thiès Nord (0.5%,  $p = .053$ ). Combined with the results from the second estimation step, it is clear that both cost and catch-

ability underlie separate positive trends, where the latter dominates. Likely, larger and better equipped boats are one reason for this twofold change. Due to this trend, the ranking in competitiveness changes during the study period, and net cost in 2009 is highest in Fleuve. Seasonality is very pronounced, as highlighted by the size of monthly dummies, of which ten are significant ( $p \leq .004$ ). The minimum catchability occurs in autumn and one smaller dip in February. The most productive months are June and December. In June, catchability net cost more than doubles if compared to its February value, and shows a five-fold increase if compared to its September value.

**Result 1.** *The SST shock has a large positive and significant effect on catchability.*

A positive deviation of regional SST from the central long term mean by half a standard deviation<sup>9</sup> would lead to an increase in catchability by factor 1.34 ( $sw_t = 0.588$  with  $p < .001$ ). We interpret the sign as an indication of the biomass' distance from the coast. If the water warms early in the year, they movement inshore during April to June starts early (Brochier et al., 2018), which is favorable for the fishery. If weather phenomena are regionally different, con- or divergence of productivity and short term changes in the productivity ranking are possible. For example, SST shocks in spring are usually positive in Thiès Sud and negative in Fleuve. Lagged precipitation is significant only at the 20% level ( $sw_{pl} = -0.132$  with  $p = .185$ ), and its impact is smaller and negative. We attribute this to technical aspects of catchability, namely a shear effect that impedes purse seine fishing, and possible stronger currents that adversely affect maneuverability.

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<sup>9</sup>During the study period, shocks lay between -0.78 – 0.82 standard deviations.

Table 1: Estimation of (14b), (14a) and (14c) and CPUE separately (13)

	First step	Second step	CPUE sep.
Param.	Coeff./Robust and bootstrapped std. error		
$\chi$	0.207** (0.103)		0.195 (0.171)
$\delta_1$	1.007*** (0.215)		0.992*** (0.230)
$\delta_2$	0.708*** (0.192)		0.574** (0.254)
$\delta_3$	0.944*** (0.215)		0.779*** (0.276)
$\delta_4$	1.215*** (0.238)		1.099*** (0.244)
$\delta_5$	1.415*** (0.259)		1.139*** (0.260)
$\delta_6$	1.626*** (0.279)		1.458*** (0.223)
$\delta_7$	0.726*** (0.235)		0.528 (0.343)
$\delta_8$	0.575*** (0.199)		0.543** (0.273)
$\delta_{10}$	0.216 (0.188)		0.064 (0.284)
$\delta_{11}$	1.068*** (0.211)		1.035*** (0.230)
$\delta_{12}$	1.357*** (0.245)		1.442*** (0.245)
$sw_t$	0.588*** (0.167)		0.791*** (0.202)
$sw_{p1}$	-0.132 (0.100)		0.049 (0.151)
$\nu_0$	-0.148 (0.183)		
$\eta$	-2.354*** (0.505)		
$e$	1.056* (0.555)		
$\ln \bar{p}_{FL}$	7.961*** (0.462)		
$\ln \bar{p}_{TN}$	7.436*** (0.394)		
$\ln \bar{p}_{CV}$	4.559*** (0.091)		
$\ln \bar{p}_{TS}$	7.049*** (0.439)		
$\ln g_{FL}$	-2.344 (1.659)		
$\ln g_{TN}$	-2.236 (1.607)		
$\ln g_{CV}$	-2.268 (1.640)		
$\ln g_{TS}$	-1.177 (1.650)		
$\tau_{nFL}$	0.015*** (0.003)		
$\tau_{nTN}$	0.005* (0.003)		
$\tau_{nCV}$	0.004 (0.003)		
$\tau_{nTS}$	0.003 (0.002)		
$\ln q_{0FL}$		-3.608*** (0.126)	-3.303 (2.084)
$\ln q_{0TN}$		-3.796*** (0.202)	-3.625* (2.049)
$\ln q_{0CV}$		-3.959*** (0.248)	-3.768* (2.110)
$\ln q_{0TS}$		-3.206*** (0.175)	-2.930 (2.092)
$\tau_{qFL}$			0.026*** (0.002)
$\tau_{qTN}$			0.015*** (0.004)
$\tau_{qCV}$			0.008 (0.005)
$\tau_{qTS}$			0.006** (0.003)
$\tau_{sFL}$		0.011*** (0.002)	
$\tau_{sTN}$		0.008*** (0.003)	
$\tau_{sCV}$		0.001 (0.005)	
$\tau_{sTS}$		0.003 (0.003)	

(FL=Fleuve, TN=Thiès Nord, CV=Cap Vert, TS=Thiès Sud)

\*  $p < .10$ , \*\*  $p < .05$ , \*\*\*  $p < .01$

## 4.2 Estimation results: Markets

**Result 2.** *Sector equilibrium cost is a non-linear function of harvest. The cost elasticity  $\hat{\epsilon} + 1$  is significantly higher than 1, it lies at 2.056. Revenues decrease in harvest for three of four regions. The inverse price elasticity  $0 \leq \hat{\nu} \leq 0.492$  depends negatively on population density.*

Our model estimates an approximately quadratic cost function ( $p = .057$ ). The convex cost structure limits effort levels. Fleuve’s cost function is steepest, followed by Thiès Nord, Cap Vert and Thiès Sud. This fits with the fact that observed effort levels show the largest variability for Thiès Sud, and maximum monthly effort observed is far lower in Fleuve (2462 DAS) and Thiès Nord (2149 DAS) than in the other regions. On the other hand, effort during the study period never fell below 991 DAS in Thiès Sud, in particular due to the outstanding productivity in this region. Aggregate monthly 2001 cost at mean effort levels, using naive re-transformation, lay at 96.2 million FCFA in Fleuve compared to 90.5 million FCFA in Thiès Sud. According to our model, this constitutes actual income to labor and capital. Cost increases for all regions over the study period.

The inverse price elasticity  $\hat{\nu}$  depends negatively on population density ( $p < .001$ ). For the study period, Cap Vert’s inverse price elasticity goes to zero. Consumers can choose between many substitutes and are very sensitive to price changes. By contrast, we estimate elasticities between 0.376 and 0.492 (Std. Dev.=0.028) for the other regions. Here, the price changes elastically with harvest of *Sardinella aurita*. Figure 3 compares regional inverse demand functions<sup>10</sup> that would result from the estimated parameters under the mean, maximum and minimum population density observed. Population

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<sup>10</sup>Retransformation bias was ignored for this illustration. We expect prices shown here to be slightly downward biased.

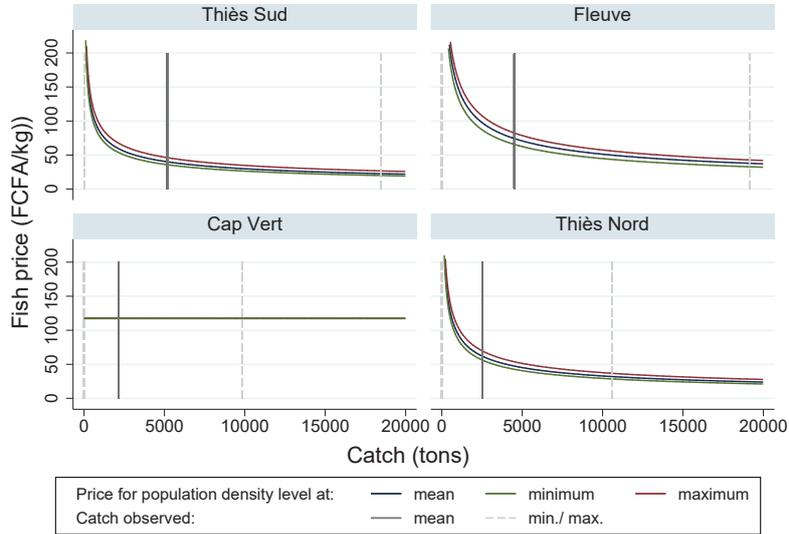


Figure 3: Fitted regional demand functions

density increased continuously over the study period. The price response is strongest in Fleuve, driven by a higher scale factor,  $\hat{p}_i$  ( $p < 0.001$ ). Prices are also highest in Fleuve in general. A relevant price change occurs over nearly the whole observed catch range. Consumers willingness to pay is higher in general, and *Sardinella aurita* is not easily substituted even at medium to high levels. For Thiès Nord and Thiès Sud, the response is large for small catch values, indicating that consumers bear consequences of fish scarcity only if the supply is very low. Consumers are easily willing to substitute other food for *Sardinella aurita*, if its supply is at high or medium levels. However, once a certain low-availability-threshold is crossed, consumers willingness to pay increases rapidly. We interpret this as a situation where food affordability in general is good, but *Sardinella aurita* plays an important role as a specific food source, such as for protein, micro-nutrients or as an

important cultural ingredient. Thus, consumers are willing to reduce their consumption strongly, but are unwilling to fully dispense with it. The vertical lines mark mean, minimum and maximum harvest levels. It is interesting to see that the mean harvest level in Thiès Sud lies far to the right of this point, whereas for Fleuve and especially Thiès Nord, mean harvest levels are closer to it. Open access harvest, all else equal, increases over time. This translates into a negative (zero for Cap Vert) mean trend in the open access price given by (9) of 0.6% in Thiès, 0.8% in Cap Vert and 2% in Fleuve.

**Result 3.** *Open access harvest is an increasing concave function of biomass. Except for Cap Vert, the open access price is a decreasing convex function of biomass.*

This is due to  $\frac{\chi - \nu}{1 - \chi} < e$ . For both producers and consumers, the marginal benefit of a larger stock is decreasing. All else equal, a 1% increase in stock size entails a mean increase in open access harvest of 0.314% and a drop in prices of 0.125% (except in Cap Vert). A more elastic demand, as in Cap Vert, means that harvest and aggregate surplus are more sensitive to biomass fluctuations, and therefore less prone to over-fish.

## 5 The welfare effects of changing economic and environmental conditions

### 5.1 Welfare effects on sector and regional level

Since we used a logarithmized model for estimation in section 3 and detected a substantial re-transformation bias when using naive re-transformation, we use smearing re-transformation to avoid re-transformation bias (e.g. Duan, 1983; Manning, 1998). Due to heteroscedasticity, smearing is done group-wise

for each region, by predicting standard errors as a positive non-linear function of the predictor<sup>11</sup>. A graphical comparison between predicted and observed levels of harvest and prices illustrates that the re-transformation strategy leads to convincing results (see the graphs provided in the supplementary online material B.4).

Table 2: Regional yearly equilibrium harvest (tons per year) and mean equilibrium fish prices (FCFA/kg) for different biomass levels under open access

Region	Harvest & price					difference from mean (%)				
	TS	FL	CV	TN	Sen.	TS	FL	CV	TN	Sen.
$h_{oa,mean}$	66,648	46,221	27,227	22,639	162,736					
$h_{oa,min}$	51,643	37,560	20,360	17,455	127,018	-23	-19	-25	-23	-22
$h_{oa,max}$	78,482	52,776	32,723	26,752	190,733	18	14	20	18	17
$p_{oa,mean}$	29	87	110	80						
$p_{oa,min}$	31	97	110	89		10	12	0	12	
$p_{oa,max}$	27	81	110	74		-6	-7	0	-7	

TS: Thiès Sud, FL: Fleuve, CV: Cap Vert, TN: Thiès Nord, Sen.: Senegal. Mean biomass: 199,000t, minimum: 116,000t, maximum: 282,000t. Numbers are rounded to full thousands of FCFA.

**Result 4.** *Over the study period, the artisanal purse seine fishery for *Sardinella aurita* has generated an average yearly total rent of 10.6 billion FCFA.*

This compares to 0.16% of the Senegalese GDP in 2010 and 6.56% of the GDP generated by fisheries only, which contributes 2.5% to overall GDP (Agence Nationale de la Statistique et de la Démographie, 2015a). The

<sup>11</sup>This heterogeneity likely stems from the fact that higher harvest levels entail a higher heterogeneity in vessels. More detailed data on vessels is not available. Hence, we are not successful to model this heteroscedasticity explicitly here.

number also amounts to more than five times the yearly biomass rent earned through the current EU-Senegal fishery agreement for 16,000 tons of tuna and Southern hake per year (0.96 billion FCFA/year) (European Union, 2017).

For comparative statics, we use a baseline value for consumer and fishers' surplus based on levels of population density, cost and productivity trends from June 2005, i.e. the middle of the study period. We use mean biomass (199,000 t) and climate variables at their long-term mean levels.

Table 2 compares mean equilibrium prices as well as total yearly equilibrium harvest and rents. Prices are substantially lower and less prone to biomass variation in Thiès Sud than in the other regions. Fleuve is more sparsely populated and likely lacking in substitutes. Prices are higher than elsewhere, except in the capital region, where fish is most expensive. Total mean consumer rents (4.3 billion FCFA) outperform fishers' rents (4.2 billion FCFA) (see the supplementary online material for a table on rents).

## 5.2 Welfare effects on individual level

To look at individual level fishers' surplus (FS), we use data on the number of purse seine canoes available from CRODT (Thiao et al., 2008), and multiply it by 20 to account for the people working on each purse seine canoe (Ba et al., 2017). The calculated number of fishers involved in the sector amounts to 2940 in Thiès Sud, 2560 in Fleuve, 1420 in Cap Vert and 1180 in Thiès Nord. We use population data for 2008 to compare individual consumer surplus (CS) and total rent (TR). This leaves us with an overall coastal population of 2,431,298 people or 21% of the Senegalese total population. Note that this is only a means of making the results more apprehensive. De facto benefits will not be equally distributed.

Average Senegalese food expenditures lay at 176,249 FCFA in 2010 ac-

Table 3: Regional prices for grain baskets (2010 level FCFA)

Region	Thiès Sud	Fleuve	Cap Vert	Thiès Nord	Senegal
Price/5 kg basket	1,147	1,345	1,278	1,147	1,145

According to the Agence Nationale de la Statistique et de la Démographie (2016). No GDP or consumption data, nor prices for meat, are available on regional level. To compare impacts between regions, we use the total price (2010 level FCFA) for an agricultural basket that consists of one kg of each of the five important grains in Senegal (Table 3)(Agence Nationale de la Statistique et de la Démographie, 2010). Food price levels are elevated in Fleuve, which puts the higher price estimated for this region into perspective. We will now analyze individual level rents as presented in Table 4.

**Result 5.** *Consumer surplus (total rents) per capita account for 1.79% (2.01%) of per capita yearly food expenditures in 2010. Individual average fishers' rent can cover between 132% (Thiès Sud) and 614% (Cap Vert) of average per capita food expenditures.*

On average, each inhabitant in the studied regions, i.e. one fifth of Senegal's population, receives a mean rent of 3.27 baskets every year. Considering that in Fleuve and Thiès, more than 40% of the households still lived below the poverty line in 2006 (Government of Senegal, 2006), this could well mean that the poverty threshold is crossed. Even more important is its role for consumers who depend more on the fish as food or at low levels of provision, such as during the low season. The rent per unit of fish increases at low provision levels, where the willingness to pay is very high and unit cost are low. Comparing total individual rent, the fishery is about twice as important

Table 4: Regional yearly coastal per capita/ per fisher rents for different biomass levels under open access (individual total rent given per capita)

Region	Rents in 1000 FCFA (grain baskets)				
	TS	FL	CV	TN	Sen.
$CS_{oa,mean}$	2 (1.53)	9 (6.96)	0 (0.00)	2 (1.48)	2 (1.52)
$CS_{oa,min}$	1 (1.30)	8 (6.30)	0 (0.00)	1 (1.26)	2 (1.34)
$CS_{oa,max}$	2 (1.70)	10 (7.41)	0 (0.00)	2 (1.63)	2 (1.65)
$FS_{oa,mean}$	233 (203)	556 (414)	1,082 (847)	515 (450)	525 (447)
$FS_{oa,min}$	197 (172)	503 (375)	809 (633)	441 (385)	437 (372)
$FS_{oa,max}$	258 (225)	593 (441)	1,301 (1,018)	569 (496)	592 (504)
$TR_{oa,mean}$	3 (2.82)	15 (10.83)	1 (1.15)	3 (2.66)	4 (3.27)
$TR_{oa,min}$	2 (1.78)	13 (9.69)	1 (0.86)	2 (1.65)	3 (3.02)
$TR_{oa,max}$	3 (2.94)	16 (11.85)	2 (1.39)	3 (2.75)	4 (3.47)

TS: Thiès Sud, FL: Fleuve, CV: Cap Vert, TN: Thiès Nord, Sen.: Senegal. Mean biomass: 199,000t, minimum: 116,000t, maximum: 282,000t. Numbers are rounded to full thousands of FCFA, and to two decimals for grain basket measures.

in the Thiès regions than in Dakar, and 11 times more important in Fleuve. It lets Fleuve consumer's afford the equivalent of 35 kg of grain per person and in a mean year.

Resource fluctuations change equilibrium harvest and prices. If biomass drops from its mean to the minimum level, the total catch difference amounts to 35,7180 t or 22% of total mean catch. Prices increase by 0 – 10 FCFA per kg. The most substantial price response happens in Thiès Nord and Fleuve. Our data shows that on average, 17% of catches were made between August and October. Monthly equilibrium harvest at minimum biomass levels in Thiès Nord during this period would result in an equilibrium price to the left of the point of highest curvature of the inverse demand function (see Figure 3). It comes close to this point in Fleuve.

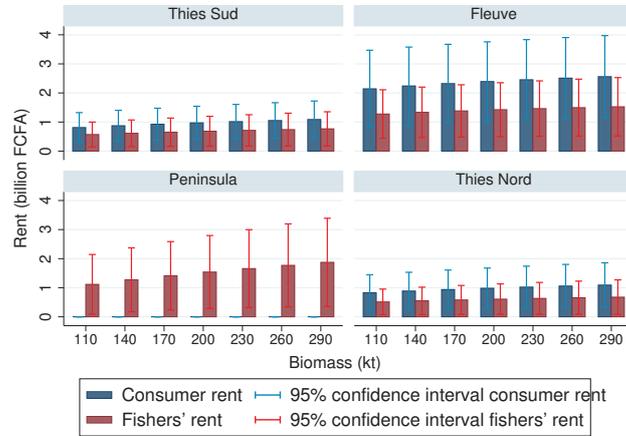


Figure 4: Regional fisher and consumer rents at different biomass levels

Figure 4 shows the predicted aggregate rents for different levels of biomass.

**Result 6.** *Biomass fluctuations exhibit the largest relative impact on harvest in the well developed market region around Dakar. By contrast, in regions with a large fishery far from the capital, food security is most sensitive to biomass changes.*

Fishers' rent is most sensitive to biomass fluctuations in Cap Vert, owing to the perfect price elasticity of consumers. Between the mean and maximum biomass value, Cap Vert's aggregate fishers' rent sees an increase of nearly 0.32 billion FCFA or 20%. There, the yearly difference between maximum and minimum biomass is as high as 385 baskets, compared to only 53 baskets in Thiès and 66 in Fleuve. This is linked to the strong fluctuation in annual harvest (5496 t). By contrast, fishers' rent increases by only 0.09 billion FCFA or 7% in Fleuve, and consumer rent by 0.16 billion FCFA (7%). The equilibrium harvest is more robust to biomass changes due to the response in prices.

For the aggregate Senegalese coastal population, a drop from the maximum to the minimum biomass would entail moderate consequences for food security. The national total rent per capita would shrink by half a grain basket per year. However, the same number for Fleuve amounts to 2.16 baskets. Each inhabitant could afford an additional 11 kg of grain per capita. For regions that lie far from well developed markets, the artisanal fishery is of particular importance for food security.

**Result 7.** *The short term impact of SST shocks in June lies in the range of 0.5 to 1 grain basket per coastal inhabitant.*

The difference of SST between plus/ minus 1.5°Celsius (0.5 standard deviations) has a larger positive effect on short term food security than the 166,000 t drop of biomass discussed above. However, since this is a static analysis, effects on future biomass levels are not comprised, meaning that long term food security is still a different issue. See figure 10 in the supplementary material for more insights.

## 6 Policy implications and conclusion

The empirical bio-economic model proposed in this paper is soundly based on resource economic theory. By means of this model, we identified relationships between a fishery's productivity, supply and demand characteristics. These cannot be estimated separately from each other. The underlying drivers are changes in biomass and environmental variables, as well as market development and factor markets. One contribution of the paper is to identify these relationships. A second contribution is to propose a model that estimates these effects from the reduced form open access market equilibrium. These results still hold when changing environmental conditions induce changes

in actual effort variability. The third contribution is the application of the proposed empirical methods to the Senegalese purse seine fishery.

Our results underline that the fishery plays an important role for food security. At the per capita level, consumer surplus (total rent) accounts for 1.79% (2.01%) of food expenditures. The results can inform future resource management, for example concerning decisions upon the closing of fishing contracts with foreign nations. Moreover, the estimation of welfare impacts allows to compare stock elasticities of consumers and producers. This can clarify the political feasibility of resource management options and help towards a well informed debate between interest groups. Our analysis of environmental impacts and fishery vulnerability provides a starting point for precautionary policies. Our results show that regions differ substantially in market characteristics. While the commodity is of no appreciable food relevance in the capital region, more remote regions strongly depend on the resource for food in general and as a protein supply. Climate change may impact food security, in particular when the current equilibrium is close to the curve point on the inverse demand line, such that consumers are sensitive to the supply quantity. Since the underlying theory establishes causal justifications, qualitative results also provide insights into similar artisanal fisheries around the globe, where data is often unavailable.

## A Appendix

### A.1 Data Summary for economic and biological variables

Table 5: Summary statistics of variables over observations used in main estimation

	Mean	Sd	Min	Max
<b>Thiès Sud</b> ( $N = 95$ )				
Monthly. Landings (tons)	5,281.37	4,149.52	16.71	18,457.11
CPUE (tons/DAS)	2.62	1.90	0.02	8.31
Fish price (FCFA/kg)	47.09	33.01	12.39	270.73
Population density ( 1000/km <sup>2</sup> )	0.31	0.03	0.28	0.35
<b>Fleuve</b> ( $N = 100$ )				
Monthly. Landings (tons)	4,677.24	3,827.70	4.07	19,144.76
CPUE (tons/DAS)	4.92	3.47	0.09	15.36
Fish price (FCFA/kg)	96.36	66.30	21.55	416.85
Population density ( 1000/km <sup>2</sup> )	0.27	0.02	0.24	0.30
<b>Cap Vert</b> ( $N = 86$ )				
Monthly. Landings (tons)	2,368.53	2,189.89	1.81	9,835.82
CPUE (tons/DAS)	1.49	1.19	0.00	4.18
Fish price (FCFA/kg)	155.70	262.01	17.29	1,931.39
Population density ( 1000/km <sup>2</sup> )	12.78	0.50	12.05	13.48
<b>Thiès Nord</b> ( $N = 93$ )				
Monthly. Landings (tons)	2,671.24	2,822.59	5.47	10,599.29
CPUE (tons/DAS)	2.63	2.27	0.01	9.41
Fish price (FCFA/kg)	90.26	57.08	21.55	416.85
Population density ( 1000/km <sup>2</sup> )	0.28	0.02	0.25	0.32
<b>Aggregate Senegal</b>				
Biomass (tons)	199,000	56,310	116,000	282,000

## A.2 The Cost Function

Harvesting is described by

$$h_{it} = q_i(m, W_{it}) E_{it} x_y^x, \quad (15)$$

Effort is assumed to be produced by means of labor  $l$  and capital  $k$  using Cobb-Douglas technology with constant returns to scale:

$$E_{it} = l_{it}^\varphi k_{it}^{1-\varphi} \quad (16)$$

with  $\varphi \in (0, 1)$ . The supply functions of both inputs are assumed to be iso-elastic. Both production factors cannot be transferred between fisheries of different species, which makes sense if the fisheries are very different and/or the fishing seasons vary. Supply of both input factors is thus defined as:

$$w_{it}(l_{it}) = \omega_i l_{it}^\zeta, \quad (17)$$

$$r_{it}(k_{it}) = \kappa_i k_{it}^\psi, \quad (18)$$

where  $\zeta$  ( $\psi$ ) denote the inverse supply elasticity of labor (capital) and  $w_{it}$  ( $r_{it}$ ) is the wage rate (capital rental rate). When supply of labor is perfectly elastic the wage rate equals the "global" wage rate  $\omega_i$  ( $\kappa_i$  for capital, respectively).

Fishers minimize their costs to determine their optimal harvest quantity in each period. They have to take local factor markets into account when they decide on their harvest strategy.

Solving the representative firm's cost minimization problem

$$\begin{aligned} \min_{l_{it}, k_{it}} \quad & w_{it}l_{it} + r_{it}k_{it} \\ \text{s.t.} \quad & \text{Eqs (1), (16)} \end{aligned}$$

leads to the factor demand functions

$$l_{it} = \frac{h}{q_i(m, W_{it}) x_y^\chi} \left( \frac{\varphi}{1-\varphi} \frac{r_{it}}{w_{it}} \right)^{1-\varphi}, \quad (19)$$

$$k_{it} = \frac{h}{q_i(m, W_{it}) x_y^\chi} \left( \frac{1-\varphi}{\varphi} \frac{w_{it}}{r_{it}} \right)^\varphi, \quad (20)$$

as well as the cost function that is linear in harvest, and thus entails equal average and marginal cost:

$$C_{it}(h_{it}, w_{it}, r_{it}; x_y) = \frac{w_{it}^\varphi r_{it}^{1-\varphi}}{\varphi^\varphi (1-\varphi)^{1-\varphi}} \frac{h_{it}}{q_i(m, W_{it}) x_y^\chi}. \quad (21)$$

In labor and capital market equilibrium, the equilibrium wage and capital rental rate is (using (19) in (17), (20) in (18) respectively):

$$w_{it} = \omega_i l_{it}^\zeta = \omega_i \left( \frac{h_{it}}{q_i(m, W_{it}) x_y^\chi} \right)^\zeta \left( \frac{\varphi}{1-\varphi} \frac{r_{it}}{w_{it}} \right)^{\zeta(1-\varphi)}, \quad (22)$$

$$r_{it} = \kappa_i k_{it}^\psi = \kappa_i \left( \frac{h_{it}}{q_i(m, W_{it}) x_y^\chi} \right)^\psi \left( \frac{1-\varphi}{\varphi} \frac{w_{it}}{r_{it}} \right)^{\psi\varphi}. \quad (23)$$

Using (22) and (23) in (21), the market equilibrium cost function becomes

$$c_{it}(h_{it}, x_y) = c_i \left( \frac{h_{it}}{q_i(m, W_{it}) x_y^\chi} \right)^{e+1},$$

with

$$c_i = \left( \frac{\omega_i}{\varphi} \right)^{\frac{\varphi(1+\psi)}{1+\psi\varphi+\zeta(1-\varphi)}} \left( \frac{\kappa_i}{1-\varphi} \right)^{\frac{(1-\varphi)(1+\zeta)}{1+\psi\varphi+\zeta(1-\varphi)}} > 0. \quad (24)$$

and

$$e = \zeta \frac{\varphi(1+\psi)}{1+\psi\varphi+\zeta(1-\varphi)} + \psi \frac{(1-\varphi)(1+\zeta)}{1+\psi\varphi+\zeta(1-\varphi)} \geq 0. \quad (25)$$

### A.3 Robustness Checks

Results on alternative models are listed in tables 6 and 7. Regional differences depend to a large extent on elasticities. We let  $e$  depend on species importance, using the regional share of *Sardinella* catch in total catch to account for closer work opportunities related to fishing. Monthly data on total catch per species is available from the Directorate of Maritime Fisheries (DPM) (Direction des pêches maritimes, 2001-2008). It is available for Dakar, Fleuve and aggregate Thiès. We weigh the Thiès data to differentiate Thiès Nord and Thiès Sud using yearly CRODT data (Thiao et al., 2008). We change the model in the following equation:

$$e(S_{it}) = \exp(e_0 + \zeta S_{it}) \quad (26)$$

where  $S_{it}$  is defined as *Sardinella aurita* catch over total catch. Column 1 shows the expected negative and significant  $\hat{\zeta}$ . If the market is more concentrated on *Sardinella aurita*, alternative employment opportunities in fishing are few and therefore,  $\hat{e}$  is lower. The mean size of  $\hat{e}$  (0.943 – 1.359) and  $\hat{\nu}$  (0 – 0.483) doesn't change much. Thus, while this model may give a better explanation on the causes of a higher or lower elasticity, it does not invali-

date the results from our main estimation. With  $R^2$  between 37 and 41 for the three equations, the small benefit with respect to model fit seems not to outweigh the disadvantage of dropping 24 observations due to missing data.

We run the original model excluding Cap Vert to analyze the importance of the capital region for estimation results (column 2). The sharp increase in  $R^2$  for the price equation is not surprising: It seems that with regard to market mechanisms, the three other regions are quite alike in contrast to the capital region around Dakar. Stock elasticity  $\hat{\chi}$  is slightly higher, and baseline catchability slightly lower. The effect of lagged precipitation shocks is now larger and significant at the 5% level. By contrast, it becomes very small and insignificant in the model excluding Thiès Sud (column 3). We use the latter to test whether the insignificant estimation result on  $\hat{g}_i$  for the region has distorted other results. We conclude that the precipitation effect is strongest in this region. This makes sense considering the proximity of the Saloum Delta, that serves as fishing ground for the fishers from Thiès Sud. In the latter model,  $\hat{\chi}$  is a little higher and insignificant. The most pronounced change concerns the cost elasticity. Cost elasticity parameter  $\hat{e}$  is substantially higher but insignificant.

We also tested additional models with respect to climate controls (see columns 4-5). The runner-ups with respect to BIC values were the following two:

$$\text{Non-linear SST shock: } f(W_{it}) = sw_t SST_{sh,i} + sw_{t2} SST_{sh,i}^2 \quad (27)$$

$$\text{Including wind: } f(W_t) = sw_w WINDSPEED_{sh} \quad (28)$$

Squared SST has a negative coefficient (-0.220), but is insignificant. Together with SST's coefficient at 0.556, this shows that the relationship between catchability and SST shocks could be concave. Wind-speed has a

negative impact (-0.177). It is significant at the 10% level only if SST is unaccounted for. It is likely that wind-speed affects technical harvesting conditions. Cost elasticity parameter  $e$  is slightly higher in the non-linear SST shock model, and slightly lower in the model with wind-speed.

Important for our model is to find a fitting specification for catchability. The specification in the main model restricts the seasonal profile to equal peaks and lows throughout the year across regions, and to an amplitude that increases in  $q_{i9}$ . We test these assumptions using the following alternative specification for seasonality in step 1 (column 6):

$$q_i(m, W_{it}) = (1 + q_{i1} \sin(tt + q_{i2})) \exp(f(W_{it})) \geq 0$$

with  $tt = \frac{\pi m}{3}$ . This restricts the pattern to two equally sized regular peaks and low's per year, but is more liberal regarding cross-regional restrictions. Using a mathematical and graphical analysis, we confirm that peaks and lows happen indeed in the same month for all regions. Amplitude increases in baseline catchability. While differences in baseline catchability are larger between Fleuve, Thiès Nord and Cap Vert, the overall order is preserved as in the original model.

Table 6: Robustness results: Harvest productivity

Param.	<i>Sard. aurita</i> share	w/o Cap Vert	w/o Thiès Sud	Nonlin. SST	Incl. wind	Sinus q
$\chi$	0.199* (0.105)	0.281** (0.112)	0.266 (0.163)	0.232** (0.105)	0.271*** (0.102)	0.193* (0.104)
$\delta_1$	0.928*** (0.193)	0.922*** (0.225)	1.512*** (0.516)	1.036*** (0.229)	1.060*** (0.233)	
$\delta_2$	0.598*** (0.170)	0.629*** (0.185)	1.145*** (0.428)	0.736*** (0.212)	0.713*** (0.202)	
$\delta_3$	0.849*** (0.195)	0.913*** (0.206)	1.379*** (0.490)	0.970*** (0.231)	0.904*** (0.227)	
$\delta_4$	1.058*** (0.210)	1.240*** (0.215)	1.633*** (0.542)	1.247*** (0.249)	1.146*** (0.237)	
$\delta_5$	1.270*** (0.239)	1.382*** (0.239)	1.769*** (0.599)	1.450*** (0.275)	1.337*** (0.265)	
$\delta_6$	1.435*** (0.245)	1.713*** (0.261)	1.895*** (0.637)	1.664*** (0.297)	1.511*** (0.271)	
$\delta_7$	0.546*** (0.204)	0.885*** (0.178)	0.616 (0.406)	0.731*** (0.245)	0.668*** (0.240)	
$\delta_8$	0.435** (0.178)	0.585*** (0.184)	0.416 (0.324)	0.584*** (0.204)	0.562*** (0.198)	
$\delta_{10}$	0.140 (0.171)	0.315* (0.167)	0.067 (0.298)	0.229 (0.195)	0.196 (0.182)	
$\delta_{11}$	0.964*** (0.184)	1.091*** (0.214)	1.289*** (0.445)	1.092*** (0.222)	1.085*** (0.221)	
$\delta_{12}$	1.187*** (0.211)	1.215*** (0.205)	1.828*** (0.598)	1.394*** (0.261)	1.329*** (0.249)	
$sw_t$	0.510*** (0.162)	0.597*** (0.165)	0.642* (0.336)	0.556*** (0.163)		0.343** (0.139)
$sw_{p1}$	-0.198** (0.094)	-0.222** (0.107)	-0.076 (0.169)			0.001 (0.102)
$sw_{t2}$				-0.220 (0.312)		
$sw_w$					-0.177* (0.107)	
$\tau_{sFL}$	0.012*** (0.001)	0.012*** (0.001)	0.006 (0.005)	0.011*** (0.001)	0.011*** (0.001)	0.013*** (0.001)
$\tau_{sTN}$	0.008** (0.003)	0.006 (0.004)	0.005** (0.002)	0.008*** (0.001)	0.009*** (0.001)	0.010** (0.004)
$\tau_{sCV}$	0.002 (0.004)		0.001 (0.004)	0.001 (0.008)	0.001 (0.004)	0.001 (0.003)
$\tau_{sTS}$	0.005** (0.002)	0.004** (0.002)		0.003 (0.004)	0.004*** (0.001)	0.004* (0.003)
$\ln q_{0FL}$	-3.410*** (0.070)	-4.517*** (0.096)	-4.589*** (0.148)	-3.901*** (0.021)	-4.316*** (0.059)	-2.408*** (0.134)
$\ln q_{0TN}$	-3.592*** (0.132)	-4.714*** (0.316)	-4.751*** (0.130)	-4.090*** (0.185)	-4.542*** (0.078)	-2.626*** (0.101)
$\ln q_{0CV}$	-3.755*** (0.120)		-4.915*** (0.187)	-4.259*** (0.417)	-4.710*** (0.017)	-2.839*** (0.560)
$\ln q_{0TS}$	-2.993*** (0.082)	-4.126*** (0.014)		-3.490*** (0.387)	-3.922*** (0.079)	-1.992*** (0.023)
$q_{1TN}$						-0.376*** (0.095)
$q_{1TS}$						-0.438*** (0.089)
$q_{1CV}$						-0.230** (0.112)
$q_{1FL}$						-0.415*** (0.083)
$q_{2TN}$						-1.068*** (0.265)
$q_{2TS}$						-1.283*** (0.154)
$q_{2CV}$						-1.459*** (0.451)
$q_{2FL}$						-1.349*** (0.182)

\* p<.10, \*\* p<.05, \*\*\* p<.01, Robust std. errors in parentheses. (FL=Fleuve, TN=Thiès Nord, TS=Thiès Sud, CV=Cap Vert)

Table 7: Robustness results: Markets and statistics

Param.	<i>Sard. aurita</i> share	w/o Cap Vert	w/o Thiès Sud	Nonlin. SST	Incl. wind	Sinus q
$\nu_0$	-0.053 (0.203)	0.075 (0.190)	-0.355 (0.300)	-0.172 (0.185)	-0.200 (0.187)	-0.137 (0.203)
$\eta$	-2.834*** (0.587)	-2.627*** (0.554)	-3.034*** (0.908)	-2.360*** (0.512)	-2.340*** (0.524)	-2.358*** (0.524)
$e$	0.308 (0.547)	1.044 (0.732)	2.041 (2.642)	1.145* (0.619)	0.933* (0.495)	0.605 (0.427)
$\zeta$	-0.366*** (0.108)					
$\ln \bar{p}_{FL}$	7.839*** (0.457)	8.533*** (0.564)	6.802*** (0.357)	7.872*** (0.456)	7.791*** (0.449)	7.995*** (0.587)
$\ln \bar{p}_{TN}$	7.318*** (0.381)	7.929*** (0.482)	6.420*** (0.302)	7.358*** (0.389)	7.289*** (0.381)	7.466*** (0.511)
$\ln \bar{p}_{CV}$	4.558*** (0.091)		4.559*** (0.091)	4.559*** (0.091)	4.559*** (0.091)	4.559*** (0.091)
$\ln \bar{p}_{TS}$	6.919*** (0.430)	7.592*** (0.542)		6.965*** (0.434)	6.892*** (0.426)	7.082*** (0.565)
$\ln g_{FL}$	-1.886 (1.684)	-3.217 (2.243)	-1.665 (2.662)	-2.411 (1.682)	-3.422** (1.546)	-2.683 (1.927)
$\ln g_{TN}$	-1.909 (1.637)	-3.305 (2.127)	-1.560 (2.583)	-2.300 (1.636)	-3.317** (1.487)	-2.539 (1.829)
$\ln g_{CV}$	-1.675 (1.691)		-1.458 (2.665)	-2.346 (1.673)	-3.369** (1.510)	-2.695 (1.918)
$\ln g_{TS}$	-0.423 (1.704)	-2.105 (2.208)		-1.229 (1.677)	-2.245 (1.534)	-1.524 (1.902)
$\tau_{nFL}$	0.014*** (0.003)	0.014*** (0.003)	0.021*** (0.007)	0.015*** (0.003)	0.014*** (0.003)	0.011*** (0.003)
$\tau_{nTN}$	0.006** (0.003)	0.008** (0.003)	0.009* (0.005)	0.005* (0.003)	0.004 (0.003)	0.003 (0.003)
$\tau_{nCV}$	0.003 (0.003)		0.004 (0.005)	0.004 (0.003)	0.003 (0.003)	0.004 (0.002)
$\tau_{nTS}$	0.001 (0.002)	0.002 (0.003)		0.002 (0.002)	0.001 (0.002)	0.000 (0.002)
N step 1	350	264	267	374	374	374
N step 2	423	321	315	423	423	423
$R_p^2$	0.37	0.53	0.15	0.36	0.35	0.32
$R_c^2$	0.40	0.36	0.47	0.41	0.39	0.35
$R_h^2$	0.41	0.35	0.46	0.38	0.37	0.28
No. var. <i>p</i>	30	26	26	29	28	26
No. var. <i>c</i>	8	6	6	8	8	8
No. var. <i>h</i>	30	26	26	29	28	26
BIC step 1	1883	1316	1499	2027	2036	2090
BIC step 2	1222	880	908	1217	1232	1260

\* p<.10, \*\* p<.05, \*\*\* p<.01, Robust std. errors in parentheses. (FL=Fleuve, TN=Thiès Nord, TS=Thiès Sud, CV=Cap Vert)

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## B Supplementary online material

### B.1 Data Summary for weather variables

We extract data relevant to Senegalese waters from the available grid of  $0.75^\circ$ longitude x  $0.75^\circ$ latitude. For wind, SST and salinity, we use regional boxes that only contain sea or coastal areas. For precipitation, we use a larger, aggregate coordinate box that also includes inland coordinates to include potential river-runoff effects. Within each coordinate box, data is averaged. We create for each variable a shock term  $var_{sh} = (var - var_{ltm})/var_{sd}$  with  $var_{sd}$  representing the regional standard deviation of the monthly long-term mean. We define  $var_{ltm}$  as the 30-year long term monthly mean value from 1981-2010 on average for the whole (coastal) region, such that for SST and wind variables, shocks can also capture regular deviations between regions. Coordinates as well as a data summary are provided in 8. Data contains no missings. It is provided, as in the main part, by the European Centre for Medium-Range Weather Forecasts.

Table 8: Summary statistics of the weather used for robustness

	Mean	Sd	Min	Max
<b>Thiès Sud</b> (17.25W – 18.75W & 13.50N – 15.00N)				
SST (° Celsius)	24.5101	3.0069	18.5728	28.5381
Wind speed (m/s)	5.2665	1.2621	3.0604	8.0403
Zonal windstress ( N./m <sup>2</sup> )	-0.0028	0.0237	-0.0727	0.0302
Meridional windstress ( N./m <sup>2</sup> )	-0.0349	0.0279	-0.0950	0.0094
<b>Fleuve</b> (17.25W – 18.75W & 15.00N – 16.50N)				
SST (° Celsius)	23.9887	3.0636	18.7395	28.6313
Wind speed (m/s)	5.9958	1.2922	3.2699	8.4265
Zonal windstress ( N./m <sup>2</sup> )	-0.0087	0.0268	-0.0831	0.0330
Meridional windstress ( N./m <sup>2</sup> )	-0.0485	0.0286	-0.1016	-0.0011
<b>Cap Vert</b> (17.25W – 18.75W & 14.25N – 15.75N)				
SST (° Celsius)	23.3461	2.7444	18.5298	28.3813
Wind speed (m/s)	5.9536	1.1481	3.3267	8.2508
Zonal windstress ( N./m <sup>2</sup> )	-0.0100	0.0273	-0.0794	0.0328
Meridional windstress ( N./m <sup>2</sup> )	-0.0489	0.0257	-0.1003	-0.0034
<b>Thiès Nord</b> (17.25W – 18.75W & 14.25N – 15.75N)				
SST (° Celsius)	24.0571	3.0009	18.5298	28.3813
Wind speed (m/s)	5.6409	1.2841	3.0984	8.2508
Zonal windstress ( N./m <sup>2</sup> )	-0.0070	0.0259	-0.0794	0.0328
Meridional windstress ( N./m <sup>2</sup> )	-0.0428	0.0280	-0.1003	0.0049
<b>Aggregate Senegal</b> (15.75W – 18.75W & 13.50N – 16.50N)				
Aggregate precipitation (mm/d)	0.5081	0.8955	0.0000	4.0833

## B.2 Estimation graphs

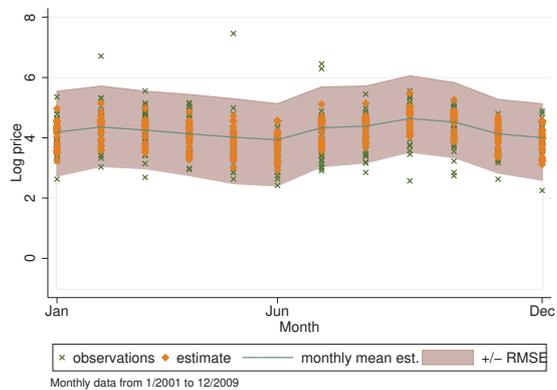


Figure 5: Estimation fit for (14b)

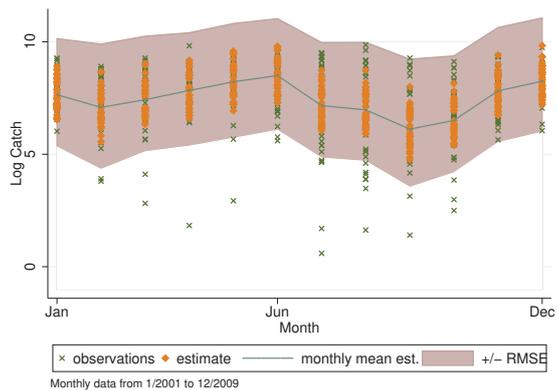


Figure 6: Estimation fit for (14a)

### B.3 Comparison of two-step model and separate CPUE estimation

In section 3, we argued that the estimation of environmental effect using the *CPUE*-equation could be subject an endogeneity bias. Here, we compare results from the two step estimation to results from a separate estimation of the *CPUE* function.

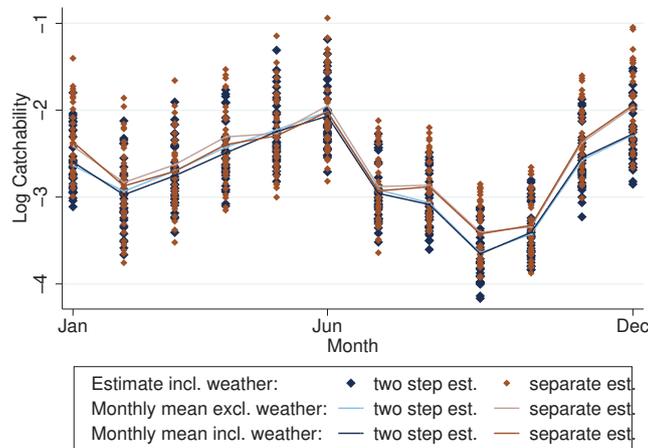


Figure 7: Catchability estimates for the joint and separate model

We use the same 374 observations as in the first step of the full model. The  $R^2$  value is higher than in the second step regression by 2 percentage points. Both models vary only slightly with respect to model fit.

Small differences occur concerning the estimated coefficients (see column 3 in table 1). Figure 7 compares estimated log catchability. Baseline catchability in the period between March and July is similar for the two models, whereas catchability is slightly lower in the two-step model during the rest of

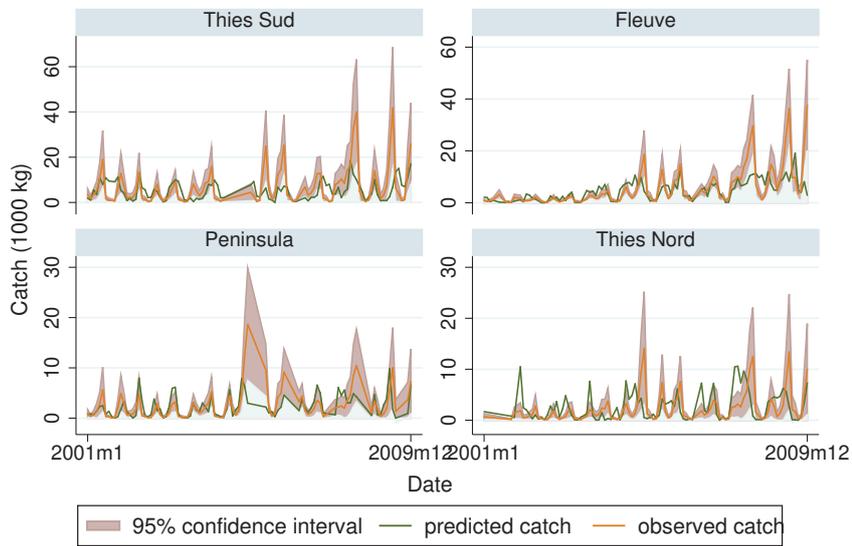
the year. This can be viewed as an upwards correction for spring and early summer. We conclude that fishing days are associated with less actual effort in spring months compared to the rest of the year. Fish are close to shore during these months.

The effect of SST shocks on catchability is corrected downwards, but this difference is not significant at the 95% level. If a model accounts for variability in actual effort, the impact of SST shocks appears weaker. The opposite is true for lagged precipitation. Its coefficient is negative in the two-step model, but insignificant. A negative coefficient could be explained by reduced visibility. The schooling parameter  $\hat{\chi}$  is positive and slightly lower at 0.195 in the separate model, but insignificant. The weak difference in the size of  $\hat{\chi}$  shows that the effort parameter does not vary a lot with biomass. However, once environmental coefficients are indeed exogenous, the importance of biomass changes are more explicit and significant. Other parameter do not exhibit noticeable differences.

Our correction leads to differences in parameter estimation, advocating that a bias exist, but it is merely small. In this particular case, using inaccurate effort data does not lead to a substantial bias. A more detailed measurement would not substantially improve estimation results.

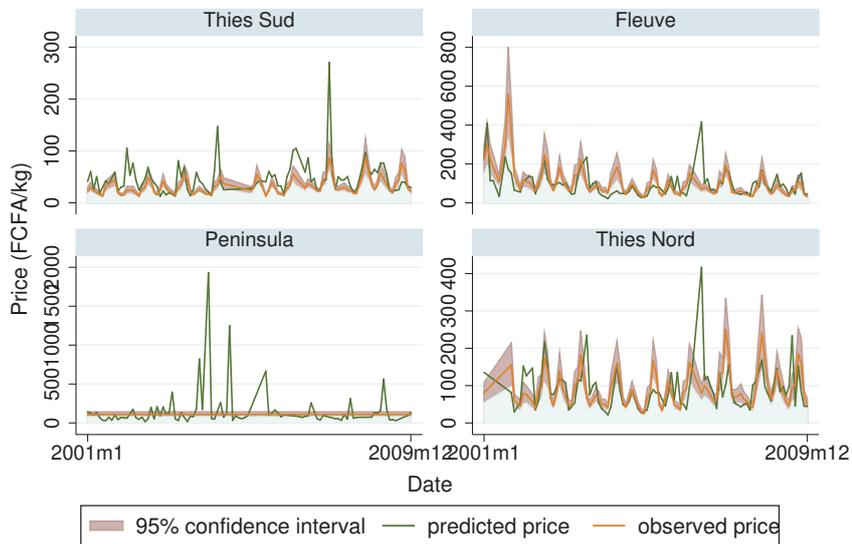
#### **B.4 Estimation graphs: Fit after retransformation**

Figure 8: Comparison between observed and predicted values for *Sardinella aurita* catch within the study period



Please note the different y axis scales in this graph.

Figure 9: Comparison between observed and predicted values for *Sardinella aurita* prices within the study period



Please note the different y axis scales in this graph.

## B.5 Aggregate rents for different biomass levels

Table 9: Regional yearly fishers' and consumers' rents (1000 FCFA) for different biomass levels under open access

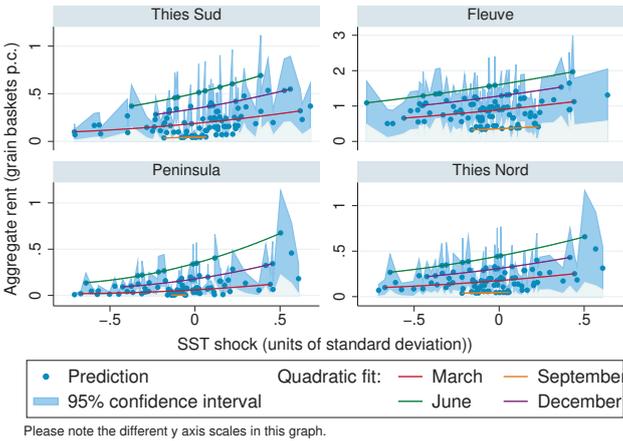
Region	Rents					difference from mean (%)				
	TS	FL	CV	TN	Sen.	TS	FL	CV	TN	Sen.
<i>CS<sub>oa,mean</sub></i>	971,344	2,390,750	0	981,591	4,343,684					
<i>CS<sub>oa,min</sub></i>	824,501	2,163,658	0	841,270	3,829,430	-15	-9	-25	-14	-12
<i>CS<sub>oa,max</sub></i>	1,078,919	2,547,810	0	1,083,827	4,710,556	11	7	20	10	8
<i>FS<sub>oa,mean</sub></i>	683,762	1,423,947	1,536,775	607,823	4,252,307					
<i>FS<sub>oa,min</sub></i>	580,394	1,288,690	1,149,174	520,934	3,539,192	-15	-9	-25	-14	-17
<i>FS<sub>oa,max</sub></i>	759,487	1,517,494	1,846,972	671,131	4,795,084	11	7	20	10	13
<i>TR<sub>oa,mean</sub></i>	1,655,106	3,814,697	1,536,775	1,589,414	8,595,991					
<i>TR<sub>oa,min</sub></i>	1,404,895	3,452,348	1,149,174	1,362,204	7,368,622	-15	-9	-25	-14	-14
<i>TR<sub>oa,max</sub></i>	1,838,406	4,065,304	1,846,972	1,754,958	9,505,640	11	7	20	10	11

TS: Thiès Sud, FL: Fleuve, CV: Cap Vert, TN: Thiès Nord, Sen.: Senegal.  
Mean biomass: 199,000t, minimum: 116,000t, maximum: 282,000t.

## B.6 Rents as a function of SST

Figure 10 shows the distribution of rents over the year by means of four exemplary months, as well as the impact of SST shocks on the aggregate rent in grain baskets per capita. The length of the lines shows the extent to which SST shocks vary for each of the four months shown. SST shocks in June alone may vary food security for a certain year by 0.5 – 1 grain basket per coastal inhabitant.

Figure 10: Dependence of regional fisher and consumer rents on SST shocks (1 standard deviation  $\approx$  an SST shock of 3°Celsius, depending on the region.)



# Climate change adaptation and the role of fuel subsidies: An empirical bio-economic modeling study for an artisanal open-access fishery

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**Abstract:** Climate change can severely impact artisanal fisheries and their role for food security. We study climate change effects on the triple bottom line of ecological productivity, fishers' incomes and fish consumption, for an artisanal open-access fishery. We develop an empirical, stochastic bio-economic model for the Senegalese artisanal purse seine fishery and compare the simulated fisheries' development using different climate projections. We find that economic adaptation processes may amplify effects of climate variations. The regions' catch potential increases with climate change, induced by stock distribution changes. This escalates over-fishing, which outruns the incipiently favorable climate change effects under three of four climate predictions. Without policy action, the fishery is estimated to collapse in 2030-2035 on average. If fuel subsidies are abolished, ecological sustainability and fisheries' welfare contribution increase regardless of the climate projection.

**JEL Classification:** Q22, Q25, Q54

**Keywords:** climate modeling, adaptation, fuel subsidies, artisanal fishing, renewable resource policy, common pool resources

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# 1 Introduction

Predicting climate change effects on oceans and fisheries has drawn intense scientific attention over the past decade (Arnason, 2008; Béné et al., 2010; Pauly et al., 2013; Hughes et al., 2003). Changes in wind regime and sea surface temperature (SST) are expected to affect the Atlantic habitat. Upwelling-favorable winds are expected to increase in the north, decrease in the south (Cropper et al., 2014; Marcello et al., 2011) and thus change primary productivity. Pauly et al. (2013) reported an increase in global mean water temperature at time of catch of  $0.19^{\circ}\text{Celsius}$  per decade, due to fish stock redistribution. The economic effects may be strong in particular for artisanal fishing communities, where the dependence on fish as a protein source and on fishing income is high (Belhabib et al., 2015; Béné et al., 2010; Ding et al., 2017).

For 14 Northwest African countries, Lam et al. (2012) projected an average climate change induced decrease in landed fish of 25.9% between 2000 and 2050, associated with the loss of 50% of available jobs in the fishery. Other countries could benefit due to an enhanced catch potential (Arnason, 2008; Cheung et al., 2010). Due to the complexity and global nature of the studies, they rely on simplifying assumptions such as constant per capita consumption and landings according to biological catch potential or economic growth (Arnason, 2008; Pauly et al., 2013; Failer, 2014; Lam et al., 2012). However, changes may be dampened or intensified, when economic actors, in this case fishers and consumers, adapt. In open-access artisanal fisheries, where local market feedbacks are typically strong, such adaptation processes are important. For example, fishers may adapt by changing the used amounts of fuel, capital and labor to fish. As a result, over-fishing may increase or decrease with rising harvest potential. Non-linear changes in equi-

librium harvest and fish prices arise (see the first paper in this dissertation). While this is scarcely analyzed in fisheries models (Belhabib et al., 2016a), Osborne et al. (2013) explicitly modeled adaptation into a crop model, which turned negative impacts into positive crop yield gains. Both uncertainty in climate projection, as well as these economic changes and their uncertainties are important for policy makers to take into account. Therefore, this paper aims to simulate the impact of climatic changes on an artisanal open access fishery under endogenous economic adaptation. High uncertainty exists with respect to climate change projections, in particular concerning the amplitude of climate change and the extent of climate variability. Hence, for a robust understanding of climate change adaptation, it is necessary to compare how the fishery develops under different projections and to explore which climate scenario traits are important determinants.

Jewell et al. (2018) recently spotlighted the link between climate change and fuel subsidies. The price for fossil fuels also shapes the adaptation process in fisheries. The importance of fuel for fishing has been underlined in the literature (e.g Daurès et al., 2013; Suuronen et al., 2012; Willmann and Kelleher, 2009). One third of the global output value is taken up by fuel costs (Willmann and Kelleher, 2009). Higher fuel prices, all else equal, decrease harvest. This reduces over-fishing, such that the equilibrium stock level is higher and more stable. Fuel cost also affect the distance fishers are willing to travel for catch (Prellezo et al., 2009). Thus, it is a potentially important determinant for how severe climate change effects are felt, how uncertain they are and how (much) adaptation takes place. At the same time, fuel subsidies constitute one of the most widely used policy instruments: Sumaila et al. (2016) estimate that an annual 7.7 billion US Dollar of fuel subsidies were paid to fisheries globally. Several authors have found a detrimental impact on

fish stocks (Harper et al., 2012; Sumaila et al., 2008). Fishing fleets benefit from a subsidy decrease if the stock effect is large enough (Da-Rocha et al., 2017). On the other hand, it has been argued in World Trade Organization (WTO) discussions that developing countries' fisheries may need subsidies to help maintain food security and alleviate poverty (Yu and Fonseca-Marti, 2005). Against this background, this paper evaluates how climate change outcomes for the fishery can be positively shaped if fuel subsidies are abolished.

We develop an empirical bio-economic model for the *Sardinella aurita* fishery by artisanal purse seines in Senegal, that takes into account climate effects on reproduction of the fish stock, productivity of harvesting, feedbacks on local input and output markets, and fuel subsidies. Climate has a dynamic effect on yearly stock growth through changes in upwelling intensity, but also an effect on catchability, and thus fishing pressure, through fish stock distribution. We simulate the development of biomass, harvest and prices and compare outcomes concerning the fisheries contribution to food and income security. Results of different climate model projections and different fuel subsidy policies are compared. Our results are informative for policy makers, as they shed light on the effect of such a policy under the joint consideration of endogenous adaptation of actors and climatic changes. In addition, they show how small climate scenario differences may be amplified to larger economic differences, compare the relevance of different model traits and reveal how strongly outcomes depend on the policy regime.

The next section describes the data and methods used in the biological and economic model parts, as well as the simulation strategy and climate scenarios. Results are presented and discussed in Section 3.

## 2 Methods and materials

### 2.1 Biology and climate impacts on stock growth of Senegalese *Sardinella aurita*

*Sardinella aurita* is a migratory small pelagic schooling species. The species occurs along the continental shelf between Morocco and Guinea Bissau (Brehmer et al., 2007). Recent findings support the separability of the stock into sub-populations (Bacha et al., 2016; Braham et al., 2014; Brochier et al., 2018; Corten et al., 2013; Durand et al., 2013), with one group along Senegal and Southern Mauritania. Spawning in Senegal peaks in fall and spring (Thiaw et al., 2017).

To estimate climate impacts on biomass growth, we use stock assessment data for *Sardinella aurita* by the FAO working group on the assessment of small pelagic fish off Northwest Africa. In the years 1995–2006, fishery independent surveys were carried out in the fourth quarter of each year by the research vessel R/V Dr FRIDTJOF NANSEN (Toresen et al., 2001, 2002; Krakstad et al., 2003, 2004, 2005, 2006). National surveys provide estimates for 2007–2009 (FAO, 2008, 2011a,b)<sup>2</sup>. Figure A.1 in the Appendix shows yearly abundance estimates. The development over time shows substantial variability, which has been attributed to upwelling variability and associated variations in primary productivity (Diankha et al., 2015; Corten et al., 2013; Thiaw et al., 2017).

The habitat is characterized by high productivity due to its upwelling system (Lathuiliere et al., 2008). Alongshore wind stress brings cool, nutrient-rich water to the surface (Cropper et al., 2014). In such upwelling systems,

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<sup>2</sup>The working group used regression models to account for occasional regional gaps.

small pelagic reproduction has been found to depend mainly on two factors: retention of larvae and primary productivity. Both are influenced by wind conditions (Bacha et al., 2017; Binet, 1997; Brochier et al., 2009, 2018; Cury and Roy, 1989; Tiedemann et al., 2017; Zeeberg et al., 2008). According to Thiaw et al. (2017), the lagged spring and autumn upwelling indices have a significant positive effect on *Sardinella aurita* abundance, because they spur primary productivity. On the other hand, wind stress can influence retention negatively, because larvae drift off to areas where they can not survive (Bakun, 1996; Cury and Roy, 1989). Due to the broad continental shelf in the main spawning area, retention is high in general (Brochier et al., 2009). We make use of monthly reanalysis data using the ERA-Interim product, available from by the European Centre for Medium-Range Weather Forecasts (ECMWF, 2012) to calculate a seasonal coastal upwelling index (CUI) from wind stress using standard procedures (Cropper et al., 2014) (see B.1 in the supplementary material). We average over the area between 13.5 – 16°N and 17.25 – 18°W. Our index shows the regionally typical pattern: Upwelling is strongest in winter, and relents between June and October.

We estimate the effect of upwelling on yearly stock growth (surplus production of the stock), defined as the biomass difference between consecutive years plus catches. Data on annual Senegalese and Gambian catches for the period 1995–2013 is taken from the FAO assessment report (FAO, 2013). We add reported catches by legal foreign trawlers from the ‘Sea around us’ database (Belhabib et al., 2014, 2016b). The Senegalese purse seine fleet share in total harvest fluctuates around 90%. This is because the stocks’ main habitat is the Senegalese exclusive economic zone, where other fleets have limited access. A summary of the data-set used in estimation is provided in A.2.

We assume a standard logistic growth model, with spawning stock biomass (SSB) lagged by one year,  $x_{y-1}$ , where  $y$  denotes the year in which biomass growth is observed. The intrinsic growth rate  $r + f(UP_y)$  depends on upwelling intensity  $UP_y$ , and we use  $K$  to denote the (constant) carrying capacity for the fish stock. Adding a normally distributed shock  $\varepsilon_y^s$ , net growth  $g_y$  of the fish stock in year  $y$  is thus given by

$$g_y = (r + f(UP_y)) x_{y-1} \left(1 - \frac{x_{y-1}}{K}\right) + \varepsilon_y^s \quad (1)$$

The error term  $\varepsilon_y^s$  is approximately normally distributed with an estimated standard deviation of 80.29 kt per year. The function  $f(UP_y)$  denotes a linear sum of upwelling impacts, where various structures were tested. We considered alternative specifications with respect to lag structure, seasons, SST, an alternative upwelling index based on SST, and with respect to the size of the biomass or biomass growth of the Mauritanian stock group to check for migration flows. We also tested alternatives with weather impacts on the carrying capacity, but models with environmental effects on the natural growth rate generally performed better than models with environmental effects on carrying capacity  $K$ , or on the quadratic term in general. The model was chosen based on the Bayesian information criterion and adjusted  $R^2$ . In the chosen model, the one year lagged fall (October-December) and winter (January-March) CUI have a linear influence on the natural growth rate:

$$r + f(UP_y) = r + r_{Cw}CUI_{winter,y-1} + r_{Cf}CUI_{fall,y-1} \quad (2)$$

The model features an adjusted  $R^2$  of 92%, which is non-surprising considering that only 14 observations (1996–2009) are available and upwelling

has been established as main driver by previous research. The inclusion of upwelling explains 28% of the variation compared to the model without climate impacts. Tests for serial correlation, heterogeneity and skewness did not detect any issues at the 5% level. In the following, we present results and marginal effects shortly. Section A.3 includes technical details as well as alternative specifications.

The carrying capacity is estimated at 302 kt, and significant at the 1% level ( $p < .001$ ). The positive impact from fall upwelling ( $p = .016$ ), is partly canceled out by a negative impact from winter upwelling ( $p = .001$ ). The latter could be linked to lower retention, colder water temperatures unfavorable for the autumn larvae and may as well delay spring spawning. Thiaw et al. (2017) also report a negative sign for winter upwelling, which however was insignificant. As the mean SSB  $x_{y-1}$  (199.5 kt) lies above the maximum sustainable yield, the marginal effect at means of an increasing SSB on stock growth is negative at -1.21 kt. An increase in the upwelling indicators by 1  $\frac{m^3}{s}$  per 100m coastline leads to a growth reduction of 18.49 kt concerning winter upwelling, and an increase of 20.61 kt for fall upwelling. Figure 1 shows the stock growth effect of varying one environmental variable between its minimum and maximum observed level for fall and winter upwelling respectively, where the respective other upwelling variable is held constant at its mean<sup>3</sup>. The graph shows that stock growth varies slightly more with winter upwelling than with fall upwelling. Predicted growth at maximum sustainable yield SSB ranges between 100 and 430 kt (66–285% of SSB) within the study period, based only on upwelling variation.

We use available harvest and climate data for 2010 – 2014 to simulate

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<sup>3</sup>Observed values lay between 0.2509 and 0.4103  $\frac{m^3}{s}$  per m coastline for winter upwelling and 0.1243–0.2418  $\frac{m^3}{s}$  per m coastline for fall upwelling.

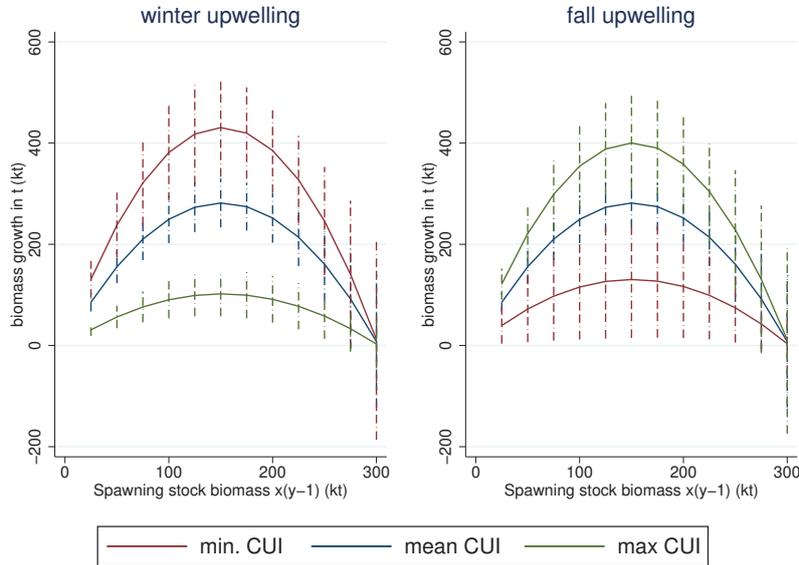


Figure 1: Sensitivity of biomass growth to a simultaneous variation of spawning stock biomass ( $x_{y-1}$ ) and upwelling. Dashed lines mark the 95% confidence interval variation.

the development of the stock for 2010 – 2014. The model provides plausible results (see Figure A.1 in the Appendix). These predictions are used in the economic part.

## 2.2 Economy and climate impacts on harvesting costs

Fishers harvesting decisions are affected by climatic conditions, prices for fish, fuel and labor, technological progress and the stock level. We use a similar economic data-set as previous studies (Diankha et al., 2017; Thiao, 2009). We model purse seines targeting *Sardinella aurita* in four Senegalese regions, namely Thiès Sud, Thiès Nord, Fleuve and the Dakar peninsula called Cap Vert, and aggregate results afterwards. We use monthly regional data on

purse seine<sup>4</sup> catches (tons), prices (FCFA/kg) and effort (days at sea, DAS) for 2001–2013, provided by the Centre of Oceanographic Research of Dakar-Thiaroye (CRODT). All prices are given in units of 2010-level FCFA, which is the abbreviation for the Senegalese currency Franc de la Communauté Financière d’Afrique (FCFA), after deflation with yearly World Bank Consumer Price Index data (The World Bank, 2017). We use regional *Sardinella aurita* prices, but fill in gaps with prices from the neighboring region or alternatively the price for *Sardinella maderensis*, the closest substitute (4% of observations). We prolong the time series of annual biomass data (cf. Section 2.1) by use of our own stock predictions for 2010 – 2013 (see Figure A.1). This allows us to make use of 187 additional data-points, which is desirable in particular for a more robust estimation of time trends. It is also important when looking at fuel impacts, as fuel prices typically are more variable over the long term<sup>5</sup>. Monthly local fuel price data is obtained from the annual reports of the Directorate of Maritime Fisheries (Direction des pêches maritimes, 2001, 2002, 2003, 2004, 2005, 2006, 2007, 2008, 2009, 2011). Prices are given in units of FCFA/liter. Local fuel prices and global prices for the internationally traded crude oil “Brent” are highly correlated. A strong upward trend can be observed until 2008. After 2008, fuel prices fell to the level of 2005, followed again by a gradual increase. For climate impacts, we again make use of the ERA Interim Reanalysis product at a monthly time scale. We average over regional coordinate boxes between 13.5–16.5°N and 17.25–18.75°W. The data-set is summarized in A.2.

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<sup>4</sup>Purse seines exhibited an annual catch share of more than 80% for 2001–2013 in all regions but Thiès Sud (57%).

<sup>5</sup>The estimation results for the time period 2001–2009, including only observed biomass levels, and further alternative specifications are provided as supplementary material in section B.2

Supply and demand are simultaneously estimated via the reduced form using robust standard errors. We estimate 32 parameters in three equations from 561<sup>6</sup> observations. A Bayesian information criterion 4056 and an  $R^2$  of 32–34% indicate a good model fit. Appendices A.4 and A.5 provide technical details on the model and estimation.

We assume an iso-elastic inverse demand function for fresh *Sardinella aurita*. Our estimates show that inverse demand is decreasing and convex in harvest. This means that consumers are willing to pay a higher price if the fish supply is scarce, and the marginal effect decreases with the quantity supplied. This aligns with the literature finding that fish is sold mainly on local markets (Ba et al., 2017; Dème et al., 2012; Failler, 2014). *Sardinella aurita* is an important consumption good for these local markets, and consumers respond to quantity changes. Furthermore, the price elasticity of demand is found to depend negatively on population density ( $p = .003$ ). This is sensible, as population density can be taken as a proxy for the size of the market. Larger markets, in turn, spur the supply of various different products at affordable prices, and reduce the consumers dependence on this particular fish. We assume that a linear time trend affects prices. Our empirical estimates show that prices are subject to a monthly positive linear time trend of 0.2% ( $p = .076$ ).

The harvesting technology is modeled as a constant-returns-to-scale Cobb-Douglas function from a capital-labor-composite and fuel. This means that fishers can substitute between fuel, capital and labor: If one of these inputs becomes more expensive, the fisher is able to partly replace it by other in-

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<sup>6</sup>These are monthly regional observations between 2009-2013 with few, unsystematic gaps.

puts<sup>7</sup>. Harvest production is assumed to depend positively on biomass. At larger biomass values, catches easier, as fish are easier located. The “catchability” parameter is used for scaling. A linear time trend on catchability reflects unobserved changes over time. Monthly dummies<sup>8</sup> are introduced to represent regular harvest seasonality, for example due to biomass growth, northwards stock migration in summer and cultural events that impact fishing (Corten et al., 2013; Thiaw et al., 2017; Zeeberg et al., 2008). Moreover, harvest success depends on climate variables, which we assume to enter as an exponential function, where the exponent is made up of linear and quadratic terms of climate variables.

We infer the following results from estimation: The output elasticity of the capital-labor composite is 0.815 ( $p < .001$ ). The resulting output elasticity of 0.185 for fuel means that fuel expenses make up for 18.5% of total fishing cost. Harvest production also depends on biomass at an estimated elasticity of 0.222 ( $p = .002$ ): Harvest increases in biomass, but the elasticity is rather small, as should be expected for a schooling fishery. Fish are easier located at a larger biomass, but as fish form schools, this effect is comparatively weak: Once a school is located, a large catch can be made without searching further. We estimate a positive linear time trend on catchability at a monthly rate of 0.9% ( $p < .001$ ), which we interpret to reflect technical

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<sup>7</sup>Several estimation studies agree that substitution possibilities exist in fisheries, such as Bjørndal (1989); Campbell (1991); Comitini and Huang (1967); Squires (1987); Valle et al. (2003). We choose a substitution elasticity of one to keep the model simple and tractable.

<sup>8</sup>One dummy variable is used per month, that equals one if the observation has occurred in the respective month, and zero otherwise. Its coefficient thus measures the impact on the outcome variable that stems from the time in the year when the observation occurs. For example, if a certain cultural event takes place each December that keeps fishers from harvesting, the use of monthly dummies would show a negative coefficient for the December dummy.

progress. Furthermore, we estimate monthly dummies and find that catch productivity is highest in spring and winter, and lowest in late summer. Monthly dummies are all significant at least at the 10% level ( $p \leq .064$ ).

To estimate the influence of climate variables on the catchability, we tested several specifications including sea surface temperature (SST), wind speed and direction, as well as precipitation. We refer the reader to the supplementary material for robustness checks (B.2). An important determinant of catchability is the SST. We find a non-linear dependence with a peak at 25.4°Celsius, a threshold which is usually crossed between May and June, with  $sw_t = 1.276$  ( $p = .002$ ) and  $sw_{t2} = -0.025$  ( $p = .005$ ) respectively. This is in line with the literature that finds a nonlinear dependence and optimal catch temperatures between 21 and 27°Celsius (Bacha et al., 2017; Diankha et al., 2015; Zeeberg et al., 2008). The stock shifts inshore in spring, when upwelling recedes and the temperature rises. The earlier this occurs, the earlier will fish be within easy catching distance (Brochier et al., 2018). When the temperature becomes too high, *Sardinella aurita* migrates northwards and out of immediate reach (Thiaw et al., 2017). Other climate impacts were not found to be significant.

According to model assumptions, fishers minimize costs subject to the prices for capital, labor and fuel. Capital and labor are supplied on local markets and are not perfectly malleable following Quaas et al. (2017) and our findings in the previous dissertation chapter. Hence, we assume increasing and convex iso-elastic inverse supply functions: In equilibrium, wages and the cost of capital increase with the amount of capital and labor used by the fishery. Fuel supply is perfectly elastic, prices are determined on the world market. We specify the resulting equilibrium cost function to be quadratic, following Arnason et al. (2004) and our findings in the previous

chapter of this dissertation (see the supplementary material, section B.2, for robustness). Fuel prices already explain a large part of the strong cost trend found in previous literature (Ba et al., 2017). A linear cost time trend is added to include remaining unobserved trends in factor prices and the size of factor units. The trend parameter is estimated to be positive at the 1% level ( $p = .010$ ). Net linear time trends in total, ceteris paribus, lead to an increase in fishing pressure of a monthly 0.8–1.0%, a result which however is pitted against rising fuel prices, market development and changing climate conditions. With continued market development, equilibrium harvest becomes more sensitive to input changes, particularly biomass. As consumers become less dependent on the fish supply, prices remain stable across large ranges of biomass. The cost reduction effect of a larger biomass becomes more important in relative terms. For the subsequent simulation, we need to model how population density as well as fuel prices develop in the future. Data on population density as described above and data on Brent oil prices, available from the U.S. Energy Information Administration (EIA, 2018), are used to estimate linear trends into the future. Afterwards, the trend parameters are assumed to decline linearly over a period of twenty years, as is standard for economic models, e.g. DICE (Nordhaus, 1993). For population density, we observe lower growth rates for more dense regions, as is in line with the decreasing UN population projections (United Nations, 2017). We also observe a lower productivity trend rate for the longer time horizon (see B.2) and a decreasing trend in energy prices worldwide.

Important model dynamics, as by our empirical results, can be summarized as follows:

Climate enters the economic model in two ways: It affects the growth of the stock and changes the amount of fish that can be harvested sustainably.

Higher stock levels decrease harvesting costs. Secondly, SST has a nonlinear, convex impact on harvesting costs, as it affects the spatial distribution of the stock. An increase in SST can thus increase the propensity to over-fish.

A higher fuel price leads to a steeper equilibrium cost curve and thus lower fishing pressure. In contrast to capital interest and wages, fuel prices are independent from the fuel quantity used by the fishery. This leaves the fishery particularly sensitive to fuel price changes. An increasing fuel price pushes downwards the curve that defines harvest as a function of the stock and thus reduces over-fishing. For a varying stock growth curve, this means that high growth years are allowed to cushion against following low growth years. Under low fuel prices, the fishers would immediately catch more, thus swiftly lowering the biomass. Varying both climate models and fuel price trend sheds light on the interaction between the two, as adaptation takes place. The system is less susceptible to climate impacts under high fuel prices, as they have a relative dampening impact on biomass and SST induced changes in the cost function. In summary, we expect to find that abolishing fuel subsidies will prove beneficial for the sector.

### **2.3 Climate projections**

High uncertainty exists with respect to reanalysis products and bio-geochemistry effects of coastal warming (Barton et al., 2013; Cropper et al., 2014; Ndoye et al., 2014; Sydeman et al., 2014). For example, while climate models generally agree that sea surface temperatures will rise throughout the 21st century, the extent of this rise varies among them. To take this model uncertainty into account, we use the output of two different Earth System models with two different formulations each to investigate the consequences the model spread has for artisanal fisheries. This comparison also allows us to ana-

lyze the importance of certain traits and differences for the fishery. The use and comparison of different climate models can improve the overall understanding of climate impacts and the variability of outcomes, as weaknesses are partly compensated for and greater reliability is achieved (Fraedrich and Leslie, 1987; Fritsch et al., 2000). Two of our projections (ECE-o and ECE-bc) are descended from the EC Earth model. The two others (NESM-o and NESM-bc) are based upon the Norwegian Earth System Model (NorESM). ECE-o and NESM-o are the original model versions, whereas ECE-bc and NESM-bc have been bias corrected<sup>9</sup>. All models use the representative concentration pathway (RCP) 8.5 as basis for radiative forcing, i.e. a business as usual continued forcing.

All four projections show a systematic bias to observed values of SST and wind-stress partly attributable to initialization in the 19th century. We use a standard offline nudging approach (e.g. Hawkins et al., 2013; Huntingford et al., 2005; Staffell and Pfenninger, 2016) for each climate scenario and apply constant monthly factors directly on the data. The coefficients are estimated through a regression model to fit the ERA reanalysis data used to estimate the biological and economic parts. The proportional approach outperforms an approach of adding a constant in our case. The fit is better for SST than for wind stress, as the SST development is far more systematic.

In table A.6 in the appendix, we compare the four projections concerning mean, trend, standard deviation and cyclical behavior of key weather impacts. On average, both winter and fall upwelling show a slight decrease over time for all four models, and are predicted to be stronger under NESM-o and

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<sup>9</sup>For ECE-bc, bias correction was achieved through adaptation of the ocean mixing parameter in the ocean model part. For NESM-bc, bias correction was applied by replacing SST from the ocean model part with anomalies before running the atmospheric model, and vice versa with wind stress. The estimated bias was projected into the future.

NESM-bc, than under ECE-o and ECE-bc. All mean values for winter upwelling for the period 2014–2079 lie below the average observed value during the estimation period (2001–2013). The upper level of the 95% confidence interval falls below the maximum observed value. For fall upwelling, only NESM-o and NESM-bc averages lie above the estimation period mean. For these two, the 95% confidence interval falls fully within the span of observed values.

A strong upward trend in SST is evident in all four projections (Figure 2). Scenarios ECE-o and ECE-bc feature a higher average temperature than NESM-o and NESM-bc in particular after 2030. They also show a higher variability in yearly means. The difference between warm and cold years is more pronounced. In addition, the seasonal cycle amplitude as well as the pertaining standard deviation are larger under ECE-o and ECE-bc.

## 2.4 Simulation strategy

We run the simulation from the year 2014 until the year 2079 or alternatively until the fishery collapses. To account for catches from other, mostly artisanal, fleets, we multiply the modeled Senegalese purse seine catches by a factor of 1.083, estimated from historical averages. We use a monthly time step, linearly interpolating fish population growth (which is estimated based on yearly data), including the stochastic term.

To evaluate policy alternatives, we consider two scenarios. The development of the mean annual fuel price over time for each of the scenarios is shown in Figure 3. The first is the business as usual case (BAU). A proportionate subsidy of 30.7% (Seck and Sy, 2008) in form of tax exemptions forms the most important part of subsidies (Ba et al., 2017; Sumaila et al., 2008) since the 1960s. The second scenario considers the case where the

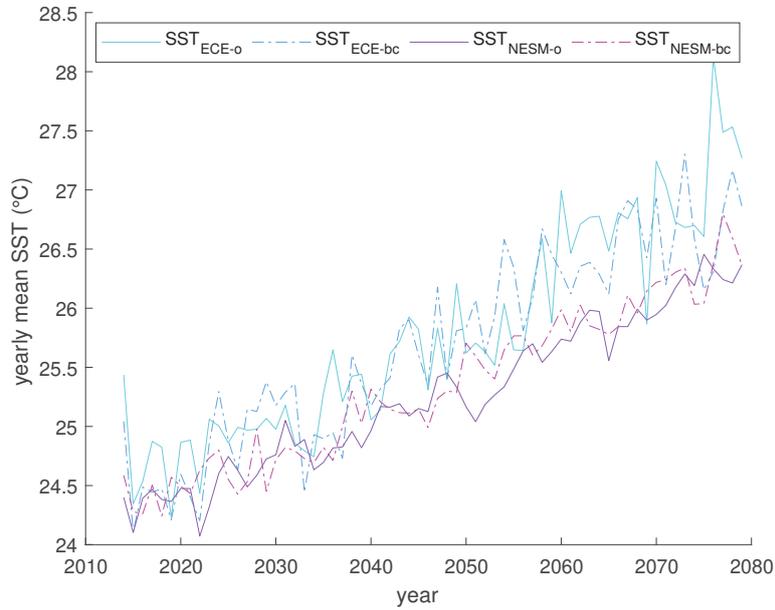


Figure 2: Mean yearly SST over time for different climate models

de-tax rate is linearly decreased over fifteen years until subsidies are fully eliminated (“melt-down”, md), which thus allows for a gradual transition for fishers and consumers. The price reaches its plateau in 2034, but its level is about 600 FCFA higher under the the reform scenario than under BAU.

Below, we first take a closer look at changes in stock growth and the results from spatial stock distribution on catchability. Afterwards, we analyze the model behavior at mean growth and harvest pressure, and take a closer look at how the equilibrium between the two changes over the decades. This allows us to compare the effects of climate projections on the fishery for a situation with a stable climate i.e. disregarding short-term variability. We proceed to analyze the dynamic system and focus first on the sustainability of the fishery and the propensity for stock collapse. We then turn to the

analysis of welfare effects. Subsequently, we explore the effects of abolishing fuel subsidies on sustainability and welfare.

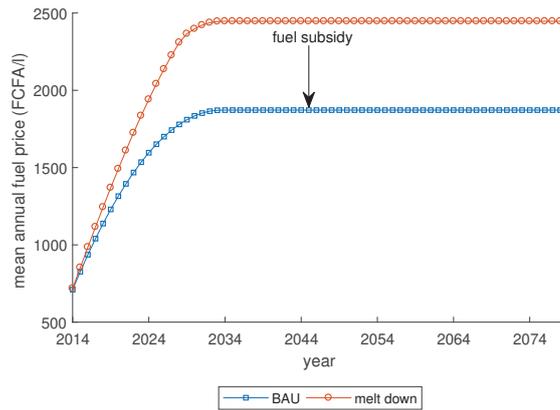


Figure 3: Mean annual fuel price development under different fuel price scenarios

### 3 Results and Discussion

#### 3.1 Biological processes and catchability under different climate models

In section 2.3, we discussed that both winter and fall upwelling show a slight decrease over time for all four models, and are predicted to be stronger under NESM-o and NESM-bc than under ECE-o and ECE-bc. The decrease in winter upwelling is beneficial for stock growth, while a decline in fall upwelling is harmful. The overall resulting natural growth rate development is shown

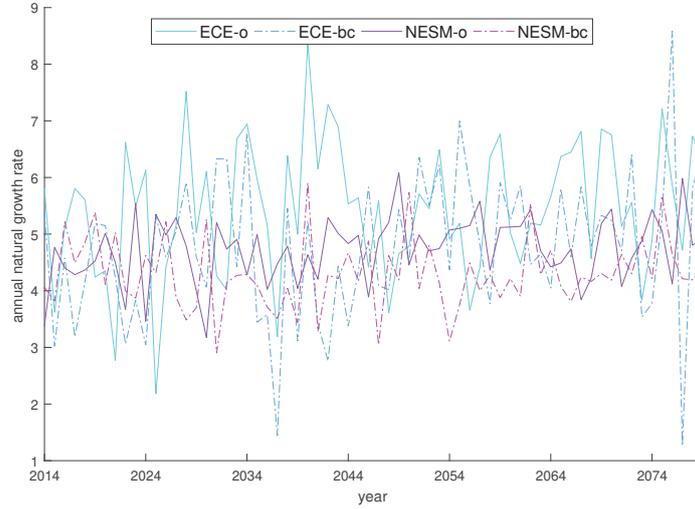


Figure 4: Annual climate affected natural growth rate  $r + f(UP_y)$  for different climate projections

in Figure 4. Clearly, its variability is higher under ECE-o and ECE-bc for both seasons, which is in line with the higher upwelling variability. Average system productivity is highest under ECE-o. It is lowest under NESM-bc, in particular due to the second half of the time horizon. We see an upward trend for ECE-o and ECE-bc. In the other two projections, the natural growth rate shows no detectable trend, however, a distinct dip is visible in the medium term between 2036-2057 under ECE-bc.

SST and monthly dummies enter the harvest function in a jointly multiplicative term. Hence, the SST effect on harvest pressure is strongest during the high season between February and May. These months, especially April and May, have a particularly high catchability also due to biological processes uncontrolled by SST. Figure A.3 in the appendix shows the development of harvest pressure over time for four exemplary months. During the

high season, the fishery becomes cheaper over time, as the SST approaches the optimum temperature. The fish remain in the close-to-shore area for a longer period than before, where they are easily caught. Between June and December, the temperature increase leads to a decrease in catchability from 2040 on-wards under all climate projections. Fish leave the close-to shore area slightly earlier than before. However, these months are generally less important for the fishery anyway. For both periods, the impact is stronger for ECE-o and ECE-bc, as is the variability. Overall, we see a severe increase in catchability induced by the SST trend. Towards the end of the time horizon, this trend is either approximately stable (ECE-bc, NESM-o, NESM-bc) or reversed (ECE-o), when SST lies above the optimum point already during spring. Then, the Senegalese waters finally become too warm for the species, that would permanently relocate northwards. These results are summarized as follows.

**Result 1.** *The impact of upwelling on stock growth is projected to remain largely unchanged compared to historical values. A slight increase is anticipated under ECE-o and ECE-bc. The most important climate impact over time is exerted by SST, that drives fishing costs downwards during spring.*

NESM-bc features a comparatively high total harvest pressure over the whole time horizon. At the beginning of the time horizon, yearly harvest pressure is also high under ECE-o, and in the medium term, ECE-bc shows the highest harvest pressure. Under NESM-o, harvest pressure is consistently low.

Our model includes additional factors that impact the harvest curves. Market development provides increasing substitution possibilities for consumers. As a consequence, equilibrium harvest becomes more sensitive to the stock level, leading to a steeper harvest function early in the time hori-

zon and a lower equilibrium stock value. In addition, an positive trends in fuel prices and technological development combine to a net low positive trend, that strengthens the upward shift in harvest functions until 2033. By our assumptions, these trends dwindle to zero until 2033.

**Result 2.** *In addition to climate impacts, the propensity to over-fish is increased by technological development. Market development leads to a lower equilibrium stock. Increasing fuel prices only insufficiently offset the other impacts.*

### 3.2 Bioeconomic equilibrium analysis

We analyze the model behavior at mean growth and harvest pressure, and take a closer look at how the equilibrium between the two changes over the decades. This allows us to compare the effects of climate projections on the fishery for a situation with a stable climate i.e. disregarding short-term variability.

Figure 5 shows yearly total harvest as a function of biomass, as well as biomass growth, for exemplary years under ECE-o and BAU. We choose growth with a year lead on harvest, because we modeled growth in year  $y$  to depend on spawning stock biomass one year before that. The interpretation of the graph is as follows: If the growth function lies above harvest, the stock grows net. In a non-variable, deterministic model, the rightmost interception of the two would mark the dynamically stable positive equilibrium (see Figure 5) where harvest is exactly offset, such that fishers in the next year would be able to benefit from a stock exactly as large as in the year before. For harvest years 2013 and 2078, such a point exists. For 2047, though, the harvest curve lies far above the growth curve. The only stable equilibrium in such a graph would be a biomass of zero. If this were the case for longer than

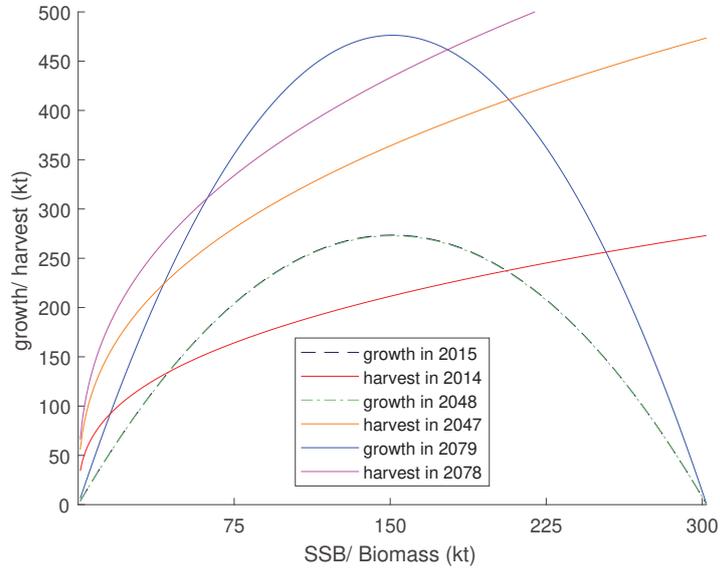


Figure 5: Annual harvest and biomass growth as a function of (spawning stock) biomass for exemplary years under ECE-o.

a few periods, biomass would collapse in the deterministic case. Note that these are only singular, exemplary years though. Due to climate variability, they can not be taken as a reference for whole periods.

In Figure 6, we show how this equilibrium changes over time for all four climate projections and under the two fuel price scenarios considered. Consider first the black crosses that indicate the BAU case where fuel subsidies are maintained. A downward trend in equilibrium biomass is recognizable under all four climate projections. The number of years where fishing is unsustainable, marked with an equilibrium value of zero, also increases. Under ECE-o, few such years alternate with relatively favorable years and equilibrium biomass around 200 kt. For NESM-bc, after 2028, the fishery sees only very few sustainable years. After roughly 2030, a dangerous period arises

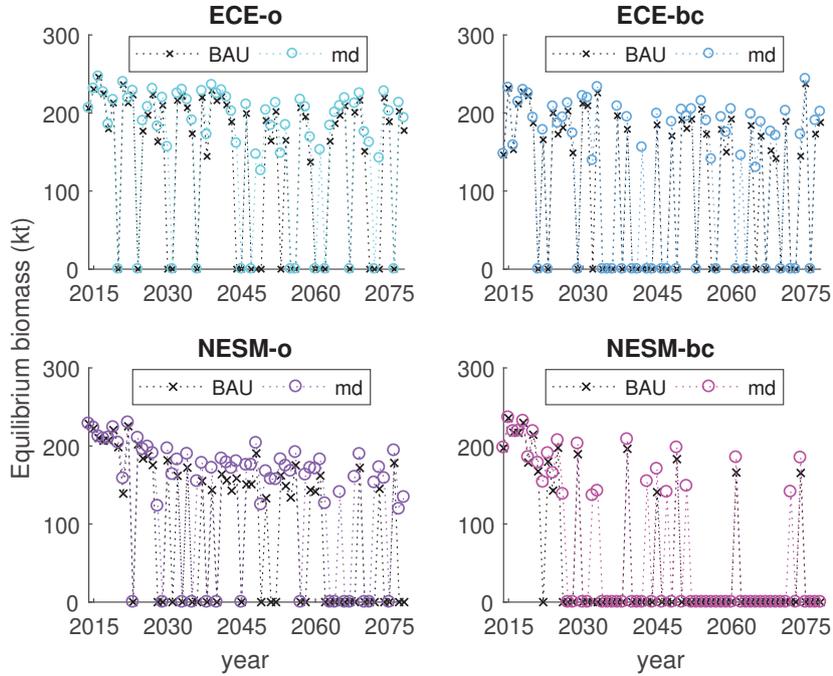


Figure 6: Development of the stable equilibrium over time under different climate projections and fuel subsidy scenarios (business as usual, BAU and melt-down, md).

under NESM-o and ECE-bc, where over-fishing and extinction is likely. This development only ends late in the time horizon, when the SST is too high throughout the year and harvest decreases again. In the long term, unsustainable harvesting years prevail for NESM-o, NESM-bc and ECE-bc.

**Result 3.** *The catch potential increases through higher growth and lowered costs through the SST impact. Reduced costs increase future over-fishing. Its impact outruns the incipiently favorable climate change effects in three of four projections under BAU fuel subsidies. The fishery remains sustainable under the ECE-o climate projection.*

If fuel subsidies are (gradually) abolished, harvest pressure is lower, such that a higher equilibrium biomass results (see Figure 6). Unsustainable years occur less often, in particular under NESM-o. Ensuring the survival under ECE-bc and NESM-bc will prove very difficult in the medium term, when productivity is still relatively low and harvest pressure high, and even under the melt-down scenario, numerous unsustainable years arise.

### **3.3 Stochastic futures: sustainability under business as usual fuel subsidies**

The deterministic, average results are subject to additional pressure from climate variability. One particular consequence of variability is a greater propensity to collapse. More variable climate conditions, such as under ECE-o and ECE-bc, may lead more often to situations where stock survival is threatened. This depends in particular on the bio-economic equilibrium biomass around which the actual stock fluctuates driven by the variable climate. If this equilibrium stock size is large, it works as a strong buffer against climatically unfavorable years.

To analyze the systems sustainability, we compute the mean time of survival. This standard measure in population viability analysis evaluates stock persistence facing perturbations (e.g Lande, 1993; Leigh, 1981; Palamara et al., 2013). For each combination of climate projection (4) and fuel subsidy scenario (2), we run the model 1000 times, over which we compute means to capture that the fishery is unequally variable.

Figure 7 shows one scatter plot for eight different models – the combination of four climate projections and two policy scenarios. The mean time of survival is indicated on the y-axis. To compare welfare across climate projections, we use the mean net present value (NPV), indicated on the x-axis.

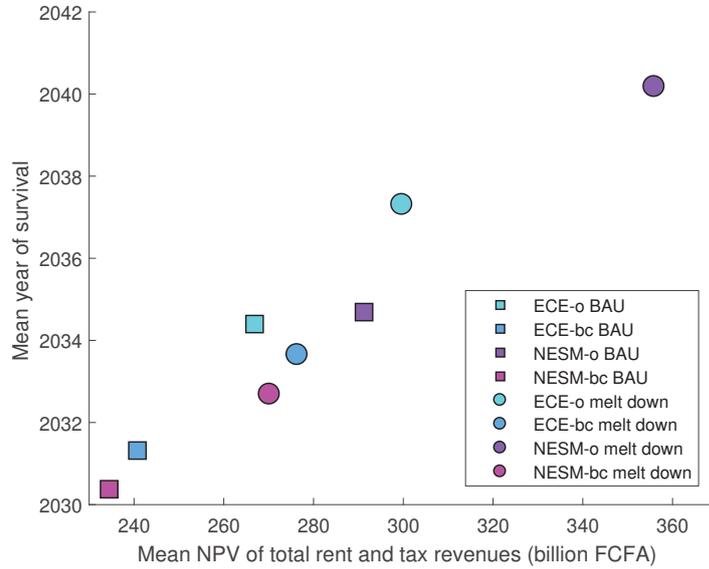


Figure 7: Mean survival horizon and value of the fishery under different climate models and policy scenarios. Colors represent climate projections, shapes represent fuel subsidy scenarios.

The welfare impact will be discussed in the next subsection, 3.4.

Colors indicate the underlying climate projection. Shapes indicate the fuel price scenario. Consider the squares that show how the fishery performs under different climate scenarios in the business as usual case, where fuel subsidies are maintained. As expected, variability under ECE-o is so high that the fishery turns out to under-perform. The fishery can not reap the whole benefits of its favorable climate prediction. Short periods of high biomass alternate with long periods of slow replenishment. This dampens mean survival relative to the underlying high productivity. NESM-o becomes steadily more unsustainable in the medium term, leading to extinction around 2035. Under ECE-bc, this effect also plays a role, in particular in the early years.

Variability is high, which contributes to a comparatively low sustainability even before 2030. During the early 2030s, the fishery is particularly vulnerable due to its low productivity and high harvest pressure. During this time, variability in almost all runs eventually leads to extinction. Mean survival under NESM-o is in line with the deterministic equilibrium. Variability is too low to have a substantial impact here. Between NESM-o and ECE-o, variability is a game changer: NESM-o now outperforms ECE-o, even though the latter showed a superior equilibrium sustainability. NESM-bc provides the least favorable climate prediction. Nearly from the start, the low productivity is unable to counter the steadily increasing harvest pressure, and the species goes extinct early on. Therefore, variability is of little relevance.

**Result 4.** *The BAU scenario is not dynamically sustainable under any of the four climate projections. The fishery on average survives only until 2030–2035. To ensure greater sustainability, resource managers ought to consider policy actions. Variability can be a game changer concerning the relative performance under different climate projections.*

We can now also measure climate uncertainty, which we define as the spread in outcomes due to different climate projections. Between NESM-o and NESM-bc, climate uncertainty amounts to 4.5 years of mean survival times, i.e. 26% of NESM-bc's value. The two bias-corrected projections, that were specifically adapted to better reproduce the observed climate, are the two with the lowest mean survival time. This indicates that if a study relies only on original models, outcomes may be upward biased.

### 3.4 Stochastic futures: welfare impacts under business as usual fuel subsidies

Total sector benefits include the fisheries role as a safety net, i.e. income provision (producer surplus or “fisher surplus”, FS), and its direct contribution to food security (“consumer surplus”, CS). Consumer surplus is the excess willingness to pay for fish above the monthly equilibrium price. For our downward sloping demand curve in a digram with price on the y-axis and quantity demanded on the x-axis, it is the area below the curve and above the horizontal line drawn at the equilibrium price (see B.3). Fishers earn rents because of their role in providing capital and labor to produce harvest. Fishers surplus can be calculated by summing the areas below the equilibrium price and above the inverse supply curve for capital and labor, respectively. Adding up fisher surplus and consumer surplus gives a welfare measure for food security, that takes into account the availability of substitutes, and thus changes in the fishers and consumers’ dependence on fresh *Sardinella aurita*.

To compare welfare across climate projections, we use the mean net present value (NPV)<sup>10</sup> of total rents in 2014<sup>11</sup> generated in the fishery at an assumed discount rate of 3%. For the scenarios with reduced subsidy, we add the savings of tax revenue. We again compute means over 1000 runs.

We calculate an average fisher surplus of 8.77 billion FCFA in 2014 and a consumer surplus of 5.47 billion FCFA. At a typical price of 1,145 FCFA for a 5kg-basket of local grains (see the previous dissertation chapter), this

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<sup>10</sup>This standard economic measure computes the sum of all future benefits in monetary units and weighs future benefits by a discount factor to capture that money that is immediately available is worth more than money available later in the future.

<sup>11</sup>All rents are reported in terms of 2014-based FCFA.

amounts to a yearly 946 baskets for each of the roughly 8100 fishers involved, and 1.96 baskets per inhabitant of the coastal region studied (2.4 million, about 21% of the total Senegalese population). These baskets constitute an additional gain for the fishers (consumers), compared to a situation where the resource would not be available to them and they would have to work in different sectors (consume different products). Using observed harvest and prices, we calculate a mean yearly total rent value of 14.97 billion FCFA for 2004-2013. These compare well with the summed benefits from 2014, i.e. 14.24 billion FCFA. We conclude that our simulation produces plausible results.

In Figure 7, the mean NPV is indicated on the x-axis. Again, we first concentrate on the squares, i.e. the business as usual case. High variability under ECE-o also has a dampening effect on rents. Firstly, this is a direct consequence of shorter survival times. Secondly, ECE-o's survival year profile is right-tailed: Extinction is most likely at the beginning of the time horizon, when harvest curves are flattest. The biomass usually goes extinct early-on, and the relatively high sustainability is a consequence of few runs with very long survival. Due to discounting, the extra rents per occasional additional survival year contribute only a small amount to the NPV. In particular, the yield is lower than under NESM-o, which is less productive, but very stable. Yields are very low under ECE-bc and NESM-bc, i.e. the two bias corrected models. The low productivity in NESM-bc leads to a lower potential NPV. Over-fishing and low sustainability in both ECE-bc and NESM-bc also translate to low expected rents.

Using the range of total rents as a metric, climate uncertainty amounts to 57 billion FCFA, which constitutes 24% of the lowest NPV of total rents. Fishers' rent difference accounts for 64% of this gap. We conclude that

the effect of climate uncertainty is moderate. This is a direct consequence of low sustainability: Short survival times mean that differences in climate projections in the medium-term rarely affect rents, because in most cases, the resource by then has gone extinct. Figure 8 shows the distribution of benefits between fishers and consumers for the eight models considered. The effect on income security is larger than on food security. This results mostly because the model predicts that markets develop and consumers' dependence on fresh *Sardinella aurita* declines. In relative terms, consumers mean surplus share is highest under ECE-bc, but the difference across models is exceedingly small.

**Result 5.** *The sectors contribution to food security under BAU as measured by the mean NPV of fishers producer and consumer surplus amounts to 232–291 billion FCFA. One third of this can be attributed to a direct contribution from consumer surplus, and two thirds to an indirect contribution via the sectors' function as an income safety-net. The spread between climate projections is moderate at 57 billion FCFA. This is a direct consequence of low sustainability.*

To separately analyze changes in annual rents under climate change and to complement literature findings, we also compare un-discounted rents in different decades for each model (see also Table 7 in the supplementary material). Climate change is costly under projections ECE-bc and NESM-bc, as well as for the NESM-o BAU scenario due to actors' adaptation. For the whole Senegalese artisanal fishery, Lam et al. (2012) suggested a loss of 13% in jobs until 2050. Comparing between 2014-2023 rents and 2034–2043 rents, we see changes between -97% and 52% under BAU. Mean losses lie at 27% when fuel subsidies continue. This result only holds due to the (small but positive) possibility of very large benefits under ECE-o. On average, the resource will have gone extinct by 2050 in all eight model-scenario-combinations consid-

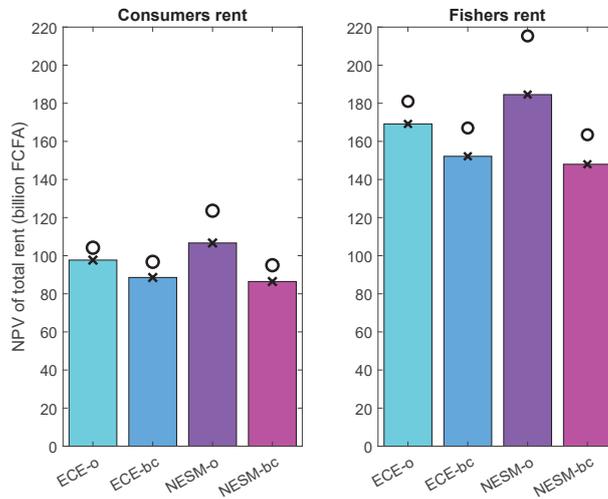


Figure 8: NPV of total rents per model (Bars represent rents under BAU. Shapes represent fuel subsidy scenarios: Crosses: BAU, circles: melt-down.)

ered, such that the potential mean yield for 2054-2063 equals zero under all projections but ECE-o. The risk is substantial.

**Result 6.** *Under three of four climate projections, the sectors yield potential is reduced in the medium- and long-term. Until 2043, mean rents are reduced by more than a quarter.*

### 3.5 Welfare impacts if fuel subsidies are abolished

In Figure 7, the circles mark the melt-down subsidy reform case. This is the outcome if fuel subsidies were gradually decreased and finally fully abolished in 2030. In the most extreme case, NESM-o, this increase reaches 5.4 years mean survival time increase or 62 billion NPV of total rents. It can increase the BAU value by 21%. Between 11.7 and 17.0 billion FCFA of public funds

(around 4.5% of total rent NPV) are additionally generated in this scenario.

Thus, not only are fuel subsidies expensive for tax payers, they also reduce welfare in total. If fuel subsidies are abolished, climate change may on average even turn out slightly beneficial concerning un-discounted rents, i.e. the sectors current value yields (see Table 7 in the Appendix). While they may achieve a redistribution of rents from fishers to consumers, this effect is small and dearly bought with an overall lower consumer rent, as visible in Figure 8. The difference to the x-axis-values in Figure 7 amounts to the discounted public funds that are additionally generated through the tax. The WTO discussion argument that fuel subsidies could help alleviate poverty and maintain food security does not hold for the studied fishery.

**Result 7.** *If fuel subsidies are abolished, the NPV of total rents increases regardless of the climate projection. Abolishing fuel subsidies also largely maintains the current distribution of rents between consumers and fishers.*

The beneficial effect of removing fuel subsidies is not equally large across climate projections. Gains due to increased survival time are large for all scenarios, but largest under NESM-o. Under NESM-o, the abolition of fuel subsidies suffices for the resource to survive for a substantially longer amount of time. For NESM-bc and ECE-bc, policy gains are positive, but the impact is not large enough to survive the projected short run increase in harvest pressure. Rent gains are mostly driven by increased survival time. Under ECE-o, the mean survival year profile, compared to the case with fuel subsidies, is more right skewed than before. Therefore, rent gains per additional survival year are low. In summary, if the climate projection is associated with substantial extinction risks, abolishing fuel subsidies will not turn the tide. If however the extinction risk only results from a relatively short unsustainable period of over-harvesting or from moderate variability, fuel subsidies

abolition can help to bridge these periods.

The rent difference between policy scenarios varies between 33 and 62 billion FCFA, that is, 12-21% of the BAU rent value. Even larger, however, is the uncertainty stemming from the different climate projections, in particular since outcome uncertainty is increased through fuel subsidy reform. Differences in climate models now translate into larger differences in ensuing rents, i.e. up to 84 billion FCFA between the melt-down case under NESM-bc and NESM-o. This constitutes 31% of the lower total NPV. Climate characteristics, in particular the variability and the lower end of the variation, govern the responsiveness of the system to an abolition of fuel subsidies. The increase in uncertainty mostly stems from larger differences in survival times, and longer survival in general. The longer the time of survival, the more climate change comes into effect, leading to greater uncertainty. The counteracting force, namely the dampening effect of larger fuel prices on climate impacts, is weak.

**Result 8.** *Differences in climate projections lead to a spread in the welfare outcome that amounts to more than double the spread between fuel scenarios.*

The main effect of climate change concerns the spatial stock distribution: Biomass becomes more vulnerable to Senegalese purse seines over a certain time horizon, because the fish spend more time in the close-to-shore area. Abolishing fuel subsidies could buy time to bridge this transition period. The effectiveness of this measure depends on the climate development. It would be particularly effective under low variability and a weak SST trend. If either variability or the SST trend proves too strong, this measure is insufficient. A proper resource management system that goes beyond the mere abolishment of subsidies, such as a binding limit on annual harvest, would be needed to ensure sustainability in the long term. Still, there is good news: Productivity

is still high under all projections but NESM-bc, such that rents and yields remain high if a proper management is installed. However, if the spatial stock redistribution effect crosses national boundaries, such a management would require multinational cooperation.

**Result 9.** *Abolishing fuel subsidies can buy time to counter a dangerous decrease in harvesting costs associated with increased over-fishing. A proper resource management system is needed to ensure sustainability in the long term.*

## 4 Conclusion

Our results can inform policy making, as they shed light on the effect of climate change and counteracting measures while incorporating endogenous adaptation of actors. Seemingly beneficial climate impacts, such as a cost reduction due to climate-induced movement of the fish stock, may turn out negative as they increase the propensity to over-fish. Future market and factor price development is part of our analysis. This offers insights into possible policy responses. It also reveals the role of major drivers of climate change adaptation and shows that adaptation can also dampen climate change impacts on the fishery, such as through a downward sloping inverse demand curve combined with market development. Moreover, our findings reveal a large uncertainty of outcomes with respect to the different climate projections, even when qualitative patterns of the climate trajectories are preserved and the differences seem small in the original climate data. In addition, we explicitly show the dramatic extent to which the range of outcomes under different climate projections is affected by the policy choice.

## A Appendix

### A.1 Development of *Sardinella aurita* abundance in Senegalese waters

Figure A.1 shows abundance of *Sardinella aurita* in Senegalese and Gambian waters in the fourth quarter of each year, as used in FAO working group stock assessments (Toresen et al., 2001, 2002; Krakstad et al., 2003, 2004, 2005, 2006). National surveys provide estimates for 2007-2009 (FAO, 2008, 2011a,b). Data points for 2010-2013 are own predictions as detailed in 2.1.

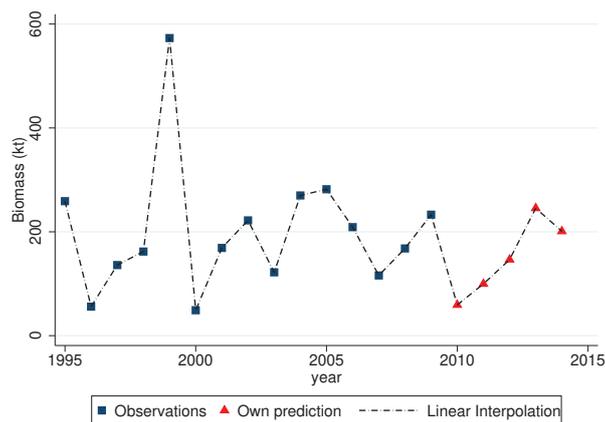


Figure A.1: *Sardinella aurita* abundance estimated by Nansen surveys and national surveys for the Senegalese and Gambian waters and own predictions

### A.2 Summary of the estimation data-set

Table 1: Summary statistics of the data-set used for estimation

	Mean	Sd	Min	Max
Growth estimation (yearly, 1996–2009)				
Spawning stock biomass (kt)	199.50	129.79	49.00	573.00
Total harvest (kt)	181.85	51.57	121.85	272.58
Biomass growth (kt)	179.99	218.89	-402.15	562.19
Windstress CUI (winter) ( $\frac{m^3}{s}$ per m coastline)	0.32	0.04	0.25	0.41
Windstress CUI (fall) ( $\frac{m^3}{s}$ per m coastline)	0.19	0.03	0.12	0.24
Economic estimation (monthly, 2001–2013)				
Regional Landings (t)	3,768.30	3,583.12	0.90	19,144.76
CPUE (t/DAS)	2.90	2.56	0.00	15.36
Fish price (2010-level FCFA/kg)	131.71	160.41	16.58	2,556.85
Fuel price (2010-level FCFA/l)	485.38	112.26	208.18	731.36
Population density (# of people/1000 * km <sup>2</sup> )	3.34	5.46	0.24	14.02
SST (° Celsius)	24.08	3.00	18.53	28.63

### A.3 Biomass growth estimation: Details and robustness

We estimate the effect of environmental variables on yearly stock growth for *Sardinella aurita* found within the Senegalese and Gambian exclusive economic zones,  $x_y$ . We use annual biomass growth  $g_y$  defined as the sum of the biomass difference between consecutive years and harvest  $H_y$ , as dependent variable. Biomass growth is positive except in year 2000. We interpret the negative value in 2000 as an overshooting of biomass over its carrying capacity under optimal conditions, which is remedied in the following year. Overshooting of carrying capacity can happen in populations of small pelagic fish with short life span and high recruitment. For species as affected by changing environmental conditions, this is to be expected. We model reproduction using the standard logistic growth model with spawning stock biomass (SSB)  $x_{y-1}$ , carrying capacity  $K$  and natural reproduction rate  $r$ .

The growth function is estimated as:

$$g_y = x_y - x_{y-1} + H_y = (r + f(UP_y)) x_{y-1} \left(1 - \frac{x_{y-1}}{K}\right) + \varepsilon^s \quad (3)$$

where  $\varepsilon^s$  denotes the error term with normal distribution and standard deviation 80.29 kt. In the simulation, this will enter as a stochastic term.  $f(UP_y)$  denotes a linear sum of impacts, where various structures were tested. We considered alternative specifications with respect to lag structure, seasons, SST, an alternative upwelling index based on SST, and with respect to the size of the biomass or biomass growth of the Mauritanian stock group to check for migration flows. We also tested alternatives with weather impacts on the carrying capacity, but models with environmental effects on the natural growth rate generally performed better than models with environmental effects on carrying capacity  $K$ , or on the quadratic term in general.

Results are reported in table Table 2. As a robustness check, we present results for the model without climate impacts (column 1), as well as for the model that provided the best fit with respect to adjusted  $R^2$  and Bayesian information criterion (BIC). The final chosen model is presented in the right-most column. We include it here for easier comparison. The lower section includes marginal effects at means.

Both models presented below estimate a linear environmental impact on  $r$ . Note that in case the biomass overshoots the carrying capacity, this also means that environmental stressors increase mortality<sup>12</sup>. We interpret this as a situation where the favorable climate conditions also favor the predators' development. The inclusion of environmental variables increases model fit

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<sup>12</sup>We explored to what extent estimation results are driven by the negative observation of biomass growth in 2000. Results when this data-point is left out differ only slightly. Upwelling coefficients and carrying capacity become slightly larger.

by 28–30 percentage points in adjusted  $R^2$ .

The result for the intrinsic growth rate in the pure model  $r = 2.22$  is consistent with (Pech et al., 2001)’s results, who estimate  $r = 2$ , and  $K = 117kt$ . However, the estimated carrying capacity  $K = 419kt$  is  $> 3$  times the size estimated by them. Figure A.2 shows that the pure model underestimates growth at lower stock sizes and overestimates growth at larger stock sizes. It also fails to explain the substantial variation around the basic quadratic function.

In model 2, lagged spring wind-stress CUI and summer SST CUI<sup>13</sup> have a positive and significant impact on biomass growth. We interpret this as a positive impact on both fall and spring spawning cohorts, as primary productivity is higher. The baseline  $r$  is negative: If no upwelling occurs in spring and summer, natural mortality exceeds recruitment. A short simulation to test model performance (see Table 3.) reveals that biomass overshoots the carrying capacity early. Negative growth alone, even when disregarding harvest, then immediately outruns biomass and the stock goes extinct. We conclude that model 2 is not a good estimate for biomass growth.

Some studies discuss the influence of SST on recruitment success (Brochier et al., 2009; Diankha et al., 2015; Mbaye et al., 2015; Zeeberg et al., 2008). However, we do not find a particular impact. The influence of SST likely acts primarily through fish re-location (Diankha et al., 2018). The Mauritanian stock has a positive and significant influence on the pure growth function (model 1). Once climate is controlled for, this influence vanishes. Mauritanian biomass growth doesn’t significantly impact the growth of the Senegalese stock group.

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<sup>13</sup>Note that the definition of the SST CUI index leads to a negative sign if upwelling is positive and vice versa.

Table 2: Estimation results biological part (standard errors in parentheses)

Parameter	model 1	model 2	Chosen model
$K$	418.75*** (24.15)	290.99*** (13.29)	302.13*** (18.22)
$r$	2.22*** (0.42)	-4.06** (1.51)	6.77* (3.50)
$CUI_{Wspring,y-1}$		48.11*** (7.01)	
$CUI_{SSTsummer,y-1}$		-5.05*** (1.24)	
$CUI_{Wwinter,y-1}$			-27.29*** (6.08)
$CUI_{Wfall,y-1}$			30.41** (10.55)
$N$	14	14	14
adjusted $R^2$	0.64	0.92	0.92
$AIC$	185	165	166
$BIC$	186	167	168
Variable (mean)	Marginal effects at mean <sup>+</sup>		
$x_{y-1}$ (199.5kt)	0.10.	-1.39.	-1.21.
$CUI_{Wspring,y-1}$ ( $4.0 \frac{m^3}{s100m}$ )	..	30.17.	..
$CUI_{SSTsummer,y-1}$ ( $-11.56^\circ \frac{C}{10}$ )	..	-31.68.	..
$CUI_{Wwinter,y-1}$ ( $32.3 \frac{m^3}{s100m}$ )	..	..	-18.49.
$CUI_{Wfall,y-1}$ ( $19.0 \frac{m^3}{s100m}$ )	..	..	20.61.

<sup>+</sup>One unit change in variable leads to absolute change in growth of ... 1000 t.  
 \* p<.10, \*\* p<.05, \*\*\* p<.01

Table 3: Predictions of *Sardinella aurita* biomass development for observed harvest levels

year	$H_y$	model 1		model 2		model 3	
		$\hat{g}_y$	$\hat{x}_y$	$\hat{g}_y$	$\hat{x}_y$	$\hat{g}_y$	$\hat{x}_y$
2010	195.10	229.55	267.45	355.70	393.60	21.28	59.18
2011	224.68	214.62	257.40	-913.07	-744.15	265.21	99.72
2012	211.49	220.28	266.18	-11383.12	-12338.77	258.22	146.45
2013	144.62	215.39	336.95	-2.88E+06	-2.89E+06	243.64	245.46
2014	240.60	146.18	242.55	-6.79E+10	-6.79E+10	196.11	200.98

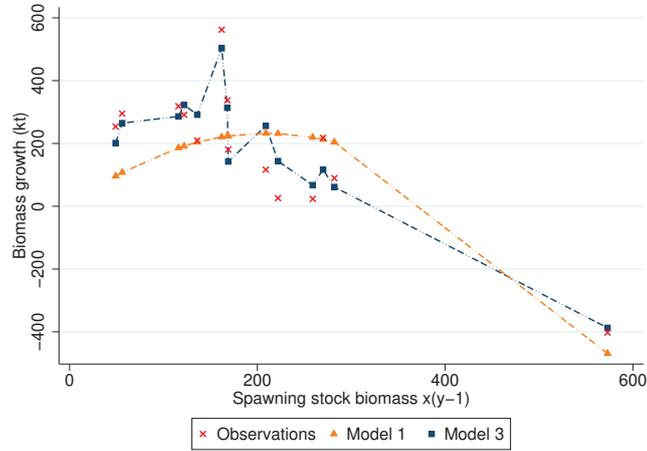


Figure A.2: Growth curves for the Senegambian *Sardinella aurita* stock group, models 1 and 3

#### A.4 Economic model: Technical details

Our economic study period runs from January 2001 to December 2013. In addition to yearly biomass data for 2001 – 2009, we also use our own stock assessment from section 2.1 for the years 2010 – 2013. The general time period  $t$  is one month. Part of the data is only available per year, denoted by subscript  $y$ . We use subscript  $m$  to denote a dependence on one particular month and subscript  $i$  to denote the region.

Harvest is produced from capital  $k_{it}$ , labor  $l_{it}$  and fuel  $f_{it}$  by the following nested Cobb-Douglas function:

$$H_{it} = q_i(m, W_{it}) x_y^x (l_{it}^\gamma k_{it}^{1-\gamma})^\varphi f_{it}^{1-\varphi} \quad (4)$$

with  $\gamma, \varphi \in (0, 1)$ . The technology exhibits constant returns to scale. Fish-

ers can substitute between fuel, capital and labor<sup>14</sup>. The stock elasticity of biomass (Clark, 1990)  $\chi > 0$  is expected to be positive and close to zero, since we model a schooling fishery.

Catchability  $q_i(m, W_{it})$  of the fish species depends on the month  $m$  and on environmental factors  $W_{it}$ . This defines the variability of the species vulnerability to purse seines, as well as the changes in the vertical and horizontal distribution of the fish. Monthly dummies, denoted by  $\delta_m$ , represent regular harvest seasonality. We assume that monthly dummies do not vary across regions in order to reasonably limit the number of parameters. For simplicity, we assume that all influences have a direct effect on catchability. In reality, some effects may exert their influence rather on factor cost directly. Catchability is assumed to be of the following form:

$$q_i(m, W_{it}) = q_{i0} \exp \left( \sum_{m=1, m \neq 9}^{12} (\delta_m D_m) + sw_t SST + sw_{t2} SST^2 \right) \geq 0, \quad (5)$$

where  $q_{i0}$  is the reference baseline catchability in September. According to our estimation, SST has a non-linear, concave influence on catchability, as  $sw_{t2}$  is estimated negative and small enough. Other weather influences, such as upwelling, precipitation, wind speed and wind stress, were not found not be significant.

Since data on fuel input is only available for the whole fishing sector, not for the purse seine fishery in particular, we use a dual approach with fuel prices instead. Fishers use the optimal amount of fuel by equalizing marginal

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<sup>14</sup>Several estimation studies agree that substitution possibilities exist in fisheries, such as Bjørndal (1989); Campbell (1991); Comitini and Huang (1967); Squires (1987); Valle et al. (2003). We choose a substitution elasticity of one to keep the model simple and tractable.

cost, i.e. the cost for one unit of fuel  $\Phi_{it}$ , and marginal revenue, subject to optimally chosen capital and labor amounts.

$$\frac{\partial p_{it} H_i}{\partial f_{it}} = (1 - \varphi) p_{it} q_i(m, W_{it}) x_y^\chi (l_{it}^\gamma k_{it}^{1-\gamma})^\varphi f_{it}^{-\varphi} \stackrel{!}{=} \Phi_{it} \quad (6)$$

$$\Leftrightarrow f_{it} = \left( \frac{\Phi_{it}}{(1-\varphi)p_{it}q_i(m,W_{it})} \right)^{-\frac{1}{\varphi}} x_y^\chi l_{it}^\gamma k_{it}^{1-\gamma} \quad (7)$$

Reinserting this into the harvest production function, and dividing by the capital labor composite  $l_{it}^\gamma k_{it}^{1-\gamma}$ , we can define productivity by the following catch per unit of capital-labor composite ( $CPUb_{it}$ ) function:

$$h_{it} = \left( (1 - \varphi)^{1-\varphi} q_i(m, W_{it}) \left( \frac{p_{it}}{\Phi_{it}} \right)^{1-\varphi} x_y^\chi \right)^{\frac{1}{\varphi}} l_{it}^\gamma k_{it}^{1-\gamma} \quad (8)$$

$$\Leftrightarrow CPUb_{it} = \left( (1 - \varphi)^{1-\varphi} q_i(m, W_{it}) \left( \frac{p_{it}}{\Phi_{it}} \right)^{1-\varphi} x_y^\chi \right)^{\frac{1}{\varphi}} \quad (9)$$

This expression will be used for estimation. However, in order to estimate the full system, we additionally need two equations concerning harvest and prices. To derive these, we start with the derivation of the cost function.

Fishers minimize total cost. They are price takers with respect to factor prices. The Lagrangian optimization problem and the first order conditions

for this minimization problem read:

$$L = w_{it}l_{it} + r_{it}k_{it} + \Phi_{it}f_{it} - \rho \left( q_i(m, W_{it})x_y^\chi (l_{it}^\gamma k_{it}^{1-\gamma})^\varphi f^{1-\varphi} - \bar{H} \right) \quad (10)$$

$$\Phi_{it} = \rho q_i(m, W_{it})x_y^\chi (1 - \varphi) (l_{it}^\gamma k_{it}^{1-\gamma})^\varphi f^{-\varphi} \quad (11)$$

$$w_{it} = \rho q_i(m, W_{it})x_y^\chi \varphi \gamma (l_{it}^\gamma k_{it}^{1-\gamma})^\varphi f^{1-\varphi} \frac{1}{l_{it}} \quad (12)$$

$$r_{it} = \rho q_i(m, W_{it})x_y^\chi \varphi (1 - \gamma) (l_{it}^\gamma k_{it}^{1-\gamma})^\varphi f^{1-\varphi} \frac{1}{k_{it}} \quad (13)$$

We derive the following factor demand expressions for fuel, capital and labor from the first order conditions:

$$k_{it}^D = \frac{h_{it}}{q_i(m, W_{it})x_y^\chi} \left( \frac{r_{it}}{(1 - \gamma)} \right)^{\varphi(1-\gamma)-1} \left( \frac{w_{it}}{\gamma} \right)^{\varphi\gamma} \left( \Phi_{it} \frac{(\varphi)}{1 - \varphi} \right)^{1-\varphi} \quad (14)$$

$$l_{it}^D = \gamma \frac{r_{it}k_{it}}{w_{it}(1 - \gamma)} = \frac{h_{it}}{q_i(m, W_{it})x_y^\chi} \left( \frac{r_{it}}{(1 - \gamma)} \right)^{\varphi(1-\gamma)} \left( \frac{w_{it}}{\gamma} \right)^{\varphi\gamma-1} \left( \Phi_{it} \frac{(\varphi)}{1 - \varphi} \right)^{1-\varphi} \quad (15)$$

$$f_{it}^D = \frac{h_{it}}{q_i(m, W_{it})x_y^\chi} \left( \frac{r_{it}}{(1 - \gamma)} \right)^{-\varphi(\gamma-1)} \left( \frac{w_{it}}{\gamma} \right)^{\varphi\gamma} \left( \frac{(\varphi)}{1 - \varphi} \right)^{-\varphi} \Phi_{it}^{-\varphi} \quad (16)$$

Inserting factor demand into  $C = w_{it}l_{it} + r_{it}k_{it} + \Phi_{it}f_{it}$  leads to a cost function that is linear in harvest and decreases in biomass:

$$C = \frac{h_{it}}{q_i(m, W_{it})x_y^\chi} \left( \frac{r_{it}}{(1 - \gamma)} \right)^{\varphi(1-\gamma)} \left( \frac{w_{it}}{\gamma} \right)^{\varphi\gamma} \left( \Phi_{it} \frac{(\varphi)}{1 - \varphi} \right)^{1-\varphi} \frac{1}{\varphi} \quad (17)$$

Thus, marginal cost equals average cost in terms of the fishers' supply decision. Capital and labor inverse supply functions are assumed to be upward sloping (see Quaas et al. (2017) and our model in the previous chapter of this dissertation). This reflects the localized nature of markets for these two factors, as well as the imperfect malleability of both inputs. Workers obtain a particular skill set to work in the fishery. Capital is invested into a

particular type of boat and gear. These two processes are not easily reversed, such that at low demand, supply prices will be low. On the other hand, they may become increasingly steep, as factor demand increases. Then, the supply prices for capital and labor form an increasing and convex function of the respective factor demand. We assume the following iso-elastic inverse supply functions for labor and capital, respectively:

$$w_{it}(l_{it}) = \lambda_i l_{it}^\psi, \quad (18)$$

$$r_{it}(k_{it}) = \kappa_i k_{it}^\zeta, \quad (19)$$

Fuel supply, on the other hand, is perfectly inelastic at price  $\Phi_{it}$ . The reason is that fuel prices are exogenous to the regional Senegalese market, they follow world market prices for crude oil. We derive symmetric equilibrium factor prices for labor and capital, using factor demands from (14)–(16) in (18) and in (19):

$$w_{it} = \left( \left( \kappa_i (1 - \gamma)^\zeta \right)^{\varphi(1-\gamma)\psi} \left( \frac{h_{it}}{q_i(m, W_{it}) x_y^x} M \Phi_{it}^{1-\varphi} \right)^{\psi(\zeta+1)} (\lambda_i \gamma^\psi)^{1+\zeta-\zeta\varphi(1-\gamma)} \right)^T \quad (20)$$

$$r_{it} = \left( \left( \kappa_i (1 - \gamma)^\zeta \right)^{1+\psi-\psi\varphi\gamma} \left( \frac{h_{it}}{q_i(m, W_{it}) x_y^x} M \Phi_{it}^{1-\varphi} \right)^{\zeta(1+\psi)} (\lambda_i \gamma^\psi)^{\gamma\varphi\zeta} \right)^T \quad (21)$$

with

$$M := \left( \frac{1}{(1 - \gamma)} \right)^{\varphi(1-\gamma)} \left( \frac{1}{\gamma} \right)^{\varphi\gamma} \left( \frac{\varphi}{1 - \varphi} \right)^{1-\varphi} \quad (22)$$

$$T = \frac{1}{(1 + \psi)(\zeta + 1 - \zeta\varphi(1 - \gamma)) - \psi\varphi\gamma(\zeta + 1)} \quad (23)$$

Inserting equilibrium factor prices into the cost function leads to the equilibrium cost function, which is non-linear in equilibrium harvest:

$$C = c_i \left( \frac{h_{it}}{q_i(m, W_{it}) (1 - \varphi)^{1-\varphi} x_y^\chi} \Phi_{it}^{1-\varphi} \right)^{e+1}$$

With cost elasticity parameter  $e$  and region-specific scaling parameter  $c_i > 0$ :

$$e = \frac{(1 - \gamma) \zeta \varphi + (\zeta + \gamma) \varphi \psi}{(1 + \psi) (\zeta + 1 - \zeta \varphi (1 - \gamma)) - \psi \varphi \gamma (\zeta + 1)}$$

$$c_i = \left( \left( \frac{1}{\varphi} \right)^{1+\gamma\zeta+(1-\gamma)\psi} \left( \frac{\kappa_i}{1-\gamma} \right)^{(1-\gamma)(1+\psi)} \left( \frac{\lambda_i}{\gamma} \right)^{\gamma(\zeta+1)} \right)^{\frac{\varphi}{(1+\psi)(\zeta+1-\zeta\varphi(1-\gamma))-\psi\varphi\gamma(\zeta+1)}}$$

We fix cost elasticity parameter  $e = 1$ , thus specifying a quadratic cost function, following Arnason et al. (2004) and our own findings in the previous chapter of this dissertation.

Inverse demand is an iso-elastic, decreasing function of harvest. Our estimation results show that the inverse price elasticity  $\nu$  depends negatively on regional population density  $B_{i,y}$ , which we interpret a proxy for the availability of substitutes<sup>15</sup>. With that, inverse demand is given by:

$$p_{it} = \bar{p}_i h_{it}^{-\nu(B_{i,y})} = \bar{p}_i h_{it}^{-\exp(\nu_0 + \eta B_{i,y})} \quad (24)$$

with inverse price elasticity  $0 \leq \nu(B_{i,y}) < 1$ .

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<sup>15</sup>We use density instead of total population in order to account for the differences in market area size.

## A.5 Estimation model and estimation results

To estimate supply and demand simultaneously, we derive the reduced form equations. The fishery operates under open-access, such that profits are zero in equilibrium. We set unit equilibrium cost equal to the equilibrium price. The equilibrium harvest level then reads:

$$h_{it} = \left( \frac{\bar{p}_i}{c_i} \left( q_i(m, W_{it}) (1 - \varphi)^{1-\varphi} x_y^\chi \Phi_{it}^{-(1-\varphi)} \right)^{e+1} \right)^{\frac{1}{\nu+e}} \quad (25)$$

Harvest pressure  $M$ , as referenced in 2.3, is defined as the factor in front of biomass in (25), summed over all four regions:

$$M := \sum_{i=1}^4 \left[ \left( \frac{\bar{p}_i}{c_i} \left( q_i(m, W_{it}) (1 - \varphi)^{1-\varphi} \Phi_{it}^{-(1-\varphi)} \right)^{e+1} \right)^{\frac{1}{\nu+e}} \right] \quad (26)$$

Inserting (25) back into (24) leads to the following reduced form expression for the equilibrium price:

$$p_{it} = \bar{p}_i^{\frac{e}{\nu+e}} c_i^{\frac{\nu}{\nu+e}} \left( q_i(m, W_{it}) (1 - \varphi)^{1-\varphi} x_y^\chi \Phi_{it}^{-(1-\varphi)} \right)^{-\frac{\nu(e+1)}{\nu+e}} \quad (27)$$

To achieve full identification, we will also use harvest productivity in our estimation. The fish price in (9) is substituted by its reduced form function, such that:

$$CPUb_{it} = (\bar{p}_i^e c_i^{\nu})^{\frac{1-\varphi}{\varphi(e+\nu)}} \left( q_i(m, W_{it}) (1 - \varphi)^{1-\varphi} x_y^\chi \Phi_{it}^{-(1-\varphi)} \right)^{\frac{e(1-\nu)+\nu\varphi(1+e)}{\varphi(e+\nu)}} \quad (28)$$

We introduce a linear time trend  $\tau_q$  to capture technical progress in the fishery that is unobserved, since we lack data on boat and motor size and

other technical characteristics. We add a linear time trend on  $c_i$  to include unobserved trends in factor prices and size of factor units. A time trend on  $\bar{p}_i$  was found to be significant for the long term estimation. All time trends are assumed to be equal across regions. Equal trends would be expected at least in the long term, as regions interact and converge. Our estimation showed that this is adequate, and that a linear trend is superior to a convex trend in the long term. Taking logs, including trends and adding an error terms provides the full system of three reduced form equations to be jointly estimated:

$$\ln p_{it} = \frac{\nu}{(\nu + e)} \left( \frac{e}{\nu} (\ln \bar{p}_i + \ln(1 + \tau_p(t - t_0))) + \ln c_i + \ln(1 + \tau_c(t - t_0)) - (e + 1)HR \right) + \epsilon_{ht} \quad (29)$$

$$\ln h_{it} = \frac{1}{(\nu + e)} (\ln \bar{p}_i + \ln(1 + \tau_p(t - t_0)) - \ln c_i - \ln(1 + \tau_c(t - t_0)) + (e + 1)HR) + \epsilon_{ht} \quad (30)$$

$$\ln CPUb_{it} = \frac{1 - \varphi}{\varphi(e + \nu)} (e (\ln \bar{p}_i + \ln(1 + \tau_p(t - t_0)) + \nu (\ln c \ln(1 + \tau_c(t - t_0)))) + \frac{e(1 - \nu) + \nu\varphi(1 + e)}{\varphi(e + \nu)} HR) + \epsilon_{ct} \quad (31)$$

with

$$HR := \ln q_i(m, W_{it}) + (1 - \varphi) \ln(1 - \varphi) + \chi \ln x_y + \ln(1 + \tau_q(t - t_0)) - (1 - \varphi)\Phi_{it} \quad (32)$$

The model is estimated using iterated feasible generalized least squares.

Table 4: Main estimation results economy

	Coeff./std. error
$\chi$	0.222*** (0.073)
$\varphi$	0.815*** (0.051)
$\ln Q_{0FL}$	-17.246*** (4.537)
$\ln Q_{0TN}$	-18.102*** (4.528)
$\ln Q_{0CV}$	-18.620*** (4.549)
$\ln Q_{0TS}$	-17.582*** (4.532)
$\delta_1$	1.179*** (0.348)
$\delta_2$	1.175*** (0.370)
$\delta_3$	1.397*** (0.366)
$\delta_4$	1.508*** (0.361)
$\delta_5$	1.567*** (0.345)
$\delta_6$	1.305*** (0.280)
$\delta_7$	0.529** (0.235)
$\delta_8$	0.428** (0.212)
$\delta_{10}$	0.370* (0.200)
$\delta_{11}$	0.856*** (0.203)
$\delta_{12}$	1.263*** (0.278)
$sw_t$	1.276*** (0.405)
$sw_{t2}$	-0.025*** (0.009)
$\tau_q$	0.009*** (0.002)
$\nu_0$	-0.640*** (0.216)
$\eta$	-1.862*** (0.618)
$\ln \bar{p}_{FL}$	6.968*** (0.356)
$\ln \bar{p}_{TN}$	6.570*** (0.311)
$\ln \bar{p}_{CV}$	4.702*** (0.113)
$\ln \bar{p}_{TS}$	6.276*** (0.351)
$\tau_p$	0.002* (0.001)
$\ln c_{FL}$	-3.127*** (0.544)
$\ln c_{TN}$	-4.018*** (0.399)
$\ln c_{CV}$	-5.003*** (0.375)
$\ln c_{TS}$	-5.138*** (0.389)
$\tau_c$	0.010*** (0.004)

\* p&lt;.10, \*\* p&lt;.05, \*\*\* p&lt;.01

Results are reported in Table 4 and diagnostic statistics listed in Table 5<sup>16</sup>. We choose between models including different weather impacts by means of the Akaike and Bayesian information criterion (AIC and BIC, respectively) and model fit. This leads to a specification where only SST influences catchability, which is included as the non-linear specification  $sw_tSST + sw_{t2}SST^2$ . We employ robust standard errors, since heteroscedasticity is present in the harvest equation. The inverse demand price elasticity depends negatively on population density. For Thiès Sud, Thiès Nord and Fleuve, it lies between 0.252 and 0.339. For Cap Vert,  $\hat{\nu}$  goes to zero, prices are independent of quantities.

Table 5: Statistics for main estimation results economy

Stat.	Value
N	561
No. variables	32
$R^2$ eq. price	.34
$R^2$ eq. harvest	.32
$R^2$ eq. CPUE	.32
AIC	3917
BIC	4056

## A.6 Climate model characteristics

The following table shows statistics that characterize SST and wind stress development for the four climate projections. Figure 2 shows the development of annual mean SST.

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<sup>16</sup>Note that for simplicity, the reported  $\ln Q_{0i}$  is a composite term, where  $Q_{0i} := q_{0i}(1 - \varphi)^{1-\varphi}$

Table 6: Climate model statistics

	ECE-o	ECE-bc	NESM-o	NESM-bc
<i>SST</i> (°Celsius)				
Mean (2014-2079)	25.778	25.680	25.246	25.334
Mean (2014-2023)	24.750	24.482	24.346	24.473
Mean (2070-2079)	27.141	26.700	26.224	26.331
Standard deviation	3.374	3.333	3.100	3.056
95% confidence interval, upper	32.391	32.222	31.322	31.324
95% confidence interval, lower	19.165	19.156	19.170	19.344
Mean seasonal amplitude	9.339	9.269	8.125	8.004
Std. deviation seasonal amplitude	0.937	0.714	0.282	0.251
<i>CUI<sub>winter</sub></i> ( $\frac{m^3}{s}$ per m coastline)				
Mean (2014-2079)	0.232	0.255	0.311	0.319
Mean (2014-2023)	0.257	0.288	0.327	0.323
Mean (2070-2079)	0.206	0.240	0.299	0.306
Standard deviation	0.032	0.053	0.020	0.013
95% confidence interval, upper	0.295	0.359	0.350	0.344
95% confidence interval, lower	0.169	0.151	0.272	0.294
<i>CUI<sub>fall</sub></i> ( $\frac{m^3}{s}$ per m coastline)				
Mean (2014-2079)	0.165	0.163	0.213	0.205
Mean (2014-2023)	0.172	0.165	0.218	0.216
Mean (2070-2079)	0.150	0.163	0.208	0.201
Standard deviation	0.0274	0.026	0.011	0.014
95% confidence interval, upper	0.219	0.214	0.235	0.232
95% confidence interval, lower	0.111	0.112	0.191	0.178

### A.7 Harvest pressure over time

We call harvest pressure  $M$  the multiplier in front of biomass in equilibrium harvest (A.5). It depends on SST, fuel prices, monthly dummies, population growth and trends. Figure A.3 shows the development over time for four exemplary months. We chose May, June, December and January here because they constitute the transition months with temperatures often around the optimum temperature, 25.4°Celsius.

### A.8 Undiscounted rents over time (table 7)

Model	2014–2023		2034–2043		2054–2063	
	BAU	melt-down	BAU	melt-down	BAU	melt-down
ECE-o	192	188	292	242	288	286
ECE-bc	182	179	113	131	0	0
NESM-o	191	187	147	285	0	305
NESM-bc	192	189	5	92	0	0

Table 7: Development of undiscounted rents (in billion 2014-based FCFA)

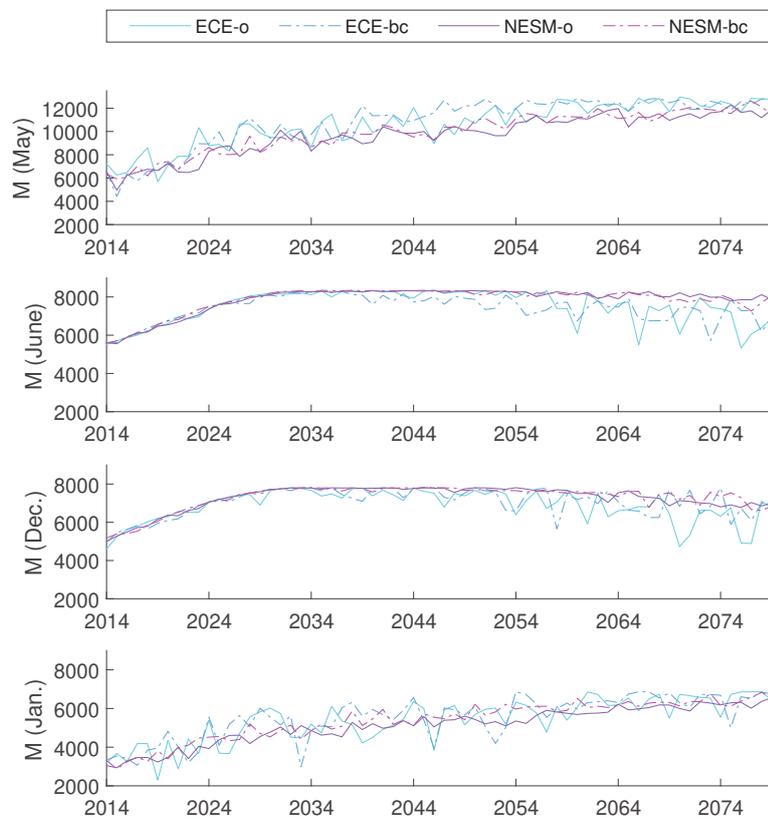


Figure A.3: Harvest pressure over time for different climate models

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## B. Supplementary online material

### B.1 Use of climate data and calculation of coastal upwelling indicators

For climate impacts, we again make use of the ERA Interim Reanalysis product at the monthly time scale. Same as in the main part, the data is provided by the European Centre for Medium-Range Weather Forecasts. We average SST over one  $1.5 \times 1.5^\circ$  coordinate box between  $13.5\text{--}16.5^\circ\text{N}$  for each of the catch areas for Thiès Sud, Cap Vert/ Thiès Nord and Fleuve, holding the longitudinal component constant over regions ( $17.25\text{--}18.75^\circ\text{W}$ ).

**Coastal upwelling indicator:** We calculate Ekman transport  $EK$  using wind stress ( $WS$ ) data from quadrants closest to shore but not overlapping with land. We average over the coordinate box between  $13.5\text{--}16^\circ\text{N}$  and  $17.25\text{--}18^\circ\text{W}$ . Subscript  $u$  denotes the the zonal (west–east) component and  $v$  the meridional component  $v$ :

$$EK_u = \frac{WS_v}{1025 \frac{\text{kg}}{\text{m}^3} 2 * \sin(\text{lat}) * 7.292 \times 10^{-5} \frac{1}{\text{s}}} \quad (33)$$

$$EK_v = -\frac{WS_u}{1025 \frac{\text{kg}}{\text{m}^3} 2 * \sin(\text{lat}) * 7.292 \times 10^{-5} \frac{1}{\text{s}}} \quad (34)$$

Then we calculate the coastal upwelling indicator (in  $\frac{\text{m}^3}{\text{s}}$  per meter of coastline) as:

$$CUI^W = -\sin\left(\varphi - \frac{\pi}{2}\right) EK_u + \cos\left(\varphi - \frac{\pi}{2}\right) EK_v \quad (35)$$

with  $\varphi$  defining the mean angle between the shoreline and the equator ( $90^\circ$ ).

**SST upwelling indicator:** The SST upwelling index (in °Celsius) is defined as the difference between the coastal SST (17.25W) and the SST five degrees further towards the open ocean for each latitudinal point (22.5W):

$$CUI^S = SST_{coast} - SST_{ocean} \quad (36)$$

## B.2 Estimation of the economic part: Robustness checks

This section provides evidence of the robustness of our economic estimation results with respect to the cost elasticity, the use of our own stock assessment biomass estimates as well as the use of North sea crude oil prices as an instrument for fuel prices. Results are reported in Table 8 and Table 9, with regions denoted by TS for Thiès Sud, FL for Fleuve, CV for Cap Vert and TN for Thiès Nord.

The cost function was assumed to be largely quadratic in section A.4. The first two columns show that results remain robust for lower and higher values of the cost elasticity. The first alternative,  $e + 1 = 1.8$ , performs slightly worse with respect to the Bayesian criterion. Stock elasticity  $\hat{\chi}$  and boat production elasticity  $\hat{\varphi}$  are lower. For  $e + 1 = 2.2$ , results are very similar to the main estimation, except for a slightly higher  $\hat{\chi}$ . Cost parameters start slightly lower, with a monthly trend of 1.3%. Consequently, the mean positive net trend on equilibrium harvest is reduced to 0.7–0.9% here.

Column 3 in Table 8 shows that most results remain robust if only the biomass estimates from the original data-set are used, i.e. 2001 – 2009. Stock elasticity  $\hat{\chi}$  is now slightly lower at 0.186. Catchability still depends on SST, but the effect is no longer significantly non-linear. This combines with relatively higher baseline catchabilities and a stronger trend on catchability. The ensuing mean  $\hat{\nu}$  is still close to zero for Cap Vert and between 0.385–

0.436 for the other regions. The net trend in equilibrium harvest increases to 3.21–4.57%. We conclude that the stock assessment results are plausible and compare well with the results gained only from the original biomass data. Not surprisingly, trends are sensitive to a shortening of the time period analyzed, likely because they are not perfectly constant and depend on technological breakthroughs and economic cycles.

To look at robustness with regard to fuel prices, we instrument them using North sea crude oil prices for the Brent type (columns 4 and 5). For the short time period, results are similar to those obtained with the regional fuel prices. For the time horizon that additionally includes years 2010–2013 however, the results are not plausible, in particular,  $\hat{\varphi} > 1$ . However, there is also a noticeable decoupling of the two price time series: While correlation of logarithmized prices for regional fuel and Brent is at 84% for 2001–2009, it only shows a correlation of 49% for 2010–2013. We believe that the fact that regional price movements are apparently important should still not be regarded as a problem for endogeneity: It is clear that at a yearly mean fuel use of only 50,322,000 l for the whole artisanal fishery, the purse-seine sub-sector is too small to have a notable influence on fuel prices. Indeed, if it is indeed the regional fuel price that is relevant, we would not expect robust results for a time period where Brent and regional fuel prices develop in opposite directions.

Table 8: Robustness results: Harvest productivity

Parameter	$e = 0.8$	$e = 1.2$	Short time horizon	Short/ Brent prices	Long/ Brent prices
$\chi$	0.202*** (0.068)	0.239*** (0.078)	0.186* (0.095)	0.178* (0.095)	0.186*** (0.069)
$\phi$	0.724*** (0.045)	0.885*** (0.054)	0.734*** (0.044)	0.771*** (0.047)	1.777*** (0.108)
$\ln Q_{OFL}$	-16.287*** (4.187)	-18.020*** (4.819)	-12.583*** (4.403)	-12.363*** (4.372)	-11.408*** (4.142)
$\ln Q_{ORN}$	-17.039*** (4.178)	-18.956*** (4.811)	-13.276*** (4.387)	-13.087*** (4.355)	-13.300*** (4.127)
$\ln Q_{OCV}$	-17.527*** (4.197)	-19.497*** (4.833)	-13.705*** (4.416)	-13.523*** (4.386)	-14.165*** (4.158)
$\ln Q_{ORS}$	-16.509*** (4.182)	-18.443*** (4.815)	-12.908*** (4.400)	-12.734*** (4.369)	-12.928*** (4.136)
$\delta_1$	1.048*** (0.323)	1.288*** (0.368)	1.932*** (0.373)	1.958*** (0.372)	1.004*** (0.333)
$\delta_2$	1.052*** (0.343)	1.279*** (0.392)	1.898*** (0.397)	1.939*** (0.393)	0.810** (0.364)
$\delta_3$	1.259*** (0.339)	1.514*** (0.387)	2.124*** (0.387)	2.143*** (0.384)	1.049*** (0.360)
$\delta_4$	1.360*** (0.335)	1.633*** (0.382)	2.285*** (0.377)	2.291*** (0.375)	1.192*** (0.353)
$\delta_5$	1.415*** (0.320)	1.692*** (0.365)	2.199*** (0.359)	2.195*** (0.359)	1.436*** (0.332)
$\delta_6$	1.173*** (0.260)	1.414*** (0.297)	1.964*** (0.295)	1.966*** (0.294)	1.333*** (0.266)
$\delta_7$	0.467** (0.221)	0.581** (0.247)	0.868*** (0.234)	0.875*** (0.234)	0.626*** (0.196)
$\delta_8$	0.385* (0.198)	0.463** (0.224)	0.653*** (0.189)	0.652*** (0.195)	0.496*** (0.189)
$\delta_{10}$	0.334* (0.187)	0.398* (0.210)	0.235 (0.179)	0.271 (0.177)	0.387** (0.170)
$\delta_{11}$	0.774*** (0.188)	0.923*** (0.215)	1.130*** (0.197)	1.166*** (0.198)	0.766*** (0.185)
$\delta_{12}$	1.133*** (0.258)	1.370*** (0.294)	1.730*** (0.295)	1.768*** (0.292)	1.010*** (0.283)
$sw_t$	1.226*** (0.374)	1.314*** (0.429)	0.709* (0.392)	0.639* (0.388)	1.055*** (0.369)
$sw_{t2}$	-0.024*** (0.008)	-0.026*** (0.009)	-0.011 (0.009)	-0.010 (0.008)	-0.021*** (0.008)
$\tau_q$	0.008*** (0.002)	0.010*** (0.003)	0.028*** (0.006)	0.038*** (0.008)	-0.005*** (0.000)

\*  $p < .10$ , \*\*  $p < .05$ , \*\*\*  $p < .01$ , Std. errors in parentheses

Table 9: Robustness results: Markets and statistics

Parameter	$e = 0.8$	$e = 1.2$	Short time horizon	Short/ brent prices	Long/ brent prices
$\nu_0$	-0.690*** (0.218)	-0.603*** (0.214)	-0.571** (0.264)	-0.604** (0.264)	-0.712*** (0.108)
$\eta$	-1.737*** (0.603)	-1.951*** (0.626)	-1.087 (0.795)	-1.005 (0.783)	-0.000 (0.011)
$\ln \bar{p}_{FL}$	6.924*** (0.359)	7.004*** (0.354)	7.992*** (0.495)	7.963*** (0.490)	8.476*** (0.440)
$\ln \bar{p}_{TN}$	6.533*** (0.314)	6.600*** (0.309)	7.538*** (0.425)	7.517*** (0.420)	7.981*** (0.381)
$\ln \bar{p}_{CV}$	4.693*** (0.112)	4.710*** (0.114)	4.866*** (0.121)	4.872*** (0.119)	8.259*** (0.393)
$\ln \bar{p}_{TS}$	6.246*** (0.355)	6.301*** (0.348)	7.259*** (0.483)	7.241*** (0.476)	8.125*** (0.454)
$\tau_p$	0.002* (0.001)	0.002* (0.001)	-0.002 (0.001)	-0.002 (0.001)	0.001 (0.001)
$\ln c_{FL}$	-2.486*** (0.441)	-3.816*** (0.635)	-4.204*** (0.492)	-3.801*** (0.522)	8.886*** (1.173)
$\ln c_{TN}$	-3.198*** (0.324)	-4.876*** (0.463)	-4.674*** (0.386)	-4.344*** (0.414)	5.890*** (0.960)
$\ln c_{CV}$	-3.988*** (0.305)	-6.054*** (0.436)	-5.390*** (0.380)	-5.075*** (0.401)	4.142*** (0.882)
$\ln c_{TS}$	-4.095*** (0.315)	-6.218*** (0.452)	-5.803*** (0.355)	-5.503*** (0.383)	4.479*** (0.924)
$\tau_c$	0.007*** (0.002)	0.013** (0.006)	0.008*** (0.003)	0.009*** (0.003)	0.002 (0.004)
$N$	561	561	374	374	561
No. variables	32	32	32	32	32
$R^2$ eq. price	0.34	0.34	0.38	0.38	0.36
$R^2$ eq. harvest	0.31	0.31	0.33	0.33	0.29
$R^2$ eq. CPUE	0.32	0.32	0.38	0.37	0.31
$AIC$	3921	3915	2408	2412	3914
$BIC$	4060	4053	2534	2538	4053

\* p<.10, \*\* p<.05, \*\*\* p<.01, Std. errors in parentheses

### B.3 Rents in the fishery

$$FS_{it} = \frac{e}{1+e} c_i (1 + \tau_c \Delta t) \left( \frac{h_{oait}}{q_i(m, W_{it}) (1 - \varphi)^{1-\varphi} x_y^\chi (1 + \tau_q \Delta t)} \Phi_{it}^{1-\varphi} \right)^{e+1} \quad (37)$$

$$CS_{it} = \frac{\nu(B_{iy})}{1 - \nu(B_{iy})} \bar{p}_i h_{oait}^{1-\nu(B_{iy})} \quad (38)$$



# Over-capitalization in fisheries with irreversible investment and factor substitution

KIRA LANCKER\*

**Abstract:** Depletion of fish stocks is a severe issue for sustainability and food security. One major problem is over-capitalization. A better understanding of the theoretical implications of capital as an irreversible investment input is necessary. Using Hamiltonian derivation and numerical comparison, this article studies the qualitative and quantitative implications when irreversibly invested capital can be substituted by flexibly adaptable inputs such as labor. It compares investment incentives under open access and investment under optimal management across different levels of complementarity. The results show that, if factor substitution is possible, capital will always be fully used. Due to this, transition paths are smooth. The possibility of substitution can attenuate over-capitalization, because of lower investment incentives under open access.

**JEL Classification:** D24, Q22, Q25, E22

**Keywords:** non-malleable capital, fisheries, overcapacity, factor substitution, stock elasticity, bio-economic model, environmental management, optimal control, property rights

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# 1 Introduction

Depletion of fish stocks is a severe issue for sustainability, food and income security (Pauly et al., 2002). Predatory fish stocks have been strongly reduced to about 10% of pre-industrial fish stocks (Myers and Worm, 2003). One major cause is over-capitalization of modern fisheries, i.e. the employment of capital at a level above the optimal level (Clark and Munro, 2017; Myers and Worm, 2003; Ward et al., 2004; Weber, 1995). A better understanding of the theoretical implications of capital as an input is necessary to improve management and to prevent the detrimental impact of instant over-capitalization for newly developing fisheries, such as meso-pelagic fish species (Irigoien et al., 2014).

“Irreversible investment” means that disinvestment is infeasible or costly (Clark et al., 1979; Eisenack et al., 2006; Rust et al., 2016). Investment in fishing capital is typically irreversible, as capital in fisheries is often specific to the area, species, fishing method, and local regulations. Fishing capital is also not useful in other branches of the economy (Nøstbakken et al., 2011; Ward and Sutinen, 1994). Slow depreciation leads to a situation where capital, once invested, stays in the fishery for decades (Daurès et al., 2006). Overinvestment occurs when an un-managed fishery happens to be at a biomass level above its long-term steady state. Investment incentives under open access do not take into account the stock externality. When capital is not fully malleable, the transition to the optimal long-term equilibrium stock is gradual and costly even under optimal management, and more so under open access (Boyce, 1995; Clark et al., 1979; McKelvey, 1985). The classic linear dynamic optimization problem under irreversible investment has been extensively studied (Clark et al., 2005; Hannesson, 1987; Jørgensen and Kort, 1997; Kennedy, 1989; Sandal et al., 2007). It includes two stock variables –

biomass and invested capital – and harvest production by effort and capital under perfect complements. The problem of over-capitalization and gradual transition paths persists when non-linearities, for example concerning the price for capital, are introduced (Eisenack et al., 2006; Sandal et al., 2007; Poudel et al., 2013).

Biomass and capital are standardly modeled as substitutable production inputs even in the linear case (Schäfer, 1957). However, the literature rarely addresses the case where capital can be partly substituted by a flexibly adaptable input, such as labor or fuel. This article studies qualitative and quantitative implications when irreversibly invested capital can be substituted by flexibly adaptable inputs, following a constant elasticity of substitution (CES) harvest production function, while maintaining the assumption that biomass can substitute for the other production inputs. The continuous time optimal control approach under optimal management optimizes over two stocks: Invested capital and biomass. I provide an analytical comparison of the model’s qualitative behavior for varying levels of complementarity and highlight qualitative differences. Secondly, the article proceeds to numerically compare investment incentives under open access and investment optimal management.

I show that both the factor input ratio between capital and malleable inputs, as well as the marginal cross-product between capital and biomass change over the transition path, if factor substitution is possible. Capital will always be fully used and transition paths are smooth. The possibility of substitution can attenuate over-capitalization. In our example, over-capitalization at any level of starting biomass above the long-term equilibrium is lower, the better the substitution possibilities. This results from lower investment incentives: Fishers perceive that the system remains for

long in a lower profitability state, and invest less. Furthermore if the optimal steady state lies below the maximum sustainable yield the minimum biomass attained during transition is lower under open access for all levels of complementarity, and the system remains over-capitalized for most of the transition path.

This article is structured as follows: Section 2 reviews the literature on irreversible investment in fisheries and presents empirical evidence on substitution possibilities. Section 3 introduces the model and analyzes the effect of substitutability on investment incentives under open access. An analysis of the framework under optimal management is presented in section 4. Section 5 analyses the extent of over-capitalization by comparing the findings from the two previous sections. The article finishes with a short conclusion.

## **2 Literature review**

### **2.1 Irreversible investment: Theoretical literature**

The seminal papers on irreversible capital investments in fisheries are Clark et al. (1979), looking at optimal management, and McKelvey (1985), who focuses on the open-access case. In their main version, both assume a Schäfer harvest production function (Schäfer, 1957) that is linear in biomass<sup>1</sup>. Capital and effort are perfect complements. Once invested, capital can not be disinvested again and is available at zero further use cost. Capital cost are sunk and capital practically becomes a cost-less factor of production. If

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<sup>1</sup>During model setup and instrument analysis, McKelvey (1985) allows for convex fishing cost, convex inverse demand and concave harvest. However, transition analysis is restricted to the linear formulation, due to tractability.

capital is defined to be “non-malleable”, it does not depreciate such that any invested amount of capital is available into eternity. The term “quasi-malleable”, by contrast, refers to capital that depreciates over time (Clark et al., 1979).

In an open access environment, a long-term steady state exists where total profit is zero (McKelvey, 1985)<sup>2</sup>. Fishers’ will exactly invest the depreciated amount in each period, and irreversible investment is not an issue. By contrast, if biomass at the start lies above this level, capital jumps up above the steady state capital level. Fishers will continue to use all capital already invested, as long as operating profit is non-negative. Biomass is gradually reduced. If capital is quasi-malleable, biomass finally converges back to its long-term equilibrium level, once capital has depreciated enough. A similar trajectory occurs under optimal management (Clark et al., 1979). However, the stock externality is taken into account. The steady state is determined by the Golden rule, such that the own rate of interest of the stock, including marginal growth and the stock effect, equals the social discount rate. Under open access and starting at a trajectory at or above the long term steady state, the fishery is over-capitalized, investment is higher than optimal (McKelvey, 1985). This can be corrected by regulating harvest and capital input separately (McKelvey, 1985)<sup>3</sup>.

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<sup>2</sup>Fishers are assumed to have perfect foresight with respect to future profits. See Bjørndal and Conrad (1987); Rust et al. (2016) for analyses using myopic foresight or projection bias.

<sup>3</sup>The authors also highlight that, whenever there is a binding constraint on investment or harvest for all future periods, using a single instrument, namely a tax on harvest, is sufficient for optimal management. Two instruments are required whenever it is optimal to invest but use less than the full capital at the same time.

Apart from these two models, the focus on a perfect complements case with stock elasticity equal to unity is also found in most of the remaining literature on imperfectly malleable capital (Botsford and Wainwright, 1985; Charles and Munro, 1985; Clark et al., 2005; Hannesson, 1987; Jørgensen and Kort, 1997; Kennedy, 1989; Rust et al., 2016; Sandal et al., 2007). An early attempt to non-linearize the Clark-model was presented by Boyce (1995). However, harvest and cost are assumed to be independent of biomass. Sandal et al. (2007) model non-malleability as an asymmetric convex cost-function of investment, leading to a more conservative exploitation approach. The more recent literature has gradually included non-linearities also with respect to the biomass effect on operating profit. Poudel et al. (2013) allow for a downward sloping inverse demand curve. Eisenack et al. (2006) use a generalized form of non-linear harvesting costs that are decreasing in biomass, such that capital and biomass are non-linear substitutes. They reproduce the result of initial over-capitalization. The same is true for Singh et al. (2006), who allow for non-linear revenues and non-linear, stock-dependent harvesting costs.

As a conclusion, non-linearities have increasingly been introduced and have been shown to change dynamics. However, non-linear harvest functions have rarely been analyzed. In particular, studies do not examine the situation where the triple substitution between biomass, capital and malleable factors of production is possible.

## **2.2 Empirical evidence**

Empirically, some evidence exists that capital is not perfectly malleable. Ward and Sutinen (1994) showed that fishing firms easily enter the fishery when profits increase, but are less likely to leave the sector upon declining

profits. Clark and Lamberson (1982) were able to show that a model including irreversible investment based on Clark et al. (1979) could adequately reproduce the investment cycle in pelagic whaling. Eythórsson (1996) proved that with the advent of an ITQ management system in Iceland, capital rose suddenly as banks accepted the ITQs as loan security. They did not accept physical capital, which points toward irreversibility of this form of investment (Nøstbakken et al., 2011). Malleability of capital is also a function of opportunity costs, in particular concerning close-by alternative fishing opportunities (Campbell et al., 2000; Grafton, 1996; Pascoe and Revill, 2004; Pradhan and Leung, 2004). Using a hedonic approach, Daurès et al. (2006) estimate that capital in French fisheries depreciates at a rate of around 4%.

Table 1 summarizes available empirical evidence of substitution possibilities between capital and variable inputs. Comitini and Huang (1967) find effort production to be representable by a Cobb-Douglas function including labor and capital inputs. Squires (1987) estimates a translog effort production function. According to Campbell (1991), the Tasmanian lobster harvest production can adequately be represented as a CES function. The estimated elasticity of substitution is 0.75. Valle et al. (2003) find an Allen elasticity of substitution of 0.09 between tonnage and boat days and 0.4 between horsepower and boat days. It is concluded from this brief review that substitution between capital and other effort input factors in harvesting is possible in many fisheries. They are, however, likely to be gross complements rather than gross substitutes.

Table 1: Estimations on substitution elasticities and distribution factors

Reference	Effort prod. function	input factors (capital first)	Substitution elasticity	Distribution factor (capital)	Fishery
Comitini and Huang (1967)	CES	extent of vessel utilization, crew-days-fished	1	0.25	North Pacific halibut
Squires (1987)	translog	ton-days-absent crew-days-fished energy consumption (F)	(K), 0.726 (L,K), (L), 2.125 (F,K), 1.946 (L,F)	0.321	New England otter trawl
Bjørndal (1989)	translog	fixed factor of vessel characteristics, boatdays/ trips	composite 1	$0.68 - 0.81^4$	North Sea herring
Campbell (1991)	CES	number of pots, factors	variable 0.75	0.37	Tasmanian lobster
Valle et al. (2003)	translog	tonnage/ boat days	horsepower, 0.09 / 0.4	$0.19 - 0.2$	European Anchovy

### 3 A model of an open access fishery with factor substitution under irreversible investment

#### 3.1 Theoretical model

A fishery sector uses two factors of production, effort  $E_t$  and capital  $K_t$ , where  $t$  denotes the point in (continuous) time. Effort is to be interpreted as a composite of all freely adjustable fisheries inputs, such as labor and fuel. It is flexibly adaptable. Capital, on the other hand, is non- or quasi-

malleable. It can for example be measured by means of insurance value, vessel characteristics such as size and tonnage or vessel replacement costs (e.g Brandt, 2007; Jensen, 1998; Nøstbakken, 2012)<sup>5</sup>. Following the literature, the model allows for upward jumps in investment, but disinvestment is not possible, so investment  $I_t$  is bounded from below by zero,  $0 \leq I_t \leq \infty$ . Investment has constant unit cost  $\theta$ . Capital  $S_t$  depreciates at rate  $0 \leq \delta < 1$ . The amount  $K_t$  of capital actually used in the fishery cannot exceed the amount of capital available, so  $K_t \leq S_t = S_0 e^{-\delta t}$ .

Biomass  $B_t$  enters the production function linearly. Catchability  $q$  scales harvest productivity per input. While all these assumptions closely follow the literature, the extension considered here is that the harvesting technology is given by a constant elasticity of substitution (CES) production function:

$$H_t = G_t(B_t, K_t, E_t) = q B_t \left( \alpha K_t^{\frac{\sigma-1}{\sigma}} + (1 - \alpha) E_t^{\frac{\sigma-1}{\sigma}} \right)^{\frac{\sigma}{\sigma-1}} \quad (1)$$

Capital and effort are assumed to be gross complements, i.e.  $0 \leq \sigma \leq 1$ . Under full flexibility of inputs, this entails positive and decreasing marginal products for capital  $G_{K_t}(B_t, K_t, E_t) > 0$ ,  $G_{K_t, K_t}(B_t, K_t, E_t) < 0$  and effort  $G_{E_t}(B_t, K_t, E_t) > 0$ ,  $G_{E_t, E_t}(B_t, K_t, E_t) < 0$ , as well as a positive cross-derivative between effort and capital  $G_{E_t, K_t}(B_t, K_t, E_t) > 0$ . The specification (1) includes the case of perfect complements considered in the previous literature for the limit  $\sigma \rightarrow 0$  and the Cobb-Douglas case for the limit  $\sigma \rightarrow 1$ .

Using effort costs a constant unit price  $c$ . The price for a unit of the harvested resource is denoted by  $p$  and assumed constant. Let us first focus on the effort decision<sup>6</sup>. Fishers choose effort input  $E_t$  subject to optimal

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<sup>5</sup>A substantial part of the literature discusses this issue, with particular focus on measuring in-homogenous characteristics of vessels, such as technological advance (Nøstbakken et al., 2011).

<sup>6</sup>Optimal effort input can be derived in conjunction with the general Hamiltonian

capital input  $K_t \leq S_t$ , using constrained operating profit maximization:

$$\max_{E_t} \left\{ p q B_t \left( \alpha K_t^{\frac{\sigma-1}{\sigma}} + (1-\alpha) E_t^{\frac{\sigma-1}{\sigma}} \right)^{\frac{\sigma}{\sigma-1}} - c E_t \right\} \quad (2)$$

Profit-maximizing effort is a linear function of optimal capital input:

$$E_t = \left( \frac{\alpha}{1-\alpha} \right)^{\frac{\sigma}{\sigma-1}} \left( \left( \frac{c}{p q B_t} \right)^{\sigma-1} (1-\alpha)^{-\sigma} - 1 \right)^{\frac{\sigma}{1-\sigma}} K_t \quad (3)$$

Optimal effort is positive if and only if

$$B_t > \frac{c}{p q} (1-\alpha)^{\frac{\sigma}{1-\sigma}} = B_* \quad (4)$$

with  $\frac{\partial B_*}{\partial \sigma} < 0$  since  $0 < \alpha < 1$ . Effort is proportional to  $K_t$  and in contrast to the perfect complements case, the proportionality factor is an increasing and convex function of  $B_t$  within the domain  $B_t > B_*$ . After inserting (3) into (1), one arrives at an expression for harvest subject to biomass and linear in optimal capital input:

$$H_t(B_t, K_t) = q B_t \left( 1 - \left( \frac{c}{p q B_t} \right)^{1-\sigma} (1-\alpha)^\sigma \right)^{\frac{\sigma}{1-\sigma}} \alpha^{\frac{\sigma}{\sigma-1}} K_t \quad (5)$$

Effort is a necessary input, such that harvest is zero if (4) does not hold. After the short-term decision on effort is accounted for, capital and biomass remain imperfect substitutes. Their marginal rate of technical substitution under  $0 < \sigma < 1$  depends positively on biomass. For all levels of capital and biomass, it is strictly larger than under perfect complements. This means that at higher biomass levels, an increase in biomass needs to be larger to offset the decrease in harvest due to depreciating capital than at lower biomass values. Operating profit  $\pi_t$  is defined as:

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optimization explained below. However, for the sake of explanation, we will first focus on the derivation of effort input here, and proceed to the investment decision afterwards.

$$\begin{aligned}
\pi_t(B_t, K_t, E_t) &= pH_t(B_t, K_t) - cE_t(B_t, K_t) \\
&= c \left( \frac{\alpha}{1-\alpha} \right)^{\frac{\sigma}{\sigma-1}} \left( (1-\alpha)^{-\sigma} \left( \frac{c}{pqB_t} \right)^{\sigma-1} - 1 \right)^{\frac{1}{1-\sigma}} K_t
\end{aligned} \tag{6}$$

Furthermore, I follow the literature and assume that biomass growth  $g(B_t)$  follows the logistic function (Schäfer, 1957) with natural growth rate  $z > 0$  and carrying capacity  $CC > 0$ :

$$g(B_t) = zB_t \left( 1 - \frac{B_t}{CC} \right) \tag{7}$$

Fishers maximize inter-temporal total profit, taking into account capital dynamics and the non-negativity constraint on investment  $I_t$ . Whenever harvest is positive  $S_t = K_t$  follows from the fact that operating profit and harvest is linear in capital  $K_t$ . They take future biomass development as given in their investment choice, but they disregard the stock externality, which sets this problem apart from the problem of a sole owner, a “race to fish” occurs. The interaction between fishers then leads to an equilibrium pattern of investment and harvesting, which will be characterized in the following. A current value Hamiltonian approach is used to derive an expression for the switching curve and the steady state. the fishers current-value Hamiltonian function reads:

$$\mathcal{H} = \pi_t(B_t, K_t) - \theta I_t + \mu_t (I_t - \delta K_t) + \nu_t I_t \tag{8}$$

Let  $0 \leq \rho \leq 1$  denote the fishers’ discount rate. Industrial fishing can be expected to exhibit discount rates close to the market interest rate, disregarding risk mark-ups. The shadow value of capital is denoted by  $\mu_t$ , and  $\nu_t$  is the shadow price of disinvestment, i.e. the slack variable of the non-negativity

constraint. The following Kuhn-Tucker-condition and two dynamic differential equations follow from the Hamiltonian first order conditions:

$$\theta = \mu_t + \nu_t \text{ with } \nu_t \geq 0, I_t \geq 0, \nu_t (I_t - 0) \stackrel{!}{=} 0 \quad (9)$$

$$\dot{K}_t = I_t - \delta K_t \quad (10)$$

$$\dot{\mu}_t = (\rho + \delta) \mu_t - \frac{\pi_t}{K_t} \quad (11)$$

The first equation states that the shadow price of capital must be smaller or equal to the unit price of capital  $\theta$ , where the equality is strict whenever investment is positive. The second equation simply details capital dynamics, consisting of investment and depreciation (10). Equation (11) describes the change in the shadow price of capital, i.e. the current value of one more unit of invested capital. Furthermore, biomass increases with biomass growth, but is reduced by harvest. Thus, stock dynamics are given by the additional third dynamic differential equation:

$$\dot{B}_t = g(B_t) - H_t(B_t, E_t, K_t) \quad (12)$$

I proceed with an analysis of the steady state, before turning to transition paths. In steady state, biomass growth equals harvest. Fishers invest exactly the amount of capital that depreciates in the same period. The shadow value of capital  $\mu_t$  equals the unit price for capital, and operating profit is zero. The corresponding steady state biomass level is:

$$B^* = \frac{1}{pq} \left( ((\rho + \delta) \theta)^{1-\sigma} \alpha^\sigma + c^{1-\sigma} (1 - \alpha)^\sigma \right)^{\frac{1}{1-\sigma}} \quad (13)$$

By (10), investment is positive in steady state and replaces exactly the capital that depreciates. At any point in time  $\tau$  when investment is positive,

the shadow value of capital equals the marginal cost of investment,  $\mu_t = \theta$ . Integrating (11), this condition can be written as:

$$\mu_\tau = \int_\tau^\infty \frac{\pi_t}{K_t} e^{-(\rho+\delta)(t-\tau)} dt \stackrel{!}{=} \theta \quad (14)$$

In line with the term used in previous literature, we term the curve in biomass-capital-state-space, that is defined by this equation, “investment switching curve”.

I will now turn to an analysis of transition paths for starting points at  $B_t > B^*$ , and capital given by a value below the investment switching curve. Starting at  $B_t > B^*$ , fishers will invest such that a jump up to the investment switching curve occurs. Since operating profit increases monotonously in biomass, it is clear that no investment would take place until  $B^*$  is reached again. For  $B_t > B_*$ , all available capital is used,  $K_t = S_t$ . If  $B_t$  is below that level, optimal effort is zero, and thus harvest as well as operating profit are zero. Effort is a necessary input, such that output falls to zero at this point, and capital is no longer used.

Consider the case where capital is non-malleable, i.e. it does not depreciate. If a trajectory in biomass-capital state space, with biomass on the x-axis, starts on the investment switching curve, it will continue horizontally to the left. At some point, the capital invested will be insufficient to continue to decrease the biomass: Growth will be equal to harvest. Because capital does not depreciate, this point constitutes a long-term steady state in this setting. Under  $\delta = 0$ , the curve that connects all combinations of biomass and capital that constitute these steady states is called “trap curve” in the

previous literature. We use  $\dot{B}_t = 0$  to derive this trap curve:

$$K_{TL}(B_t) = \frac{z}{q} \left(1 - \frac{B_t}{CC}\right) \left(1 - \left(\frac{c}{pqB_t}\right)^{1-\sigma} (1-\alpha)^\sigma\right)^{-\frac{\sigma}{1-\sigma}} \alpha^{\frac{\sigma}{1-\sigma}} \quad (15)$$

The trap curve is downward sloping and for  $0 < \sigma$  convex in biomass. For quasi-malleable capital (Clark et al., 1979),  $\delta > 0$ , the trap line can be reached exactly vertically, as  $\dot{B}_t$  goes to zero and  $\dot{S}_t$  is strictly negative<sup>7</sup>. In a diagram with biomass on the x-axis and capital on the y-axis, it constitutes the “turning point” of the trajectory, where biomass stops decreasing and starts growing again.

It is the aim to compare the importance and extent of the over-capitalization-problem across different realizations of  $\sigma$ . For such a comparison to be meaningful across different substitution elasticities, the distribution parameter  $\alpha$  should be adapted such that the model yields the same marginal rate of technical substitution at a specific factor input ratio (Klump and Grandville, 2000; Klump and Saam, 2008). The transition dynamics towards a long-term steady state dynamics are characterized by a market failure that stems from the joint problem of a common pool resource and irreversible investment. Once the system is in its long-term equilibrium, this problem ceases to be relevant, as investment under quasi-malleable capital is always positive from that point on-wards. However, the factor returns that the system generates in its long-term equilibrium still shape the market failure, as long as capital invested at the beginning of the time horizon has not fully depreciated at the instant where the long-term equilibrium is reached.

Hence, the system is normalized such that the return on invested capital in the long-term steady state is equal across  $0 \leq \sigma \leq 1$  (see Section A.1 in the Appendix for a Hamiltonian derivation of perfect complements results).

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<sup>7</sup>A necessary condition is that  $\delta$  is large enough such that  $\frac{d\dot{S}_t}{dt}$  goes to infinity

Equal steady state capital levels are achieved by setting the distribution parameter  $\alpha$  to satisfy:

$$\frac{\partial K^*}{\partial \sigma} = 0 \iff \frac{c}{1 - \alpha} = \frac{(\rho + \delta)\theta}{\alpha} \quad (16)$$

This normalization ensures equal capital intensity and equal harvest per unit of capital at steady state. Then, the model returns the perfect complements long-term steady state level of biomass regardless the level of  $\sigma$ . The steady state coincides with the tangential point of the family of harvest functions defined by varying  $\sigma$ . For any level of  $\sigma$ , long-term steady state biomass levels then coincide without varying catchability. This condition preserves income shares at the long-term equilibrium levels across different levels of substitutability. The behavior of the fishery, once in steady state, will be the same across  $0 \leq \sigma \leq 1$ . However, the behavior for transition paths differs.

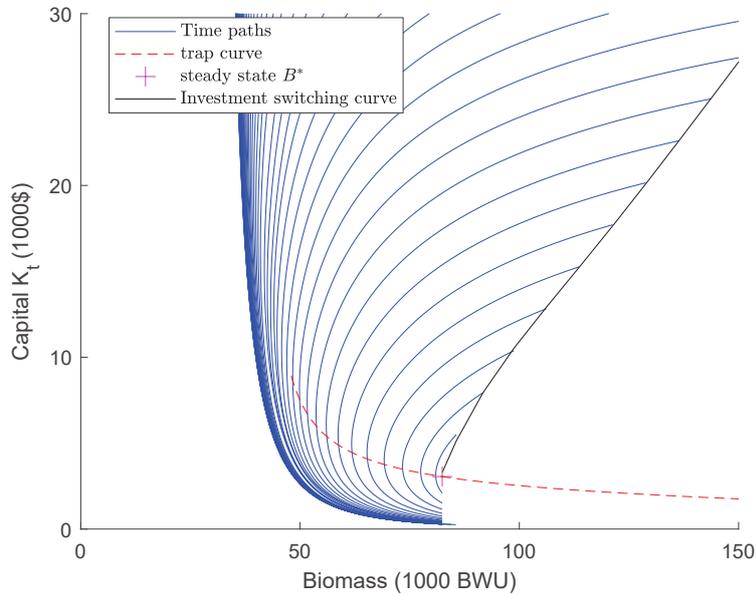
The example from Clark and Lamberson (1982) is used to compare our CES specification with the perfect complements case most often covered in the literature. The example features Antarctic pelagic whaling in the 20th century and is used also as the example for irreversible investment in the textbook by Clark (1990). The parametrization is presented in the Appendix (see A.2). In the standard parametrization,  $\alpha = \frac{1}{3}$ .

### 3.2 Qualitative Comparison

The paper's main interest concerns the transition dynamics for trajectories starting at  $B_0 \geq B^*$  and initial capital below the switching curve. This section analyzes the numerical outcome for different levels of  $0 \leq \sigma \leq 1$ . Plotting transition paths emanating from the switching curve at  $B_0 > B^*$

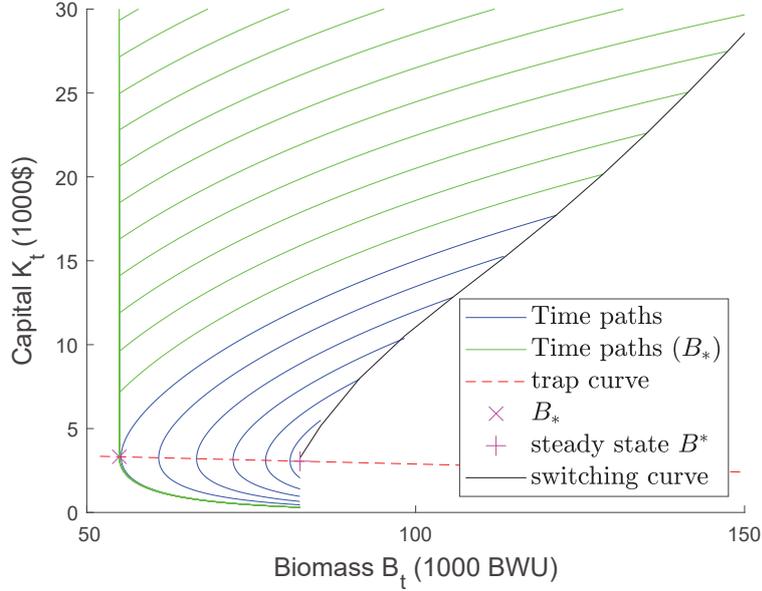
for a strictly positive substitution elasticity, in this example  $\sigma = 0.6$ , results in the B-K-state-space-diagram shown in Figure 1. Figure 2 shows the corresponding transition paths for the perfect complements case. These results replicate those of McKelvey (1985). Figures showing time paths of capital shadow value  $\mu_t$  are provided in Section A.5.

Figure 1: Stock-capital-transition paths,  $\sigma=0.6$ .



Capital first jumps up to the switching curve, such that total expected profit per unit of capital equals the unit cost of capital. This cost stems from both discounting and depreciation. As capital is at first above steady state level, biomass decreases, then increases again when capital has depreciated enough. Once the steady state is reached, a second pulse investment leads to the employment of capital at  $K^*$  (not shown). In all future periods,

Figure 2: Stock-capital-transition paths,  $\sigma=0$



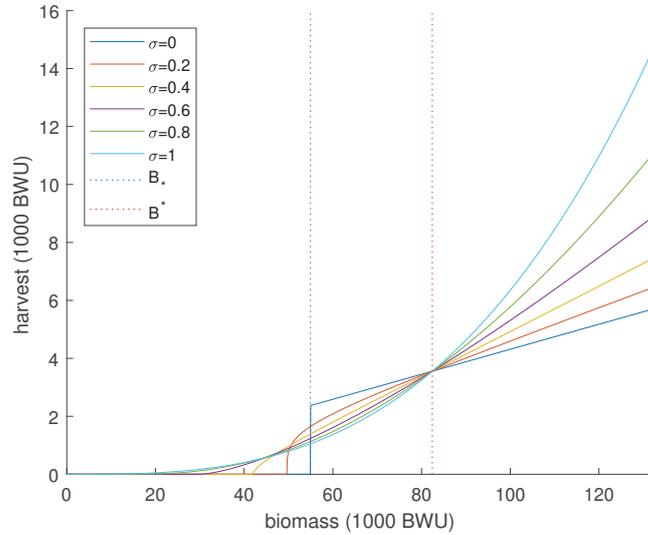
depreciated capital is exactly substituted by new investment, such that non-malleability no longer has efficiency effects. Due to the normalization given above, long term equilibria coincide for all levels of  $\sigma$ . In this example,  $B^* = 0.21CC$ , i.e smaller than the maximum sustainable yield, such that growth to the left of  $B^*$  is a concave increasing function of biomass.

Two main differences result from varying  $\sigma$ . The first is that effort and capital are now substitutable, to a limited degree. This is of particular importance when capital is abundant at the beginning of the time horizon, and when capital is scarce at the end of the time horizon. The second is that the cross production elasticity between biomass and capital,  $H_{B_t, K_t}$  changes with changing biomass over time. It is constant under perfect complements,

but depends on biomass for  $\sigma > 0$ <sup>8</sup>.

Figure 3 compares harvest levels over biomass levels. Capital for each harvest function is set equal to  $K_*$  i.e. the respective capital that would lead to  $\dot{B}_t = 0$  under perfect complements at  $B_* = \frac{c}{pq}$ . At a given level of biomass  $B_t$ , the higher  $\sigma$ , the larger is harvest if  $B_t > B_*$ , and the smaller is harvest if  $B_* < B_t < B^*$ . The reason is that harvest is convex in biomass for  $0 < \sigma$ . Thus, if a path starts to the right of the long-term steady state, after initial investment at the same point  $(B_0, I_0)$ , biomass would be faster reduced under high levels of  $\sigma$ .

Figure 3: Harvest over biomass for different levels of  $\sigma$  at  $K_*$




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<sup>8</sup>The condition for this dependence to be positive is  $B_t > B_* \left( \frac{\sigma}{1-\sigma} \right)^{\frac{1}{\sigma-1}}$ . A sufficient condition for this is  $\sigma > 0.5$ . This means that there are cases for which  $H_{B_t, B_t} > 0$ .

The biomass level at which operating profit goes to zero,  $B_*$ , decreases in  $\sigma$ . For a Cobb-Douglas harvest production function,  $B_* \rightarrow 0$ . It follows from the previous analysis that the level of capital per biomass along the trap curve increases in  $\sigma$ . Trap curves across all considered levels of  $\sigma$  are tangent at  $B^*$ . Due to the non-linearity of harvest in biomass, trap curves for  $\sigma > 0$  are decreasing and convex in stock size. For the normalization given above,  $\frac{\partial K_{TL}}{\partial \sigma} > 0$  for  $B_t < B^*$ : the trap curve becomes steeper for a higher  $\sigma$ .

**Proposition 1.** *If the system is normalized to equal steady states for  $0 \leq \sigma \leq 1$ , the trap curve is decreasing and convex in biomass and increases in  $\sigma$ . For  $0 < \sigma$ , the curve is strictly convex. The biomass level at which operating profit goes to zero is given by  $B_* = \frac{c}{p \cdot q} (1 - \alpha)^{\frac{\sigma}{1-\sigma}}$ .  $B_*$  decreases in  $\sigma$ . For the turning point of the trajectory to be situated at an equal biomass, the corresponding capital stock has to be higher, the higher  $\sigma$ .*

Factor substitution leads to another qualitative difference in model dynamics. For biomass approaching  $B_*$  from above, the bracket in (15) goes to zero, such that  $K_{TL}$  goes to infinity. The trap line therefore never crosses the vertical line above  $B_*$  for finite levels of capital. As long as depreciation is strictly positive, a trajectory starting at the switching curve has to cross this line exactly vertically, since the line connects all combinations of biomass and capital for which  $\dot{B}_t = 0$ . By consequence, a fishery with  $0 < \sigma \leq 1$ ,  $\delta > 0$  and where initial capital investment is bounded from above (due to the fact that biomass is bounded from above) never reaches  $B_*$  and operating profit for this fishery must always be strictly positive. There is no instance where capital, once invested, is unused. The trajectory stays to the right of the trap curve until the turning point, where biomass starts to rise again.

During this time, harvest is highly capital intensive.<sup>9</sup>

On the other hand, under perfect complements, trajectories may strike  $B_*$ , which for  $K_t > K_*$  lies to the right of the trap line, when the trajectory is not fully vertical. The trap line crosses  $B_*$  at  $K_*$ . Once biomass falls below this level, harvesting falls to zero until biomass has grown back to profitable levels. Here, harvest equals biomass growth until  $K_t$  has depreciated to  $K_*$ , the transition moves along the vertical line. Both capital and effort are employed at very low levels. Operating profit equals zero. Then, the path leaves  $B_*$  and grows again until it reaches  $B^*$ . Note that between  $B_*$  and  $B^*$ , the paths are all identical, leading to an identical minimum capital at the end of the transition path. This minimum capital level is therefore defined by  $K_*$  and the time of transition between  $B_*$  to  $B^*$ . This is in contrast to the cases with substitutability, where the remaining capital continues to depend on  $B_0$ .

**Proposition 2.** *For  $0 < \sigma$ , the trap curve approaches  $B_*$  from the right. It has no interception with the vertical line above  $B_*$ . For  $\sigma = 0$ , the trap line intercepts this vertical line at  $K_* = \frac{z}{q} \left(1 - \frac{B_*}{CC}\right)$ .*

These features need to be taken into account when numerically computing the trajectories. A perfect complements production function requires a multi-point solution procedure with a two case distinction. If trajectories fall short of  $B_*$ , a straightforward single region solution suffices. However, the case where trajectories reach  $B_*$  requires the distinction of three regions, where the transitions occur upon reaching  $B_*$ , upon reaching (vertically) the point

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<sup>9</sup>Minimum effort per unit capital along the trajectory does not coincide with the turning point though: While turning,  $\dot{\psi}_t < 0$ , since biomass is momentarily stable and capital decreases. Thus, at this point, effort per unit capital increases.

where the trajectories leave  $B_*$  again as well as  $B^*$  as the end point (see Section A.4). All three time horizons need to be determined separately, and the system requires nine boundary conditions. This is costly in terms of both accuracy of the numerical solution and computation time. By contrast, cases with a substitution elasticity above zero allow for a single region solution, where only one time horizon needs to be determined.

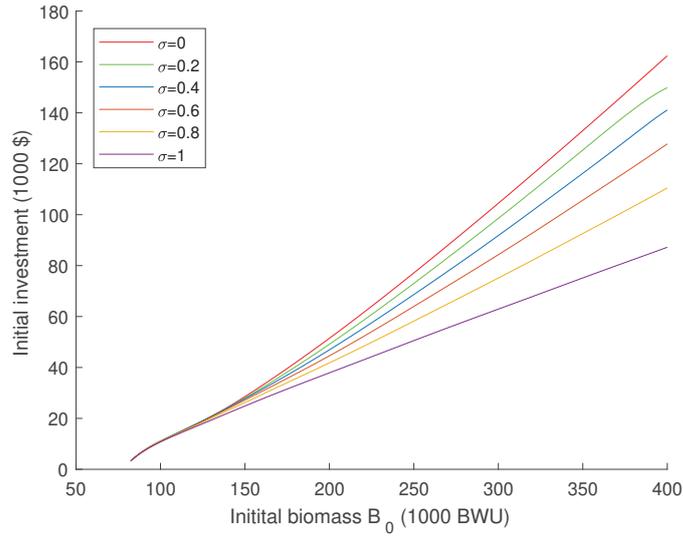
**Proposition 3.** *The better substitution possibilities are, the larger becomes the imbalance between high operating profit per unit capital at high biomass levels, and low operating profit per unit capital at low biomass levels.*

The instantaneous net rate of return on capital is increasing and convex in biomass, and increases in  $\sigma$  for all values of biomass, except at  $B^*$ , where it is independent of  $\sigma$  (see Figure 12 in the Appendix). This means that for trajectories starting at  $(B_t > B^*, K_t > K^*)$ , early harvest and operating profit are substantially larger at high values of  $\sigma$ . Income shares between labor and capital change over time for  $0 < \sigma$ , because the capital labor ratio changes. While operating profit increases in  $\sigma$  for all values of biomass larger than  $B_*$ , the income share of capital decreases in  $\sigma$  whenever  $B^* > B_t$  and vice versa. If the system remains for long in the low profitability state at a low biomass, investment incentives will be low.

### 3.3 Numerical results

To compare initial investment incentives while varying  $\sigma$ , switching curves are compared, i.e. the initial investment level as a function of initial biomass (see Figure 4). Higher levels of  $\sigma$  entail a lower switching curve. Curves with lower substitution possibilities are also steeper. This is accompanied by a higher minimum biomass under better substitution possibilities, as long

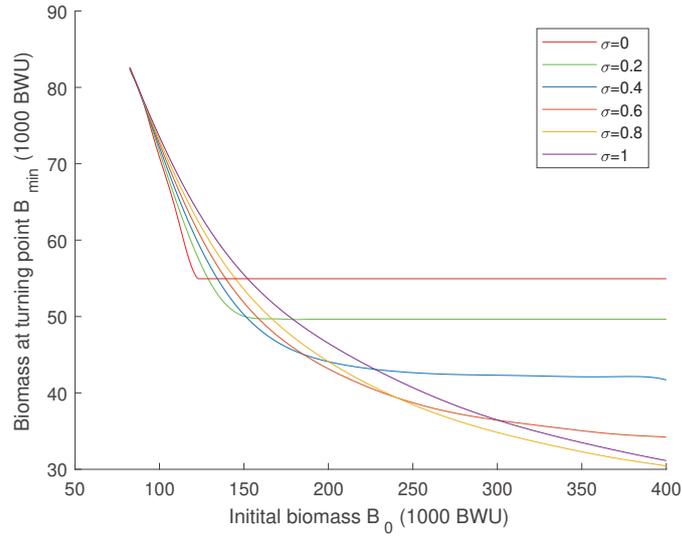
Figure 4: Open access investment switching curve for different realizations of  $\sigma$  as a function of initial biomass



as  $B_0$  is not too large (see Figure 5). Once  $B_0$  becomes very large, fishing technologies with low values of  $\sigma$  are stalled in their downward dynamics by  $B_*$  under perfect complements and by a close to vertical trap line for all other realizations of the CES function. Interestingly, this stalling does not change the sign of relative investment incentives. When trajectories under perfect complements reach  $B_*^{PC}$ , the switching curve becomes even steeper relative to the other curves. The same happens for low but positive values of  $\sigma$ , although stalling is a more gradual phenomenon here.

Time to equilibrium is slightly longer for low values of  $\sigma$ , in particular for medium levels of  $B_0$ . Thus, while minimum biomass may be far lower for example under Cobb-Douglas-technology than under perfect complements, the biomass also recovers faster due to the initially lower investment.

Figure 5: Open access minimum biomass for different realizations of  $\sigma$  as a function of initial biomass



To understand the underlying dynamics better, let us now turn to a comparison of specific trajectories and their pertaining operating profit time paths. Figure 6 compares the paths that run tangent to the perfect complements biomass level  $B_* = \frac{c}{pq}$ . These paths show the minimum initial biomass level necessary to induce investment large enough that paths with  $0 < \sigma$  reach or undercut  $B_*$ . For any higher initial biomass, minimum ensuing biomass will necessarily be smaller under  $0 < \sigma$  than under perfect complements. Under any lower initial biomass will substitution be favorable for biological sustainability (cf. Figure 5).

Figure 7 shows the associated operating profit per unit of invested capital for the time between initial investment and reaching  $B^*$ . Time paths with a high substitution elasticity start out with initially very high capital earnings,

and end up with slightly higher profit per unit of capital. By contrast, in the medium term, the shadow value gain is higher for lower realizations of  $\sigma$ . In our case, the necessary additional capital under higher substitution elasticities to fish the biomass down to the identical level will only be invested if initial profits are high enough, i.e. if initial biomass is higher. This example shows how the relative position of switching curves is driven by the distribution of profit over time. The conclusion is that when trajectories start at the same initial biomass, the possibility to substitute leads to a substantially lower profit per unit capital in the medium term that, for our example, dominate higher initial and long term earnings.

Figure 6: Paths through  $B_*^{PC} = \frac{c}{pq}$  over different values of  $\sigma$

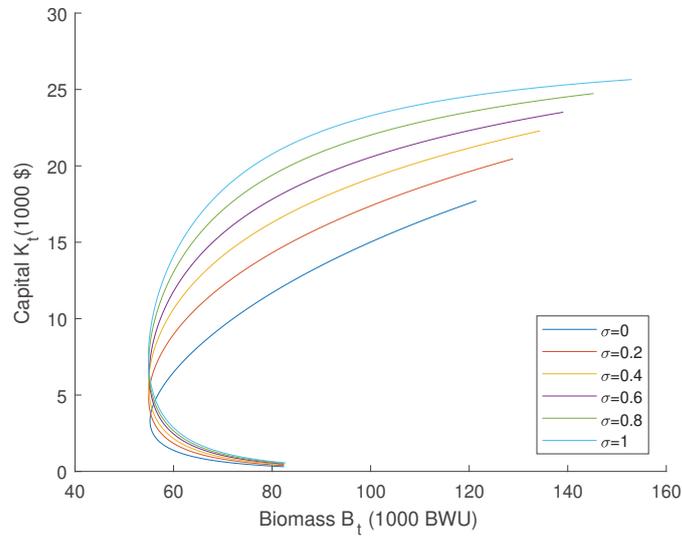
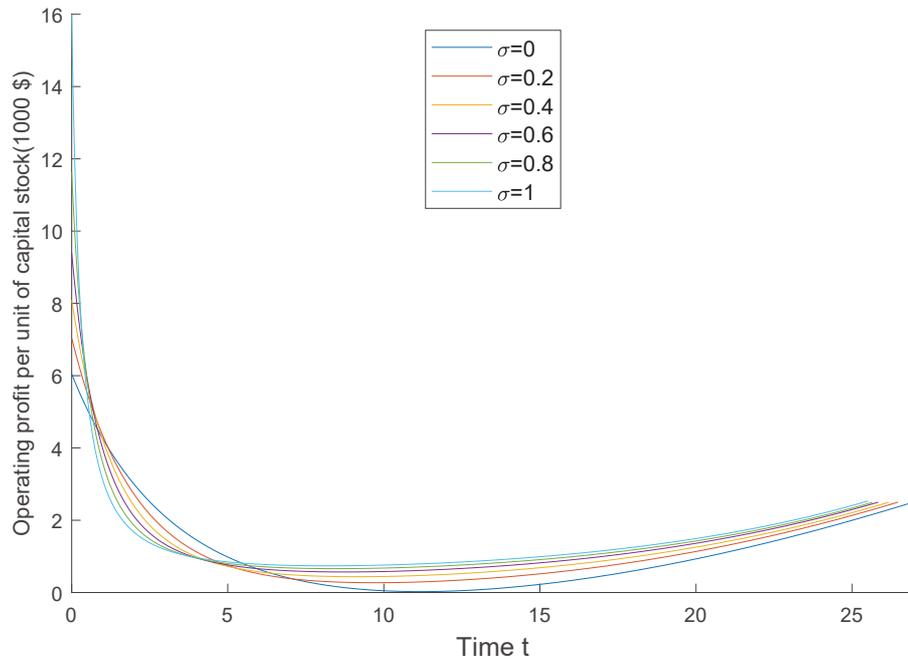


Figure 7: Current operating profit per unit of invested capital for paths through  $B_*^{PC}$  over different values of  $\sigma$



## 4 A model of an optimally managed fishery with factor substitution under irreversible investment

### 4.1 Theoretical model

In this section, optimal investment and the optimal transition paths for  $0 < \sigma \leq 1$  are derived. Consider the model with harvest production, biomass growth and prices as presented in 3.1. A tilde above the variable distinguishes

variables for the optimal case from variables for the open access case where necessary. Kuhn-Tucker-conditions with multiplier  $\tilde{\nu}_t$  are used to account explicitly for non-negativity of investment. The capital stock  $S_t$  and used capital  $K_t$  are now explicitly distinguished. The Kuhn-Tucker-multiplier  $\phi_t$  accounts for the inequality  $S_t - K_t \geq 0$ . Capital dynamics are described by  $\dot{S}_t = I_t - \delta S_t$  and enter with multiplier  $\tilde{\mu}_t$ . The current-value welfare maximizing Hamiltonian function reads (see Section A.9 for technical details):

$$\begin{aligned} \mathcal{H} &= \pi_t - \theta I_t + \tilde{\mu}_t (I_t - \delta S_t) + \phi_t (S_t - K_t) + \tilde{\nu}_t I_t + \psi (g(B_t) - G(B_t, K_t, E_t)) \\ &= p q B_t \left( \alpha K_t^{\frac{\sigma-1}{\sigma}} + (1-\alpha) E_t^{\frac{\sigma-1}{\sigma}} \right)^{\frac{\sigma}{\sigma-1}} - c E_t - \theta I_t + \tilde{\mu}_t (I_t - \delta S_t) + \phi_t (S_t - K_t) + \tilde{\nu}_t I_t \\ &\quad + \psi_t \left( g(B_t) - q B_t \left( \alpha K_t^{\frac{\sigma-1}{\sigma}} + (1-\alpha) E_t^{\frac{\sigma-1}{\sigma}} \right)^{\frac{\sigma}{\sigma-1}} \right) \end{aligned} \quad (17)$$

Optimal effort now results from a dynamic optimization process. It depends on the stock level, optimal capital used  $K_t$  and the stock shadow price  $\psi_t$ :

$$E_t(B_t, K_t, \psi_t) = \left( \frac{\alpha}{1-\alpha} \right)^{\frac{\sigma}{\sigma-1}} \left( \left( \frac{c}{(p-\psi_t)qB_t} \right)^{\sigma-1} (1-\alpha)^{-\sigma} - 1 \right)^{\frac{\sigma}{1-\sigma}} K_t \stackrel{!}{\geq} 0 \quad (18)$$

Note that in contrast to effort input under open access (3) effort is reduced by the stock shadow price. Inserting (18) back into the first order equations, leads to the following harvest function:

$$H_t(B_t, K_t, \psi_t) = q B_t \alpha^{\frac{\sigma}{\sigma-1}} \left( 1 - \left( \frac{c}{(p-\psi_t)qB_t} \right)^{1-\sigma} (1-\alpha)^{\sigma} \right)^{\frac{\sigma}{1-\sigma}} K_t \quad (19)$$

Effort and harvest depend positively on used capital  $K_t$  and biomass  $B_t$  and negatively on the stock shadow price  $\psi_t$ . Either,  $\phi_t > 0$  and  $E_t > 0$  or

$K_t = H_t = \phi_t = 0$ . Since capital cost are sunk once investment has taken place, the first case entails  $K_t = S_t$ . The following condition separates the two cases, and by that describes the “stock switching curve”:

$$\psi_t \stackrel{!}{=} p - \frac{c}{qB_t}(1 - \alpha)^{\frac{\sigma}{1-\sigma}} \quad (20)$$

If the left hand side exceeds the right hand side, harvest is zero. If the right hand side exceeds the left hand side, harvest is strictly positive. Thus, if a trajectory started at  $\psi_t > p - \frac{c}{qB_t}(1 - \alpha)^{\frac{\sigma}{1-\sigma}}$ , biomass would grow and harvest would commence only upon reaching this curve, and be positive with  $K_t = S_t$  afterwards. Condition (20) holds with equality at a stock level strictly above the open access lower stock level  $B_*$ . Below this stock size, zero harvest is optimal. We will focus on the case for which harvest is positive, which leads to the following system of differential and Kuhn-Tucker conditions (see A.6 in the Appendix for conditions in the second case, i.e.  $H_t = 0$ ):

$$\theta = \tilde{\mu}_t + \tilde{\nu}_t \text{ with } \tilde{\nu}_t \geq 0, I_t \geq 0, \tilde{\nu}_t (I_t - 0) \stackrel{!}{=} 0 \quad (21)$$

$$\dot{\tilde{\mu}}_t = (\rho + \delta) \tilde{\mu}_t \quad (22)$$

$$- (p - \psi_t) \frac{H_t(B_t, K_t, \psi_t)}{K_t} \left( 1 - \left( \frac{c}{(p - \psi_t)qB_t} \right)^{1-\sigma} (1 - \alpha)^\sigma \right) \quad (23)$$

$$\dot{\psi}_t = \psi_t (\rho - g'(B_t)) - (p - \psi_t) \frac{H_t(B_t, K_t, \psi_t)}{B_t} \quad (24)$$

$$\dot{S}_t = I_t - \delta S_t \quad (25)$$

In the optimal steady state with positive harvest, depreciated capital is exactly replaced, such that  $\tilde{\nu}_t = 0$  and the shadow value of capital equals the

buying price of capital  $\theta$ . Stock growth equals harvest. Fishing is optimal if the own rate of interest of the stock, including marginal growth and the stock effect, equals the social discount rate. The corresponding steady state biomass level is defined by the Golden rule:

$$g'(\tilde{B}^*) + \frac{g(\tilde{B}^*)}{\tilde{B}^*} \frac{(((\rho + \delta)\theta)^{1-\sigma} \alpha^\sigma + c^{1-\sigma} (1-\alpha)^\sigma)^{-\frac{1}{\sigma-1}}}{pqB_t - (((\rho + \delta)\theta)^{1-\sigma} \alpha^\sigma + c^{1-\sigma} (1-\alpha)^\sigma)^{-\frac{1}{\sigma-1}}} = \rho \quad (26)$$

The corresponding steady-state capital stock is given by:

$$\tilde{K}^* = \frac{g(\tilde{B}^*)}{q\tilde{B}^*} \alpha^{\frac{\sigma}{1-\sigma}} \left( 1 - \left( \frac{c}{(p - \tilde{\psi}_*)q\tilde{B}^*} \right)^{1-\sigma} (1-\alpha)^\sigma \right)^{\frac{\sigma}{\sigma-1}} \quad (27)$$

with

$$\tilde{\psi}_* = p - \frac{1}{q\tilde{B}^*} (((\rho + \delta)\theta)^{1-\sigma} \alpha^\sigma + c^{1-\sigma} (1-\alpha)^\sigma)^{\frac{1}{1-\sigma}} \quad (28)$$

Solving (22) would provide a function for the investment switching curve. This curve defines the points where biomass is higher than the steady state biomass,  $\tilde{\mu}_t = \theta$ , and investment is zero after the initial jump along the trajectory until reaching the steady state from below. Due to the non-linearities stemming from the shadow price for biomass in (22) and from the non-linear nature of harvest production, this problem does not have a closed-form solution. Compared to the same differential equation under open access, the capital shadow price development is reduced by an expression for the shadow price of the stock  $\psi_t$ . A larger stock shadow value reduces the shadow price of capital. Since biomass is bounded by its carrying capacity, investment is bounded as well. We will subsequently assume that for trajectories emanating from  $B_0 > \tilde{B}^*$ , investment behavior will be similar to that under perfect complements in that one initial jump occurs, and investment is subsequently zero until the steady state is reached. This is an awkward assumption and

owing to the complicated dynamics in the model under optimal management. However, it is plausible that this particular behavior is similar as under perfect complements. It also makes sense from a logical perspective: As long as biomass is below the steady state level  $\tilde{B}^*$ , the optimal solution under malleable capital would be a harvest moratorium to increase biomass to its long-term level as fast as possible. Above  $\tilde{B}^*$ , the switching curve increases in  $B_0$ , and investment exceeds the equilibrium level. Biomass will decrease afterwards. From the investment switching curve, the path would not continue horizontally (with positive investment), because that would mean there is a point after which investment is no longer positive, but this point lies strictly above the investment switching curve. This is not possible by definition of the investment switching curve.

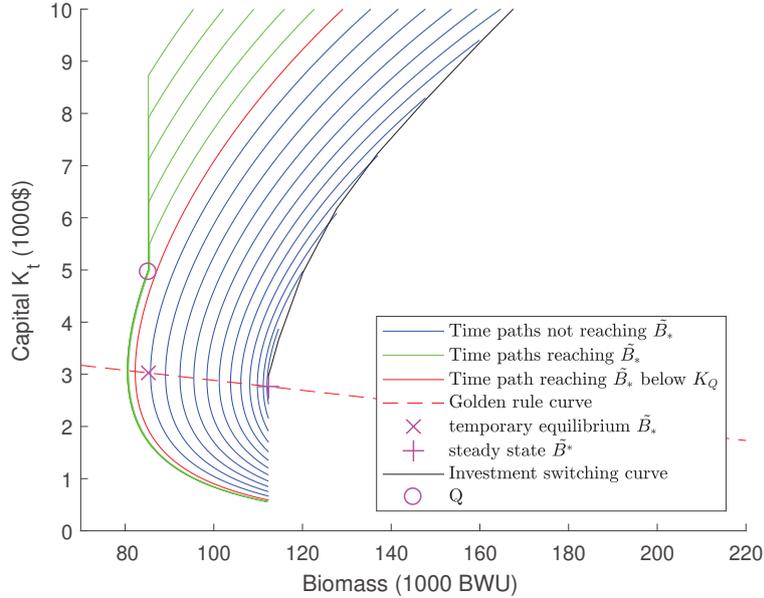
## 4.2 Qualitative comparison

For the following comparison, the text will refer to Figure 8 and Figure 9, that show transition paths for an initial biomass starting above  $\tilde{B}^*$ . We show here the perfect complements case (see Section A.7 in the Appendix for a Hamiltonian derivation of perfect complements results) and  $\sigma = 0.6$  as an example for behavior under a strictly positive substitution elasticity between effort and capital. Figures showing the time paths of capital shadow value  $\tilde{\mu}_t$  emanating from the investment switching curve are provided in A.10. Since the intention is to show all qualitative differences, the depreciation rate is slightly decreased and set equal to  $\delta = 0.1$  only for the sake of these two figures<sup>10</sup>. The figures show also trajectories that emerge from the stock

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<sup>10</sup>Under the standard parametrization,  $\delta = 0.15$ . Then, perfect complements trajectories do not reach the important point  $Q$ , which will be discussed below, for any level of  $B_0 < CC$ .

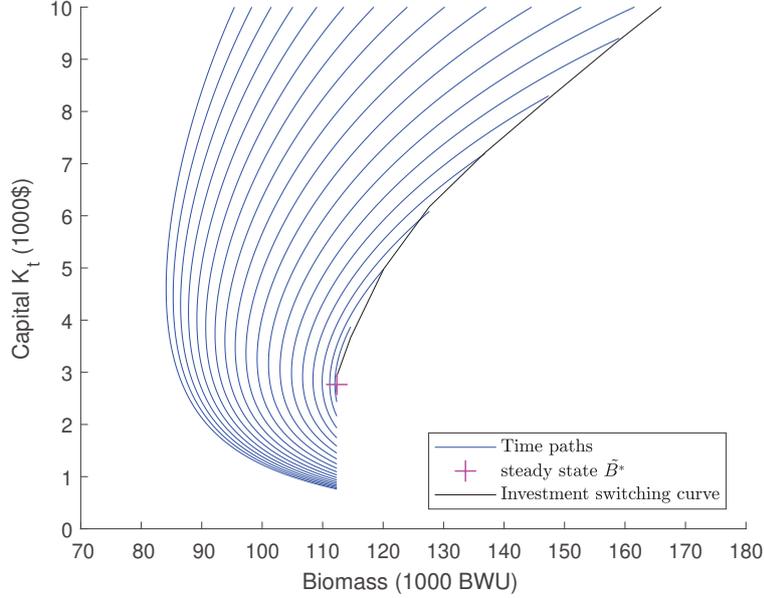
Figure 8: Stock-capital-transition paths under optimal management,  $\sigma=0$



switching curve, where initial capital is exogenously above the stock switching curve at the beginning. The Golden rule curve is also shown for perfect complements, which coincides with the trap curve under open access. The figures will be explained as the comparison proceeds.

Qualitative differences arise in particular concerning the turning point, where biomass starts to grow again. Using (16) in (26) and (A.53) shows that upper Golden rule biomass levels as well as the corresponding equilibrium capital levels are equal across  $0 \leq \sigma \leq 1$  under the standard normalization given by (16). Comparing this with the open access levels, optimal management requires a higher biomass and a lower capital stock. The optimal steady state thus lies at a point strictly below the open access investment switching curve.

Figure 9: Stock-capital-transition paths under optimal management,  $\sigma=0.6$



**Proposition 4.** *The optimal steady state requires a higher biomass and a lower capital stock than the steady state under open access.*

Under perfect complements, and if the initial capital stock is large enough, the system approaches a short-term steady state at the lower level Golden Rule stock  $\tilde{B}_*$ . The lower level Golden rule only differs from the upper Golden rule level (A.53) in setting  $\theta = 0$ . The stock switching curve, i.e. the curve that gives the level of biomass below which a harvesting moratorium is optimal, meets this lower Golden rule level at the point  $(\tilde{B}_*, \tilde{K}_*)$  for non-malleable capital ( $\delta = 0$ ) and above this at some point  $(\tilde{B}_*, \tilde{K}_Q)$  named  $Q$  for quasi-malleable capital ( $\delta > 0$ ). Below point  $Q$ , the stock switching curve lies to the left of this level, such that a moratorium is optimal above  $K_Q$ . Once capital has depreciated enough, a kink occurs at point  $Q$ , followed by

a leftwards curve before the trajectories turn and biomass is restored to its long-term steady state. Due to this kink, transition paths are identical from  $Q$  on-wards, and lead to identical capital levels upon reaching  $\tilde{B}^*$ .

Figure 8 shows that under perfect complements, three different types of trajectories can emerge from  $B_0 > \tilde{B}^*, K_0 > \tilde{K}^*$ . Blue lines mark those trajectories that do not reach  $\tilde{B}_*$  and continue smoothly towards the long term steady state. One red path shows that it is possible that a path meets  $\tilde{B}_*$  below point  $Q$ , defined as the intersection point of the stock switching curve and  $\tilde{B}_*$ , and then continues on smoothly. The green paths exhibit a kink: They run into the fix lower Golden rule level  $\tilde{B}_*$ , continue vertically until  $Q$ , before they all follow an identical path towards  $\tilde{B}^*$ . Hence, at point  $Q$ , the trajectories directly reach the stock switching curve.

By contrast, this can not happen if capital and effort are imperfect complements. The social planner has the leniency to determine optimal harvest independently from the capital stock  $S_t$ . She does so by using all capital available, and adapting effort input. Therefore, there is no excess capital as long as harvest is positive, which is different from the perfect complements case. Capital is never unused along the trajectories, and  $\tilde{\mu}_t$  does not fall to zero (which is the case under perfect complements). Therefore, we may not simply disregard investment cost and derive some lower steady state level, as presented in Clark et al. (1979) for the perfect complements case<sup>11</sup>. Paths are always smooth<sup>12</sup>, no lower short term steady state occurs.

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<sup>11</sup>This operation actually requires a steady state in which  $\tilde{\mu}_t = \theta 0$ , which is then set to zero.

<sup>12</sup>Due to the smooth nature of trajectories with  $0 < \sigma$ , programming is again reduced to a single region problem (see Section A.8), instead of a two case distinction with three regions in case the lower level Golden rule stock is reached, that is needed to solve the

This has one more implication for the trajectories. Under  $0 < \sigma$ , in the immediate vicinity of the stock switching curve, harvest is infinitesimally small. Therefore, the stock switching curve can only be met by trajectories if, along the trajectories, harvest goes to zero. However, in that case, the trajectory turns already before, at a higher biomass level.

**Proposition 5.** *Turning occurs strictly to the right of the stock switching curve for  $0 < \sigma$ . Trajectories under perfect complements meet the stock switching curve at point  $Q$ , if the initial biomass is high enough.*

Under  $\sigma > 0$ , the optimal turning point biomass level depends on  $t$ , as is subsequently denoted by  $\tilde{B}_{t^*}$ . This can be shown by setting  $\dot{B}_t = 0$ , inserting (23), and solving for  $S_t$  as a function of  $B_t$ , to derive the analogue for the trap curve under open access. This function encompasses all capital stock levels for which  $S_t > \tilde{S}^*$  and their corresponding Golden Rule turning point stock level,  $\tilde{B}_{t^*} < \tilde{B}^*$ . Thus, it must also pass through  $\tilde{B}^*$ .

Under perfect complements, it was possible to find the lower Golden rule stock level by setting  $\dot{\psi}_t = 0$  due to the fact that capital was actually in excess, and the biomass level did constitute an actual steady state for some time whenever a trajectory met this biomass level at a high capital level. The trap curve did not depend on the shadow price of the stock at all, because harvest fully depends on capital. In the case where capital can substitute for flexible inputs, there is no excess capital, and it is not feasible to set the time derivative of the stock shadow price to zero, since the level of used capital changes throughout the trajectory. In addition, the social planner can now decide on capital input and harvest separately. This entails that harvest always depends on  $\psi_t$ . Therefore, (29) depends on the time derivative of  $\psi_t$

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perfect complements problem.

at the turning point, which must be negative, since capital decreases and biomass is constant.

$$\tilde{S}_{GR} = \alpha^{\frac{\sigma}{1-\sigma}} \frac{g(\tilde{B}_{t^*})}{q \tilde{B}_{t^*}} \quad (29)$$

$$\left( 1 - (1 - \alpha)^\sigma \left( \frac{c}{p q \tilde{B}_{t^*}} \right)^{1-\sigma} \left( \frac{p \left( \rho - g'(\tilde{B}_{t^*}) + \frac{g(\tilde{B}_{t^*})}{\tilde{B}_{t^*}} \right)}{p(\rho - g'(\tilde{B}_{t^*})) - \dot{\psi}_{GR}} \right)^{1-\sigma} \right)^{\frac{\sigma}{\sigma-1}}$$

If capital is perfectly non-malleable,  $\dot{\psi}_t = 0$ . If the system starts at  $B_0 > \tilde{B}^*$ , it approaches a steady state biomass  $\tilde{B}_* < \tilde{B}^*$ . The Golden rule curve (29) for  $\delta = 0$  is downward sloping and convex in biomass. For  $\delta = 0$ , it lies strictly above the curve for  $\delta > 0$  due to  $\dot{\psi}_{GR} < 0$ : If capital depreciates, future capital scarcity would lead to an even lower turning biomass than for  $\delta = 0$ . The same result holds under perfect complements.

## 5 Over-capitalization

Over-capitalization is defined as the employment of capital at a level above the optimal level. Now that investment levels under open access and under optimal management have been computed, a comparison of the two sheds light on the extent of over-capitalization. The analysis focuses on the case where capital is quasi-malleable.

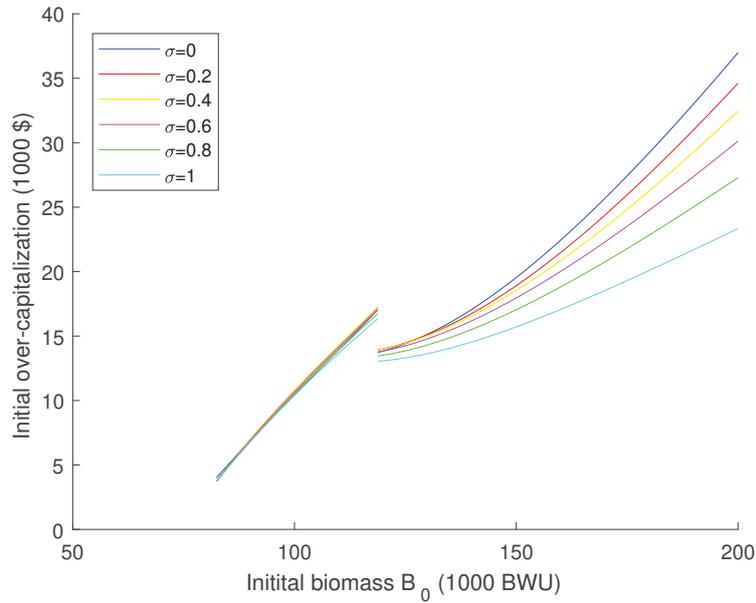
As noted in section 4.1, over-capitalization is present in the open-access steady state: The optimal steady state requires a higher biomass and a lower capital level than the open-access steady state. Over-capitalization, and associated over-fishing, is caused by the common pool resource nature of wild fish. Irreversibility is not an issue since investment is positive in steady state.

If the system started out at biomass levels above the open access steady state, and investment was reversible, the open access capital level would shortly overshoot the steady state level, but return to the steady state level once the stock was fished down. However, when accounting for irreversible investment, the investment switching curve determines initial investment and thus capital levels throughout the transition to the steady state. This transition takes longer than without this additional constraint, and involves that the biomass is temporarily fished down to levels below even the open access steady state. A similar analysis applies to the system under optimal management. While in steady state, investment is positive. Starting at a higher biomass leads to optimal investment above the optimal steady state capital level. As was already pointed out in the previous literature, the irreversibility constraint is costly to overall welfare, because of the gradual transition towards the steady state.

Using the numerical results, one can compare the investment switching curves under different levels of complementarity. Figure 10 shows the difference between investment switching curves for starting biomass levels between the open access steady state and 200kt (curves continue on up to  $CC$ ). Investment is too high for all levels of  $\sigma$  under all levels of starting biomass above the open access steady state,  $B^* < B_0$ . Between the open-access and optimal steady states, the difference between complementarity levels is minor. The difference grows larger for initial biomass levels above the optimal steady state. Initial over-capitalization decreases in  $\sigma$ . This results from decreasing investment incentives under open access. The higher the starting biomass level, the higher is over-capitalization. On the other hand, numerical results show that optimal investment is very similar under all levels of complementarity.

**Proposition 6.** *Investment is too high for all levels of  $\sigma$  under all levels of starting biomass above the open access steady state,  $B^* < B_0$ . In our example and if the system is normalized to equal steady states for  $0 \leq \sigma \leq 1$ , initial over-capitalization decreases in  $\sigma$ .*

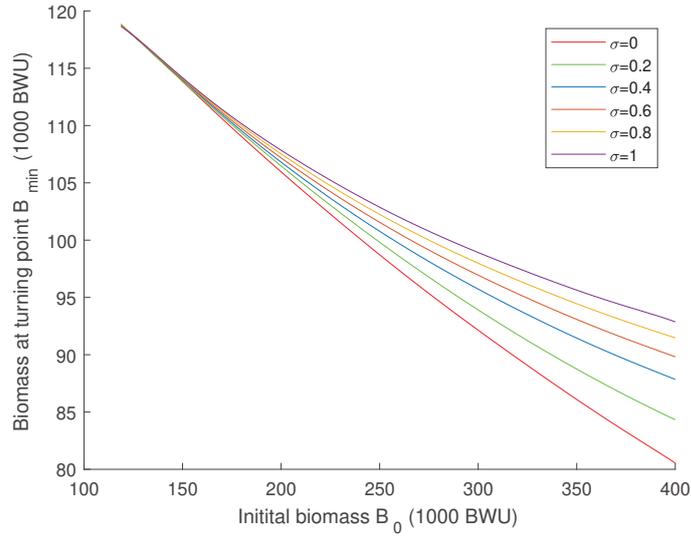
Figure 10: Absolute initial over-capitalization for different realizations of  $\sigma$  as a function of initial biomass



**Proposition 7.** *Minimum biomass attained during transition is higher under optimal management than under open access, if over-capitalization occurs and the optimal steady state lies below the maximum sustainable yield biomass.*

However, initial over-capitalization is only part of the problem. With

Figure 11: Optimal management minimum biomass for different realizations of  $\sigma$  as a function of initial biomass



irreversible investment, invested capital stays in the fishery for long time horizons. Thus, it is also important to look at transition paths. A comparison of effort levels under open access (3) and optimal management (18) shows that the latter is reduced by the shadow price of the stock. If capital and biomass levels were equal across levels of  $\sigma$ , harvest would be lower under optimal management. When in addition, initial capitalization is higher under open-access and the optimal steady state lies below the maximum sustainable yield, as is the case in our example, this means that the minimum biomass attained during transition must be lower under open access. This result is also visible from a comparison of Figures 5 and 11. This finding entails that the system remains over-capitalized, in the sense that for the associated biomass level, capital is higher than it would be under optimal management,

until after the open access trajectory turns and biomass starts growing again, i.e. for most of the transition path.

## 6 Conclusion

In open-access fisheries, over-fishing occurs because fishers' do not take into account the stock externality. They employ more capital than would be optimal, as long as the biomass level is high enough. The problem is complicated by imperfect malleability of capital in fisheries. This article set out to analyze qualitative and quantitative differences of this over-capitalization problem for different levels of complementarity between the irreversibly invested capital and flexibly adaptable inputs.

The major qualitative difference between different levels of complementarity is that whenever substitution is possible, invested capital will always be fully used. Harvest is flexibly adapted via effort input. Therefore, under both open access and optimal management, transition paths starting at a biomass level above the steady state, are smooth until at last, an upward jump in investment occurs once biomass has reached its steady state level. Trajectories turn strictly before reaching the level of the resource stock where operating profit goes to zero under open access. Factor substitution also alters the relationship between capital and biomass. The better the substitution possibilities, the larger becomes the imbalance between high profits per unit capital at high biomass levels, and low profits per unit capital at low biomass levels. The shadow value of investment at the beginning is lower: Fishers perceive that the system remains for long in a low profitability state, and invest less. According to numerical results, investment incentives are lower when complementarity is imperfect. Under optimal management, the

regulator can separately manage harvest and capital if substitution is possible. In our example, over-capitalization at any level of starting biomass above the long-term equilibrium is higher, the less substitution possibilities exist. This results from higher investment incentives.

These results are relevant for policymakers: A fishery may be economically under-exploited, for example due to a regime shift, a sudden change in policy – such as the introduction of an ongoing subsidy – or because the fishery wasn't developed formerly, such as the large mesopelagic biomass. Our results can help to prevent initial over-capitalization, and indicate that the risk of over-capitalization is particularly high when substitution possibilities are lacking.

Further research is required to understand over-capitalization better. Since the “Global fishing watch” project (Kroodsma et al., 2018) has started, information on capital involved in fishing has improved, which opens new possibilities for more detailed empirical analysis. Concerning theoretical analysis, the model can in the future be extended to a spatial model with more than one stock, such that fishers or the social planner can decide upon where to use invested capital. Furthermore, other inputs, in particular human capital, may not be perfectly malleable as well (Clark et al., 2005). The recent literature focuses on the inclusion of environmental effects. An important contribution would be the analysis of substitution when environmental seasonality causes the system to be periodic in steady state.

## Appendix

### A.1 A model of an open access fishery under perfect complements and quasi-malleable capital (McKelvey, 1985)

The following analysis is identical to (McKelvey, 1985). We shortly present the Hamiltonian derivation here for reference in the main text. Assume that capital  $K_t$  is non- or quasi-malleable and depreciates linearly at rate  $0 \leq \delta \leq 1$ . Under a Schäfer model (Schäfer, 1957) with a bell-shaped logistic growth curve for biomass:

$$g(B_t) = z B_t \left(1 - \frac{B_t}{CC}\right) \quad (\text{A.30})$$

with natural growth rate  $0 < z$  and carrying capacity  $CC$ , as well as a production function that is linear in biomass  $B_t$  and underlies a perfect-complements-constraint for the input of effort  $E_t$  and capital  $K_t$  with unit prices  $c$  and  $\theta$  respectively. Fishers dynamically maximize profit subject to the disinvestment constraint and capital dynamics. In their optimization, they take the future path of biomass as given, such that investment and harvesting patterns arise as the equilibrium between fishers' interaction. Let  $0 \leq \rho \leq 1$  denote the social discount rate. The shadow value of capital is denoted by  $\mu_t$ , and  $\nu_t$  is the shadow price of disinvestment, or the value of relaxing the non-negativity constraint by one unit. The following Kuhn-Tucker-condition and two dynamic differential equations follow from Hamiltonian first order conditions:

$$\theta = \mu_t + \nu_t \text{ with } \nu_t \geq 0, I_t \geq 0, \nu_t (I_t - 0) \stackrel{!}{=} 0 \quad (\text{A.31})$$

$$\dot{K}_t = I_t - \delta K_t \quad (\text{A.32})$$

$$\dot{\mu}_t = (\rho + \delta) \mu_t - \frac{\pi_t}{K_t} = (\rho + \delta) \mu_t - (pqB_t - c) \quad (\text{A.33})$$

In addition, stock dynamics are given by:

$$\dot{B}_t = g(B_t) - H_t(B_t, E_t, K_t) = zB_t \left(1 - \frac{B_t}{CC}\right) - qB_tK_t \quad (\text{A.34})$$

The long term steady state occurs at:

$$\pi_t = q B_t (K_t, E_t) - c E_t - (\rho + \delta) \theta K_t \stackrel{!}{=} 0 \quad (\text{A.35})$$

$$\Leftrightarrow B^* = \frac{c + (\rho + \delta)\theta}{p q} \quad (\text{A.36})$$

$$\Rightarrow K^* = \frac{z}{q} B^* \left(1 - \frac{B^*}{CC}\right) \quad (\text{A.37})$$

The biomass level at which operating profit is zero is given by

$$B_* = \frac{c}{pq} \quad (\text{A.38})$$

The trap line is given by

$$K_{TL}(B_t) = \frac{z}{q} \left(1 - \frac{B_{TL}}{CC}\right) \quad (\text{A.39})$$

The intercept of  $B_*$  and the trap line occurs at  $K_* = \frac{z}{q} \left(1 - \frac{B_*}{CC}\right)$ .

Under open access starting at a biomass level above the long-term steady state, fishers initially invest capital according to the “switching curve” (unless initial capital is already at or above this level) at investment time  $\tau$ :

$$\mu_\tau = \int_\tau^\infty \frac{pqB_t - c}{K_t} e^{-(\rho+\delta)(t-\tau)} dt \stackrel{!}{=} \theta \quad (\text{A.40})$$

The interpretation is that investment lies at its optimal level if the shadow value of capital equals the unit price for capital.

## A.2 Standard parametrization

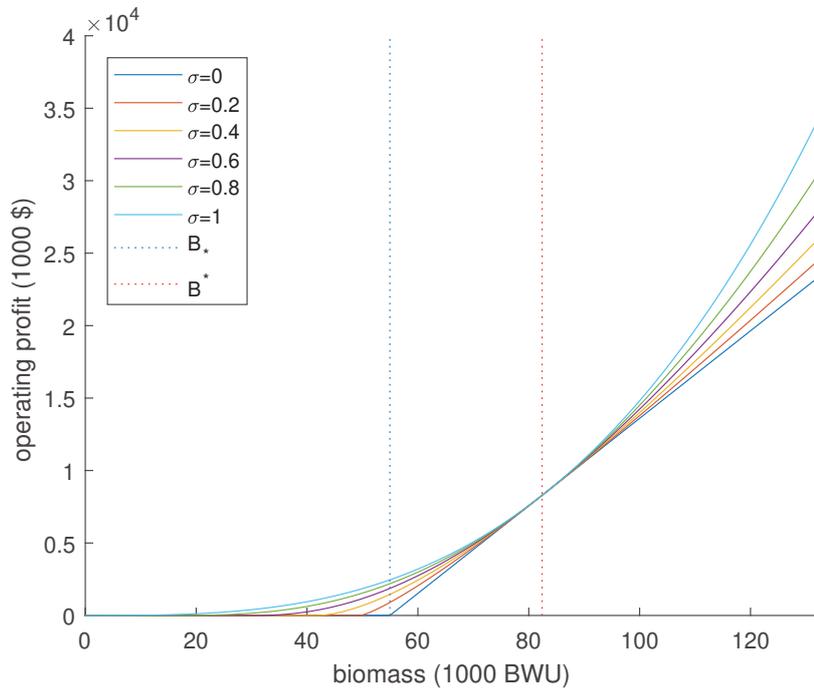
I use the example from Clark and Lamberson (1982) to compare our CES specification with the perfect complements case most often covered in the literature. The example is about Antarctic pelagic whaling in the 20th century and is used also as the example for irreversible investment in the textbook by Clark (1990) and has been reused for illustration by Eisenack et al. (2006). Thus, this has become the standard example in the literature and provides a convenient reference point. The parametrization is presented in Table 2:

Table 2: Parametrization for the irreversible investment model from Clark and Lamberson (1982):

Original parameter name	Parameter name	Parameter value	Parameter definition	unit of measurement
$X_t$	$B_t$	–	whale stock at time $t$	blue whale units <sup>13</sup>
$K_t$	$K_t$	–	capital used at time $t$	factory units (factory and catcher vessel) per catcher day
$E_t$	$E_t$	–	effort used at time $t$	catcher days
$r$	$z$	0.05	natural growth rate	–
$K$	$CC$	400000	carrying capacity	BWU
$q$	$q$	0.000013	catchability	–
$p$	$p$	7000	price per blue whale unit	\$/BWU
$c$	$c$	5000	variable cost per unit of effort	\$/catcher day
$\frac{c_i}{\alpha}$	$\theta$	10000	buying price of capital	\$/per capital unit
$\delta$	$\rho$	0.1	discount rate	–
$\gamma$	$\delta$	0.15	depreciation rate	–

### A.3 Figure: Operating profit under different levels of $\sigma$

Figure 12: Operating profit  $\pi_t$  over biomass for different levels of  $\sigma$  at  $K_*$



### A.4 Implementation in Matlab: Open access

To compute results under perfect complement, implementation in Matlab is achieved using the boundary value problem solver `bvp5c` in a three-region-setting (multi-point boundary value problem). Implement the model by use

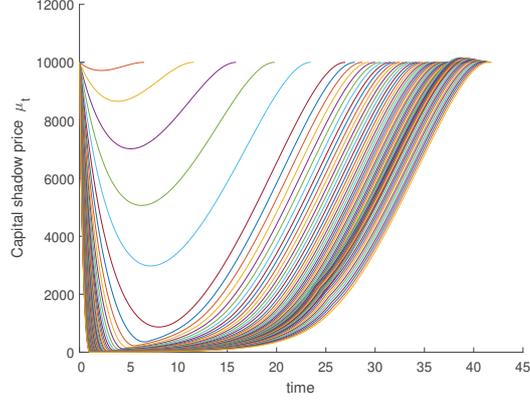
of three ordinary differential equations for biomass, capital and the shadow price of capital. The multi-point formulation is needed due to the nonlinearities in the differential equations at the two points where lower level steady state biomass is achieved and left again. These two points in time form the boundaries of the first two regions. The third region is identical for all transition paths that reach the lower steady state level and encompasses the transition from lower level steady state up to upper level steady state biomass. Boundary conditions are initial capital and capital shadow price values as well as final shadow price and smoothing conditions for the transition between regions. A fourth boundary condition, namely that the biomass path ends at  $B^*$ , is used to solve for the correct time horizon. Since this has to be done twice in the multi-point setting, namely for the first and last region's time horizon, this is costly in terms of both accuracy of the numerical solution and computation time. The solver starts in the immediate vicinity of the long-term equilibrium. The program iterates outwards and updates the initial guess for the solution with each step.

A major difference of production functions with  $\sigma > 0$  is that this multi-point solution procedure is no longer required, and only one time horizon needs to be solved for. The numerical implementation in Matlab is done straightforward using the `bvp5c` solver. A regional implementation using a multi-point formulation is no longer necessary. Apart from this, programming proceeds as explained above.

## **A.5 Capital shadow price development under open access**

The following Figures, 13 and 14, are the paths of  $mu_t$  corresponding to Figures 2 and 1, respectively.

Figure 13: Capital shadow price  $\mu_t$  for  $\sigma = 0$  under open access



## A.6 Conditions for the optimal management case and in case $H_t = 0$

The following Hamiltonian first-order conditions and Kuhn-Tucker conditions describe the system under optimal management for  $\sigma > 0$  in case  $\psi_t > p - \frac{c}{qB_t}(1 - \alpha)^{\frac{\sigma}{1-\sigma}}$ :

$$\theta = \tilde{\mu}_t + \tilde{\nu}_t \text{ with } \tilde{\nu}_t \geq 0, I_t = 0 \quad (\text{A.41})$$

$$\dot{\tilde{\mu}}_t = (\rho + \delta) \tilde{\mu}_t \quad (\text{A.42})$$

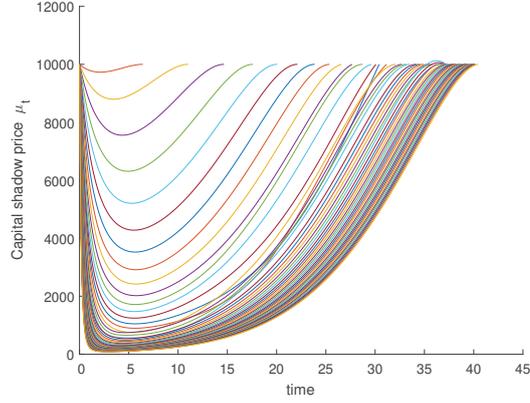
$$\dot{\psi}_t = \psi_t (\rho - g'(B_t)) \quad (\text{A.43})$$

$$\dot{S}_t = -\delta S_t \quad (\text{A.44})$$

$$\dot{B}_t = g(B_t) \quad (\text{A.45})$$

$$(\text{A.46})$$

Figure 14: Capital shadow price  $\mu_t$  for  $\sigma = 0.6$  under under open access



### A.7 A model of an optimally managed fishery under perfect complements and quasi-malleable capital (Clark et al., 1979)

The following analysis is identical to (Clark et al., 1979). We shortly present the Hamiltonian derivation here for reference in the main text. The current-value welfare maximizing Hamiltonian function reads:

$$\begin{aligned}
 \mathcal{H} &= \pi_t - \theta I_t + \tilde{\mu}_t (I_t - \delta K_t) + \nu_t I_t + \psi (g(B_t) - G(B_t, K_t, E_t)) \\
 &= (p q B_t - c) K_t - \theta I_t + \tilde{\mu}_t (I_t - \delta K_t) + \nu_t I_t + \psi_t \left( z B_t \left( 1 - \frac{B_t}{CC} \right) - q B_t K_t \right)
 \end{aligned}
 \tag{A.47}$$

The system is characterized by one Kuhn-Tucker-condition and four dif-

differential equations:

$$\dot{\theta} = \tilde{\mu}_t + \nu_t \quad (\text{A.48})$$

$$\dot{\tilde{\mu}}_t = (\rho + \delta) \tilde{\mu}_t - ((p - \psi_t) q B_t - c) \quad (\text{A.49})$$

$$\dot{\psi}_t = \psi_t \left( \rho - g'(B_t) + \frac{H_t}{B_t} \right) - p \frac{H_t}{B_t} \quad (\text{A.50})$$

$$\dot{K}_t = I_t - \delta K_t \quad (\text{A.51})$$

$$\dot{B}_t = g(B_t) - H_t \quad (\text{A.52})$$

In steady state, fishers should invest exactly the amount of capital that depreciates in the same period. The shadow value of capital equals the price for capital, and the shadow value of the stock equals marginal profit from one unit of harvest.

The long-term Golden rule biomass level  $\tilde{B}^*$  is determined by:

$$g'(\tilde{B}^*) + g(\tilde{B}^*) \frac{c + (\rho + \delta)\theta}{(pq\tilde{B}^* - (c + (\rho + \delta)\theta)) \tilde{B}^*} = \rho \quad (\text{A.53})$$

Fishing is optimal if the own rate of interest of the stock, including marginal growth and the stock effect, equals the social discount rate.

For the short term equilibrium, disregard capital cost and arrive at a lower level Golden rule biomass  $\tilde{B}_*$ :

$$g'(\tilde{B}_*) + g(\tilde{B}_*) \frac{c}{(pq\tilde{B}_* - c) \tilde{B}_*} = \rho \quad (\text{A.54})$$

Clark et al. (1979) demonstrated a premature-switching phenomenon below the lower level Golden rule stock. Fishing may be optimal below that level, because the abundance of capital is strictly temporary, and the coming capital shortage, leading to lower than optimal harvesting, is anticipated. The expression for the stock switching curve is derived for biomass levels

below  $\tilde{B}_*$ , setting  $\theta = 0$ . Consider trajectories start on the curve at time  $\tau_s$ . Then, the stock switching curve is defined by:

$$\psi_{\tau_s} \stackrel{!}{=} p - \frac{c + (\rho + \delta) \theta}{q B_t} \quad (\text{A.55})$$

The interpretation is that the current benefit of harvesting one unit of stock (left hand side) equals future benefits of one unit of stock (right hand side). Harvesting is optimal to the right of this increasing and concave curve. For quasi-malleable capital,  $\delta > 0$ , Clark et al. (1979) was able to prove that (A.55) meets  $\tilde{B}_*$  at point  $Q$  with  $K_Q > \tilde{K}_*$ .

## A.8 Implementation in Matlab: Optimal management

Programming of the perfect complements case proceeds as follows: First, the stock switching-curve is determined using differential equations for  $B_t$ ,  $K_t$ ,  $\tilde{\mu}_t$  and  $\psi_t$ . Initial biomass and biomass shadow price, as well as end values for the two shadow values provide boundary conditions. The time horizon is determined using  $B_T = \tilde{B}^*$ . This approach provides the point  $Q$  where the stock switching curve and the lower Golden rule level intercept.

For the transition paths starting from  $B_0 > \tilde{B}^*$ , that are used to derive the investment switching curve, a two-case distinction is necessary. In case the transition path never reaches points with  $B_t = \tilde{B}_*$  and  $K_t \geq K_Q$ , the implementation is a straightforward single-region boundary value problem. In all other cases, a three-region multi-point programming is used. The first region switch occurs when the short term steady state stock level  $\tilde{B}_*$  is reached ( $T_1$ ). The second switch at time  $T_2$  occurs in point  $Q$  and the path ends at the long-term steady-state biomass  $\tilde{B}^*$  in  $T_3$ .

Boundary conditions in addition to those defining the three time hori-

zons include  $K_0$  (exogenous),  $\tilde{\mu}_0 = \theta$ ,  $\tilde{\mu}_T = \theta$  and  $\psi_T = p - \frac{(c+(\rho+\delta)\theta)}{q\tilde{B}^*}$  and smoothing conditions for all four differential equations. Note that using starting capital instead of starting biomass as exogenous does not alter the solution, but allows to determine  $T_2$  immediately using  $K_Q = e^{-\delta T_2} K_0$ . This saves computation time.  $T_1$  and  $T_3$  again have to be determined with multiple iterations as described above using the additional boundary condition  $B_{T_3} = \tilde{B}^*$ .

For the programming of all cases where  $0 < \sigma$ , a single-region problem results. Programming to derive the two switching curves and associated trajectories proceeds similar to the single region case under perfect complements.

## A.9 Differential equations under CES optimal management

The Hamiltonian first order conditions and Kuhn-Tucker-conditions are:

$$\frac{\partial \mathcal{H}}{\partial I_t} = -\theta + \tilde{\mu}_t + \tilde{\nu}_t \stackrel{!}{=} 0 \quad (\text{A.56})$$

$$\text{with } \tilde{\nu}_t \geq 0, I_t \geq 0, \tilde{\nu}_t (I_t - 0) \stackrel{!}{=} 0$$

$$\frac{\partial \mathcal{H}}{\partial E_t} = (p - \psi_t) q B_t \left( \alpha K_t^{\frac{\sigma-1}{\sigma}} + (1 - \alpha) E_t^{\frac{\sigma-1}{\sigma}} \right)^{\frac{1}{\sigma-1}} (1 - \alpha) E_t^{-\frac{1}{\sigma}} - c \stackrel{!}{=} 0$$

$$\frac{\partial \mathcal{H}}{\partial K_t} = (p - \psi_t) q B_t \left( \alpha K_t^{\frac{\sigma-1}{\sigma}} + (1 - \alpha) E_t^{\frac{\sigma-1}{\sigma}} \right)^{\frac{1}{\sigma-1}} \alpha K_t^{-\frac{1}{\sigma}} - \phi_t \stackrel{!}{=} 0$$

$$\frac{\partial \mathcal{H}}{\partial S_t} = \phi_t - \delta \tilde{\mu}_t \stackrel{!}{=} \rho \tilde{\mu}_t - \dot{\tilde{\mu}}_t$$

$$\text{with } \phi_t \geq 0, S_t - K_t \geq 0, \phi_t (S_t - K_t) \stackrel{!}{=} 0$$

$$\frac{\partial \mathcal{H}}{\partial B_t} = (p - \psi_t) q \left( \alpha K_t^{\frac{\sigma-1}{\sigma}} + (1 - \alpha) E_t^{\frac{\sigma-1}{\sigma}} \right)^{\frac{\sigma}{\sigma-1}} + \psi_t z \left( 1 - 2 \frac{B_t}{CC} \right) \stackrel{!}{=} \rho \psi_t - \dot{\psi}_t$$

$$\frac{\partial \mathcal{H}}{\partial \tilde{\mu}_t} = I_t - \delta S_t \stackrel{!}{=} \dot{S}_t \quad (\text{A.57})$$

$$\frac{\partial \mathcal{H}}{\partial \psi_t} = z B_t \left( 1 - \frac{B_t}{CC} \right) - q B_t \left( \alpha K_t^{\frac{\sigma-1}{\sigma}} + (1 - \alpha) E_t^{\frac{\sigma-1}{\sigma}} \right)^{\frac{\sigma}{\sigma-1}} \stackrel{!}{=} \dot{B}_t$$

$$(\text{A.58})$$

## A.10 Capital shadow price development under optimal management

The following Figures, 15 and 16, are the paths of  $m\tilde{u}_t$  corresponding to Figures 8 and 9, respectively.

Figure 15: Capital shadow price  $\tilde{\mu}_t$  for  $\sigma = 0$  under optimal management

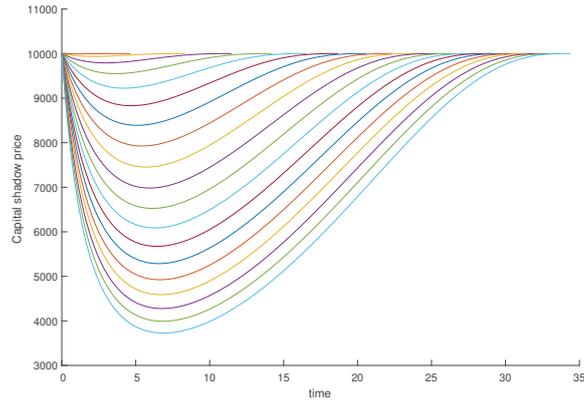
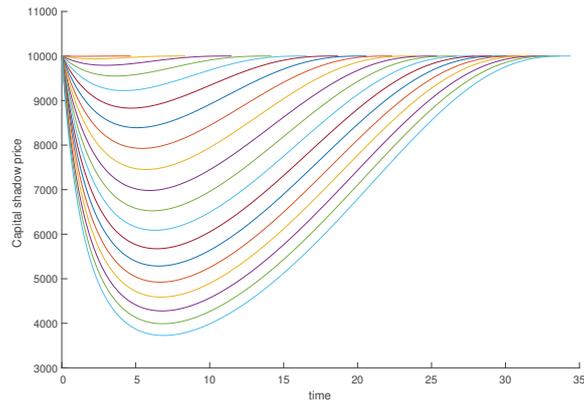


Figure 16: Capital shadow price  $\tilde{\mu}_t$  for  $\sigma = 0.6$  under optimal management



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# Increasing marginal costs and the efficiency of differentiated feed-in tariffs

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**Abstract:** We study optimal subsidies for renewable energy (RE) generation to internalize external benefits from intertemporal learning-by-doing spillovers, taking into account increasing marginal costs at the industry level due to limited availability of sites suitable for RE. We find that the optimal RE subsidy is differentiated according to productivity and derive a condition on production and spillovers under which less efficient, i.e. more costly, technologies should receive higher support, as common in actual policy-making. We show that such a support of technological diversification is optimal if the elasticity of marginal cost increase and the elasticity at which the marginal productivity benefits from learning-by-doing decrease are high.

**JEL Classification:** Q42, D83, O13, D62

**Keywords:** learning spillovers, subsidies, industrial policy, renewable energy, feed-in-tariffs, differentiation

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# 1 Introduction

In recent years, policies to internalize learning-by-doing spillovers have gained relevance in particular for, but not limited to, green technology, such as renewable energy (Fischer and Newell, 2008) or green transport (Fox et al., 2017). Many papers in the economic literature argue for technology-specific support rates (e.g. Gawel et al., 2017; Haas et al., 2008; Lehmann and Söderholm, 2017; Schmalensee, 2012). The major concern is the question how such support should be designed to avoid adverse effects from inadvertently “picking a winner” that might not be the long-term optimal choice. This is of particular importance if technologies exhibit path dependency (Acemoglu et al., 2016; Jaffe et al., 2005; Kalkuhl et al., 2012; Sandén and Azar, 2005).

The status quo in practical renewable energy (RE) support policies is to grant technology-specific subsidies that are differentiated according to generation cost with costlier technologies receiving more subsidies. This contradicts an approach of static efficiency, that is, the subsidy for the same good – green electricity – should be the same. However, the question of optimal FITs has to be answered in its dynamic learning environment. The value of the spillover externality depends inter alia on the amount of future deployment of a technology. Even if a technology exhibits higher cost due to relative immaturity, it may learn more in the future and be the optimal choice as a winner. Still, technology specific subsidies according to generation costs can hardly distinguish between ‘immaturity’ and ‘baseline costliness’ of a technology (for example due to the dependence on certain high-cost raw materials).

A related matter is the question of capacity constraints. It has previously been shown and is an intuitive result that if overall technology deployment is capped by an exogenous upper limit, this changes the dynamic outcome of

winning and losing technologies (Nachtigall and Rübbelke, 2016; Tahvonen and Salo, 2001; Wang and Zhao, 2018). Increasing marginal cost on sector level limits the value of spillovers. Then, technological diversification may be economically justified. Hence, economically sensible subsidies should take such capacity constraints into account.

In this paper, we use RE technologies as an example and develop a dynamic model to characterize how welfare-maximizing subsidies depend on current efficiency of technologies and the increasing marginal costs at the industry level that stem from overall limitations for deploying specific RE technologies. Learning leads to increased productivity and learning spillovers justify policy-intervention.

The results show that the optimal subsidy is technology-specific. Differentiation depends on learning- and production-related elasticities. We show that it is optimal to strongly support less advanced technologies, i.e. to promote diversification, if (i) marginal costs are strongly increasing, i.e. for each RE technology there is only a limited amount of suitable production sites available, and if (ii) the marginal benefit of learning-by-doing spillovers strongly decreases with experience. A necessary condition for an increasing relationship between costliness and optimal support is that sites are in limited supply. In quantitative terms, we find that for learning rates between 10-20% as typically found in empirical studies, the propensity for technological diversification is highest if the sector cost elasticity with respect to sites is at about 1.3, and thus relatively steep.

Our model thus provides a theoretical basis for the widespread and internationally applied type of RE support differentiation. It offers policy guidance for situations where a relevant spillover externality exists and more than one technology compete in the learning process, and thus beyond the

scope of RE.

The paper is structured as follows: After a short literature review in section 2, the model layout is presented in section 3 and the optimal FIT is derived. Section 4 analyses the link between costliness and optimal remuneration. The final section discusses some potential extensions and concludes.

## **2 Experience and related literature**

### **2.1 Current practice of renewable energy support policies**

In practice, renewable energy support is mostly technology-specific and differentiated according to production costs. In 2008, 19 of 22 European countries applied technology-specific tariffs (del Río, 2012). The German national action plan of 2009, for example, states that the calculation of tariffs for different technologies underlies the principle of cost-covering remuneration (Bundesumweltministerium, BMU). Rates are calculated to account for investment, operating and capital costs, tax write-off and other expenditure constituents (Fell, 2011). This induced highly differentiated tariffs. Since 2016, support is based on tendering, but auctions continue to be technology-specific (EEG 2016/2017). Ontario applied technology-specific FIT-rates as well, based on costs and a projected rate-of-return (Yatchew and Baziliauskas, 2011). According to Huang and Wu (2011), land scarcity is the primary reason for technology-specific tariffs and thus diversification in Taiwan. In China, a solar-exclusive subsidy came into effect in 2011 (Ye et al., 2017). Renewable energy certificates applied by Australia were complemented specifically by a Solar Credits Multiplier to support otherwise

non-competitive small scale PV installations (Simpson and Clifton, 2014).

## 2.2 Economic models on RE subsidies

Technology-specific subsidies for RE technologies are also commonly advised in economic literature (e.g. Haas et al. 2008; Ragwitz et al. 2005; Schmalensee 2012; Lehmann 2013). According to a simulation study by Huber et al. (2004), differentiation leads to a more significant deployment of RE in the future and hinders a lockout of promising technologies. With differentiation, cost-recovery and investment security can be ensured for several technologies at the same time at overall lower cost. For this to occur, support is to be differentiated either according to the generation cost (Courture and Gagnon, 2010; Haas et al., 2011; Mendonça, 2009) or according to technological maturity<sup>1</sup> with respect to learning effects (e.g. IEA, 2011). Further empirical evidence finds that cost-differentiated support rates promote a “more homogeneous distribution among different technologies” (Ragwitz et al., 2005), but low cost options are more effectively promoted in countries with technology-neutral systems (Böhringer et al., 2017; Johnstone et al., 2010). From an economic point of view, the trouble with this approach is that it does not expressly account for cost effectiveness. Del Río (2012) argues that while the improved adaptability of differentiated rates may lead to overall lower costs of support, technology-neutral tariffs may spur competition between technologies. If this competition is dampened, supporting less-mature and costlier technologies may lead to the massive diffusion of an expensive technology, incurring high costs in the long run.

Theoretical modeling studies link technology-specific subsidies to effi-

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<sup>1</sup>Arguably, a differentiation mode that targets cost-coverage will not be able to fully distinguish between immaturity-caused and inherent costliness of a technology.

ciency in reaching the policy goal, i.e. either abatement or spillover internalization. If the focus is on abatement, success may be technology-specific, thus justifying differentiated support rates (Lehmann and Söderholm, 2017; Streitberger et al., 2017; Wibulpolprasert, 2016). If the policy aims to internalize spillovers from learning, efficiency requires a differentiation according to, inter alia, learning and spillover rates and the mass of adopting firms (van Benthem et al., 2008; Bläsi and Requate, 2005; Lehmann, 2013; Lehmann and Söderholm, 2017; Reichenbach and Requate, 2012; Schmalensee, 2012; Shrimali and Baker, 2012). The models by Kalkuhl et al. (2012, 2013) and Kverndokk and Rosendahl (2007) show that the optimal FIT depends on parameters related to learning, production costs, and spillovers. They give an analysis on lock-in risks between technologies of different maturity levels, but no discussion on optimal differentiation strategies. Lehmann and Söderholm (2017) adds risk and uncertainty to the number of reasons why technology-specific subsidies may be cost-effective. Overall, the literature that studies technology-specific subsidies from the perspective of economic theory is limited. No study has yet resolved the question under which circumstances an optimal differentiation of FITs should give higher tariffs to more costly technologies. It remains unclear to what extent this practical approach is compatible with theoretical justification of cost effective differentiation. In addition, the impact of limited overall capacity on the optimal subsidy remains unclear.

### **2.3 Increasing marginal costs: Theory and empirical evidence**

Increasing marginal cost is a standard assumption in economic models. For RE, it is realistic to assume increasing marginal cost on both plant and

industry level. Site productivity on plant-level is subject to decreasing returns: Not all of the natural energy that a better site can provide can be as efficiently transformed as the first unit. Neither wind nor PV applications can deal with extreme wind or sun exposure. Wind turbines need to be switched off at too high wind speeds, while PV cells that become too hot lose efficiency (IEA Wind, 2012; Machniewicz et al., 2015; Radziemska, 2003). Even if that is not the case, eventually, some of the good days need to be sacrificed to do regular maintenance, that would otherwise be scheduled to occur on sub-optimal resource days (e.g. Scheu et al., 2012).

A limited overall potential for RE deployment, in particular scarce suitable sites for windmills, hydro, PV etc., forms the basis for increasing marginal costs at industry level (Mercure and Salas, 2012). Taking into account economic limitations severely decreases this potential further (Moriarty and Honnery, 2012). Our interpretation is that increasing marginal costs stem from a higher price for the energy resource (e.g. wind full load hours), if the most efficient sites are occupied first (i.e. for those with equal costs, resource quality decides upon sequence of occupation).

Several studies estimate the impact of site constraints on wind energy costs or energy yield (e.g. Honnery and Moriarty, 2009; Hoogwijk et al., 2004; de Vries et al., 2007). All indicate increasing marginal costs and a limitation of suitable sites. Wisser and Bolinger (2017) document that the “Index of Built Wind Resource Quality at 80m” declined nearly continuously between 1998–2012. This shows a trend of building wind power projects in progressively lower-quality wind resource areas. Average capacity factors have only weakly increased for projects installed from 2009 through 2012. They rebound slightly afterwards, as old plants are gradually replaced. For New Zealand’s hydro energy, Baines (1987) show that energy ratios (i.e. the ratio

of energy output to energy input for an installation) started declining after roughly 1985. This is reflected in increasing and convex unit cost of production when plotted against cumulative installed capacity (Kumar et al., 2011). Conventional energy production methodologies commonly show declining energy yield ratios as well (Hall et al., 2014).

Early economic models on RE supply have been based on the literature about clean backstop technologies that has been developed since the early 1970s (e.g. Heal, 1976; Nordhaus, 1973; Tahvonen, 1997). This literature typically assumed constant marginal costs of energy generation. An exception is made by Oren and Powell (1985), who assume that marginal costs decrease due to learning-by-doing. Later on, the dynamic literature features also papers that include increasing marginal costs on industry level (Wang and Zhao, 2018), sometimes combined with decreasing marginal cost through technical change or learning (Nachtigall and Rübberke, 2016; Kalkuhl et al., 2012, 2013; Tahvonen and Salo, 2001). Then, typically, different production technologies are used simultaneously for a long time horizon. This depends in particular on the size of the learning rate and the leniency of the capacity constraint. Notably, both characteristics depend heavily on the identity of the “winning” technology, which in turn depends on the regulators subsidy choice. As Wang and Zhao (2018) point out, capacity constraints may vary substantially between technologies and countries. This is not taken into account, except implicitly for Kalkuhl et al. (2012, 2013) who do not further discuss this trait. Similarly, in a two period dynamic model, Reichenbach and Requate (2012) incorporate industry-level increasing marginal cost via heterogeneous firms that reflect different plant locations. However, their focus is on market structure and the welfare loss when feed-in tariffs are only second-best.

## 2.4 Evidence on learning by doing and spillovers

Empirical estimates on rates of learning-by-doing in green technologies vary widely, but most lie in a range of 10–20% and nearly all percentage quotes are positive (Fischedick et al., 2012; Nykvist and Nilsson, 2015; Lindman and Söderholm, 2012; Rubin et al., 2015; Söderholm and Sundqvist, 2007). For example, Rubin et al. (2015) review 18 studies on onshore wind power learning rates and find a mean learning by doing rate of 16%, 16 studies on solar/PV power with a mean rate of 23%, and two studies on biomass power generation with a mean learning-by-doing rate of 11%.

Learning rates are decreasing with the maturity of a technology, however, as shown by the empirical observation that immature technologies tend to have a significantly steeper learning curve than mature technologies (Grübler et al., 1999). This fact has been incorporated in previous modeling studies as well (e.g. Kverndokk and Rosendahl 2007; Reichenbach and Requate 2012; Rivers and Jaccard 2006).

Learning spillovers cause a positive externality which provides a reason for economic policy intervention. This RE subsidy justification is, among others, used in models of Bläsi and Requate (2010); Helm and Schöttner (2008); Reichenbach and Requate (2012) and Jaffe et al. (2005). Table 1 provides an overview of empirical evidence for learning spillovers in RE.

## 3 The model

We consider renewable energy (RE) production in a dynamic (two period) setting. The two main features of the model are (a) learning-by-doing spillovers that increase total factor productivity in the future period depending on the scale of present RE production and (b) increasing marginal costs

Table 1: Empirical estimates of spillovers in energy related technologies

Author(s)	Technology	Spillover-rate
Irwin and Klenow (1994)	semiconductors	0.30
Zimmermann (1982)	nuclear power plants	> 0
Bostian et al. (2010) (working paper)	PV cells	0.088
Braun et al. (2010) (working paper)	wind and solar plants	> 0
Verdolini and Galeotti (2011)	energy supply and demand technologies (patent data)	> 0
Dechezleprêtre and Glachant (2014)	wind energy	> 0

at the industry level due to limited availability of sites suitable for RE production. We consider both the market equilibrium under a feed-in tariff and the social optimum to derive the optimal regulation. In the next step, we use a comparative static analysis of the market equilibrium to study the optimal differentiation of the feed-in tariffs depending on technology parameters.

### 3.1 Technology

We consider an endogenous mass  $n_t$  of RE generation devices (e.g. wind turbines or photovoltaic panels) in period  $t \in \{1, 2\}$ , where  $t = 1$  is the ‘present’ period and  $t = 2$  is the ‘future’ period. We consider each of these devices as operated by a single firm, and think of each of these firms as being very small compared to the overall size of the market. Each RE device is operated on an individual site, and RE output  $y$  (e.g., kilowatt hours per year) depends on site productivity  $s$  (e.g., the wind full load hours, or hours of sunshine) and total factor productivity  $A_t$  according to

$$y = A_t f(s), \tag{1}$$

where  $f(s)$  with  $f'(s) > 0$  describes how output depends on site productivity.

Productive sites are scarce. We assume that the most productive sites are used for RE generation, and use  $S(n_t)$  to denote the productivity of the last site in use if  $n_t$  is the total mass of RE devices, which equals the total mass of sites occupied. Total RE output in period  $t$  thus is

$$Y_t = A_t \int_0^{n_t} f(S(j)) dj. \quad (2)$$

While total factor productivity in the first period,  $A_1$ , is given, total factor productivity in period  $t = 2$  depends on production decisions in the first period due to learning-by-doing with spillovers between firms (Arrow, 1962). In terms of the model,  $A_2$  depends on cumulative output in the first period,  $Y_1$ . This assumption also means that the spillover rate is uniform and that there is no private learning, consistent with the assumption that the RE sector is competitive with a continuum of many small firms involved.

Learning-by-doing is positive,  $A_2'(Y_1) > 0$ , but at a diminishing rate  $A_2''(Y_2) < 0$ . We focus on the case in which the elasticity of the marginal increase of future productivity with present output is smaller than unity,

$$-\frac{Y_1 A_2''(Y_1)}{A_2'(Y_1)} < 1. \quad (3)$$

The interpretation is that productivity is not bounded from above,  $A_2$  goes to infinity when  $Y_1$  goes to infinity. Instead,  $Y_1$  is restrained by diminishing productivity, which also constrains learning in the sense that learning becomes costly.

### 3.2 Market equilibrium

RE firms are price takers on output and input markets. To set up one RE device, the firm has to pay the price  $F_t$  for the device and rent the site at a price  $r_t$ , which we assume to be the same, independently of site productivity for RE generation, i.e.,  $r_t$  captures the opportunity costs of using the site for RE generation.

On the output market, the RE firms compete with each other and with other firms on the overall electricity market. Let  $p_t$  denote the market price of electricity<sup>2</sup>. There may be a subsidy  $\Delta_t$  paid by the regulator, such that the producer price for RE firms becomes  $p_t + \Delta_t$ . Under constant prices within the first period,  $\Delta_t$  can be interchangeably interpreted as a feed-in premium or the markup on the price under a feed-in tariff (FIT), where  $p_t + \Delta_t$  would be the FIT. In the following, we will work under the assumption that the government pays a FIT, as this is the prevailing support scheme in Europe (Kitzing et al., 2012).

Hence, the profit  $\pi_t(j)$  for firm  $j$  in period  $t$  is

$$\pi_t(j) = (p_t + \Delta_t) A_t f(S(j)) - r_t - F_t \quad (4)$$

Profit is positive for the firms occupying the most productive sites. The overall mass  $n_t$  of RE devices is determined by the condition that the marginal

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<sup>2</sup>Electricity prices are exogenous. In practice, dampening effects on the wholesale electricity price have been shown for increased RE production (Mulder and Scholtens, 2013; Traber and Kemfert, 2011). Also, the subsidy itself may have an impact on consumer electricity prices (Traber and Kemfert, 2009). For the question of this paper – the optimal differentiation of subsidies – these effects are not relevant, although they would influence the level of the optimal feed in tariff.

firm earns no profit,

$$(p_t + \Delta_t) A_t f(S(n_t)) = r_t + F_t. \quad (5)$$

We allow for late entry and early exit, i.e.  $n_2 \geq n_1$  and  $n_2 \leq n_1$  are both possible, depending in particular on market price development. Since firms do not appropriate learning, we do not have to distinguish between incumbents and late entrants. We further assume that market prices are such that the number of firms in both periods is strictly positive, as otherwise, there would be no benefit from learning and the optimal subsidy was zero.

### 3.3 Social optimum and optimal RE support

Let  $\delta$  denote the discount factor, such that  $\delta = 1/(1+i)$ , where we use the market interest rate  $i$  as the discount rate. The social optimum is found by maximizing welfare

$$W = \max_{n_1, n_2} \left\{ p_1 Y_1 - n_1 (r_1 + F_1) + \delta (p_2 Y_2 - n_2 (r_2 + F_2)) \right\} \quad (6)$$

where  $Y_t$  is given by (2) for both periods and where total factor productivity in period  $t = 2$  depends on first period's output as  $A_2(Y_1)$ . By our assumptions, the social welfare function is jointly concave in  $n_1$  and  $n_2$ , such that the first-order conditions characterize a welfare optimum.

The conditions that determine the welfare-maximizing masses of firms in both periods can be written as

$$\left( p_1 + \delta p_2 A_2'(Y_1) \int_0^{n_2} f(S(j)) dj \right) A_1 f(S(n_1)) = r_1 + F_1 \quad (7)$$

$$p_2 A_2(Y_1) f(S(n_2)) = r_2 + F_2 \quad (8)$$

In the Appendix, we show that both  $n_1$  and  $n_2$  increase with the total factor productivity in period 1, i.e.  $\frac{dn_1}{dA_1} = n_1'(A_1) > 0$  and  $n_2'(A_2) > 0$ . The more productive the RE technology is the more firms will enter the market in period 1. Furthermore, as productivity increases output in period 1, and thus also productivity in period 2 – due to learning by doing – also the mass of RE devices in period 2 increases with  $A_1$ .

We derive the optimal RE subsidies by comparing the masses of RE devices in the market equilibrium under the subsidy (condition 5) and the conditions for the socially optimal masses of RE devices (conditions 7 and 8). We find that it is optimal not to intervene in the market in the second period, i.e. to set  $\Delta_2 = 0$ , which is a result of the assumption that there will be no third period that would benefit from further learning-by-doing.

The optimal mass of firms in the first period will be implemented by a RE subsidy

$$\Delta_1^* = \delta p_2 A_2'(Y_1) \int_0^{n_2} f(S(j)) dj \quad (9)$$

It is just equal to the marginal external benefit of output in the first period in terms of learning-by-doing spillovers – this is the discounted present value of extra output in period 2 due to extra output in period 1. With no subsidy or a subsidy below  $\Delta_1^*$ , the mass of RE devices in period 1 is smaller than socially optimal.

We now turn to our main question how  $\Delta_1^*$  should be differentiated according to different technologies. In particular we are interested in the question how the initial productivity  $A_1$  affects  $\Delta_1^*$ .

## 4 Optimal differentiation of FITs: Should costlier technologies receive higher support?

We are now ready to derive the main equation of this paper. The elasticity of the optimal RE subsidy with respect to the first period's productivity is (see Appendix):

$$\frac{A_1}{\Delta_1^*} \frac{d\Delta_1^*}{dA_1} = \overbrace{\frac{Y_1 A_2''(Y_1)}{A_2'(Y_1)} \left( 1 + \frac{n_1 f(S(n_1))}{\int_0^{n_1} f(S(j)) dj} \frac{A_1 n_1'(A_1)}{n_1} \right)}^{\text{decreasing-marginal-learning-effect}} + \overbrace{\frac{n_2 f(S(n_2))}{\int_0^{n_2} f(S(j)) dj} \frac{A_1 n_2'(A_1)}{n_2}}^{\text{learning-utilization-effect}} \quad (10)$$

If this elasticity is negative, the conclusion is that less productive, i.e. more costly, technologies should receive higher support. If this elasticity is positive, more productive technologies should receive higher support. Equation (10) shows that there is no general conclusion with respect to the optimal differentiation of RE subsidies. The two terms in equation (10) have opposite signs: The sign of the first term is negative, the sign on the second one is positive. We associate these two terms with two counteracting effects.

The first is the “decreasing-marginal-learning-effect”. For a more productive technology, output in period  $t = 1$  is higher. This increases learning-by-doing. The technology advances faster to a more mature state. Due to decreasing marginal productivity of learning, the marginal extra contribution of the FIT to spillovers will thus be smaller the more productive the technology is. The magnitude of this effect depends on the elasticity of marginal future productivity gain with respect to present output,  $-Y_1 A_2''(Y_1)/A_2'(Y_1)$ . If this elasticity is large, the industry learns faster at the beginning, but rapidly becomes mature with little further scope for learning benefits.

The second is the “learning-utilization-effect”. The mass of firms that benefit from per-firm-spillovers changes over time. All  $n_2$  firms active in period  $t = 2$  (or RE devices, as in the model’s interpretation), benefit from increased productivity due to the learning in the period before. The important feature is that knowledge is non-rival and its value for one firm will not dilute just because more firms use it. Again, limits on technology utilization would put a limit on this effect.

To further specify conditions under which it is reasonable to differentiate FITs according to costliness, we further look at the relevant elasticities. An assumption of constant elasticities, which is not required for the subsequent analysis, is common in theoretical models that include learning-by-doing (e.g. Nachtigall and Rübbelke, 2016).

Specifically, we assume that, at least locally,  $f(S(j)) \propto j^{\alpha-1}$  is a power function of  $j$ , with  $0 < \alpha < 1$ . With this specification, the elasticity

$$\alpha = \frac{n f(S(n))}{\int_0^n f(S(j)) dj} \quad (11)$$

is equal to  $\alpha$ . In a similar fashion consider that  $A_2(Y_1)$  is, at least locally, iso-elastic, i.e.  $A_2(Y_1) \propto \frac{Y_1^{1-\beta}}{1-\beta}$ , such that

$$\beta = -\frac{Y_1 A_2''(Y_1)}{A_2'(Y_1)} \quad (12)$$

with  $0 < \beta < 1$ .

Both (11) and (12) are inputs into the “experience parameter”,  $-\frac{1-\beta}{\alpha}$ . The estimation of this experience parameter is standard in empirical work concerning learning rate estimation (see Rubin et al. (2015) for an overview). Learning follows a power law: If output  $Y_1$  doubles, the fractional cost re-

duction equals  $2^{\frac{1-\beta}{\alpha}}$ . The learning rate then is defined as  $LR = 1 - 2^{-\frac{1-\beta}{\alpha}}$ . This model of learning by doing, related to unit cost, was first suggested by Wright (1936).

With this specification, still the model is not solvable in closed form, but from (8) we find that under the assumptions (11) and (12),<sup>3</sup>

$$\frac{n_2'(A_1)}{n_2} = (1 - \beta) \frac{\alpha}{1 - \alpha} \frac{n_1'(A_1)}{n_1}. \quad (13)$$

Thus, using (11) and (12) in (10), we get

$$\frac{A_1}{\Delta_1^*} \frac{d\Delta_1^*}{dA_1} = -\beta \left( 1 + \alpha \frac{A_1 n_1'(A_1)}{n_1} \right) + \alpha \frac{A_1 n_2'(A_1)}{n_2} \quad (14)$$

$$= -\beta + \alpha(1 - \beta) \frac{A_1 n_1'(A_1)}{n_1} \left( \frac{\alpha}{1 - \alpha} - \frac{\beta}{1 - \beta} \right) \quad (15)$$

Thus,  $\alpha < \beta$  is a sufficient condition such that the less productive, or more costly, technologies should receive higher support.

This shows that the elasticities of aggregate production with respect to the mass of firms and the elasticity of the learning curve are key parameters that determine whether more or less productive technologies should receive stronger support. A low value for  $\alpha$  and a high value for  $\beta$  favor a higher FIT for costlier technologies:

- (i) A high value of  $\beta$  means that the marginal benefit of current output in terms of future productivity decreases fast. If the current technology is already rather productive, there is not much scope for future learning spillovers. A high value of  $\beta$  means that the “decreasing-marginal-learning-effect” is large, thus favoring the support of technologies that

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<sup>3</sup>This can be shown by constructing an example using the specifications above in (8). We obtain  $n_1^{\alpha(1-\beta)} n_2^{\alpha-1} = k$  with some constant  $k > 0$ . Thus,  $n_2 = k^{-\frac{1}{1-\alpha}} n_1^{(1-\beta)\frac{\alpha}{1-\alpha}}$ .

are not yet advanced.

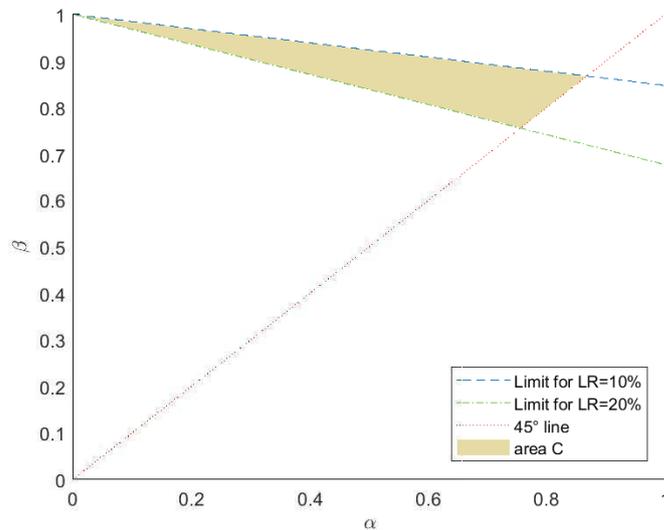
- (ii) A low value of  $\alpha$  means that marginal costs are strongly increasing – or, equivalently, marginal productivity is strongly decreasing – at firm and industry level. Scarcity of productive sites for one type of RE technology calls for diversification of RE technologies in use and thus for support of currently less advanced technologies. The low value of  $\alpha$  leads to a small “learning-utilization-effect”.

This result can provide guidance for policy-makers: Optimal differentiation depends (inter alia) on generation costs, but the sign of this dependence can be both positive or negative. Whenever sites are in strongly limited supply and sites are an important production factor, countries should tend to give a higher FIT to costlier technologies. If the limits to learning as well as the limits to utilization restrict learning benefits, diversification is optimal. By contrast, when sites are not very scarce (as for example for some countries that are especially suited for solar technology, where the entire regional energy consumption could be produced from one technology), concentration on the cheaper technology is preferable (*ceteris paribus*). Condition (15) shows that the more efficient technologies should always receive the higher support if  $\alpha$  is close to one.

To explore which is the the empirically relevant case of RE subsidy differentiation, we consider the following numerical example. Empirical estimates of learning rates concerning the reduction in unit costs were most often between 10–20% (cf. Section 2.4). For this range, the experience parameter would lie between 0.152 and 0.322. Area C in figure 1 illustrates combinations of  $\alpha$  and  $\beta$  in this range for which the sufficient condition,  $\alpha < \beta$  holds, denoted by area C. Thus, for all combinations in area C, costlier technologies should receive more support. A necessary condition for an increasing

relationship between costliness and optimal support is that sites are in moderately limited supply, i.e.  $\alpha < 1$ . The higher the learning rate, the stronger would site scarcity have to be. For a sector cost elasticity with respect to sites of 1.3 ( $\alpha = 0.77$ ), the propensity for technological diversification is highest.

Figure 1: The shaded area indicates the combinations of  $\alpha$  (the elasticity of aggregate output with respect to the mass of firms) and  $\beta$  (the elasticity of marginal future productivity with respect to current output) for which costlier technologies should receive higher support



## 5 Discussion and Conclusion

In this paper we have set up a theoretical model to study the optimal differentiation of renewable energy (RE) support policies. The rationale for RE subsidies are learning-by-doing spillovers. We have further taken into

account the limits to expand individual RE technologies that come about due to the limited availability of sites suitable for RE generation. This translates into increasing marginal costs of RE production at firm- and industry-level. Thus, two competing forces drive the dynamic development of a technology, and both depend on cumulative production in the first period: Increasing marginal costs and increasing productivity due to learning-by-doing. Using comparative statics with regard to differences in generation costs, we have provided a theoretical analysis of a very common practice in politics: The differentiation according to the level of generation cost.

Linear differentiation on the basis of generation costs cannot do the trick of efficient support alone, because the optimal support level depends on costs in several different and non-linear ways. However, the sign of optimal differentiation, so to say, the direction of differentiation, can be derived. The negative decreasing-marginal-learning-effect captures that a cheaper industry will optimally learn more, but the effect on the margin is lower. This effect tends to favor the support of less advanced technologies. The positive learning-utilization-effect goes in the opposite direction. It comes about, as more productive technologies tend to attract more firms in the future, thus extending the external benefit of learning-by-doing spillovers. We have shown that it is optimal to give higher support to more costly technologies, as it is common practice, if the elasticity of learning by doing is large and marginal costs are steeply increasing, i.e. if productive sites are scarce. In such a case, the policy-maker should seek to support a differentiated set of technologies.

Several model extensions are possible. First, we have not considered variable inputs in production, such as labor needed for maintenance of RE devices. Including such variable inputs, the model would further allow for the possibility of learning being either driven by aggregate output or by

specific inputs such as wind turbines or PV panels. Most empirical studies use installed capacity as independent experience variable, this includes turbine number and size. In addition, learning could also be caused by progress in the operational management (Neij, 1997, 1999). In such a setting, a FIT on RE output can only reach a second-best outcome. A similar analysis as done in the present paper can be applied nevertheless. Second, we have studied a two-period setting only. The present model can be extended to an arbitrary number of periods, considering total factor productivity as a state variable that changes with current output. Such an approach would allow to study how the optimal RE subsidy changes over time, although analytical results would most likely be restricted to a steady-state analysis.

Despite the abstractions necessary to generate clear insights, our analysis led to theoretical results that could inform empirical research and policy making. In terms of empirical research, an advantage of our results is that conditions on optimal differentiation of RE support are formulated in terms of elasticities, which are typically well measurable in statistical analyses. In terms of policy-making, we provide the background for the common differentiation according to the costliness of RE technologies. Specifically, we find that considering the scarcity of sites suitable for RE generation under the different technologies is an important driver for such a differentiation and the resulting diversification of RE technologies.

## Appendix

The assumption that the social welfare function  $W$  is jointly concave in  $n_1$  and  $n_2$ , implies

$$\begin{aligned} W_{n_1 n_1} &< 0 \\ W_{n_2 n_2} &< 0 \\ W_{n_1 n_1} W_{n_2 n_2} - W_{n_1 n_2}^2 &> 0. \end{aligned} \tag{A.16}$$

It is straightforward to check that the social welfare function (6) satisfies these conditions. The conditions for the social optimum, or equivalently the market equilibrium under the optimal RE subsidy, can be written as  $W_{n_1} = 0$  and  $W_{n_2} = 0$ . Differentiating with respect to  $A_1$ , we get the following conditions

$$W_{n_1 n_1} n_1'(A_1) + W_{n_1 n_2} n_2'(A_1) + W_{n_1 A_1} = 0 \tag{A.17}$$

$$W_{n_2 n_1} n_1'(A_1) + W_{n_2 n_2} n_2'(A_1) + W_{n_2 A_1} = 0 \tag{A.18}$$

Solving leads to

$$n_1'(A_1) = \frac{W_{n_1 n_2} W_{n_2 A_1} - W_{n_2 n_2} W_{n_1 A_1}}{W_{n_1 n_1} W_{n_2 n_2} - W_{n_1 n_2}^2} \tag{A.19}$$

$$n_2'(A_1) = \frac{W_{n_1 n_2} W_{n_1 A_1} - W_{n_1 n_1} W_{n_2 A_1}}{W_{n_1 n_1} W_{n_2 n_2} - W_{n_1 n_2}^2} \tag{A.20}$$

For the welfare function (6) we have

$$\begin{aligned}
W_{n_1 A_1} &= \delta p_2 A_2''(Y_1) \left( \int_0^{n_1} f(S(j)) dj \right) \left( \int_0^{n_2} f(S(j)) dj \right) A_1 f(S(n_1)) \\
&\quad + \left( p_1 + \delta p_2 A_2'(Y_1) \int_0^{n_2} f(S(j)) dj \right) f(S(n_1))
\end{aligned} \tag{A.21}$$

$$= \left( p_1 + \delta p_2 A_2'(Y_1) \left( \int_0^{n_2} f(S(j)) dj \right) \left( 1 + \frac{Y_1 A_2''(Y_1)}{A_2'(Y_1)} \right) \right) f(S(n_1)) \tag{A.22}$$

Thus, condition (3) implies  $W_{n_1 A_1} > 0$ . Moreover,

$$W_{n_2 A_1} = p_2 A_2'(Y_1) \left( \int_0^{n_1} f(S(j)) dj \right) f(S(n_2)) > 0. \tag{A.23}$$

Thus,  $n_1'(A_1) > 0$  and  $n_2'(A_1) > 0$ .

Differentiating (9) with respect to  $A_1$ , we obtain

$$\begin{aligned}
\frac{1}{\delta p_2} \frac{d\Delta_1^*}{dA_1} &= A_2''(Y_1) \left( \int_0^{n_1} f(S(j)) dj + A_1 f(S(n_1)) n_1'(A_1) \right) \left( \int_0^{n_2} f(S(j)) dj \right) \\
&\quad + A_2'(Y_1) f(S(n_2)) n_2'(A_1) \tag{A.24}
\end{aligned}$$

Rearranging leads to (10).

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**Declaration to confirm that the dissertation  
has been produced independently:**

I hereby declare that I have produced my doctoral thesis "Factor input constraints in resource dynamics" independently and without external assistance, and that I have made a significant contribution as co-author to other scientific articles. I have identified all word-for-word quotations of other authors, as well as comments based closely on other authors' ideas, and I have cited the sources according to the guidelines I received.

Date

Signature