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Jules Selles

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1 Fisheries management: what uncertainties matter?

2 Selles Jules^{1,2*}

3 ¹IFREMER (Institut Français de Recherche pour l'Exploitation de la MER), UMR MARBEC, Avenue Jean 9
4 Monnet, BP171, 34203 Sète Cedex France.

5 ²LEMNA, Université de Nantes, IEMN-IAE, Chemin de la Censive-du-Tertre, BP 52231, '44322 Nantes
6 Cedex France.

7 *corresponding author, email: jules.selles@gmail.com, tel: +33 (0)779490657

8 **Abstract —**

9
10 Uncertainty is pervasive in fisheries management. Bioeconomists have undertaken long-
11 standing effort to derive economically optimal management rules under uncertainty and
12 provide explicitly optimal feedback solutions. Based on this body of work, we determine the
13 importance of different kinds of uncertainty in the definition of harvest control rules. The
14 performances of harvest policies which dictate how harvest is determined as a function of
15 the state of the resource are sensitive to uncertainty. We discuss six sources of uncertainties
16 and illustrate how these have affected the management process. We then describe how
17 those classes of uncertainty affect optimal harvest control rules. We summarize the
18 conclusions of economists based on structural assumptions affecting objective functions
19 under different classes of uncertainties. We identify common classes of harvest control rules
20 and the resulting precaution of the harvest strategy. Finally, we discuss the opportunities to
21 develop fully adaptive management to decide upon structural assumptions through the
22 extension of Markov decision process and feedback solutions to complex models.

23
24 **Keywords—** *Bioeconomic modeling; Uncertainty; Fisheries management; Optimal resource*
25 *management; Harvest policy; Harvest strategies; Control rules.*

27 **1 Introduction**

28 Despite many fisheries are highly regulated, overexploitation of fish stocks is still a
29 problem worldwide and rebuilding fisheries is central in scientists debates (Ricard et al.
30 2009, Worm et al. 2009, Costello et al. 2016, Froese et al. 2018). The failures of fishery
31 management have been linked to the inherent characteristics of fish stocks and the
32 influence of the global market-driven by growing demand for fishery products (Seijo et
33 al. 1998, Cochrane 2000, Caddy & Seijo 2005, Sethi et al., 2010, Collette et al. 2011,
34 Longo & Clark 2012, Pons et al. 2017). Management difficulties have been also attributed
35 to ignoring uncertainties that characterize fishery systems and to respond with a lack of
36 caution in management. Risks¹ associated with uncertainties and multiple objectives
37 permeate fisheries management (Francis & Shotton 1997, Cochrane 2000, Hilborn 2007,
38 Sethi 2010). Many fisheries have experienced overfishing² as a result of risky and short
39 sighted management policies (Clark 1973b, Garcia 1996, Hilborn et al. 2001, Grafton
40 2007, Clark 2010).

41 In face of uncertainty, the concept of the precautionary approach has been employed
42 widely among nations and fishery agencies (e.g. in Regional Fishery Management
43 Organisations, RFMOs, de Bruyn et al. 2013) to account explicitly for uncertainties in
44 decision making (FAO 1996, Garcia 1996). Precautionary principles are the basis to
45 ensure that the lack of full scientific knowledge (i.e. certainty) should not be an incentive
46 to postpone effective measure to prevent unsustainable exploitation (UNCED, 1993).
47 Besides, they have been translated into the adoption of management reference points to
48 avoid risks. Limit and target reference points have been adopted and management
49 decision should ensure that the risk of exceeding limit reference points is very low and
50 that target reference points should be respected on average (FAO 1996). The biomass
51 (B_{MSY}) that can produce the maximum sustainable yield (MSY) constitutes the central
52 reference point for fisheries referred to in international agreements and instruments
53 (UNCLOS 1982, UNFSA 1995, FAO 1995). Alongside the implementation of
54 precautionary principles, the Ecosystem-Based Fisheries Management (EBFM, FAO
55 2003, Garcia et al. 2003, Pikitch et al. 2004) has promoted the development of complex

¹ Risk entails the ideas of uncertainty and loss, the Food and Agriculture Organisation (FAO) refers to average forecasted loss (FAO, 1996).

² Biological and economic overfishing (Murawski 2000 defines overfishing in the context of Ecosystem-Based Fisheries Management).

56 models integrating all features of the social-ecological system encompassing the fishery.
57 Such Integrated Ecological–Economic Fisheries Models (IEEFMs or simply bioeconomic
58 models) have been increasingly used in the support of fisheries management with the
59 aim to account for complex feedbacks effect between fishing activities, and ecosystem
60 dynamics (for a review see Lehuta et al. 2016 and Nielsen et al. 2018). However, the
61 increasing complexities of IEEFMs reduce confidence in forecasting and the ability to
62 disentangle the way in which uncertainty is propagated (Garcia & Charles 2007, Schrank
63 & Pontecorvo 2007, Rochet and Rice 2009, Kraak et al. 2010, Planque 2015). In face of
64 such difficulties, Harvest Control Rules (HCRs) have been promoted to enhance
65 transparency and to consider explicitly the ecological, economic and social goals of the
66 triple bottom line (Cochrane 2000, Hilborn 2007). HCRs provide a simple scientific
67 based management strategy which depends on available data, knowledge and
68 management objectives (Punt 2010). The main contribution of the implementation of
69 HCRs is the integration of the scientific advice into the political realm through the direct
70 proposition of management strategy to deciders (Kvamsdal, 2016). However, the
71 construction of HCRs is mainly based on empirical work and may fail to take into
72 account key uncertainties of the fishery system (Deroba & Bence 2008, Liu et al. 2016).
73 The bioeconomics literature on renewable resource and fishery management models
74 several classes of uncertainty and provide explicitly optimal feedback solutions. The
75 framework considers a social planner seeking to maximize the net present value of the
76 fishery. Optimal Instead of relying only on simulation methods to evaluate the
77 performance of control rules, HCRs derived from such bioeconomic models can provide
78 guidelines on how setting harvest policies when uncertainty is considered.

79 The objective of this review is to bring insights into the importance of different kinds of
80 uncertainty in the definition of harvest control rules. The pursuit of this goal raises an
81 important question: what uncertainties matter when determining control rules? We
82 base our review on the long-standing effort to derive economically optimal management
83 rules under uncertainty. First, we describe the place of bioeconomic modeling approach
84 and feedback solutions in fishery management under different sources of uncertainties
85 arising throughout the management process. Then, we identify the shape and the
86 cautious of optimal management strategies under the source of uncertainties previously
87 identified. Finally, we offer conclusions about the relative importance of different kind of
88 uncertainties on the definition of HCRs.

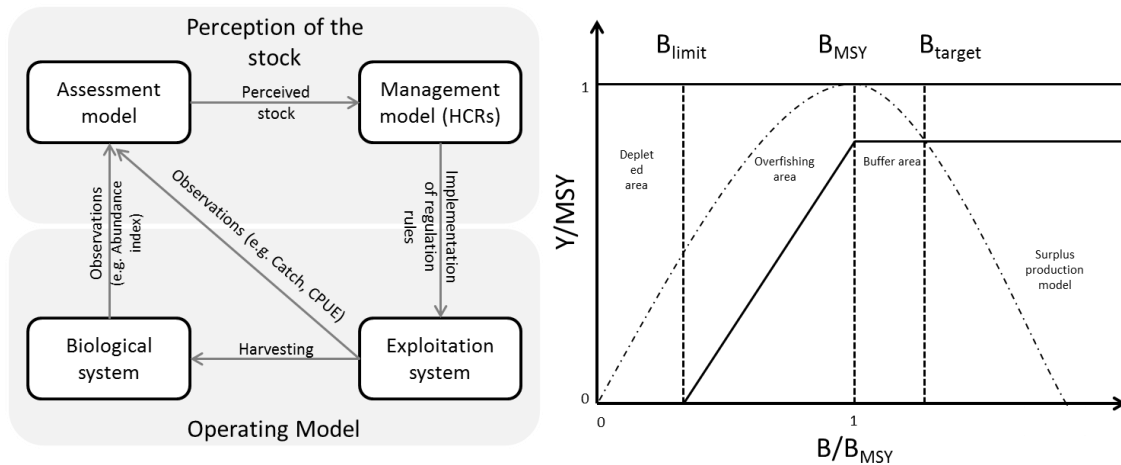
89 **2 Fishery management and uncertainties**

90 **2.1 Adaptive management, HCRs and MSE**

91 Modern fishery management promotes adaptive management (Walters, 1986) as the
92 new standard framework to address decision problems under uncertainty. Adaptive
93 management is an approach for simultaneously managing and learning about the
94 resource which consists imply to learn by doing and upgrade management policies with
95 new observations (Williams & Brown 2016). Searching for optimal harvest policy
96 corresponds to an attempt to apply adaptive management to fishery management. Clark
97 and Munro (1975) seminal work was the first attempt to develop feedback solution to
98 fishery management. They defined the optimal harvest rate as a function of the resource
99 level. Bioeconomic feedback solutions have inspired the development HCRs (Kvamsdal
100 et al. 2016). HCRs have been developed in response to the need for less complex
101 decision framework integrating the precautionary approach (Kvamsdal et al. 2016).
102 HCRs consist in a predefined series of actions (i.e. total allowable catch limits, TACs)
103 determined as a response of the observation of the state of the fishery (i.e. biological
104 information such as biomass level, Figure 1). However, HCRs are usually not derived
105 from formal IEEFMs optimization models, but are commonly simple rules based on
106 expert opinion. The latter point implies that although HCRs may include several
107 precautionary elements it does not constitute a standalone method to fully account for
108 uncertainties.

109 Management Strategy Evaluation (MSE) has been proposed as leading method for
110 coupling both IEEFMs and HCRs. It consists of associating single species management
111 model (i.e. Virtual Population Analysis VPA): a decision model (HCR) and an "operating
112 model" (IEEFM) accounting for alternative modeling hypothesis. MSEs are used to
113 evaluate the extent to which HCR achieve their goals (i.e. reaching B_{target}). Given the
114 uncertainty integrated into the operating model, MSEs are used to quantify the risk
115 represented by uncertainties throughout the decision process from observations and
116 assessment models to implementation (Butterworth 2007, Punt et al. 2010). Therefore
117 MSE based on simulation modeling has increasingly been used to evaluate the impact of
118 the main recognized sources of uncertainty in fishery systems (e.g. in the Commission
119 for the Conservation of Southern Bluefin Tuna, Kurota et al. 2010, for a review see Punt

120 et al. 2016). The objective is to find HCRs that are robust to uncertainties and to provide
 121 managers with a set of management options that encompass the precautionary
 122 approach.



123
 124 Figure 1: Conceptual framework of Management strategy evaluation (MSE) (adapted from Kell et al. 2007)
 125 and an example of a precautionary constant catch harvest control rule incorporating biomass target
 126 ($B_{target} > B_{MSY}$), buffer area and limit (adapted from Froese et al. 2010) with a hypothetical equilibrium yield
 127 (Y) from a surplus production model.

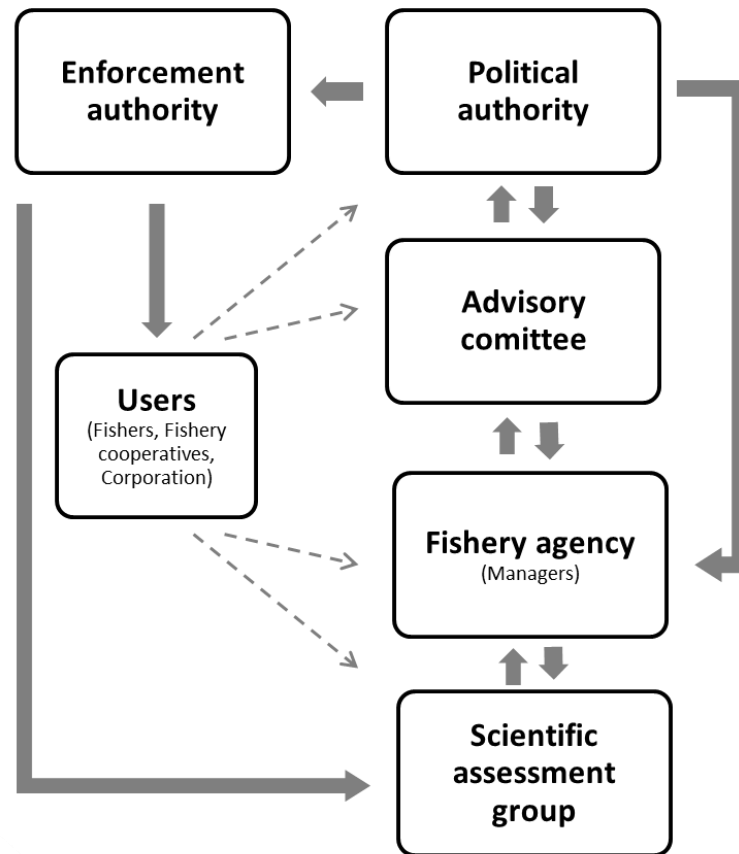
128 HCRs and MSEs found their essence in 'top-down' management scheme where a central
 129 regulatory body is in charge of the management and the evaluation of the resource. A
 130 typical decision-making structure (Figure 2) is composed of a scientific assessment
 131 group giving management advice to managers and to an advisory committee (including
 132 resource users) which in turn inform a political authority where responsibility for the
 133 final decisions lies. Each country or RFMO has its own institutional chain from scientific
 134 fisheries research to political and enforcement decisions (e.g. the Common Fisheries
 135 Policy in the European Union, Daw & Gray 2005 or in RFMOs, Lodge et al. 2007). In any
 136 case, the central institution typically sets the total allowable catch (TAC) and further
 137 inputs restrictions (e.g. seasonal, size catch limit) and specifying the enforcement
 138 procedures.

139 Large uncertainties related to resource, economic and social states are common in
 140 fishery management and lead to high transaction costs³. Williamson (1985) argued that
 141 institutions are established to minimise transaction costs. Thus, in such complex

³ Management transaction costs within fisheries can be classified into three categories included in the fishery management cycle (Abdullah et al. 1998, Figure 3): information costs related to the resource assessment, decision-making costs related to the policy making and operational costs included monitoring, control and enforcement costs (or implementation costs).

142 systems, the hierarchical and centralized structures of fishery institution have emerged
143 from the high uncertainties in the information on fishery systems (Abdullah 1998,
144 Nielsen 2003). However, the conjunction of centralised institution, high uncertainties
145 levels and complexities in model used for management have narrowed confidence and
146 legitimacy of fishery management institutions (Daw and Gray, 2005, Hauge et al. 2007,
147 Kraak et al. 2010, Dankel et al. 2012). The loss of legitimacy is, in turn, increasing
148 substantially transaction costs related to monitoring and enforcement of regulated
149 fishing activities (Abdullah 1998, Nielsen 2003). Thus, reducing uncertainty
150 surrounding scientific advice should concomitantly decrease management costs. HCRs
151 can facilitate a fisheries governance system where regulators and fishers work together
152 to decide on overall harvest strategy based on predefined HCRs (Kvamsdal et al. 2016).
153 HCRs by integrating management rules (i.e. TAC) in the realm of scientific advice reduce
154 uncertainty with regard to handling and communication of uncertainty (Rosenberg
155 2007, Kraak et al. 2010, Dankel et al. 2012).

156 Nevertheless, HCRs leave aside key political issues such as the allocation of fishing rights
157 imposing high transaction costs. They are mainly distributed on the basis of historical
158 catches negotiation (in RFMOs, Cox 2009, Bailey et al. 2013) rather than economic
159 rationality (Marszalec 2017). Rights-based management such as Individual Transferable
160 Quotas (ITQs), or cooperatives (i.e. Producers Organisations) and community quotas
161 (with or without ITQs) is a complementary solution to provide fishers with good
162 incentives for compliance and efficient allocation regulated through market (Hilborn
163 2004, Grafton et al. 2006, Beddington et al. 2007, Grafton 2008). ITQs, co-management
164 and collective actions have been brought at the forefront as the solution for improving
165 fisheries management (Beddington et al. 2007, Costello et al. 2008, Berkes 2009,
166 Gutiérrez et al. 2011, Deacon 2012). However, theoretical works and empirical
167 evidences have demonstrated that right based management does not constitute a
168 panacea (Clark, 2010, Thebaud et al. 2012, Melnychuk et al. 2012). Co-management by
169 delegating a part of management tasks to user-organizations can substantially reduce
170 transactions by decreasing monitoring and control of activity (Van Hoof, 2009).
171 Furthermore, co-management can increase the legitimacy of regulations and social
172 norms (Jentoft 1998, Nielsen 2003).



173

174 Figure 2: Conceptual decision-making structure in fisheries management (adapted from Cochrane 2000).

175 **2.2 Uncertainty in fishery management**

176 Large uncertainty is common in most fisheries management activities. To embrace
 177 uncertainties, fishery management can be viewed as an adaptive management cycle
 178 (Figure 3, Walters 1986, Fulton et al. 2011) where a central fishery agency collects
 179 information supporting decisions on regulations on annual or longer periods.
 180 Uncertainty emerges at each step of the management cycle and can act to undermine
 181 effective fishery management (Fulton et al. 2011). Previous surveys classified
 182 uncertainties related to the resource dynamics, assessment and management procedure
 183 and propose best practices to address those uncertainties (Figure 3, Hilborn & Peterman
 184 1996; Charles 1998, Regan et al. 2002, Harwood & Stocks 2003, Peterman 2004, Hill et
 185 al. 2007, Fulton et al. 2011, Link et al. 2012). Seven sources of uncertainties (sometimes
 186 called error) that are important sources of risk in fisheries management have been
 187 identified: uncertainties associated with environment conditions, observations, model,

188 socio-economic conditions, parameters, decisions and behaviours (adapted from
189 Hilborn & Peterman 1996, Figure 3).

190 **2.2.1 Environmental conditions uncertainty**

191 A major source of uncertainty in fishery systems stems from the inherent
192 unpredictability of the resource and ecosystem dynamics (Glaser et al. 2014, Planque
193 2015). In his seminal work on ecosystem resilience, Holling (1973) identified that
194 complex interactions (feedback mechanisms), stochastic and non-linear processes are
195 part of the restricting features of numerical modeling used for predictions. Without the
196 will to be exhaustive, environmental uncertainties encompass all spatio-temporal
197 variations in species and community abundance, distributions and interactions, changes
198 in life traits, periodic variability of environmental conditions or shifts in productivity
199 regimes (Link et al. 2012). For example, a typical concern in fishery management is the
200 definition of the stock recruitment relationship which is highly dependent on
201 environmental conditions and subject to random fluctuations (e.g. Fromentin et al.
202 2014).

203 **2.2.2 Observational uncertainty**

204 Uncertainty in observations arises from imperfect methods of observation and from
205 sampling error⁴. Such observation uncertainty leads to parameters estimation (or
206 inference) errors (i.e. imprecision, mis-specified parameter distributions and biased
207 parameter estimates) and structural errors (e.g. mis-specified migratory pattern and
208 stock composition). For example, the lack of fisheries-independent indices is a common
209 situation for highly migratory species (abundance indices relied mainly on catch per unit
210 effort, CPUE, Maunder & Punt 2004, Lynch et al. 2012). The logistical challenges of data
211 collection in such fishery are huge. Several sampling methods are available such as
212 tagging, larval and acoustic surveys which can provide abundance indices, but they are
213 constrained by high costs resulting in restricted spatial coverage (Leroy et al. 2015).
214 However, new methods take advantage of specific behavior of tuna species, aerial
215 surveys of tuna school counts and acoustic tagging surveys associated with fish
216 aggregating devices (FADs) are getting close to be a reliable solution to overcome this

4 Sampling error can be defined as the statistical differences between a sample of individuals and the population.

217 issue (Bauer et al. 2015, Capello et al. 2016). Mis-reporting of catch which is related to
218 illegal, unreported and unregulated (IUU) fishing is also a challenge for management of
219 highly migratory species (e.g. Fromentin et al. 2014).

220 **2.2.3 Model and parameter uncertainty**

221 Model and parameter uncertainties are the upshot of an incomplete, and potentially
222 misleading, representation of system dynamics (Hill 2007). Models are only abstractions
223 and there still be uncertainty about whether a given model structure (also called
224 structural uncertainty) is an appropriate representation of the system being studied.
225 Alternative model structures result in multiple model formulations that can achieve the
226 same level of fit to data (Lehuta et al. 2016). Model uncertainty can have a large impact
227 on achieving management objectives (Punt 2008). For example, even with the advent of
228 the EBFM, most of the models used in stock assessment are based on single-species age-
229 structured population dynamics, ignoring important ecological interdependencies.
230 Furthermore, assessment models such as Virtual Population Analysis (VPA⁵) are very
231 sensitive to several assumptions about key biological dynamics such as the natural
232 mortality (Jiao et al. 2012) and selectivity patterns (Brooks et al. 2010).

233 **2.2.4 Economical, political and social uncertainty**

234 Uncertainty in economic, political and social conditions results from market fluctuations
235 which affect species price, as well as in fixed and variable costs of fishing effort. Such
236 variations affect expected profits and consequently the short-term dynamic behavior of
237 fishing fleets (Salas & Gaertner 2004). Consequently, the magnitude of catches might
238 vary in the short-term, affecting the population abundance. For example, in case of
239 substitutable resources on global market such as tuna species, modification in both local
240 and international political conditions and decisions (e.g. TAC in RFMOs) may also
241 constitute a source of uncertainty by altering prices and therefore economic incentives
242 (Sun et al. 2015, Guillotreau et al. 2017, Sun et al. 2017).

⁵ e.g. statistical VPA used in the International Commission for the Conservation of Atlantic Tunas (ICCAT),
Porch (2003).

243 **2.2.5 Decisional uncertainty**

244 Uncertainty in decision, changes in management objectives (resulting from an
245 unpredictable behaviour of the political authority) and the existence of multiple and
246 conflicting objectives constitute an important source of uncertainty (Anderson 1984,
247 Hilborn 2007). Political, social and economic pressures can alter management decisions
248 and lead to ignoring scientific advice claiming the argument of uncertainty in the
249 scientific advice (Rosenberg 2003, Delaney et al. 2007, Rosenberg 2007, Fromentin et al.
250 2014). For example quota reductions may not be implemented (e.g. Fromentin et al.
251 2014, Piet et al. 2010, Villasante et al. 2010, O’Leary et al. 2011). In international shared
252 fisheries⁶, strategic interactions play also a crucial role in the determination of common
253 management leading to cooperation between states through international arrangements
254 and institutions (e.g. RFMOs). Compared to domestic fisheries⁷, international fisheries
255 are subject to management difficulties mainly because of a lack of cooperation between
256 states (Munro 2004, McWhinnie 2009, Teh & Sumaila 2015).

257 **2.2.6 Behavioural uncertainty**

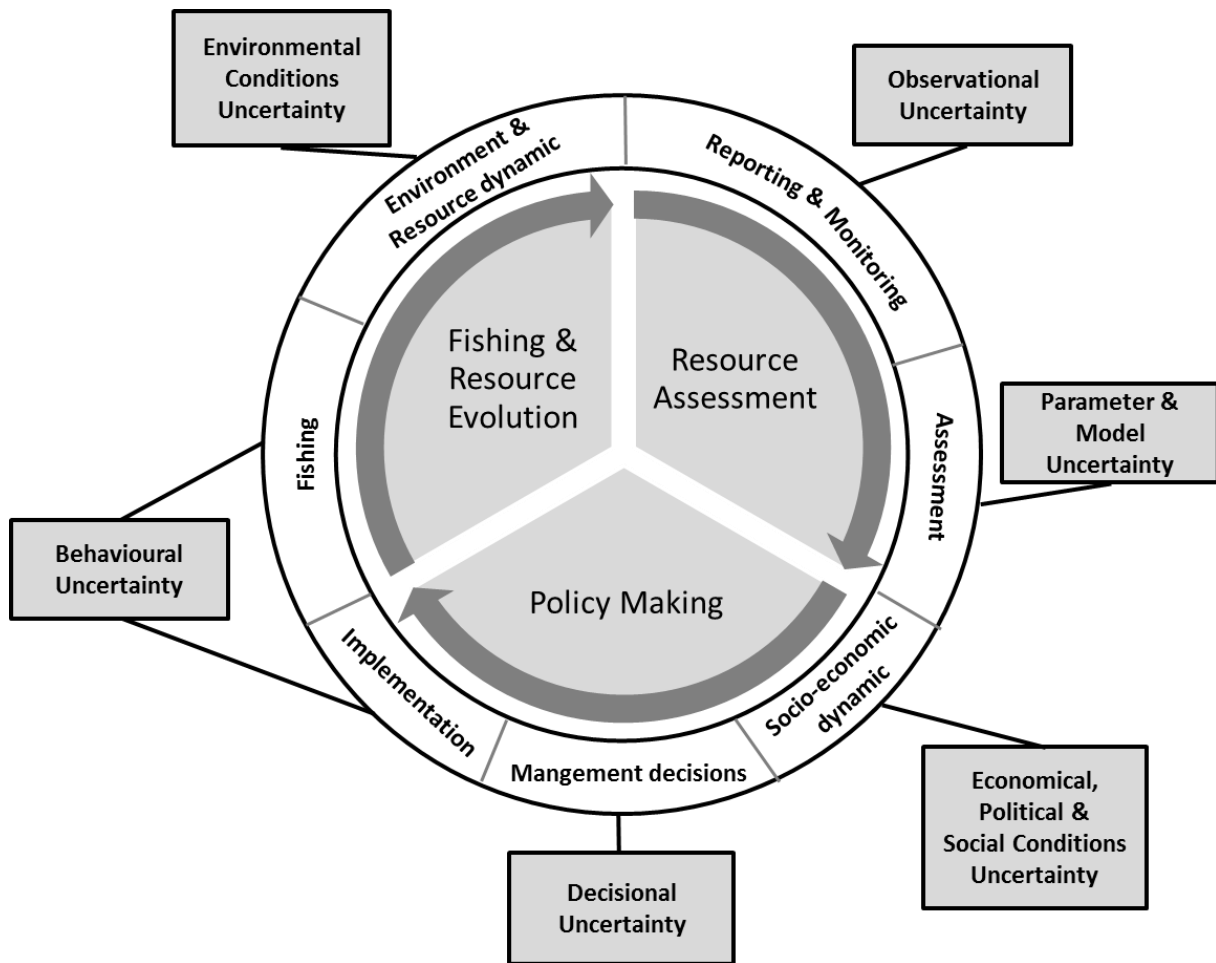
258 Uncertainty in the behaviour of resource users is the consequence of complex
259 interactions between economic and social drivers which can lead fishers to act as free-
260 rider and undermine the intent of management actions (Fulton et al. 2011). Behaviour of
261 fishers concerning their spatio-temporal allocation of fishing effort to different métiers⁸,
262 and the reliability of catch and effort data reported, can change in an unexpected way as
263 a response of management regulations (Salas & Gaertner 2004, Vermard et al. 2012).
264 Mis-alignment between managers and users objectives has been claimed as the main
265 factor driven the uncertainty in fishers’ behaviour (Grafton et al. 2006). Divergence of
266 management intentions and response of resource users often leads to complex
267 management regulations based on an accumulation of input controls (i.e. control of
268 fishing effort, qualified of ‘band-aids’ approach, Hilborn et al. 2004). Uncertainty in the
269 behavior of resource users could be also the consequence of a lack of control or an
270 inadequate enforcement policy (Fulton et al. 2011). For example, IUU fishing can emerge
271 because of lack of control or and inadequate policy can be designed if there is no a direct

⁶ Shared fisheries refer to transboundary, straddling and highly migratory stocks.

⁷ Fisheries contained within one exclusive economic zone (EEZ).

⁸ Métier means a combination of a gear, a target or group of target species.

272 link between the management lever (e.g. effort), indicator (e.g. catch) and objective (e.g.
 273 constrained levels of fishing mortality, Fulton et al. 2011).



274
 275 Figure 3: Schematic diagram of the rule-based adaptive management cycle and sources of uncertainties
 276 that can undermine fisheries management (adapted from Fulton et al 2011).

277 **3 Effect of uncertainties on optimal fishery management:**
 278 **Does precautionary management prevail in face of**
 279 **uncertainties?**

280 **3.1 Optimal fishery management problem**

281 Uncertainty is a central concern in fishery management, as described previously
 282 complex simulation frameworks have been developed integrating ecological, economic
 283 and social aspects to assess the robustness of HCRs on different kinds of uncertainty.
 284 However, this approach does not allow deriving formal management rules. Feedback

285 solutions through the application of optimal control theory extensively used in fishery
 286 economics studies have the ability to translate biological or ecological indicators (e.g.
 287 stock) into harvest advice. The so-called ‘bang-bang’ or ‘constant-escapement’
 288 management policy finds its origin in the seminal work on feedback solutions made by
 289 Clark & Munro (1975) in which the present value of the economic rent of the resource is
 290 maximised by bringing the stock to an optimal level as quickly as possible. The optimal
 291 escapement⁹ level resulting from the well-known golden rule of capital accumulation is
 292 defined at the point where the internal rate of return of the stock is equal to the social
 293 rate of discount (Clark & Munro 1975). Nevertheless, to achieve an efficient bang-bang
 294 control, management's policy mechanisms must respond promptly and accurately
 295 especially in presence of uncertainties (Roughgarden & Smith 1996). Before discussing
 296 the impact of uncertainty on the optimal policy, let’s introduce the modeling framework
 297 of a management problem with a single decision maker.

298 A typical discrete¹⁰ optimal dynamic management problem is defined as a social planner,
 299 a hypothetical fishery manager who could be a corporation, a cooperative, a government
 300 agency, or a regulatory body, someone who owns the rights to the exploitation of the fish
 301 stock and which seeks to maximise the expected net present value of the resource
 302 stock¹¹. The manager decides in each period the level of a control variable (e.g. TAC) to
 303 adjust the state variable (e.g. stock of fish). This decision is based on the current period
 304 value function (e.g. profits from fishing) and future values which are down-weighted
 305 using a discount factor. The state transition function depends on the current state and
 306 control variables which ensure the Markov property. The manager’s problem can be set
 307 as:

$$\max_{\{y_t\}} E \left[\sum_{t=0}^{\infty} \delta^t \pi(x_t, y_t, \varepsilon_t^\pi, \theta_t^\pi) \right]$$

308 Subject to:

$$x_{t+1} = f(x_t, y_t, \varepsilon_t^f, \theta_t^f)$$

309 Where $\pi(x_t, y_t, \varepsilon_t^\pi, \theta_t^\pi)$ is the objective function (value function) and $f(x_t, y_t, \varepsilon_t^f, \theta_t^f)$ the
 310 state transition function from period t to $t+1$. Each function depends on a set of
 311 variables, the state variable x_t (i.e. the stock) and control variable y_t (i.e. the yield). The

⁹ Escapement level refers to the stock level after harvesting.

¹⁰ We only illustrate the discrete case which is sufficient to illustrate the principles involved.

¹¹ We only focus our review on models grounded in subjective expected utility theory (SEU, see Shaw & Woodward 2008).

312 vectors of stochastic terms $\varepsilon_t=(\varepsilon_t^\pi, \varepsilon_t^f)$ applied on the objective function (e.g. stochastic
313 prices) or the transition function (e.g. stochastic shocks to the resource stock), vectors of
314 parameters $\theta_t=(\theta_t^\pi, \theta_t^f)$ relating to the state transition and objective functions. Finally, δ
315 represents the discount factor.

316 Those kinds of Markov decision process (Puterman 2004) are generally solved using
317 stochastic dynamic programming techniques (Marescot et al. 2013). As highlighted in
318 Deroba & Bence (2008), stochastic dynamic programming is an efficient method for
319 defining an HCR which best meets the specified objective over a long term period. HCRs
320 can be derived both analytical and numerical, but because of their complexities most
321 fishery applications are numerical (e.g. in a deterministic framework Sandal &
322 Steinsman 1997, Grafton et al. 2000, Arnason et al. 2004). The computational cost of
323 such technique is high in face of the so called issue of “the curse of dimensionality”
324 arising from searching over a wide range of policy strategy (Marescot et al. 2013).
325 Trade-offs between biological, economic realism and model complexity have limited
326 most fisheries applications to surplus production model. However recent studies have
327 tackled the resolution of optimal strategy in more complex settings such as the age-
328 structured model (e.g. Tahvonen et al. 2017). This field of studies departs from
329 simulation-based evaluation of HCRs which consider complex modeling approach
330 evaluating the trade-offs between several indicators (e.g. studies involving MSEs).

331 Since the seminal work of Reed (1979), economic literatures have undertaken to study
332 the effect of different classes of abstracted uncertainty related to the previous
333 classification on optimal resource management policy. In the following section, we will
334 discuss the relative impacts of different classes of uncertainty on the optimal policy
335 related to the dynamic management which has been exposed. However, as pointed out
336 by Holland & Herrera (2009) findings and resulting recommendations from
337 bioeconomic models relying on optimal control theory (which found their basis in the
338 Bellman’s principle of optimality, Bellman 1957) are ambiguous or conflicting in many
339 cases. Model (structural) uncertainty relating to biological or economic assumptions has
340 been found to qualitatively and quantitatively affect the optimal policy.

341 To extract consistent and salient features of optimal policy we disregard in this section
342 the literature using complex model integrating into their model, age structuration (e.g.
343 Tahvonen et al. 2017), spatial processes (e.g. Costello & Polasky 2008), multispecies
344 interactions (e.g. Poudel & Sandal 2015) or comparison of different regulation tools (fee

345 versus quotas, e.g. Weitzman 2002). We focus our analysis on risk neutral profit
346 maximization objective¹².

347 **3.2 Uncertainty and precautionary management**

348 **3.2.1 Qualitative optimal policy**

349 McGough et al. (2009) provided a useful analytical solution of a general stochastic
350 fishery model on which we will stand to review the effects of uncertainties on optimal
351 policy. They concluded that the constant escapement policy is optimal under the
352 following specific structural assumptions: i) stochastic shocks affecting the stock
353 (growth) are independently and identically distributed (i.i.d.), ii) demand is perfectly
354 elastic, iii) objective implies risk neutrality and iv) marginal harvest costs are
355 independent of the quantity harvested (i.e. Schaefer's production function). Relaxing
356 one of these conditions should imply that the constant escapement policy is not optimal.
357 They demonstrated that functional assumption (linear or non-linear in state variable,
358 harvest) made on the objective function (profit function) alter the optimality of the
359 constant escapement policy. When profit exhibit a non-linear dependence on harvest,
360 the optimal policy swift toward a biomass-based rule smoothing harvest in order to
361 decrease the magnitude of the price reduction (downward slopping demand) or
362 decrease the magnitude of the cost augmentation (Cobb Douglas' type production
363 function). Otherwise, considering a white noise (i.i.d. shocks on growth) does not affect
364 qualitatively the optimal policy, but they showed that allowing correlated environmental
365 shocks affecting the growth of the resource modify the optimal policy. The size of the
366 resource left loses its value at the expense of the size of the environmental shock which
367 provides useful information to predict future growth of the resource.

368 The constant escapement control rule is a specific policy. Catch and fishing mortality¹³
369 can also be used to define HCRs. The constant escapement rule involves taking all
370 biomass over some specified target level. The constant catch rule consists to harvest the
371 same biomass each year (or period) and leads to high fishing mortality when the

¹² Or yield maximisation which is equivalent to the profit maximization objective when profit is a linear in harvest. Furthermore, we focus on risk neutral framework and we leave the consideration about risk aversion utility function to integrate precautionary principles (Gollier et al. 2000, Chev e & Congar 2003).

¹³ Per capita mortality rate.

372 biomass is at low level¹⁴, while the constant fishing mortality maintains the same fishing
373 mortality regardless of stock abundance (see supplementary materials, Appendix A).
374 From that basic HCRs, different variants have been implemented, adding more flexibility
375 related to the biomass level, to address the different weakness, such as depensatory
376 effects which can cause resource collapse.

377 We take advantage of the review of harvest policies produced by Deroba & Bence (2008)
378 to classify optimal found in the literature in 5 classes corresponding to common control
379 rules: i) constant escapement, ii) constant catch, iii) constant fishing mortality, iv)
380 biomass-based catch and v) biomass-based fishing mortality which could be assigned to
381 shock-based policy described in the theoretical result of McGough et al. (2009). In their
382 review, Deroba & Bence (2008) referred mainly on simulation-based studies which
383 analyse the performance of common HCRs relative to different objective functions¹⁵.
384 While Deroba & Bence (2008) include complex modeling framework, the general
385 qualitative findings of McGough et al. (2009) are in line with their observations (see
386 supplementary materials, Appendix B). However, the integration of the state
387 (observation) uncertainty about the size of resource seems to alter the optimality of the
388 constant escapement policy and favor a constant fishing mortality policy.

389 Therefore, based on these criteria, we reviewed the applications of optimal control
390 theory on fishery management to disentangle the qualitative effects of different classes
391 of uncertainty (Table 1 and Table 2). We compare optimal policy in the structural
392 assumptions setting define by McGough et al. (2009) by confronting what kind of control
393 rule is optimal and if greater level of uncertainty leads to more precautionary¹⁶ policy as
394 it expected under the scientific obligations to precautionary approaches.

395 **3.2.2 Environmental conditions uncertainty - stochastic growth**

396 **3.2.2.1 Independent and identically distributed shocks**

397 In surplus production biomass model, random fluctuations affecting the growth of the
398 stock are a stylised representation of the stochasticity observed in the recruitment,
399 productivity (i.e. carrying capacity) or mortality of the stock driven by environmental

¹⁴ Constant catch rule is defined as a depensatory policy (i.e. density independent).

¹⁵ We only keep the result based on the profit or yield maximization objective which can be linked to the decomposition of McGough et al. (2009).

¹⁶ Precautionary means that uncertainty causes managers to choose less intensive harvest and maintain higher stock.

400 conditions. Since the seminal work of Reed (1979), several authors have confirmed that
401 introducing stochastic growth (i.e. multiplicative i.i.d shocks in discrete setting or a
402 Wiener process in continuous setting) does not affect the optimality of the constant
403 escapement (CE) policy (Parma 1990, Sethi et al. 2005, Nostbakken 2008, Kapaun &
404 Quass 2013). However, as McGough et al. (2009) highlight the structural assumptions
405 behind this result are very restrictive. If the objective function does not respect the
406 linearity condition in harvest, the optimal policy is no longer the constant escapement
407 (Pindyck 1984, MacDonald 2002, Kugarajh et al. 2006, Nostbakken 2008, Sarkar 2009;
408 Kapaun & Quass 2013 and Kvamsdal et al. 2016). Under the non-linearity assumption,
409 the optimal HCR vary with the resource size and fit a biomass-based catch (BBC) type
410 rule defined by Deroba & Bence (2008).

411 Furthermore, increasing uncertainty surrounding the growth of the resource has a
412 different impact in term of caution if we consider linear or a non-linear objective
413 function. Nonetheless, quantitative results show only a small absolute difference.
414 Optimal feedback policies do not seem to be strongly affected by stochastic
415 environmental uncertainties. In the linear setting, increasing the uncertainty (variance
416 of the stochastic shocks) leads to an ambiguously more cautious harvest which in turn
417 preserves the resource level to higher level. When profits are non-linear in harvest the
418 resulting cautious of HCR is ambiguous. McDonald et al. (2002), Kugarajh et al. (2006)
419 and Kvamsdal et al. (2016) found that increasing uncertainty has the same effect that
420 increasing the discount rate in the deterministic case especially at low stock level. The
421 resulting optimal HCR is, therefore, more aggressive when uncertainty is high and
422 resource is scarce. However, their logistic growth model which includes a specific
423 depensation response creates an incentive to fish down the resource when the stock
424 falls below the critical depensation level. In such case, the stock will be unable to
425 recover. When the depensation assumption is relaxed, Sarkar et al. (2009) found that the
426 optimal harvest (HCR) size is a decreasing function of the growth uncertainty. Pindyck
427 (1984) has generalized the condition in which uncertainty lead to more or less cautious
428 harvesting behaviour when stochasticity is included in a non-linear model. Growth
429 fluctuations reduce the value of the stock, and because their variance is an increasing
430 function of the stock level, there is an incentive to reduce the stock level by harvesting
431 faster. Growth fluctuations also increase in average harvesting costs and create an
432 incentive to increase harvest rate. If we consider a fixed harvest rate, the expected

433 growth rate of the stock decreased which in turn reduces the harvest rate. Therefore,
434 Pindyck concludes that the effect of uncertainty on the feedback control rule is
435 indeterminate. Kapaun & Quass (2013) came to a similar conclusion in a discrete setting
436 assuming a convex cost function and infinitely elastic demand. They demonstrated that
437 the optimal HCR could be higher or lower than in the deterministic setting.

438 A special case of non-linear objective function concerns convex profits. This situation
439 typically involves schooling fisheries which face concave cost functions. When fish
440 presents schooling behaviours, as long as fishermen have the ability to locate the schools
441 harvest does not depend on the size of the resource. This structural assumption yields
442 incentives to fish down the stock at low level increasing the risk of collapse.
443 Furthermore, this assumption turns the HCR into a pulse-fishing type which induces to
444 harvest a lot above a threshold and then let the stock growth (Maroto & Moran 2008,
445 Maroto et al. 2012). Da Rocha et al. (2014) investigated the effect of growth uncertainty
446 when increasing returns are considering. They confirmed that convex profits conduct to
447 pulse fishing, but increasing growth uncertainty tends to fit a constant escapement
448 policy.

449 Overcapacity is widely recognized as a major problem affecting world fisheries. Even in
450 a regulated fishery, overcapacity in fishing fleets in response to (temporarily or
451 cyclical)¹⁷ positive rents is a major impediment to achieving economically productive
452 fisheries (Beddington et al. 2007). Most of the studies ignore the cost of investing in
453 fishing vessels by considering the capital as perfectly malleable. Introducing costly
454 capital adjustment turns the optimal policy into a biomass-based catch type. When the
455 objective function is linear in harvest, uncertainty in growth leads in most case to a more
456 precautionary harvest of the resource (e.g. Charles and Munroe 1985). However, when
457 stocks are fast growing and capital are low cost, investment in large fleet which offers
458 the opportunity to take advantage of positive recruitments events (positive shocks),
459 becomes a reliable strategy. This result holds even if we consider the objective function
460 to be non-linear in harvest (Poudel et al. 2015). Costly capital adjustment can also be
461 linked to policy adjustment¹⁸ (e.g. TAC adjustment). When a resource fluctuates
462 randomly, biomass-based or constant escapement HCR increases variability in catch to

¹⁷ Overcapacity can result from several sources such as periodic fluctuation of fish abundance (e.g. Fréon et al. 2008), use of subsidies (e.g. Clark et al. 2004), fluctuation of variable costs (e.g. fuel price) or directly fish price which affect the profitability of the fishery (e.g. Sumaila et al. 2008). The high profitability of the initial phase of a developing fishery is typical case of overcapitalisation.

¹⁸ Transaction costs associated with revisiting past policy decisions.

463 reflect environmental variation (Deroba & Bence 2008). A trade-off between more or
464 less responsive approaches to environmental variations which can lead to more or less
465 precautionary harvest depends on the linearity assumption of the objective function and
466 the forms of policy costs (Boettiger et al. 2016, Ryan et al. 2017).

467 **3.2.2.2 Correlated and cyclical variations**

468 Considering that environmental fluctuations are serially uncorrelated is a strong
469 assumption. Many observations showed that recruitment is serially correlated induced
470 by environmental signals (e.g. Koster 2005). Furthermore, growth rates of fish stocks
471 have been shown to be non-stationary. Cyclical environmental variations over large
472 range of temporal scales independently of fishing activity have been shown to induce
473 fluctuations of fish stock. For example, several studies have shown the influence of large
474 scale climatic variations such as the El Nino Southern Oscillation (e.g. Lehodey et al.
475 1997) or long term trend in physical factors such as the temperature (e.g. Ravier &
476 Fromentin 2004).

477 McGough et al. (2009) demonstrated that when environmental fluctuations are
478 correlated or cyclical are considered the optimal policy becomes sensitive to
479 environmental shocks which fit a biomass-based fishing mortality (BBF) HCR. This
480 result is in line with studies which include correlated or cyclical variations of fish stock
481 growth (e.g. Parma 1990, Walters & Parma 1996, Singh et al. 2006 and Carson et al.
482 2009). When fluctuations are cyclical, the optimal HCR followed closely environment
483 cycles with lower escapement when conditions are poor and higher when conditions are
484 good (Parma 1990, Walters & Parma 1996 and Carson et al. 2009). This investment
485 behavior taking advantage of good environmental condition to invest in the resource
486 reinforces recruitment fluctuations. Singh et al. (2006) found close results with a model
487 included simultaneously correlated random stock growth and costly capital adjustment
488 with a non-linear objective function. Under these assumptions, they showed that optimal
489 HCR implies to build up the fleet when environmental conditions are good (positive
490 serial correlation) in anticipation of higher future catch levels and decrease fleet when
491 conditions are poor.

492 Table 1: Optimal HCRs policy and precautionary behaviour compared to the deterministic case based on a review of the available literature.

Surplus Production Model		Objective function: Maximize Profit				
		Malleable Capital/Policy		Costly Capital/Policy Adjustment		
		Linear objective function in harvest†	Non-linear objective function in harvest‡	Linear objective function in harvest†	Non-linear objective function in harvest‡	
No uncertainty	-	CE	BBC	BBC	BBC	
	Growth uncertainty (i.i.d shocks)	CE	BBC	BBC	BBC	
Parameter uncertainty	Growth uncertainty (correlated & cyclical variations)	BBF	BBF	-	BBF	
	Growth uncertainty (regime shift - endogeneous)	BBC	BBC	-	-	
	Growth uncertainty (regime shift - exogeneous)	CE	-	-	-	
	Price uncertainty (i.i.d. shocks)	BBC	-	-	-	
	Price uncertainty (correlated variations)	-	BBC	-	-	
	Growth uncertainty (correlated variations) * Price uncertainty	CE	BBC	-	-	
	Growth uncertainty (regime shift - endogeneous * i.i.d. shocks)	BBC	-	-	-	
	Growth uncertainty (regime shift - exogeneous * i.i.d shocks)	CE	-	-	-	
	Observational (State) Uncertainty	Stock size observation Uncertainty	BBC	-	-	-
		Stock size observation * Growth Uncertainty (i.i.d shocks)	BBC	CE	-	-
Regime shift uncertainty		BBC	-	-	-	

CE : Constant Escapement policy

BBC: Biomass-based catch policy

BBF: Biomass-based fishing mortality policy

† Infinitely elastic demand associated with Schaefer's type production function or yield maximization.

‡ Downward sloping demand or/and Cobb Douglas' type production function non-linear in harvest.

■ : More precautionary optimal policy

■ : Less precautionary optimal policy

□ : Ambiguous effect or no effect

493 Table 2: References used for the construction of Table 1.

Surplus Production Model		Objective function: Maximize Profit			
		Malleable Capital		Costly Capital Adjustment	
		Linear objective function in harvest†	Non-linear objective function in harvest ‡	Linear objective function in harvest†	Non-linear objective function in harvest ‡
No uncertainty	-	Clark & Munro (1975)	Sandal & Steinsman (1997); Grafton et al. (2000); Arnason (2004)	Clark et al. (1979)	Boyce et al. (1995); Sandal et al. (2007)
	Growth uncertainty (i.i.d shocks)	Reed (1979); Parma (1990); Sethi et al. (2005); Nostbakken (2008); Kapaun & Quaas (2013); Da Rocha et al. (2014)	Pindyck (1984); MacDonald (2002); Kugarajh (2006); Nostbakken (2008); Sarkar (2009); Kapaun & Quass (2013); Da Rocha et al. (2014); Kvamsdal et al. (2016)	Charles & Munro (1985)	Poudel et al. (2015)
	Growth uncertainty (correlated & cyclical variations)	Parma (1990); Walters & Parma (1996); Carson et al. (2009)	Carson et al. (2009)	-	Singh et al. (2006)
Parameter uncertainty	Growth uncertainty (regime shift - endogenous)	Polasky et al. (2011); Baggio & Fackler (2016)	Ren & Poalsky (2014)	-	-
	Growth uncertainty (regime shift - exogenous)	Reed (1988); Polasky et al. (2011); Baggio & Fackler (2016)	-	-	-
	Price uncertainty (i.i.d shocks)	Nostbakken (2006)	-	-	-
	Price uncertainty (correlated variations)	-	Kvamsdal et al. (2016)	-	-
	Growth uncertainty (multiplicative i.i.d) *	Nostbakken (2006)	Kvamsdal et al. (2016)	-	-
	Price uncertainty (correlated variations)	-	-	-	-
	Growth uncertainty (regime shift - endogenous * multiplicative i.i.d)	Baggio & Fackler (2016)	-	-	-
	Growth uncertainty (regime shift - exogenous * multiplicative i.i.d)	Baggio & Fackler (2016)	-	-	-
Observational (State) Uncertainty	Stock size observation uncertainty	Sethi et al. (2005)	-	-	-
	Stock size observation uncertainty *	Clark & Kirkwood (1986); Costello et al. (2001); Sethi et al. (2005); Memarzadeh & Boettiger (2018)	-	-	-
	Growth Uncertainty (i.i.d shocks)	Clark & Kirkwood (1986); Costello et al. (2001); Sethi et al. (2005); Memarzadeh & Boettiger (2018)	Da Rocha et al. (2014)	-	-
	Regime shift uncertainty	Baggio & Fackler. (2016)	-	-	-

† Infinitely elastic demand associated with Schaefer's type production function or yield maximization.

‡ Downward sloping demand or/and Cobb Douglas' type production function non-linear in harvest.

494

3.2.2.3 Regime shifts

495 Complex interaction and dynamic in fishery systems may induce sudden and drastic
496 switch between contrasting stable states (Scheffer et al. 2001, Folke et al. 2004).
497 Exogenous environmental shocks and fishing activity may trigger a regime shift from
498 high to low productive regimes or irreversible collapse of populations (review in Jiao
499 2009 and Kraberg et al. 2011). Catastrophic shifts such as fishery collapses have been
500 mainly attributed to overfishing as a result of economic factors and mismanagement, but
501 environmental stochasticity associated with compensatory mechanism may also be a
502 cause of fisheries collapse (Mullon et al. 2005).

503 Regime shifts pose difficult challenges for management (Crépin et al. 2012) which
504 depend whether the dominant factors are exogenously and/or endogenously
505 determined as well as on their severity and irreversibility (catastrophic consequences or
506 shift in productivity). The severity criterion appears to be less significant in the
507 determination of the precautionary of the optimal HCR. Therefore, we dissociate studies
508 on the basis of the likelihood of the shift (change in the stock growth function) is
509 exogenous or a function of management actions (e.g. TACs).

510 Reed (1988) seminal work applied a general surplus production model with a linear
511 objective function in harvest and stochastic exogenous and endogenous irreversible
512 regime shift (catastrophic collapse consequences). Uncertain exogenous shift reduces
513 the future value of the resource which gives incentives to harvest the resource in the
514 current period resulting in more aggressive HCR. However, endogenously driven shifts
515 result in more precautionary harvest which depends on how the shifting probability
516 increases as resource level decreases (density-dependent effect) compared to the
517 density-independent nature of the hazard rate function (density-independent effect).
518 When the population is able to recover after collapse (reversible shift), the resulting
519 HCR becomes more aggressive because of the reduction of the density-dependent effect.
520 Polasky et al. (2011) generalized these results considering two kinds of shifts:
521 catastrophic collapse or change in system dynamic (reduced growth). Their findings
522 confirmed Reed's outcomes, when the risk is endogenous the cautious of the resulting
523 HCR depends on the severity of the consequence of the shift which gives more weight to
524 the density-independent effect. If the shift is reversible or implies non-catastrophic
525 consequence, the resulting HCR is more cautious. On the contrary, when the shift is

526 irreversible and lead to stock collapse the resulting HCR is ambiguous depending on
527 which of the opposite density-dependent and independent effects dominate. Ren &
528 Polasky (2014) examined the optimal management problem with a general utility
529 function rather than a linear function. They demonstrated that the shape of the utility
530 function considerably affects the optimal HCR which may become more or less
531 precautionary depending on the relative magnitudes of two kinds of effects acting in
532 opposite directions. Concomitantly, a regime shift lowers the future profit from the
533 fishery which reduces the profitability of the investment in the resource. Finally, Baggio
534 & Fackler (2016) extended the previous model by considering stochastic shocks (i.i.d.)
535 and non-catastrophic reversible shifts affecting growth of the resource. Their numerical
536 analysis confirmed the analytical results from Polasky et al. (2011) emphasising the
537 influence of growth stochasticity on the cautious of the optimal HCR. They also showed
538 that the endogenous switching probability changes the optimal policy to a biomass-
539 based catch type with a far more precautionary strategy. In summary, the degree of
540 contrast and resilience (reversibility between states) as well as volatility of the resource
541 fluctuations has important impact on optimal policy.

542 **3.2.3 Economical, political and social uncertainty - Stochastic price**

543 Uncertainties related to economic conditions have been limited to market fluctuations
544 affecting fish price (Nostbakken 2006, Kvamsdal et al. 2016). Price uncertainty has been
545 found to play only a minor role in the determination of the optimal HCR. However, the
546 optimal policy is no longer a constant escapement. Kvamsdal et al. (2016) described a
547 smooth harvest policy as a function of stock size and price with a non-linear objective
548 function. Additionally, although price uncertainty has only a minor effect, volatility in
549 price leads to relatively more cautious harvest which buffers the increasing price effect
550 with the scarcity of the resource.

551 **3.2.4 Observational uncertainty – Uncertain states**

552 Perfect information has been assumed in most studies, however, fishery management
553 relies on indirect observations of fish stocks which are subject to high level of
554 uncertainties. Additionally, assessments methods are imperfect and subject to many
555 sources of bias. Relaxing the perfect observation assumption change considerably the

556 optimal HCRs and no longer fit Markov decision process framework needed to employ
557 standard stochastic dynamic programming method (Fackler & Pacifi 2014).
558 Clark & Kirkwood (1986) and Sethi et al. (2005) tackled the stock measurement
559 uncertainty problem and showed that the optimal HCR is less conservative than the
560 deterministic solution. Moreover, they found that the optimal policy becomes sensitive
561 to stock size (biomass-based catch policy) when measurement errors are introduced. In
562 the case where multiple uncertainties are confronted, measurement uncertainty has the
563 largest impact on the determination of the optimal HCR. Memarzadeh & Boettiger
564 (2018) argued that these counterintuitive results are supported by means of a
565 simplification which ensures that the transition probability between states is
566 independent of all previous states. They demonstrated through the implementation of a
567 partially observed Markov decision process¹⁹ approach which relaxed the full
568 observability assumption of the system's state that more conservative policy is optimal.
569 While state uncertainties concern primarily the size of the resource, in more complex
570 setting such as regime shift dynamics, the current regime may not be directly observed.
571 Using a partially a partially observed Markov decision approach Baggio & Fackler (2014)
572 showed that policy adjustment depends on the weight of belief in a given regime.
573 Additionally, optimal policy tends to be more or less precautionary depending on the
574 belief state. Past information are determinant in the definition the optimal policy, thus
575 anticipating future conditions may also affect the optimal HCR. Costello et al. (2001)
576 investigated the impacts of growth fluctuations shocks (i.i.d.) when an uncertain forecast
577 of environmental shocks is available. When new information is available, the optimal
578 escapement is no longer constant but varies with the shocks prevision and increases
579 substantially the profits.

580 **3.2.5 Model and parameter uncertainty**

581 Structural uncertainty arises when a system is imperfectly understood and represented
582 (Williams 2011). As we discuss previously, the choice of optimal HCR depends critically
583 on structural assumptions. The selection of an objective function and appropriate
584 uncertainties which represent the system determined the class and the precautionary of
585 the optimal HCR. The central objective in adaptive management is learning, which

¹⁹ Extension of Markov decision process in which unobservable state variables are replaced by a belief distribution and are updating with observable variables using Bayes rule (Fackler & Pacifi 2014).

586 should occur through the adjustments of decision making allowing by new information
587 (Walters 1986, Williams 2011). Model and parameter uncertainties can be addressed by
588 new modeling frameworks which extend the standard Markov decision process using
589 Bayes rule. Unknown parameters or functional forms of the system are replaced by
590 belief distributions updating through time and new information gathered (Fackler 2014,
591 Fackler & Pacifi 2014, Williams 2016, LaRiviere et al. 2017). Memarzadeh & Boettiger
592 (2018) are among the first implementations of adaptive management to renewable
593 resource management introducing model, parameters and observation uncertainties.
594 This promising framework should be a serious candidate to compete with simulation-
595 based approaches such as MSE. However, such approaches still need to select pertinent
596 structural assumptions and uncertainties to include as potential candidate to
597 characterize the system.

598 Along with the development of modeling methods to address adaptive management,
599 more complex model such as stochastic age-structured model has been studied.
600 Bioeconomic studies surveyed have been criticised for being too simple to sustain
601 management guidelines. Trade-offs between simple and more complex models such as
602 age-structured are central when we evaluate the cost-benefits of using models for
603 management which in turn reduce ease of learning and communication. However only
604 few studies have undertaken to study uncertainties effect in age structured model
605 (Holden & Conrad 2015, Tahvonen et al. 2017). They found that such as for surplus
606 biomass model, the addition of random recruitment fluctuations (i.i.d. shocks) does not
607 affect strongly the optimal HCR.

608 **3.3 Decisional uncertainty- the case of shared fisheries management**

609 Our review builds on the studies where decision making relied on a unique hypothetical
610 fishery manager who could be a corporation, a cooperative, a government agency, or a
611 regulatory body. However, many fish stocks are not solely distributed within a single
612 exclusive economic zone (EEZ). Thus, the assumption of a single manager or a
613 cooperative organization holds the responsibility of the decision making is no longer
614 acceptable. Shared fish stocks (Munro et al. 2004, Munro 2007) are a special case which
615 causes particular strategic management problems (McWhinnie 2009). Optimal
616 management studies leave aside the question of how stakeholders' strategic
617 considerations are influenced by uncertainties. Two kinds of uncertainties arise in social

618 dilemmas²⁰ such as shared fisheries, social and environmental uncertainty (van Dijk et
619 al. 2004). When we consider a group of stakeholders on which relies a common decision,
620 social uncertainty refers to the individual uncertainty about what their fellow group
621 members will decide. Whereas, environmental uncertainty relates to the characteristic
622 of the dilemma which defines the fishery system, the number of stakeholders involved
623 and also uncertainties related to fishery management previously introduced. A central
624 question in shared fisheries is, therefore, would interaction between social and
625 environmental uncertainty lead to more precautionary or to more aggressive
626 management. The economics of shared fisheries is anchored on game theory as the
627 management of internationally shared fish stocks involves the strategic interaction
628 between several countries. Several approaches have been used useful to understand
629 cooperation in such context, but two main strands of game literature applying to shared
630 fisheries can be considered, cooperative and non-cooperative dynamic or coalition
631 games (reviews in Hannesson 2011, Miller et al. 2013, Pintassilgo et al. 2015). Non-
632 cooperative games involve competition between stakeholders in which only self-
633 enforcing (e.g. through threats) cooperation are possible, while cooperative games, a
634 priori, suppose that cooperative behaviours are enforced through external binding
635 agreements (e.g. International Fisheries Agreements, IFA). Early game theory studies
636 showed that competitive behaviours lead to the well-known the tragedy of the commons
637 (Hardin 1968), while a joint exploitation of the resources is equivalent to the optimal
638 management under the sole manager hypothesis (Munro 1979). However, only a few
639 studies integrated uncertainty or incomplete information²¹ in the analysis of strategic
640 interaction in shared fisheries. Stochastic models²² provide key information to studies
641 anticipate how shocks and potential regime shifts in the system may affect the
642 cooperative solution and its stability compared to the sole ownership theoretical case. In
643 various settings included growth (recruitment), migration fluctuations, imperfect
644 monitoring or potential regime shifts, several works have shown ambiguous results of

²⁰ Social dilemma refers to a situation where a group members experience a conflict between their personal interests and the interests of the group to which they belong.

²¹ Imperfect information can concern player actions, e.g. monitoring of harvests (Laukkanen 2003, Tarui et al. 2008) or the state of the system (Laukkanen 2003).

²² Stochastic models concern growth (recruitment) uncertainty in fish-war game type (Antoniadou et al. 2013, Diekert & Nieminem 2017) or in sequential game (Laukkanen 2003), the migration pattern of fish stock under climate change in fish-wars game (McKelvey et al. 2003), potential regime shifts in productivity or collapse which are exogenous (Fesselmeyer & Santugini 2013, Sakamoto 2014, Miller & Nkuiya 2016), or endogenous (Sakamoto 2014, Miller & Nkuiya 2016) in fish-wars game.

645 uncertainty depending on the structural assumptions of the model and the solution
646 framework. Strategic interaction between countries harvesting shared stocks in a
647 context of uncertainty is a fast-growing strand of the game theory literature and
648 requires a specific analysis that we are leaving for further discussions.

649 **4 Conclusion**

650 This article explores several forms of uncertainty in economic optimal fishery
651 management which have only been tackled partially or through the lens of simulation-
652 based approaches in previous surveys (e.g. Deroba & Bence 2008, Holland & Herrera
653 2009, Liu et al. 2016, LaRiviere et al. 2017). Harvest policies have become a standard
654 framework in fishery management. The definition of a management strategy which is
655 based on the knowledge of the system ensures that the rules for how harvest will vary
656 are foreseeable to all stakeholders. Bioeconomic literature brings important insights to
657 tackle fishery management with HCRs for different forms of uncertainty. This review
658 provides guidelines on which control rules is optimal and if the objective of maximizing
659 the economic return of the fishery lead to more or less precautionary outcomes.

660 The constant escapement policy is rather an exception than the rules. Non-constant
661 economic returns and uncertainty with the exception of independent and identically
662 distributed random fluctuations have been shown as the main determinant of the class
663 of the optimal policy. Escapement is, therefore, a function of the current stock, and
664 harvests are smoothed over time to balance its effects on prices, harvesting costs and
665 the future stock. While correlated shocks and cyclical variation turns the optimal
666 escapement into a function of the current shock. Furthermore, when the system is
667 threatened by a potential regime which his triggered independently of manager actions
668 (i.e exogenous) the constant escapement policy remains optimal.

669 The common consideration that adding uncertainty should lead toward more
670 precautionary harvest is also questioning. Results are ambiguous depending on the
671 interaction between structural assumptions and type of uncertainty considered. In the
672 case of complex dynamic involving regime shift, the threat of a potential disastrous shift
673 affects the cautious of the resulting optimal policy. When an endogenous shift is present
674 optimal management involves precautionary actions that reduce the likelihood of
675 regime shift. With a potential shift whose occurrence is independent to management

676 actions, the severity and irreversibility of the shift determines the cautious of the
677 management. When the regime shift affects the productivity of the resource but does not
678 cause stock collapse, optimal management is unaffected by the potential for regime shift.
679 However, once the shift has occurred, the control rule is adjusted to fit the new
680 productivity. On the contrary, when the shift implies a disastrous collapse, the resulting
681 control rule is more aggressive to accumulate profits prior to potential destruction.
682 We have restrained the candidate models in our review to single species fisheries. Such
683 simple framework already leads to complex optimal policy and ambiguous results.
684 However, bioeconomic feedback solutions have been extended to more complex models
685 involving trophic relationship and population structured in age or stage. Such complex
686 models offer the possibility to evaluate the optimal control rule in the context of
687 ecosystem-based fisheries management and to extend the scope of feedback solution
688 which has only been relevant so far for stylized representation of the fishery system.
689 Along with the increasing complexity of models, the development of Markov decision
690 process to tackle unknown structure or unobserved states through learning process
691 offers the possibility to fully address structural uncertainty into a single framework. This
692 promising development should offer an alternative to management strategy evaluation
693 in the assessment of HCRs for different model and parameter assumptions to fully
694 implement adaptive management.
695

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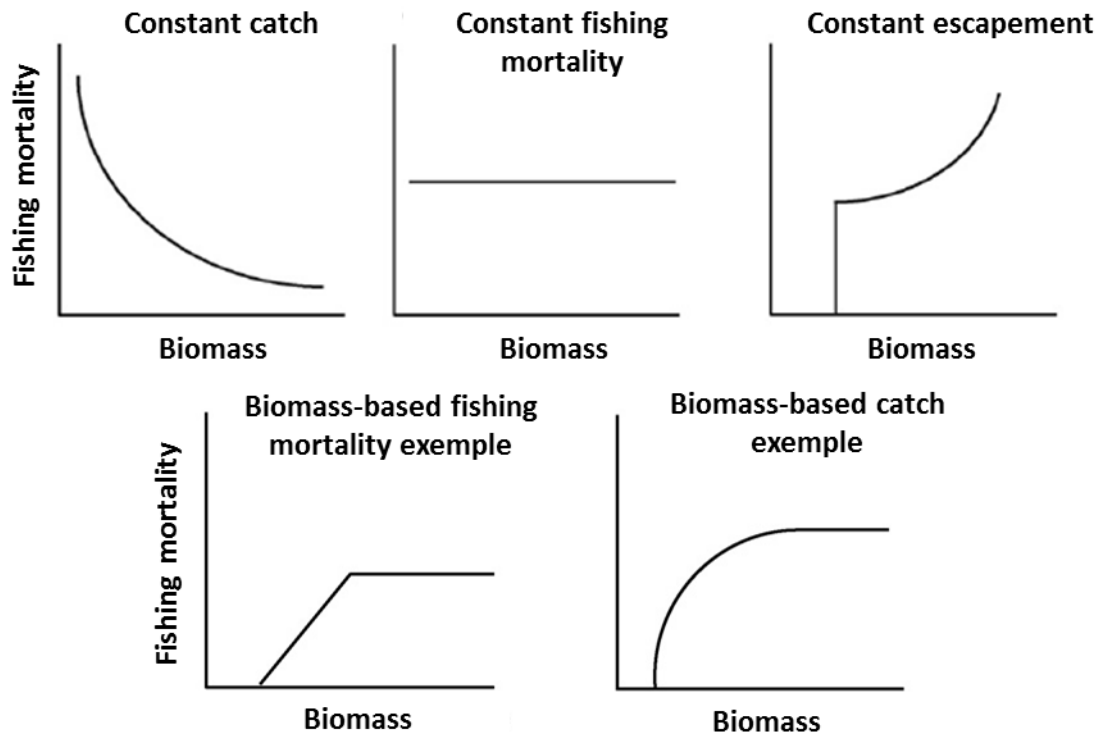
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1153 **6 Supplementary materials**

1154 Appendix A. Basic control rules and how fishing mortality (ratio) generally changes with biomass for each
1155 type (from Deroba & Bence, 2008).



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1158 Appendix B. Optimal harvest policy under different structural assumptions of profits and uncertainty
 1159 (adapted from Deroba & Bence 2008 and McGough et al. 2009).

Surplus Production Model		Objective function: Maximize Profit	
		Linear objective function in harvest†	Non-linear objective function in harvest‡
	No uncertainty	CE	BBC
Parameter	Growth i.i.d shocks	CE	BBC
uncertainty	Growth correlated shocks	BBF	BBC & BBF

CE: Constant Escapement policy

BBC: Biomass-based catch policy

BBF: Biomass-based fishing mortality policy

†Infinitely elastic demand associated with Schaefer's type production function or yield maximization.

‡ Downward sloping demand or/and Cobb Douglas' type production function non-linear in harvest.

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