Research Policy
November 2023, Volume 52 Issue 9 Pages 104864 (14p.)
https://doi.org/10.1016/j.respol.2023.104864
https://archimer.ifremer.fr/doc/00848/96015/

Explaining technical change and its impacts over the very long term: The case of the Atlantic sardine fishery in France from 1900 to 2017

Le Floc'h Pascal [1, *], Merzéréaud Mathieu [2], Beckensteiner Jennifer [1], Alban Frédérique [1], Duhamel Erwan [3], Thébaud Olivier [2], Wilson James [4]

[1] Université de Bretagne Occidentale – UMR AMURE _ Contact, France
[2] Ifremer – UMR AMURE, France
[3] Ifremer – Laboratoire de Technologie et de Biologie marine, France
[4] UQAR – Université du Québec à Rimouski, Canada

* Corresponding author : Pascal Le Floc'h, emai address : plefloch@univ-brest.fr

Abstract :

As an industry based upon the harvesting of wild resources, the fishery is often used in economics to showcase the effects of its specific nature on human behavior and the impacts of that behavior on the fish stock itself. The common-pool status usually encountered in the use of these resources makes them especially vulnerable to major shifts in the supporting ecosystems, but also to rapid technical change. In most other parts of the economy, technical change and the creative destruction that it brings along are viewed positively, and even given central role in recent theories of growth. Happily for the creatures of the ocean that are hunted, fishers do not fit the mould of Schumpetarian entrepreneurs bent on creative destruction. However, the technology that does drift onto boats has had concerning effects on the status of fish stocks with important economic and cultural consequences. We present a narrative of the French sardine fishery using the evolutionary theory of technical change. The wild binary segmentation approach was applied on a time-series of French sardine landings from 1900 to 2017. This analysis revealed three significant production change points associated with important technical changes in the fishery. The first change point, in 1927, is related to the introduction of the purse-seine in France. The introduction of the mid-water trawl is the second change point in the early 1970s. A third change point occurred in 1998, where we see a reswitch from mid-water trawl to purse-seine. Collectively, these results highlight the technological changes in sardine production that occurred, but more importantly, the impacts of these changes both on the structure of the population of sardines, and on the industry. The lesson we derive from this case study is that technical change should be considered as a succession of shifts rather than a unidirectional history.

Keywords : Time-series (C22), Economic history (N54), Technological change (031), Fishery (Q22)

Introduction

Schumpeter defines the role of the entrepreneur as being at the origin of breakthrough innovation (Schumpeter, 1939). Building on this, several explanations of how technological takes place have been suggested (Coccia, 2016). These explanations included the demand-pull and the technology-push theories (Ruttan, 1997), an evolutionary explanation of innovation (Nelson and Winter, 1982), and the notions of path-dependency and the lock-in effect (Arthur, 1989; David, 1985).

All explanations of technical change share common ways of explaining the sources of innovation. In this article, three of these are selected: (i) the pattern of competition and interaction between users of techniques, (ii) the technological trajectories on which innovations appear, (iii) the social construction of innovations.

Few papers study the diffusion modes of technological innovations in the fishing industry. The fishing sector is often considered culturally very significant but not an object of much entrepreneurial interest. Indeed, technological change can quickly call into question the sustainability of the activity with the depletion of the fish stock. The most famous example is the collapse of the cod stock in Canada with the moratorium in 1992 (Sinclair, 1996), showing that this activity is not exempt from the impacts of technical change, in combination with the other features driving the development of excess fishing capacity and overexploitation. The fishing industry has to go through the waves of innovation, even sometimes shifting back from the new production systems to older production techniques, as predicted by Sraffa (1960).

We hypothesise that major change points in a long series of fishery landings can correspond to changes in fishing technique. Fishing communities are subject to other disruptions, both biological factors (fluctuations in the environment having an impact on resources), and economic ones (price and cost variations, changes in consumer preferences, international competition in seafood markets or technical changes in how trade occurs). Consequently, the determinants of these change points can vary. These determinants are currently high on the research agenda in fisheries. However, while most specialists in renewable resources management understand that technical change plays an important role, it has only attracted limited formal research attention in fisheries (Squires and Vestergaard N., 2018; Hannesson *et al.,* 2010).

In this article, we focus on the nature of technical change as a primary source of disruption in the exploitation of fish resources. Technological change may be problematic for the sustainability of fisheries, in particular because it may not have a neutral or passive effect. Technologies that boost productivity of vessels through active or passive means may take hold early in the life of a fishery, whereas technologies and public policies aimed at sustainability are slower to develop. The question we asked ourselves was: of the important change points we see in the long term evolution of French sardine production, which were those which can be associated with technical change, and what were the implications of this change on landings?

The Sardine fishery in France is an interesting case of adoption of different catch technologies over a long period of time. This fishery is particularly iconic in France, where fisheries have an outsized influence on culture and politics, despite their relatively limited contribution to the economy. It is also a fishery that is subject to predator-prey dynamics and stock collapses, similar to what has been witnessed in other similar fisheries such as the North Sea herring fishery (Whitmarsh *et al.,* 1995). . In this case, we examine the adoption by the sardine fishery sector of a succession of three techniques – gillnet, purse-seine, mid-water trawl, respectively –over a century. We then consider the adaptation behavior of fishing communities facing the race for fish (Hannesson, 1996).

Three major technological changes occured in the sardine production system over this century: (i) the switch from the gillnet to the purse-seine technique from the 1920s, the latter being seen as more productive; (ii) the subtitution of the purse-seine technique by the mid-water trawl in the 1970s; (iii) a reswitching that occurred during the 1990s with the shift back to the purse-seine. This article focuses on the technological competition between purse-seine and mid-water trawl, in the face of what must have been substantial stock declines. These two competing production systems in turn benefited from disruptive innovations during the 1950s and 1960s, some fisheries-related but many having no genesis in the fishing industry. The development of cheap and strong nylon, used in nets, electronic navigation equipment, and the use of sonar for the detection of fish schools were major innovations, not only for the general economy, but for fishers as well (Martinussen, 2006; Valdemarsen, 2001; Thomson, 1969). Purse-seine fishing also benefited from a technological innovation with the invention of the power block by Mario Puratic in 1953.

This paper draws inspiration from Schumpeterian or evolutionary economics. The narrative uses statistical analysis, evolutionary economic theory and a careful reading of historical events. The statistical analysis is applied to a long series of more than a century of sardine production in France. The application of optimisation methods allows us to identify phases separated by a change point related to the adoption of the different technologies, after checking that these phases are stationary, or stable. The theoretical model draws on the economics of innovation inspired by evolutionary theory of technique selection (Nelson and Winter, 1982). The history of changes in production technology in fisheries is based on the accounts of research institutes specialising in maritime activities (Martinussen, 2006; FAO, 1971; Schmidt, 1971; Portier, 1970; Lecatonnoux and Laurent, 1960).

The paper is presented in four sections and a conclusion. Theoretical elements on the adoption of technical change are presented in section 1. We review the literature on innovation with regard to three key issues: competition and interaction between technologies, the historical drivers of technological trajectories and the social construction of technologies defined as the modes of coordination between the actors of a system. Section 2 describes historical events in the Atlantic sardine fishery through the lens of evolutionary economics and its application to technical change. We discuss a typology of fishing techniques, the technological trajectories in the industry, and the relationships between stakeholders (i.e. the fishers), applied R&D institutes, and the impacts on the exploited resource. Material and methods used or the empirical identification of change points indicating change points potentially induced by technical change are presented in section 3. We used segmentation models to determine the change points indicating structural modifications in the production series, allowing for the possibility that these change points did not necessarily correspond to large-scale events such as war, or economic depression/growth. Stationarity tests were proposed on the basis of the segments identified. In section 4, results show three significant changes in 1927, 1971 and 1998. The most likely narratives of these regime shifts include the influence of technological and institutional determinants, and these lead us in section 5 to examine stylized facts regarding technical change and its impacts in a fishery context. In conclusion, building on the results of our statistical analysis and our reading of the fishery's history, we highlight some fundamental issues in technological change analysis. One issue is the role of the State, encouraging technological lock-in through *ad hoc* policymaking. In other contexts, this may lead to different forms of inefficiency in the economy by rendering technological trajectories inflexible. However the problem with *ad hoc* policy making in the fisheries realm is that an artificially induced technological lock-in is provoked, which can prove unsustainable in the long run for the resource.

SECTION 1 THEORETICAL OBSERVATIONS ON THE ADOPTION OF TECHNICAL CHANGE

The literature on technical change uses three theoretical approaches, all of which are originally based upon ideas of Joseph Schumpeter. The earliest dates back to the 1960s and 1970s, and offers an explanation of economic growth from technical change (Griliches, 1957; Samuelson, 1965; Schmookler, 1966; Ruttan, 1997). The second approach comes from Nelson and Winter's work on the evolutionary theory of technical change (Nelson and Winter, 1982). Dosi (1982, 1984) also made contributions to the evolutionary theory of technical change with the concept of technological trajectory. The third approach makes a direct appeal to history in explaining why things are done as they are. In a word, history matters (Wright, 1997; North, 1991) because how we make decisions about using technologies will lead to path dependency and technological lock-in (David, 1985; Arthur, 1989). Often times, ad-hoc decisions with little consideration for principles of efficiency or economy lead to industry standards which are hard to explain, except by examining the historical record.

We use the evolutionary theory of technical change to ask and answer the following questions: How do technologies evolve relative to each other as well as from one to another? What were the historical drivers of technological trajectories in the sardine fishery? Why does the social construction of technologies matter in fisheries?

How do technologies evolve relative to each other and from one to another?

The first question addresses the co-evolution of technologies, with one mature and the other emerging. The sources of innovation whose origin remains difficult to identify (Coccia, 2016) create opportunities that are essentially incremental. The change points in the choice of a technique appear with radical innovations which are "discontinuous events" (Freeman, 1991). For example, the use of nylon was a radical innovation because it radically changed the productivity of industries such as the manufacture of fishing nets (Martinussen, 2006).

Technologies are either in competition or in interaction (Coccia, 2019, 2021; Pistorius and Utterback, 1997). In most cases, technological breakpoints is perceived as resulting from the confrontation of a mature technology reaching the end of its cycle, with an emerging technology. This is a common representation in the literature of innovation economics. Competition may be considered as the most effective model for selecting new technologies (Dasgupta and Stiglitz, 1980). However, other drivers can influence the choice for selecting one technique (Nelson and Winter, 1978; David, 1985) so that the competition model does not naturally prevail. Interactions have been shown to exist between old and new technical models (Coccia, 2019). Pistorius and Utterback (1997) propose two alternatives to the classical model of technological competition (fig. 1), buiding on the prey-predator model which can have two versions: a negative influence of the emerging technology on the mature technology and a positive influence of the old one, or *vice versa*. Another alternative to the competition model is the symbiosis model. As in evolutionary ecology (Solée et al., 2013), two techniques producing the same good can have a reciprocal positive influence. They then reinforce a mutual dependence.

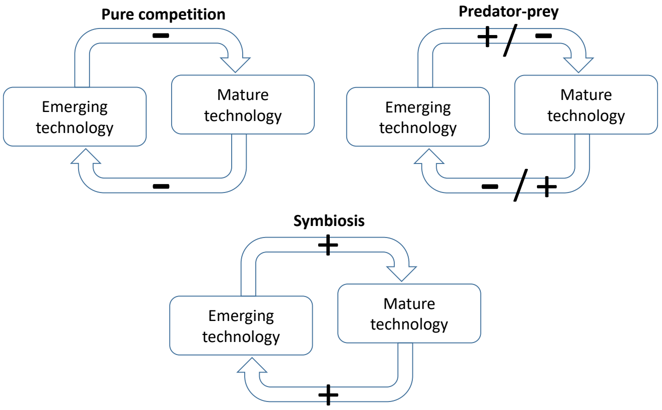

Figure 1 The three alternative representations of change from mature to emerging technologies: competition, predator-prey, symbiosis

The adoption of a new technology, and how it occurs, may depend on the model. Parts of the economy that are best explained by interaction models, whether the prey-predator model or the symbiosis model, make identifying definitive adoption more difficult. The prey-predator model leads to the final domination of a technology, but it will not necessarily be the emerging technology. A key moment of sustainable technology change may not exist if the prey-predator model reinforces the old technology (Cooper and Schendel, 1976). The coexistence of two technologies, old and new, is best illustrated by the symbiosis model.

What are the historical drivers of technological trajectories?
The answer to this second question explains the determinants of a dominant technical model. According to the previous conceptual elements, a dominant model can be an old and improved technique or a radically new technique. However, the emergence of a production model is also based on the identification of technological trajectories (Nelson, 1994; Wright, 1997; Dosi, 1982, 1988). Indeed, Nelson and Winter (1982) challenge the neo-classical narrative on technical change as lacking a historical perspective, and propose what they describe as an appreciative theory. Dosi also emphasises the historical context to interpret the determinants of technological trajectories. A cumulative process of incremental innovations continuously feeds technological trajectories (Nelson, 1994), a change in trajectory occuring through a technological breakthrough or a radical innovation[1].

Why does the social construction of technologies matter in fisheries?
The social construction of technologies means that situations must be analyzed taking into account the modes of coordination between the actors of the system (Coccia, 2010, 2020; Geels, 2019; Genis and Coles, 2008). this is in part to understand social resistance to change. Change points appear at moments in the history of techniques and communities of actors faced with the choice of techniques. The works of Arthur (1989, 1994), and David (1985), describe the phenomena of lock-in to a technology and resistance to change. The notion of a path dependency explains resistance movements, postponing a change point until the majority of users switch to the emerging technology. In the case of industries that exploit renewable resources - forestry, agriculture, marine fisheries, aquaculture – the representations and social status of thess resources must also be considered. In an article on the introduction of a new

---

[1] Dosi (1982) explained “Incremental innovation versus radical innovations can be reinterpreted in terms of "normal" technical progress as opposed to new emerging technological paradigms”. Radical innovations occur with discontinuities as technological breakthrough, modifying the rate and direction of technical change.

technique for cultivating shellfish in open seas (Callon, 1986), the author explains that the identity and role of each actor are key elements for understanding controversies and in some cases social resistance to change. And the natural resource should be considered as one of the actors[2].

In most other parts of the economy, technical change and even the creative destruction that it brings on is viewed positively. In the case of fisheries, the exploited stocks of fish are usually used in a common pool setting, making them especially vulnerable to rapid technical change. While theoretical approaches to technical change are useful for understanding technological change, explaining technical change and its consequences in fisheries thus requires a specific analytical framework.

SECTION 2 HISTORICAL DEVELOPMENTS OF PRODUCTION TECHNIQUES IN THE FRENCH SARDINE FISHERY

We use the above conceptual framework and its three core questions to examine the general development of production techniques in the marine fishing industry. This leads us to describe (i) a general typology of fishing techniques, (ii) the technological trajectories of these techniques, and (iii) the relationship between the fishers, the technical aspects of fishing activities, and the exploited resource.

How do technologies evolve relative to each other and from one to another in fisheries?
The FAO categorizes the catch techniques in two main groups: mobile gears and passive gears (fig. 2). There are many technical interactions, as two production methods can compete in the same area to catch the same species (e.g. trawls and lift nets). Competition and prey-predator patterns are common and are a source of conflict (Charles, 1992). This is a usual situation in fisheries, creating conflicts between users of old techniques and fishers seeking more productive methods (Whitmarsh, 1990; Fourt *et al.*, 2020; Sverrisson, 2002).

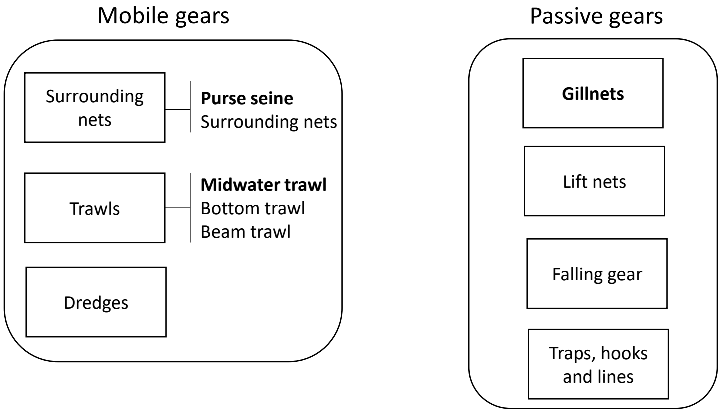

Figure 2 Technologies in fisheries
Source : adapted from FAO, 2021. Classification and illustrated definition of fishing gears, FAO Fisheries and aquaculture Technical paper 672. https://www.fao.org/documents/card/en/c/cb4966en/

---

[2] Callon (1986) wrote : "*The questions formed by the three researchers and the commentaries that they provide bring three other actors directly into the story: the scallops (Pecten maximus), the fishers of St. Brieuc Bay, and the scientific colleagues*". This paper is considered at the origin of the translation theory (Bielsa, 2022).

Beyong the broad categorization, marine fisheries in fact offer a wide variety of catching techniques separated by mode of use (FAO, 1990). Passive techniques include traps, lines, hooks and set nets. Mobile techniques involve the more energy-intensive trawling and dredging, as well as less energy intensive purse seines. In considering the ways in which these techniwues are implemented, it is customary to separate the small-scale coastal fleets from large-scale fleets. In the European context, the small-scale fleets are considered to be composed of vessels under 12 metres in length, using often multiple types of passive fishing gear (called multi-gear), while the large-scale fleets are composed of vessels of the same sizes fishing with active gear, as well as vessels over 12 metres in length, fishing with either active or passive gear, or both (European Commission, 2019).

In the French sardine fishery as in other contexts mentioned in the previous section, historical analysis proves essential in conjunction with evolutionary economics to explain how techniques interacted with each other in their adoption, and the impacts of these interactions on the stock of fish. Adoption pathways are not always simple competitive "fights to the death" with one ultimate winner, as we will illustrate with this case study. Indeed, three techniques to catch sardines were in competition or interaction: purse seine and mid-water trawl, belonging to the mobile gear category, and gill-net, a passive fishing technique belonging to the passive gear category (fig. 2). The purse seine did replace the gill nets in a competitive way. But the competition between purse seines and mid-water trawls was closer to predator-prey dynamics. This is mainly because of factor costs and up-stream innovations in the purse seine technique. As long as energy was reliable and cheap mid-water trawls dominated. But when the power block technology for purse seine pioneered in the fifties, at a time of rising energy costs, the balance tipped towards purse seines. As we will see, it is even conceivable that other disruptions might have occurred in favor of a shift back to mid-water trawls, leading to multiple cycles of dominance, before one or the other technology finally won out. Change points in sardine production, associated with long-term switches in fishing technology over the historical record of the French sardine fishery, can thus be linked to a co-evolution of technologies – gill-net, purse seine and mid-water trawl – in line with the prey-predator models of Pistorius and Utterback (1997). The impact this intensive honing of productive capacity on the stock, however, can be catastrophic if the fishery is unregulated.

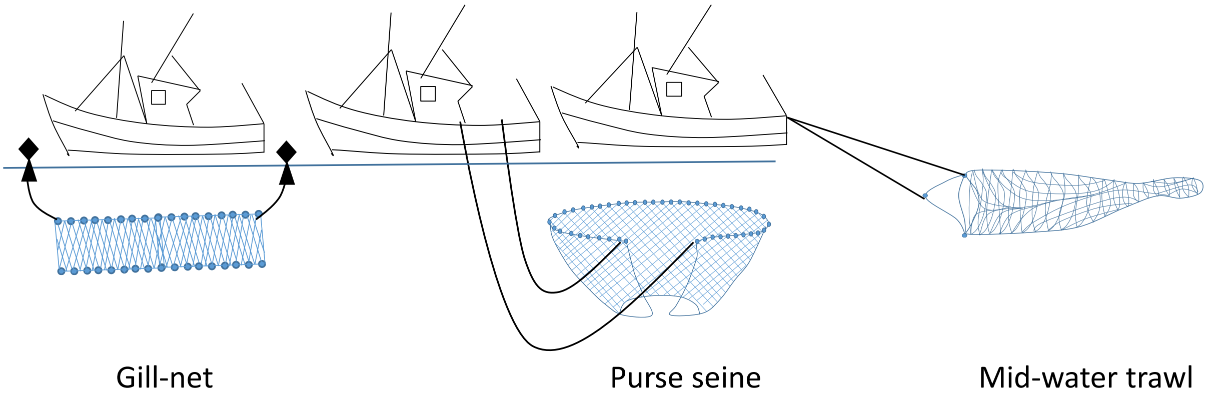

Figure 3 Gill-net, purse seine and mid-water trawl for the sardine industry

What are the historical drivers of technological trajectories in fisheries?

Le Floc'h and Fuchs (2001) have illustrated three technological trajectories in which fishers bring incremental innovations. The first is a technological trajectory of direct and indirect fishing techniques with three components: the propulsion system, hull design and fishing gears. The second trajectory is articulated around five elements defining information and communication. The third trajectory embraces processing techniques with handling operations, storage and cold chain (Le Floc'h and Boude, 1998). Technological trajectories in the fishing industry correspond to a category of production techniques, either passive or mobile. During the 20th century, they benefited from continuous and progressive improvements with only rare moments of technological breakthrough. These trajectories led to production and growth, as long as the resource remained abundant[3] (Meuriot, 1986; Smith, 2000).

Why does the social construction of technologies matter in fisheries?

The history of fishing techniques illustrates how nations and their policies affect technological trajectories, through a national system of innovations (Lundvall, 1992; Freeman, 1995). After the Second World War, coastal countries invested heavily in industrial fishing fleets. Fishing firms received technical assistance from their national institutes (Meuriot. 1986; Van Wyk and Wessels, 1987; Whitmarsh, 1990; Sverrisson, 2002; Standal, 2005). Callon (1986) provides the example of the scallop fishery in the Bay of Saint-Brieuc (France), where the fishing community, scientists, and government regulators all had a hand in determining technological trajectories. The few studies of the relationships between these three actors, such as the cases of herring (Gordon and Hannesson, 2015) or cod (Hannesson et al., 2010) have shown that it is often resource abundance that makes technical improvements possible. If the health of the resource declines, then innovative attention may decline as well. Fisheries resources are classified into at least three categories: pelagic resources, benthic resources and demersal resources. Sardines belong to the pelagic resources, the abundance of which often displays higher levels of natural variability, and for which technical improvements in the 1950s and 1960s affected direct and indirect fishing techniques (Hamre and Nakken, 1971; Green *et al.*, 1971; Brandt, 1971), but also the information and communication technology (Gislason, 1971). In France, fishers have been supported since the beginning of the 20th century by a technical institute. The first fisheries institute was created in 1918 (fig. 4). The French state has constantly played a major role by financing the maritime institutions of applied research - OSTPM, ISTPM, IFREMER - one of the missions of which was to help fishers learn new techniques.

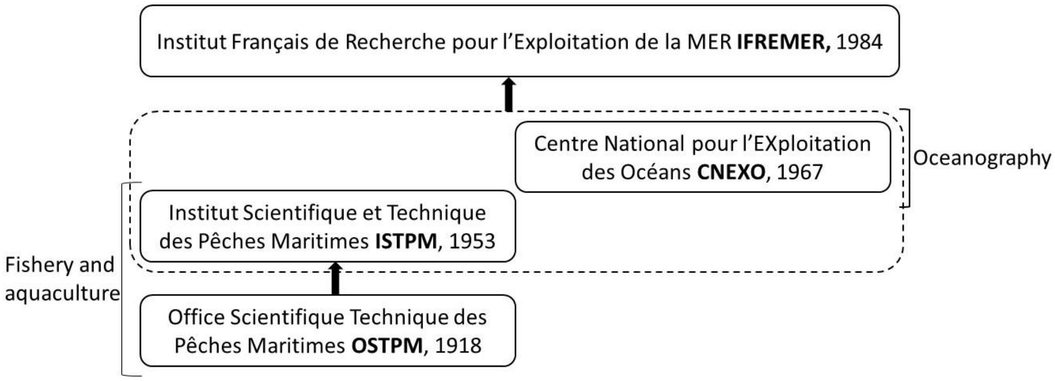

Figure 4 History of the creation of the French National Institute for Ocean Science
Source: adapted from https://wwz.ifremer.fr/en/The-Institute/History

---

[3] However, one problem with schooling fish as sardine stocks is that their landings can continue to increase even though the stock is depleted, because of the schooling behavior of the stock. This can lead to abrupt collapses and moratoria (Whitmarsh et al. 1995; Baumgartner et al., 1992).

In summary, our analysis considers a predator-prey model of technical change in the French sardine fishery along with the historical determinants of switches between technologies, and applies this to explain change points in the production of this fishery, also considering the role of social and institutional factors, notably the role of State support

SECTION 3 MATERIALS AND METHODS

3.1. Data

Our analysis relied on a reconstructed long-term series of sardine landings in France, using the available historical records. These records included archive documents, which chronicled the tasks of statistical surveying by various ministries for the Marine, Public Works and even Tourism sectors (1953) from 1900 to 1987. The reports from 1988 to 2006 were produced by the Comité des Pêches Maritimes/National Committee of fisheries. This institution manages the profession by delegation from the State by coordinating public policies in terms of production capacity, improvement of catch techniques and marketing of landed products. From 2007 to 2017, the statistical surveys of landed production were carried out by the National Establishments of Agricultural and Seafood Products (https://www.franceagrimer.fr/), a public administrative establishment under the authority of the Ministry of Agriculture and Food.

Not all the statistics were recorded in a standard format in these reports over the different periods (colonial, interwar, postwar reconstruction from 1945 to 1970, and contemporary). Consequently, validation of the production data required a grouping of the marginal fishing ports into more significant production hubs. An initial assessment of the sardine landings data identified more than 70 landing sites. During a data validation workshop, 18 major ports were selected due to their significant contributions. The majority of ports were smaller locations with a cumulative production between 1900 and 2017 of under 10,000 tonnes, or less than 1% of total production estimated at nearly 2 million tonnes over a century. Figure 5 shows the top 8 ports (>5% of cumulative production) located on the Atlantic coast, from Douarnenez to Saint-Jean-de-Luz. Four of them are identified as leading ports over one century (Douarnenez, Saint-Guénolé, La Turballe, Saint-Jean-de-Luz), with 48% of the total production from 1900 to 2017 (Le Floc'h *et al.*, 2020)[4].

---

[4] The French marine fisheries production reports are available at https://archimer.ifremer.fr/html/statistique-peches-maritimes.htm.

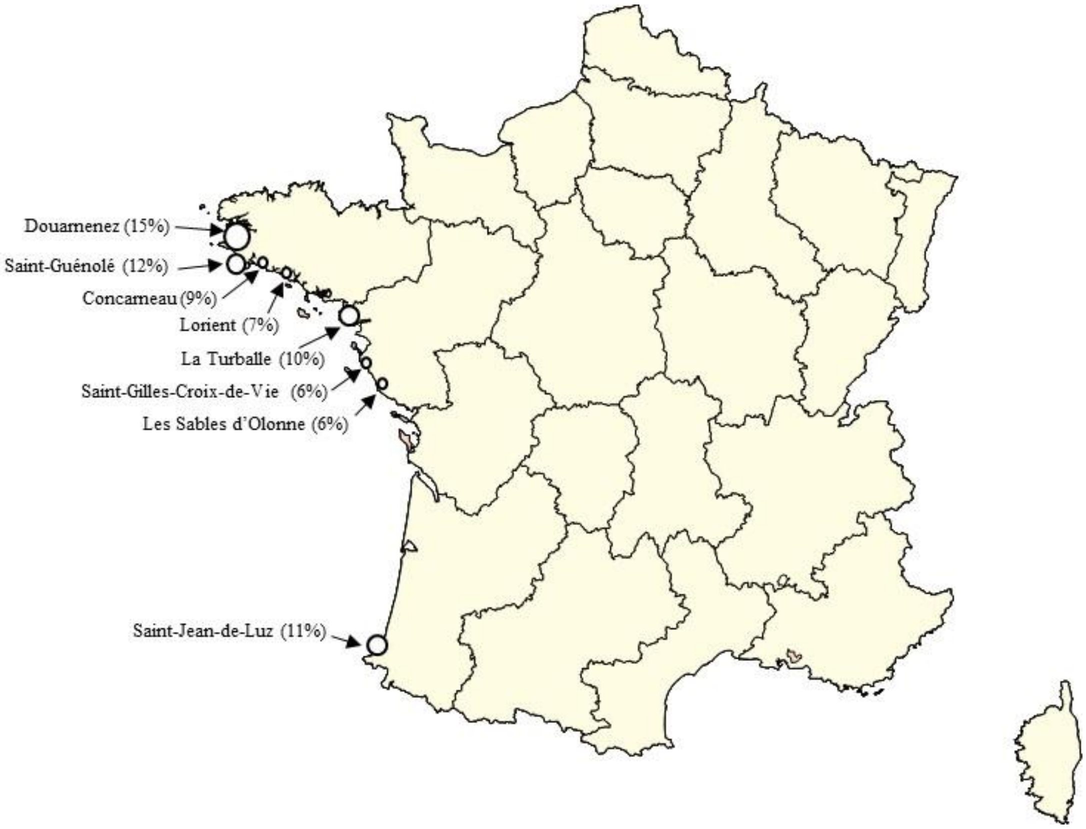

Figure 5 Major historical landings sites for the French Atlantic sardine industry with percentages representing cumulative contribution of total French sardine production over 1900-2017 from each port. Source: https://archimer.ifremer.fr/html/statistique-peches-maritimes.htm

The historical series we analysed (fig. 6) shows inter-annual fluctuations with potential causes including variation in the abundance of the resource (Veron *et al.*, 2020), changes in fishers's strategies (Le Floc'h *et al.*, 2020), decreases in demand (Dias and Guillotreau, 2004), and technological changes (this article). The long-term time series of production data, in metric tonnes, shows a steady exploitation of around 10,000 -30,000 tonnes a year, with higher production levels of up to 40,000 tonnes in the early 1900s and in the 1970s, and lower production levels of around 6,000 tonnes in 1910, 1945 and the 1980s.

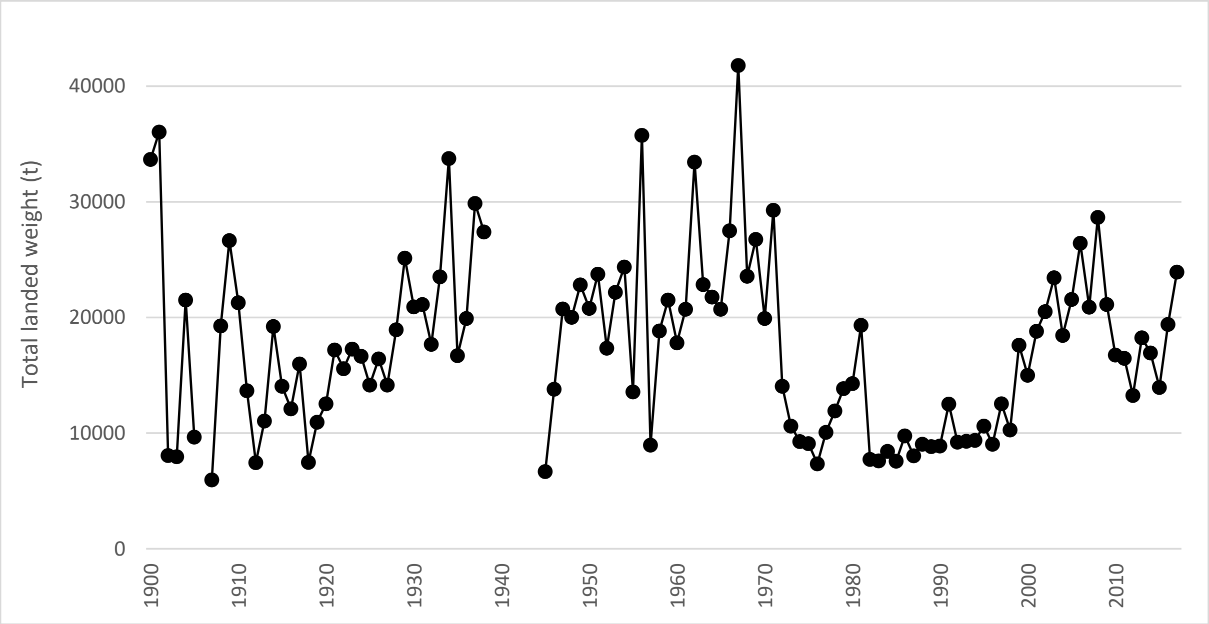

Figure 6 Total production of sardine from the Atlantic coast (weight in metric tonnes) from 1900 to 2017

While the inter-annual variability of production over this long time period may have been in part driven by fluctuations in the abundance of the resource, other factors such as technological change, may also serve to explain changes in production levels. To isolate such drivers, the following method is applied with the aim to identify change points in the historical series.

3.2. The Wild Binary Segmentation (WBS)

Statistical methods for time series segmentation and change-point detection have been widely used for more than half a century in industrial sectors (Lavielle, 2005; Kunal et al., 2020). However, its application to research in economics, particularly in the field of renewable natural resources, is more limited. The now easy access to these numerical methods through computer tools (the applications presented here are implemented in R[5]) offers new opportunities for applied work in humanities and economics. Time series segmentations approach are an alternative, sometimes complementary, to the more conventional approach of time series econometrics (Bai and Perron, 1998, 2003).

Time series segmentation offers many advantages at the operational level (shorter calculation time) as well as for results (with the optimization criterion over-segmentation is limited). For this analysis, we use the Wild Binary Segmentation (WBS) method applied to the long-term series of sardine production. In addition, stationarity analysis of the phases resulting from the segmentation method were carried out. The methodology used is a contribution to the research on long-term memory in social sciences (Teyssière and Kirman, 2007).

---

[5] R Core Team (2021). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL https://www.R-project.org/.

We aim to estimate N, the number of change-points in the time series. Binary segmentations (BS) are change-point detection techniques that proceed by successive steps of searching for an optimal point on the considered data set, most often using a CUSUM-like procedure (Fryzlewicz, 2014). The estimation of this change-point on a series $\{Yt\}$ defined on the time interval *[s;e]* relies on the maximization of $\left|\tilde{Y}_{s,e}^{b}\right|$, where $\tilde{Y}_{s,e}^{b}$ is the CUSUM statistic :

$$\tilde{Y}_{s,e}^{b} = \sqrt{\frac{e-b}{n(b-s+1)}}\sum_{t=s}^{b} Y_t - \sqrt{\frac{b-s+1}{n(e-b)}}\sum_{t=b+1}^{e} Y_t$$

where s, b, e are integers such that $s \leq b < e \leq T$ and $n = e - s + 1$. b_0 is the first change-point in the time-serie, b_1 is the second and so on.

Once the change-point has been isolated, the interval is divided into two sub-intervals, over each of which a similar procedure is carried out once again. The process proceeds recursively, so that a criterion of no significant change point is equivalent to a stop in the process within the interval considered. The method thus avoids the use of multidimensional optimisation algorithms and instead favours a simple and progressive construction of a segmentation. The consistency of the method can be demonstrated in terms of the number N and locations of optimal change-points, but this consistency is more generally verified when the detected intervals are not too narrow (spaces between two proven change-points greater than $T^{3/4}$, t=1,….,T). This method is therefore useful on series that are relatively dense in terms of information, and reasonably chaotic. The method may also prove ineffective for configurations involving specific arrangements of multiple change points.

The WBS (Wild Binary Segmentation) method eliminates the weaknesses of classic binary segmentations by carrying out maximisation measures of the CUSUM statistics not just 'globally' on a given interval, but 'locally' on random sub-samples extracted from this interval. This approach increases the probabilities of obtaining specific qualitative criteria: isolating a single change-point, relatively central to the chosen interval since in this case, the CUSUM index converges to the maximum likelihood index (Johansen, 1995; Bruggemann and Lutkepohl, 2005), which solves by randomisation potential problems caused by specific configurations.

We need two complementary stationarity tests in order to validate the segmentation results. The Augmented Dickey-Fuller (ADF) tests the null hypothesis H0 that the series is a unit root process, meaning the series is not stationary (Said and Dickey, 1984). The Kwiatkowski-Phillips-Schmidt-Shin test (KPSS) is based on the null hypothesis H0 that the data is stationary (Kwiatkowski *et al.*, 1992). For each of these tests, two versions were implemented. One was related to stationarity around a mean value (stationary in *level*), and the other was stationarity around a linear trend (stationary in *trend*). The stationarity tests were carried out on each phase identified by the segmentation of the series.

There are no official reports of sardine landings between 1939 and 1944. In addition, the annual report for 1906 has disappeared from the archives. Since the aim of our analysis is to highlight historical facts behind a numerical procedure of global segmentation, we needed to focus on the events that likely had the most contextual importance to the fishery while being methodologically coherent. Therefore, we did not divide the sample into two distinct segmentations of pre- and post-WW2 sub-periods. Rather, knowing that there was a fishery for the missing periods, we filled the missing data by imputation to get a complete series. The missing data was filled by imputation from the data for the previous and following years. For instance, we used the data from 1905 and 1907 for the missing data in 1906. The data for the period from 1939 to 1944 were computed differently to limit the impact of their imputation on the result of the segmentation procedure, which was applied to the entire time series. Thus, two distinct segmentation processes were applied to the pre-1939 and post-1945 phases, using the WBS method. The first segment of the pre-1939 adjustment defined the value imputed to 1939. The second segment of the post-1944 phase adjustment defined the value imputed to 1944. The intermediate years were then imputed by linear interpolation between these two years. This reconstitution of a series of data between 1939 and 1944 was justified based on studies conducted by historians that revealed that sardine production was maintained, as imposed by the German occupying force[6] (Fichou 2002; Marie d'Avigneau, 1958). All these data are listed in the appendix –Supplementary Table 2.

SECTION 4 RESULTS

Figure 7 shows the results of the WBS segmentation applied to the historical series of sardine landings between 1900 and 2017. When the first segment based on only two years in 1900 and 1901 is excluded (i.e., too brief, atypical, and therefore too brittle to be considered in the analysis because it is built on truncated data), the WBS procedure defines four segments: [1902-1926], [1927-1970], [1971-1997], [1998-2017].

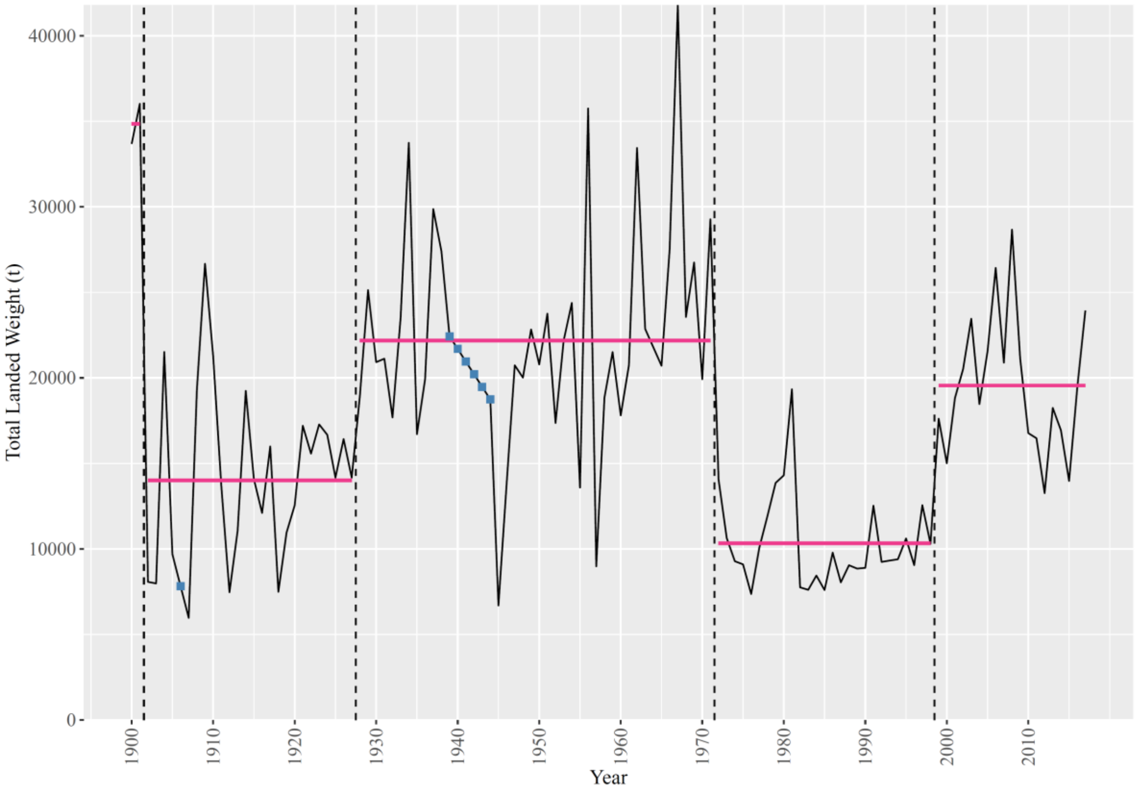

Figure 7 WBS applied to the 1900-2017 series of sardine production in France. Blue dots represent imputation for the 1906 missing observation and the linear interpolation between 1939 and 1944 while pink lines indicate four segments between change-points.

---

[6] The statistics provided by Fichou (2002) for the port of Douarnenez, the leader industrial site for sardine, are 2,100 – 400 – 1,100 - 31 and 880 tonnes respectively from 1940 to 1944.

As regards to segments 1 and 2, both the level and trend stationarity hypothesis are accepted using both ADF and KPSS tests: ADF's alternative hypothesis is accepted with 1% significance level, and KPSS' null hypothesis cannot be rejected at 10% level (nearly 5% for Ph2/Trend test). Conversely, ADF and KPSS conclusions are contradictory when applied to segments 3 and 4, on both level and trend stationnarity. KPSS leads to stationarity hypothesis validation, while ADF null hypothesis is assumed plausible at p>0.1 (p>0.05 with level stationnarity test for segment 3).

Table 1 Results of the Augmented Dickey-Fuller (ADF) and Kwiatkowski-Phillips-Schmidt-Shin (KPSS) stationarity tests (Level and Trend) applied to each WBS segments (Ph)

		Level							
		ADF				**KPSS**			
		Ph 1	**Ph 2**	**Ph 3**	**Ph 4**	**Ph 1**	**Ph 2**	**Ph 3**	**Ph 4**
Test statistic		-4.5***	-3.9***	-2.7*	-2.0	0.1***	0.2***	0.1***	0.1***
Critical values	**10%**	-2.6	-2.6	-2.6	-2.6	0.3	0.3	0.3	0.3
	5%	-2.9	-2.9	-2.9	-3.0	0.4	0.4	0.4	0.4
	1%	-3.5	-3.5	-3.5	-3.7	0.7	0.7	0.7	0.7
		Trend							
		ADF				**KPSS**			
		Ph 1	**Ph 2**	**Ph 3**	**Ph 4**	**Ph 1**	**Ph 2**	**Ph 3**	**Ph 4**
Test statistic		-4.4***	-4.1***	-2.6	-2.1	0.1***	0.1***	0.1***	0.1***
Critical values	**10%**	-3.1	-3.1	-3.1	-3.2	0.1	0.1	0.1	0.1
	5%	-3.5	-3.5	-3.5	-3.6	0.1	0.1	0.1	0.1
	1%	-4.2	-4.2	-4.2	-4.3	0.2	0.2	0.2	0.2

The three change-points (1927, 1971, 1998) highlight a major temporal effect breaking the history of the fishery's production into the four segments, or cycles. The determinants of these change points in the sardine production series can multiple. The effects of abundance or stock collapse are logical explanations. However, the migration phenomena of sardine stocks are poorly understood (Duhamel E., 2006, Bernal et al., 2007, Veron et al. 2020) and the duration of the cycles (between 20 and 30 years) appears much longer than the annual observations of the often chaotic abundance of the resource. We postulate that historical determinants of changes in production techniques played a major role in explaining these cycles, the main determinant of each cycle being of technological origin, and involving competition between an old and a new technique (fig. 8).

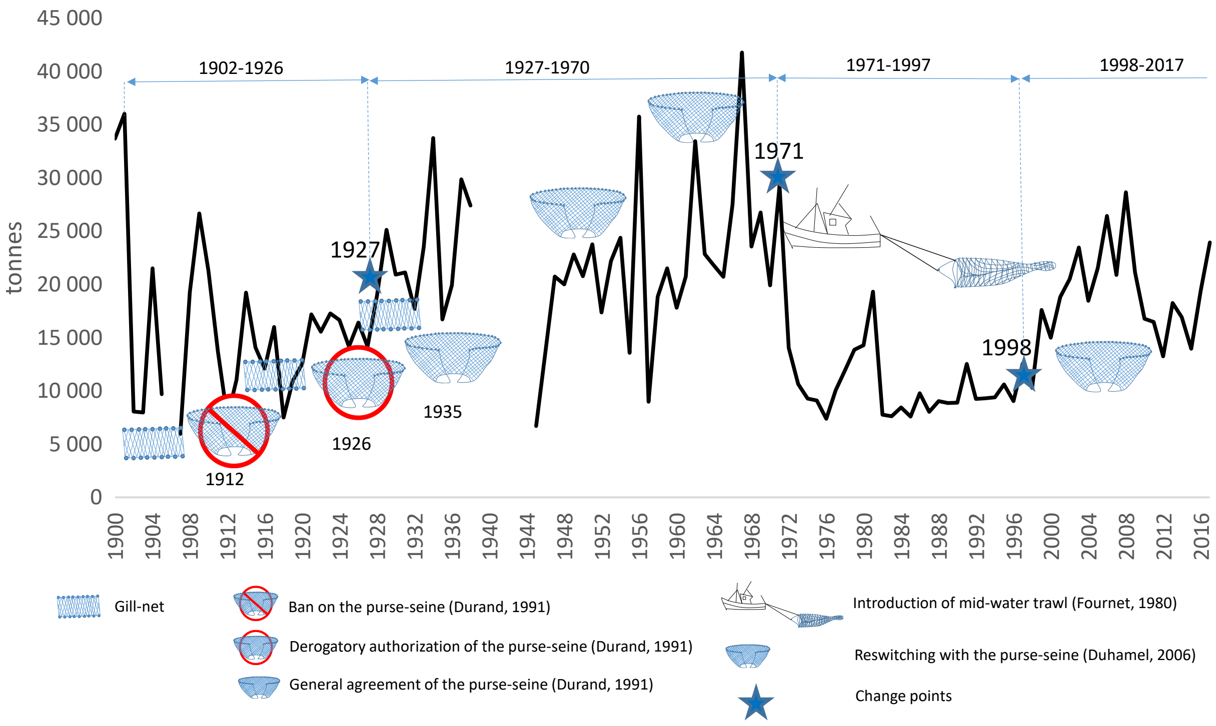

Figure 8 Identification of the four cycles in sardine production in France and corresponding utilisation of fishing techniques

Explaining technical change in 1927 and its impacts

The year 1927 was a first change-point between the phases [1902-1926] and [1927-1970] and tells the story of a competition between the gill-net, the old technique, and the purse-seine, used first for the sardine fishery in Japan in 1882 (Inoue, 1971). Purse-seine was introduced in Norway at the beginning of the 20th century and in the early 1880's in Sweden (Hamre and Nakken, 1971). Iceland adapted purse-seine for the herring in 1904 (Gislason, 1971). Although the purse-seine technique was introduced into the French sardine fishery at the beginning of the 20th century, resistance from users of the old technique led to ban by the State of the new technique in 1912 (fig. 8). In 1926, derogatory authorisations were granted, before the ban was lifted in 1935 (Durand, 1991). The dates of these political decisions were close to the first change point in 1927. The change point in 1927 can be explained by technical and social drivers. The first driver was a major technological change, where the gill-net was progressively replaced by the purse-seine from 1926, with derogatory authorisations by the French State. The majority of fishers reacted through a capacity for adaptation, strong resilience, with a still abundant resource but with weak social organisation (Durand, 1991). The South coast ports of Saint-Jean-de-Luz (fig. 5) were the first to adopt the innovation in 1925. This was allowed by fishers in 1926 on the North Atlantic coast from Saint-Guénolé (fig. 5). The French administration granted provisional authorisations to these port communities, while all the other communities refused to abandon the old technique (Durand, 1991). It was not until the end of the Second World War that the new technique was definitively adopted, across all French fishing ports. The second driver is of a social nature, with the migration of fishers from the North to the South coast. Sardine fishing is a seasonal activity, with a migration of the resource from the South of the Atlantic coast in April and May, towards the North in August and September. The migration of fisher populations in the opposite direction, from the North to the South in the early spring of 1927, triggered conflicts over access to the resource between the sedentary and nomadic fishers. Durand (1991) noted that State intervention was necessary in 1927 and that rights and duties were imposed on the two fisher populations, sedentary and nomadic.

Duhamel *et al* (2011, p.9) mention two “purse seine wars” in the port of Douarnenez, in 1951 and 1958. The fishing community in Douarnenez, using the gill-net, was the last to oppose the purse seine. A technological event ensured the dominance of the purse seine in the early sixties. A technological lock-in occurred with the purse seine technique. Indeed, a radical innovation, the Puretic power block, improved the productivity of this technique. The introduction of the power block during the 1950s in the USA is recognised as a major innovation for the purse-seine technology. Mario Puratic, a fisherman from Croatia (Island Brac, Croatia, 1904 - Santa Barbara, USA, 1993), developed a system to lift fishing nets filled with fish (Schmidt, 1971). The first technical trial was conducted in 1955 on a tuna purse-seine vessel in the USA (Green *et al*., 1960). A patent was filed with the US authorities in 1956. This innovation spread rapidly along the west coast of the United States and Canada. Schmidt (1971) reported that the *"introduction of the power block has started in many other countries, including Iceland, Norway, Portugal, South Africa, Morocco, Pakistan, Korea and Mexico"*. In 1957, the first Icelandic vessel used this equipment for herring fishing (Bardarson, 1971). In 1960, the French fisheries institute –ISTPM (fig.4) – tested this process with sardine fishers from Douarnenez to Saint-Jean de Luz (Letaconnoux and Laurent, 1960; Kurc and Laurent, 1963). Hamre and Nakken (1971) summarise the main advantages of installing the patented Puretic power-block: *"(a) saving time and labour in operating nets, (b) enabling fishers to handle larger and deeper nets, and (c) securing larger catches without assistance of other crews"*. We note from our series that sardine production was at high levels from 1960 to 1971 (fig. 8), between 20,000 and 40,000 tonnes. The spread of the power block on the purse-seine boats, a technique without competition until the end of the 1960s, most probably contributed to this high yield. However, this major innovation was not enough to eliminate the new mid-water trawl technique adapted during the same period for the sardine fisheries. The change point in 1971 in fact corresponds to the increasing adopters of the mid-water trawl (Duhamel *et al*., 2011).

Explaining technical change in 1971 and its impacts

The change point in 1971 came at a key period in the contemporary history of fisheries. World production reached 60 million tonnes in the early 1970s, which was double the production recorded by the FAO in 1960 (FAO, 2020). In the North-East Atlantic area, production in 1970 was almost at its highest level, at 10.6 million tonnes (OConnell and Le Floc'h, 2020). Mid-water trawls corresponded to this logic of high productivity, which was widespread in Northern countries from 1960 to 1980, as shown by Hannesson *et al*. (2010). The rapid technological development of fleets in Europe occurred in the fifties and sixties. It was helped by state subsidies (Standal, 2005) and support by public research institutes, with strong investment in all technological trajectories linked to fisheries (motorization, fishing gear, electronic equipment). The French administration encouraged this specialisation with subsidies for investment in industrial fishing (Meuriot, 1986). The mid-water trawl was developed after WWII in North West Europe for pelagic species, mainly herring (*Clupea harengus*). It was derived from the bottom trawl introduced in the UK around 1860 (Kenchington, 2018). The first experiments of mid-water trawl were carried out in 1937 in Germany (Brandt, 1971). France adopted the mid-water trawl for the herring artisanal fishery in 1952-1953 in the Northern fishing harbours, with the assistance of the ISTPM (fig.4) (Portier, 1970). In Canada, the same experiments for herring were engaged in 1958 with the recruitement of a former fisherman by the Department of Fishery Organisation (Johnson, 1968). The first trials on mid-water trawl for species other than herring in France began in 1960 on a small-scale fishing vessel (Portier, 1970), then in 1962 on an industrial-sized vessel (Nédélec, 1962a). The reports of the first trials gave contrasting opinions. In small-scale fishing, mid-water trawl did not allow the activity to be profitable, given the operating costs in terms of fuel and the amount of investment required. In industrial fishing, the technique offered a better guarantee with two vessels pulling the mid-water pair trawl. These experiments are not specific to the French case. Technical research institutes in Norway, Canada, Japan, the United States and West Germany conducted trials over the same period with technical adaptations to local conditions (Brandt, 1971). In the French experience, fishers were offered technical assistance from the national research institute for adapting mid water trawl to new species (Nédélec, 1962b). Without being targeted, sardines made a significant contribution to fishing. It was mainly the clusters of radical innovations (nylon, motorisation, electronic equipment, trawl lifting gear) that made the mid-water trawl more productive than purse-seine in the early 1970s. However, the diffusion of this new technology among sardine fishers was limited to a few communities in the ports of the South and Central Atlantic coast. Fournet (1980) provided convincing explanations for the adoption of mid-water trawl in 1974 in the South and Central Atlantic coast (fishing ports of Arcachon and Hendaye). The declining production of these two ports encouraged the fishers to invest in the emerging mid-water trawl technique to compete with the nearest ports specialising in purse-seine.

Explaining technical change in 1998 and its impacts

The third change-point in 1998 was a reswitching phenomenon, occuring between the phases [1971-1997] and [1998-2017]. Fishers came back to the purse-seine, and gradually abandoned the mid-water trawl (Duhamel, 2006). In 1995, total production reached 11,000 tonnes, of which 6,000 tonnes were landed by mid-water trawlers and 5,000 tonnes by purse-seiners (Duhamel, 2006). From 1997, the contribution of purse-seiners increased and slightly exceeded that of mid-water trawlers. In 2005, purse-seiners had complete control over the supply with a production of 14,000 tonnes, while mid-water trawlers were becoming marginal[7] (less than 2000 tonnes). Duhamel (2006) explained this change in behavior between mid-water trawlers and purse-seiners during the 1990s by three factors. Improvements in acoustic detection are a valuable aid in locating sardine shoals close to the coast, areas where mid-water trawlers were not allowed. The smaller size of the sardines in the coastal zone guaranteed a better price for the purse-seiners. This is the product that canneries are looking for. The third factor concerned the much higher fuel consumption of mid-water trawl (Le Floc'h *et al.*, 2012). The reswitch of technology is manifested in a withdrawal of mid-water trawlers and a greater specialisation by purse-seiners. Better control of technology allowed purse-seiners to move further offshore to hunt sardine schools without increasing the energy costs. Purse-seiners, active in the South and North of the Bay of Biscay, extended their range to the northern part by hunting sardines offshore in 2005 (fig. 9).

---

[7] We could also mention the collapse of the anchovy fishery in those same years (with a total fishing ban in place from 2005 for 5 years) on which the trawlers also depended for part of their income, and which led to the demise of their participation in that fishery. This may have helped accelerate the transition back to purse seine (Vermard et al., 2008).

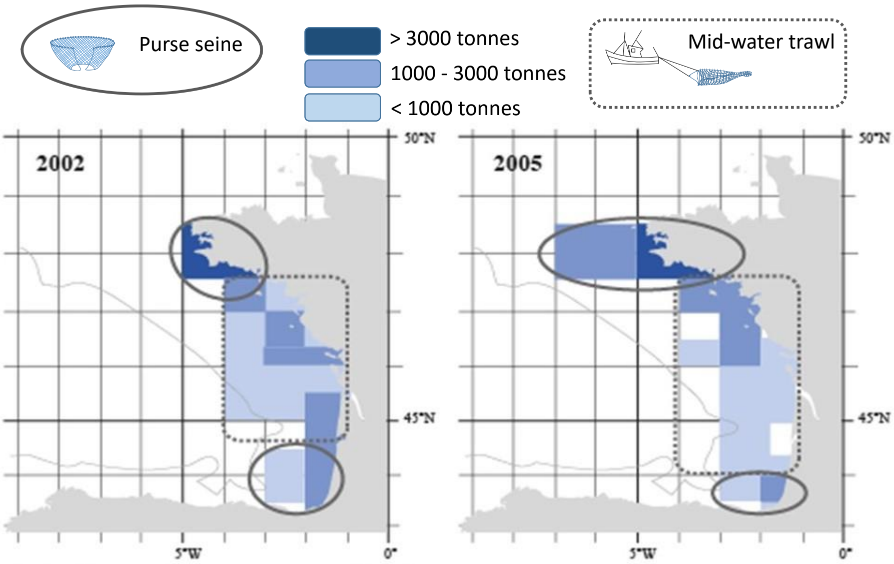

Figure 9 Spatial area of seiners and pelagic trawlers in 2002 and 2005
Source: adapted from Duhamel (2006) and Bouvet Y. (2021)

SECTION 5 DISCUSSION

Our analysis highlights two key points, from an evolutionary economics of technical change perspective. First, in our historical reconstruction of fishing techniques in the French Atlantic sardine fishery, we can identify the three properties of innovations highlighted by Nelson and Winter (1982) identified, relating to the duality of knowledge, the mode of diffusion and the localised character. Second, our analysis shows the important role of a national system of innovation supporting the fishing industry (Fagerberg *et al*., 2009 ; Le Floc'h et Fuchs, 2001). It is the technical institutes in each coastal country that promoted the adoption of new fishing techniques, which helped reduce social resistance to change.

Knowledge, diffusion and localization of innovations

The emerging superiority of the purse-seine in the nineties over the mid-water trawl highlights three properties recognised by the evolutionary approach to technical change and the diffusion process of an innovation (Nelson and Winter, 1982): *(i)* the duality of knowledge, codified and tacit knowledge; *(ii)* the mode of diffusion of innovations via feedbacks between fishers, the research institute and the resource dynamics; and *(iii)* the localised character of the choice of technique. The success of a technique depends on the ways in which knowledge is appropriated and implemented. Upon adoption, new users benefited from codified knowledge, transmitted by suppliers and research institutes. Tacit knowledge, based on experience and know-how (Hind, 2015) was also developed by fishers continuously and simultaneously adapting fishing gear (gill-net, purse-seine or mid-trawl), electronic navigation and detection equipment, and motorisation. These two aspects of knowledge formed a first property of the diffusion process (Cowan *et al.*, 2000). The history of technical change in marine fisheries confirmed the second property of the diffusion process of innovation, that of a cumulative process of technical progress by feedback between fishers, research institutes and the targeted resource (FAO, 1971; Sverrisson, 2002; Eigaard *et al*., 2014). Incremental improvements accelerated the diffusion of a new technique causing a technological lock-in (Arthur, 1989), with the old technique definitively abandoned in a pure technological competition model or effectively marginal in a prey-predator interaction model. The third property of the diffusion process is the localised nature of the choice of technique. Purse-seine and mid-water trawl, which were in competition with each other, attracted fishers from different communities. Figure 9 illustrates the localised nature of the choice of technique, with purse-seiners in the North and South of the Bay of Biscay and mid-water trawlers in the centre. This example of competition and technique feedback suggests that the choice is not only a national one, even though the major fishing nations (e.g. Norway, Japan, Scotland, Denmark) have partly shaped the history of fishing techniques since the late 19th century (Kenchington, 2018; Thomson, 1969). The local or territorial character seems to prevail in the process of adopting a new technique among fishers. There are good examples in the prevalence of the local driver: purse-seine and line in the Lofoten Islands for cod (Hannesson *et al.*, 2010), purse-seine and line in Shetland for herring (Nicolson, 1999), mid-water trawl for herring in the ports of Northern France (Portier, 1970), purse-seine for tuna in San Pedro, California (Green *et al.*, 1971).

The role of a national system of innovation in fisheries

The reason for a 40-year cycle (1927-1970) in the French Sardine fishery is partly due to the slow diffusion of the purse-seine because of strong social resistance of the users of the old technique. The resistance of fishers in many ports is also a reflection of the insufficient demonstration of novelty in the use of the purse-seine technique compared to the gill-net until the early 1950s, before the invention of nylon for example (Martinussen, 2006). The evolutionary literature on technical change explained that the decision to adopt a new method of production weakened a path of dependence linked to the weight of a community's history (North, 1991). Social resistance by “old-timers” does not necessarily reflect a refusal of technical change. National technical institutes encouraged fishers to adopt new catching methods after the Second World War. In a certain way, European countries have built a national system of innovation in fisheries (Lundvall, 1992; Freeman, 1995). These national systems of innovation provided information on the technological adaptations of new fishing gears (FAO, 1971). The debate was focused on the key role attributed either to the private entrepreneurs or the state. Smith (2000) argues that “*industrialisation has remained predominantly a private sector process*”. Fishers as private entrepreneurs play the key role in the diffusion process of innovations with the financial support provided by the administration. Martinussen (2006) detailed the adoption of nylon in Norway. The introduction of this innovation, that replaced cotton and hemp for the use of nets, was State-led in 1948. However, according to Martinussen: “*the fishers play an active role …as users of new technology and they give their feedback to the producers if the devices do not work, thus creating new innovations*”. In the case of switching techniques, that defined the change of technological systems, the administration governed the diffusion of the new fishing gear. In the UK, the Herring Industry Board encouraged the British fishers to convert from gill-net to purse-seine in 1966, by giving financial support to the first movers (Whitmarsh *et al.*, 1995). In France, the national research institute –ISTPM– conducted several experiments on the mid-water trawl and purse-seine. However, it seems that the superiority of mid-water trawl over purse-seine did not survive a 27-year business cycle, from 1971 to 1998, before the reswitching phenomenon occurred.

Limits

Our analysis is limited to the historical and economic study of technical change in the study of long cycles and change points for sardine exploitation on the French Atlantic coast. Clusters of innovations and technical changes are not the only determinants of change points identified by segmentation methods. Explanations of these change points might also involve considering international markets. Sardine imports from Portugal and Morocco have provided the bulk of the supply to the French market since the beginning of the 20th century (Dias and Guillotreau, 2004). Price fluctuations, which are less empirically correlated with changes in techniques than physical production, are more a response to the determinants of international trade and the effects of resource abundance. A logical follow-up to this research should focus on the explanatory elements of long term price movements. It is therefore not only in the history of techniques that the elements for understanding change points are to be found. The analysis of international trade could be considered by integrating cyclical events (protectionist measures, currency devaluations) and structural events (changes in consumer behavior and new marketing trends for seafood products). This would be an extension of the present research.

CONCLUSION AND POLITICAL IMPLICATIONS

The research applied to a long-term time series of sardine landings in France has offered new perspectives by statistically identifying the change points that suggest a structural change, combined with more focused historical research to understand how these structural changes may have come about. Segmentation methods, although little used in the field of social sciences, can nevertheless be adapted to re-examine past events. Narratives on these key moments in the history of an industry help demonstrate the role of technical change, which causes conflictual situations between those who did not want to adopt the new technologies and those who were willing to do so.

Some important points deserve to be highlighted in the concluding remarks. First, the historical record in France shows that the French State, like other public agencies in other countries, was not indifferent in its approach to technology identification and promotion. In the late sixties, one group used the old technique – purse seine –, increasing their specialisation, while the other group experimented with the new technique – the mid-water trawl– as the first adopters in the 70’s. Should the innovators, as Schumpeterian-style entrepreneurs, therefore be seen as the least resilient because they abandoned the historical path of purse-seine or they are the most resilient as they have sought new ways of maintaining and even developing their production of sardine? While this helped fishers in the short term, the results later caused significant difficulties for public policy, as the adoption of mid-water trawl may have accelerated stock depletion of sardine as well as other stocks prosecuted by the same fleets such as anchovy, eventually contributing to another technological switch.

Second, our historical analysis shows that in most of the cycles we identified in the fishery, large fractions of the fishing industry demonstrated some resistance to change, rather than continuous production of disruptive radical technologies, with State support being needed to make change happen at industry scale. This has explanations in the need for visibility of the industry, when developing their business plans. A need which is often put forward by the industry when discussing the variability in fishing quotas advice with a request for more stability in fishery policy.

This may serve to explain the resistance of some fleet segments to change, and the duration of cycles before a transition finally occurs.

Third, one may wonder whether the reswitching to purse seine in the 1990s means a definitive abandonment of the mid-water trawl. As discussed above, purse-seiners have specialised in a niche market by offering better quality sardines. The search for greater added value is the result of an agreement between purse-seiners and canneries located in the same area (Le Floc'h *et al*, 2020). So the purse seiners can be seen as more conservative, specialising in the provision of high quality smaller inshore sardines for a special segment of the canned market. The interplay between stock resilience, State promotion of certain technologies, and different adoption strategies of fishers according to which markets they served may thus help to explain the resistance of the purse seine fleet and the demise of the trawl technology.

Public management implications

There are many examples of overexploitation or collapse of stocks, some of which are long-standing (Jackson *et al.*, 2001). The first signs of overexploitation of the resource in the English North Sea trawl fishery appeared at the end of the 19th century (Cushing, 1988), under the pressure of the “first industrialization of fisheries” (Whithmarsh, 1990). In the UK herring industry, the damage caused by mid-water trawls on the resource and its spawn were identified in 1967, from the introduction of the technique. Finally, the rise and fall of the herring industry in the West of Scotland expanded on a short period of time, from the mid 60’s to the mid 70’s (Whithmarsh *et al.,* 1995). The collapse of the cod fishery in Canada certainly affected the fishing communities of Newfoundland. The future of highly fisheries-dependent regions in the Northwest Atlantic became economically unclear (Sinclair 1996). The announcement by the Canadian government with a Moratorium on cod fishing on 2 July 1992 is surely a change point in the realm of fisheries. Public agencies are faced with a complex issue, supporting diversification or specialization of communities in maritime areas, which are strongly dependent on fishing activities. There is even potential for a reswitching of techniques from the new to the old. During the 1990s, commercial fishers in France reinvested in the old technique, purse-seine, because the newer technology, the mid-water trawl eventually was regarded as biologically damaging and consequently economically non-effective.

Finally, our study shows that applied research on the segmentation of long series of fisheries landings data as well as detailed historical studies should be encouraged in order to better understand the challenges that both public managers and the fishing community face when trying to preserve biodiversity and maintain sustainable fisheries. Many fish and invertebrate stocks are now close to extinction due to the maintenance of unselective production techniques. There is currently a global phenomenon of sequential overexploitation of certain species due to a demand that far exceeds the availability of natural resource stocks. A part of this is explained by passive adoption and State led promotion of various capture technologies. A reduction in the State-led promotion of various innovations for capturing fish might be replaced by an increased effort by both the fishing industry and the State at identifying fishing techniques which are more selective and less destructive for non-target species, that are less harmful to the underlying ecosystem, and that promote more effective public management aimed at sustainability. There are by now many examples of such innovations, and they are likely to revolutionize how fisheries are conducted and managed[8]. But above all, our research suggests that in future no state should repeat the error of provoking unsustainable technological lock-ins in fisheries. The simple reason for this is that while human capacity for innovation is thought by many specialists in the economics of growth to be boundless, the productive capacity of marine ecosystems is not.

---

[8] Some examples of recent innovative approaches in fisheries: the development of satellite monitoring of fishing operations (Block *et al*., 1998); labelling approaches (Giacomarra *et al*., 2021); the organisation of new marketing channels at local level (Salladarré *et al*., 2018).

References

Arthur W.B., 1989. Competing technologies, increasing returns, lock-in by historical events. *The Economic Journal*, 99, 116-131.

Arthur W.B., 1994. *Increasing returns and path dependence in the Economy*. The University of Michigan Press, 224p. https://www.jstor.org/stable/10.3998/mpub.10029

Bai J., Perron P., 1998. Estimating and testing linear models with multiple structural changes. Econometrica, 66 (1), 47–78.

Bai J., Perron P., 2003. Computation and analysis of multiple structural change models. Journal of Applied Econometrics, 18, 1–22.

Bardarson H.R., 1971. Deck Equipment for Purse Seining, 283-287, in *Modern fishing gear of the world*. Fishing News (Books) Ltd., London.

Baumgartner T.R., Soutar A., Ferreira-Bartrina V., 1992. Reconstruction of the history of Pacifc sardine and Northern anchovy populations over the past two millennia from sediments of the Santa Barbara basin, California, *California Cooperative Oceanic Fisheries Investigations Reports*, 33,24-40.

Bernal M., Stratoudakis Y., Coombs S. *et al*. 2007. Sardine spawning off the European Atlantic coast: characterization of spatio-temporal variability in spawning habitat, *Progress in Oceanography*, 74, 210-227. https://doi.org/10.1016/j.pocean.2007.04.018

Bielsa E. 2022. For a translational sociology: Illuminating translation in society, theory and research, *European Journal of Social Theory*, *25*, 3, 403-421. https://doi.org/10.1177/13684310211002132

Block B.A., Dewar H., Farwell C., Prince E.D., 1998. A new satellite technology for tracking the movements of Atlantic bluefin tuna, *PNAS*, 95, 16, 9384-9389. doi: 10.1073/pnas.95.16.9384

Blundell R., Griffith R., Van Reenen J., 1999. Market Share, Market Value and Innovation in a Panel of British Manufacturing Firms, *The Review of Economic Studies*, 66, 529-554. https://doi.org/10.1111/1467-937X.00097

Brandt A.V., 1971. One-boat midwater trawling, 450-456, in Kristjonsson H. (ed.), Modern fishing gear of the World: 3 – Fish finding, purse seining, aimed trawling, FAO, Fishing News (Books) LTD, London, 569p.

Bruggemann R., Lutkepohl H., 2005. Practical Problems with Reduced-rank ML Estimators for Cointegration Parameters and a Simple Alternative. Oxford Bulletin of Economics and Statistics, 67 (5), 673- 690. https://doi.org/10.1111/j.1468-0084.2005.00136.x

Callon M., 1986. Some elements of a sociology of translation: domestication of the scallops and the fishers of St Brieuc Bay, *The Sociological Review*, 32, 1, 196-233. https://doi.org/10.1111/j.1467-954X.1984.tb00113.x

Charles A. T., 1992. Fishery Conflicts: A Unified Framework, *Marine Policy*, 16, 5, 379-393. doi.org/10.1016/0308-597X(92)90006-B

Coccia M., 2010. The Asymmetric path of Economic Long Waves, *Technological Forecasting & Social Change*, 77, 730-738. doi:10.1016/j.techfore.2010.02.003

Coccia M., 2016. Sources of technological innovation: Radical and incremental innovation problem-driven to support competitive advantage of firms, *Technology Analysis & Strategic Management*, 1-14. http://dx.doi.org/10.1080/09537325.2016.1268682

Coccia M., 2019. *Comparative Theories of the Evolution of Technology*, in Farazmand A., (ed.), *Global Encyclopedia of Public Administration, Public Policy, and Governance*. doi.org/10.1007/978-3-319-31816-5_3841-1

Coccia M. 2020. Asymmetry of the technological cycle of disruptive innovations, *Technology Analysis & Strategic Management*, 1462-1477. doi: 10.1080/09537325.2020.1785415

Coccia M., 2021. *Technological innovation*, doi: 10.1002/9781405165518.wbeost011.pub2

Cooper A.C., Schendel D., 1976. Strategic responses to technological threats, Business Horizons, 19, 1, 61-69. doi.org/10.1016/0007-6813(76)90024-0

Cowan R., David P.A., Foray D., 2000. The explicit economics of knowledge codification and tacitness. *Industrial and Corporate Change*, 9 (2), 211-253. doi. /10.1093/icc/9.2.211

Cushing D.H., 1988. The Provident Sea. Cambridge University Press, Cambridge, UK.

Dasgupta P., Stiglitz J., 1980. Industrial Structure and the Nature of Innovative Activity, *The Economic Journal*, 90, 358, 266-293. doi.org/10.2307/2231788

David P., 1985. Clio and the economics of QWERTY. *American Economic Review*, 75, 2, 332-337. https://www.jstor.org/stable/1805621

Dias J., F., Guillotreau P., 2004. *Nearly two centuries of fish canning: an historical look at european exports of canned fish*. Proceedings of the IIFET Conference, Tokyo, Japan. https://www.researchgate.net/publication/280945477_Nearly_two_centuries_of_fish_canning_an_historical_look_at_european_exports_of_canned_fish

Dosi G., 1982. Technological paradigms and technological trajectories: a suggested interpretation of the determinants and directions of technical change. *Research Policy*, 11, 147-162. doi.org/10.1016/0048-7333(82)90016-6

Dosi G., 1984. *Technical Change and Industrial Transformation: The Patterns of Industrial Dynamics*. In: Technical Change and Industrial Transformation. Palgrave Macmillan, London. https://doi.org/10.1007/978-1-349-17521-5_3

Dosi, G., 1988. *The nature of the innovative process, 221-228*. In Dosi G., Freeman C., Nelson R., Silverberg G., Soete L. (eds), *Technical Change and Economic Theory*. London: Pinter, 656p.

Duhamel E., Laspougeas C., Fry A., 2011. Rapport final du programme d'embarquements à bord des bolincheurs travaillant dans le Parc naturel marin d'Iroise, IFREMER, 41p. https://archimer.ifremer.fr/doc/00065/17593/15116.pdf

Duhamel E., 2006. The French sardine fishery. ICES Working Group on the assessment of Mackerel, Horse Mackerel, Sardine and Anchovy, Galway, 5-14 September 2006. https://archimer.ifremer.fr/doc/2006/acte-2292.pdf

Durand M.H., 1991. La crise sardinière française: les premières recherches scientifiques autour d'une crise économique et sociale, in Cury, P., & Roy, C. (eds.). Pêcheries ouest africaines : variabilité, instabilité et changement, ORSTOM, Paris, 1991, 26-36.

Eigaard O.R., 2009. A bottom-up approach to technological development and its management implications in a commercial fishery. ICES Journal of Marine Science, 66, 916-927.

Eigaard O.R., Marchal P., Gislason H., Rijnsdorp A.D., 2014. Technological Development and Fisheries Management. Reviews in Fisheries Science & Aquaculture, 22 (2), 156-174. doi: 10.1080/23308249.2014.899557

European Commission, 2019. *The 2019 Annual Economic Report on the EU Fishing Fleet*, Joint Research Center Science for Policy Report. https://stecf.jrc.ec.europa.eu/reports/economic.

Fagerberg J., Mowery D.C., Verspagen B., 2009. The evolution of Norway's national innovation system, *Science and Public Policy*, 36, 6, 431-444. doi: 10.3152/030234209X460944

FAO, 1971. Modern fishing gear of the World: 3 – Fish finding, purse seining, aimed trawling, Kristjonsson H. (ed.), Fishing News (Books) LTD, London, 569p.

FAO, 1990. Definition and classification of fishing gears categories. FAO Fisheries Technical Papers, n°222, Roma, 107p

FAO, 2020. Fishery and Aquaculture Statistics. FAO yearbook, Roma. http://www.fao.org/fishery/static/Yearbook/YB2018_USBcard/navigation/index_content_capture_e.htm

FAO, 2021. *Classification and illstrated definition of fishing gears*, FAO Fisheries and aquaculture Technical paper 672. https://www.fao.org/documents/card/en/c/cb4966en/

Fichou J.C., 2002. La conserverie de poisson, 1939-1945: une activité sinistrée? *Guerres mondiales et conflits contemporains*, 3, 207, 61-75. doi 10.3917/gmcc.207.0061

Fournet P., 1980. Le chalutage pélagique dans les eaux côtières du sud-ouest de la France. *Norois*, 106, 277-287. doi: https://doi.org/10.3406/noroi.1980.3890

Fourt M., Faget D., Perez T., 2020. Fighting the Minotaur: Resistance to technological change in the Mediterranean sponge fishing industry, 1840-1922. *International Journal of Maritime History*, 32 (2), 337-353. doi: 10.1177/0843871420920958

Freeman C., 1991. Innovation, changes of techno-economic paradigm and biological analogies in Economics. *Revue économique*, 42 (2), 211-232.

Freeman C., 1995. The 'National System of Innovation' in historical perspective. *Cambridge Journal of Economics*, 19, 5-24. https://doi.org/10.1093/oxfordjournals.cje.a035309

Fryzlewicz P., 2014. Wild binary segmentation for multiple change-point detection. The Annals of Statistics, 42 (6), 2243-2281. doi: 10.1214/1 4- AOS 1 245

Geels F.W., 2019. Socio-technical transitions to sustainability: a review of criticisms and elaborations of the Multi-Level Perspective, *Current Opinion in Environmental Sustainability*, 39, 187-201. doi.org/10.1016/j.cosust.2019.06.009

Genus A., Coles A.-M., 2008. Rethinking the multi-level perspective of technological transitions, *Research Policy*, 37, 1436-1445. doi:10.1016/j.respol.2008.05.006

Giacomarra M., Crescimanno M., Vrontis D., Pastor L.M., Galati A., 2021. The ability of fish ecolabels to promote a change in the sustainability awareness, *Marine Policy*, 123. https://doi.org/10.1016/j.marpol.2020.104292

Gislason T., 1971. The Icelandic technique of sonar guided purse, pp206-217, in Kristjonsson H. (ed.), Modern fishing gear of the World: 3 – Fish finding, purse seining, aimed trawling, FAO, Fishing News (Books) LTD, London, 569p.

Gordon D.V., Hannesson R., 2015. The Norwegian winter herring fishery: a story of technological progress and stock collapse. Land Economics, 91 (2), 362-385. doi: 10.3368/le.91.2.362.

Green R.E., Perrin W.F., Petrich B.P., 1971. The American tuna purse seine fishery, pp182-194, in Kristjonsson H. (ed.), Modern fishing gear of the World: 3 – Fish finding, purse seining, aimed trawling, FAO, Fishing News (Books) LTD, London, 569p.

Griliches Z., 1957. Hybrid corn: an exploration in the economics of technological change, *Econometrica*, vol. 25, 501-522. https://www.jstor.org/stable/1905380

Hamre J., Nakken O., 1971. Technological aspects of the modern Norwegian purse seine fisheries, pp225-231, in Kristjonsson H. (ed.), Modern fishing gear of the World: 3 – Fish finding, purse seining, aimed trawling, FAO, Fishing News (Books) LTD, London, 569p.

Hannesson R., 1996. Fisheries mismanagement: the case of the North Atlantic cod, John Wiley and Sons Ltd, Oxford, UK, 168p.

Hannesson R., Salvanes K.G., Squires D., 2010. Technological Change and the Tragedy of the Commons: The Lofoten Fishery over 130 Years. Land Economics, 86 (4), 746-765. doi: 10.3368/le.86.4.746

Hind E.J., 2015. A review of the past, the present, and the future of fishers' knowledge research: a challenge to established fisheries science. ICES Journal of Marine Science, 72 (2), 341-358. doi:10.1093/icesjms/fsu169

Inoue M., 1971. History of purse seining in Japan, pp158-161, in Kristjonsson H. (ed.), Modern fishing gear of the World: 3 – Fish finding, purse seining, aimed trawling, FAO, Fishing News (Books) LTD, London, 569p.

Jackson, J. B., Kirby M. X., Berger W. H., et al., 2001. Historical overfishing and the recent collapse of coastal ecosystems. Science 293, 629-637.

Johansen S., 1995. Likelihood-based Inference in Cointegrating Vector Autoregressive Models. Oxford University Press, Oxford.

Johnson W.W., 1968. Midwater trawling in Canada, Department of Fisheries of Canada. https://waves-vagues.dfo-mpo.gc.ca/Library/40630092.pdf

Kenchington T.J., 2018. The introduction of the otter trawl. The Northern Mariner, XVIII, 4, 327-346. https://www.cnrs-scrn.org/northern_mariner/vol28/tnm_28_327-346.pdf

Kunal S., Vinodh M., Chandrashekhar G.R., 2020. Pitfalls in long memory research. Cogent Economics and Finance, 8 (1), https://doi.org/10.1080/23322039.20 20.1733280.

Kurc G., Laurent T., 1963. Modifications à l'installation du power-block et de ses accessoires à bord du « Roselys », *Science et Pêche*, 116, juin, 4p. https://archimer.ifremer.fr/doc/1963/publication-7050.pdf

Kwiatkowski D., Phillips P. C. B., Schmidt P., Shin Y., 1992. Testing the null hypothesis of stationarity against the alternative of a unit root: How sure are we that economic time series have a unit root?, *Journal of Econometrics*, 54, 1-3, 159-178. https://doi.org/10.1016/0304-4076(92)90104-Y.

Lavielle M., 2005. Using penalized contrasts for the change-point problem. Signal Processing, 85, 1501–1510. https ://doi.org/10.1016/j.sigpro.2005.01.012

Lecatonnoux R., Laurent T., 1960. Compte-rendu préliminaire des travaux du Roselys en 1960. Le Power-block ou poulie motrice servant à la remontée des filets, *Science et Pêche*, 6p., 86, octobre. https://archimer.ifremer.fr/doc/00000/7186/

Le Floc'h P., Boude J.-P., 1998. L'approche évolutionniste et l'industrie des pêches maritimes: une application à la flottille chalutière bretonne, *Cahiers d'Economie et sociologie rurales*, 46-47, 71-92. doi : https://doi.org/10.3406/reae.1998.1570

Le Floc'h P., Alban F., Merzéréaud M., Duhamel E., 2020. Identification des points de rupture dans la série longue des productions de sardine en France (1900-2017). Revue d'Economie industrielle, 170 (2), 49-78. doi.org/10.4000/rei.9023

Le Floc'h P., Daurès F., Guyader O., Wilson J., 2012. A Case Study of Technological switching and Technological Lock-in in the French Fisheries Sector: Why is Sustainable Change so Difficult? Canadian Journal of Agricultural Economics, 60, 541-559. doi: j.1744-7976.2012.01259.x

Le Floc'h P., Fuchs J., 2001. Economics of science in fishery sector : The Euroepan case, *Marine Policy*, 25, 133-142. doi.org/10.1016/S0308-597X(01)00004-5

Lundvall, B.-A. (ed.), 1992. National Systems of Innovation: Towards a Theory of Innovation and Interactive Learning, London, Pinter

Marie d'Avigneau A., 1958. L'industrie des conserves de poissons en France métropolitaine : analyse économique du développement de la branche et diagnostic des entreprises. Rennes, Université de Rennes, Faculté de droit, 604p

Martinussen, A. O. (2006). Nylon fever: Technological innovation, diffusion and control in Norwegian fisheries during the 1950s. Maritime Studies (MAST), 5 (1), 29-44.

Meuriot E., 1986. Fishing fleet replacement: The French policy from 1945 to 1983. Marine Policy, 10 (4), 294-309.

Nédélec C., 1962a. Le chalut pélagique à un seul bateau pour la pêche industrielle – Compte-rendu des essais effectués par la « Thalassa » en 1962, Institut Scientifique et Technique des Pêches Maritimes, 110. https://archimer.ifremer.fr/doc/1962/publication-7043.pdf

Nédélec C., 1962b. Essais de chalut-bœuf pélagique en Bretagne, Institut Scientifique et Technique des Pêches Maritimes, 102. https://archimer.ifremer.fr/doc/1962/publication-7068.pdf

Nelson R.R., 1994. The Co-evolution of Technology, Industrial Structure, and Supporting Institutions, *Industrial and Corporate Change*, 3, 1, 47–63. https://doi.org/10.1093/icc/3.1.47

Nelson R.R., Winter S.G., 1978. Forces generating and limiting concentration under Schumpeterian competition, *Bell Journal of Economics*, 9, 2, 524-548. doi.org/10.2307/3003597

Nelson R.R., Winter S.G., 1982. An evolutionary theory of economic change. Cambridge, The Belknap Press of Harvard University Press, 437p.

Nicolson J.R., 1999. Shetland Fishers – Celebrating 50 years of the Shetland Fishers's Association, The Shetland Times Limited, Lerwick.

North D.C., 1991. Institutions. The Journal of Economic Perspectives, 5, 97-112, http://doi.org/10.1257/jep.5.1.97.

OConnell S., Le Floc'h P., 2020. The Atlantic: The driving force behind ocean circulation and our taste for cod. The Conversation. https://theconversation.com/the-atlantic-the-driving-force-behind-ocean-circulation-and-our-taste-for-cod-146534

Pistorius C.W.I., Utterback J.M., 1997. Multi-mode interaction among technologies, Research Policy, 26, 67-84. doi.org/10.1016/S0048-7333(96)00916-X

Portier M., 1970. Le chalutage pélagique. Institut Scientifique et Technique des Pêches Maritimes, 188. https://archimer.ifremer.fr/doc/1970/publication-6994.pdf

Ruttan V.W., 1997. Induced innovation, evolutionary theory and path dependence: sources of technical change. *The Economic Journal*, 107, 1520-1529.

Said S. E., Dickey D. A., 1984. Testing for Unit Roots in Autoregressive-Moving Average Models of Unknown Order, *Biometrika*, 71, 3, 599-607. https://doi.org/10.2307/2336570.

Salladarré F., Guillotreau P., Debucquet G., Lazuech G., 2018. Some good reasons for buying fish exclusively from communitysupported fisheries: the case of Yeu Island in France. *Ecological Economics*, 153, 172-180. doi: 10.1016/j.ecolecon.2018.07.017

Samuelson P.A., 1965. A theory of induced innovation along Kennedy-Weizsacker lines, *Review of Economics and Statistics*, vol. 47, 343-356. https://www.jstor.org/stable/1927763

Sarpong, D., S. Dong, and G. Appiah. 2016." Vinyl Never say Die": The re-Incarnation, Adoption and Diffusion of Retro-Technologies. *Technological Forecasting and Social Change* 103: 109–118. http://dx.doi.org/10.1016/j.techfore.2015.10.012

Schmidt P.G., 1971. The Puretic power block and its effect on 1959 modern purse seining, 400-413, in *Modern fishing gear of the world*. Fishing News (Books) Ltd., London.

Schmookler J., 1966. *Invention and Economic Growth,* Cambridge, MA: Harvard University Press.

Schumpeter A.J., 1939. Business Cycles. A Theoretical, Historical, and Statistical Analysis of the Capitalist Process, McGraw-Hill, New York.

Sinclair P.R., 1996. Sustainable development in fisheries dependent regions? Reflections on Newfoundland cod fisheries. Sociologia Ruralis, 36 (2), 224-235. doi.org/10.1111/j.1467-9523.1996.tb00018.x

Smith H. D., 2000. The industrialization of the world ocean. Ocean & Coastal Management, 43, millenium essay, 11–28. doi.org/10.1016/S0964-5691(00)00028-4

Solée R.V., Valverde S., Rosas Casals M., Kauffman S.A., Farmer D., Eldredge N., 2013. The evolutionary ecology of technological innovations, *Complexity*, 18, 4, 15-27. https://doi.org/10.1002/cplx.21436

Squires D., Vestergaard N., 2018. Rethinking the commons problem: Technical change, knowledge spillovers, and social learning, *Journal of Environmental Economics and Management*, 91, 1-25. https://doi.org/10.1016/j.jeem.2018.06.011

Sraffa P., 1960. The Production of Commodities by Commodities- Prelude to a Critique of Economic Theory, Cambridge, UK, Cambridge University Press.

Standal D., 2005. Nuts and bolts in fisheries management – a technological approach to sustainable fisheries? Marine Policy, 29, 255–263. doi.org/10.1016/j.marpol.2004.04.004

Sverrisson A., 2002. Small Boats and Large Ships: Social Continuity and Technical Change in the Icelandic Fisheries, 1800-1960. Technology and Culture, 43, 2, 227-253. doi: 10.1353/tech.2002.0092

Teyssière, G., & Kirman, A., 2007. Long memory in economics. Springer, 389p.

Thomson D.B., 1969. The seine net - Its origin, evolution, and use. Fishing News (Books) Ldt, London, 192p

Valdemarsen J. W., 2001. Technological trends in capture fisheries. Ocean & Coastal Management, 44, 635–651. doi.org/10.1016/S0964-5691(01)00073-4

Van Wyk R.J., Wessels J. P.H., 1987. Focussing a co-operative industrial research institute: A case study, *Research Policy*, 16, 1, 39-48. https://doi.org/10.1016/0048-7333(87)90005-9

Vermard Y., Marchal P., Mahévas S., Thébaud O., 2008. A dynamic model of the Bay of Biscay pelagic fleet simulating fishing trip choice: the response to the closure of the European anchovy (*Engraulis encrasicolus*) fishery in 2005, Canadian Journal of Fisheries and Aquatic Sciences, 65, 11, 2444-2453. https://doi.org/10.1139/F08-14

Veron M., Duhamel E., Bertignac M., Pawlowski L., Huret M., 2020. Major changes in sardine growth and body condition in the Bay of Biscay between 2003 and 2016: Temporal trends and drivers. *Progress In Oceanography*, 182, 102274. https://doi.org/10.1016/j.pocean.2020.102274

Whitmarsh D., 1990. Technological change and marine fisheries development. Marine Policy, 14 (1), 15-22. doi.org/10.1016/0308-597X(90)90034-O

Whitmarsh D., Reid C.A., Gulvin C., Dunn M.R., 1995. Natural Resource Exploitation and the Role of New Technology: a Case-history of the UK Herring Industry. Environmental Conservation, 22, 103-110. doi.org/10.1017/S0376892900010146

Wright G., 1997. Towards a More Historical Approach to Technological Change, *The Economic Journal*, 107, 444, 1560-1566. https://doi.org/10.1111/j.1468-0297.1997.tb00066.x

Supplementary Table 2 the historical series for sardine in France

Année	Tonne	Année	Tonne	Année	Tonne
1900	33683	1939	*nd*	1978	11925
1901	36025	1940	*nd*	1979	13862
1902	8073	1941	*nd*	1980	14300
1903	7982	1942	*nd*	1981	19333
1904	21516	1943	*nd*	1982	7754
1905	9685	1944	*nd*	1983	7610
1906	*nd*	1945	6695	1984	8443
1907	5971	1946	13808	1985	7601
1908	19278	1947	20735	1986	9782
1909	26669	1948	20017	1987	8046
1910	21275	1949	22829	1988	9047
1911	13686	1950	20787	1989	8851
1912	7469	1951	23755	1990	8895
1913	11062	1952	17365	1991	12526
1914	19242	1953	22183	1992	9240
1915	14075	1954	24381	1993	9321
1916	12106	1955	13586	1994	9396
1917	15993	1956	35752	1995	10611
1918	7496	1957	8984	1996	9054
1919	10949	1958	18848	1997	12557
1920	12545	1959	21508	1998	10300
1921	17198	1960	17811	1999	17615
1922	15574	1961	20731	2000	15011
1923	17282	1962	33443	2001	18823
1924	16672	1963	22861	2002	20514
1925	14172	1964	21786	2003	23457
1926	16424	1965	20713	2004	18468
1927	14172	1966	27506	2005	21558
1928	18960	1967	41796	2006	26430
1929	25133	1968	23564	2007	20890
1930	20919	1969	26747	2008	28667
1931	21124	1970	19922	2009	21143
1932	17689	1971	29274	2010	16770
1933	23525	1972	14064	2011	16471
1934	33743	1973	10636	2012	13264
1935	16710	1974	9280	2013	18244
1936	19916	1975	9099	2014	16938
1937	29871	1976	7369	2015	13975
1938	27408	1977	10073	2016	19407
				2017	23943