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A bridge between continuous and discrete-time bioeconomic models: Seasonality in fisheries[☆,☆☆]

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ABSTRACT

We develop a discretization method to construct a discrete finite-time bioeconomic model, corresponding to bioeconomic models with continuous-time growth function, but allowing the analysis of seasonality in fisheries. The discretization method consists of three steps: first, we estimate a proper growth function for the continuous-time model with the Ensemble Kalman Filter. Second, we use the Runge-Kutta method to discretize the growth function. Third, we use the Bellman approach to analyze the optimal management of seasonal fisheries in a discrete-time setting. We analyze both the case of quarterly harvest and the case of monthly harvest, and we compare these cases with the case of annual harvest. We find that seasonal harvesting is a win–win optimal solution that provides higher harvest, higher optimal steady state equilibrium, and higher economic value than annual harvesting. We also demonstrate that the discretization method overcomes the errors and preserves the strengths of both continuous and discrete-time bioeconomic models.

1. Introduction

There is a fundamental choice to be made when developing a bioeconomic model for fisheries management: discrete or continuous-time modelling.

Continuous-time bioeconomic models are based upon the assumption that biological processes, such as growth, and human activity, such as harvesting, are taking place continuously, while in discrete-time bioeconomic models, they are taking place at discrete time steps (usually annual).

Continuous-time models have proved to be useful for analytical purposes (Clark, 2010). In addition, continuous-time models may serve as a conceptual framework and guideline for discrete-time models, despite the difficulty they present in terms of estimation. However, continuous-time models are unable to encompass sequential effects, commonplace in real world fisheries, due to the fact that the response of fish stocks to external factors, such as harvesting, is instantaneous. Moreover, biological processes, like spawning, and human activity, such as harvesting, are seasonal rather than continuous over time (Clark 2010; Bjørndal and Munro, 2012). In addition, data are usually available on an annual basis. For these reasons, discrete-time models, which are generally an approximation of continuous-time models, are often used to analyze the optimal management of commercial fisheries. As pointed out by Bjørndal and Munro (2012), it is often not only necessary, but also appropriate to turn to discrete-time models, especially when using empirical models. In addition, most of the modelling of economic time series works with discrete time, yet time is in fact continuous (Sims, 2008). Models of human cooperation from the viewpoint of statistical physics are also developed in discrete-time (Perc 2016; Wang et al., 2016; Perc et al., 2017).

Most of the literature on bioeconomic modelling of fisheries uses both discrete and continuous-time models indistinctly without a

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clear biological or economic justification. However, it is not obvious how discrete and continuous-time models are related to each other and, consequently, this is not a trivial choice, especially in fisheries economics, since they can provide different policy advice with significant implications for fish stock sustainability.

Errors in mathematical modelling of the natural growth function of fish stocks are frequently found in the literature on bioeconomic modelling of fisheries in a continuous-time setting. In particular, most natural growth functions used in continuous-time models, which are inserted into differential equations, are estimated in discrete time, which uses difference equations (e.g. Agnarsson et al., 2008, for the cod fisheries). This is despite the fact that the dynamical properties of discrete and continuous-time population dynamics are entirely different (Gyllenberg et al., 1997).

Approximation errors involved in developing discrete-time models are commonly assumed by most economists to be trivially small, but the approximation error can be important under certain conditions (Sims, 2008).

From an economic point of view, discrete-time bioeconomic models neglect the change in stock during harvesting when considering that harvest costs depend on the stock at the start of the year, and consequently discrete-time models may incur systematic errors by underestimating or overestimating harvesting costs. A continuous cost function is the appropriate cost function when the harvesting process is dependent on stock density, and the fraction of the stock harvested within a season is significant (Maroto et al., 2012).

Thus, knowledge of the relationship between continuous and discrete-time models is crucial in order to avoid biologically and economically meaningless models that can lead to erroneous (suboptimal) policy advice, with the consequent uncertainty regarding the appropriate bioeconomic model that should be used to ensure long term sustainability.

The aim of this paper is to develop a discretization method which allows us to build a bridge between continuous and discrete-time bioeconomic models by overcoming the errors and by preserving the strengths of both approaches.

On the other hand, current discrete-time bioeconomic models are designed on an annual basis where annual biological and fisheries data are used by these models to find that the solution converges to an annual optimal steady-state equilibrium where both biological processes, like the growth of the species, and fishing activity take place only once a year.

There are, however, various reasons why seasonality may be relevant in fisheries. One such reason, for example, may be the seasonal pattern of migration of most exploited fish stocks, which leads to seasonal harvests (e.g. Pelletier and Mahevas, 2005, and references therein; Hannesson et al., 2010, and Hermansen and Dreyer, 2010, for the case of North-East arctic cod; Hannesson, 2013, for the case of mackerel; Smith et al., 2016, for the case of cod, haddock, and saithe).

From the point of view of policy advice, most commercial fisheries are also managed on an annual basis where the collection and management of annual biological and fisheries data are used by management agencies, like the International Council for the Exploration of the Sea (ICES), to provide annual advice regarding stock status, reference points, and total allowable catches (TACs). In addition, in real world fisheries, annual TACs are allotted to different vessel groups which, however, target the resource in different seasons. Moreover, they are usually based on political decisions, rather than optimal bioeconomic criteria, with the consequent considerable effects upon the health of the stock and the economics of the fishery (e.g. Armstrong and Sumaila, 2001, and Armstrong et al., 2014, for the case of NEAC).

The optimal management of seasonal fisheries has become a hot topic in bioeconomic modelling, particularly considering that neither discrete nor continuous-time models are able to cope with the complex phenomenon of seasonality in fisheries. When considering one-year time increments, discrete-time models neglect seasonality. Continuous-time models also neglect it when considering time-independent optimal feedback policies.

Based on the discretization method, in this paper we develop a discrete finite-time bioeconomic model which allows us to analyze the optimal management of seasonal fisheries using the Bellman approach.

Using the North-East Arctic cod stock by way of illustration, the main contributions from this article are, first, in contrast to the natural growth function used in continuous-time bioeconomic models, which is often erroneously estimated in discrete-time, a proper continuous-time natural growth function, which is a differential equation, is estimated using the Ensemble Kalman Filter. In addition, we use the fourth order Runge-Kutta method to show that the proper natural growth function estimated in continuous-time is quite different to what is estimated in discrete-time.

Second, we use the Bellman approach to show that seasonal harvesting (quarterly or monthly harvest) is a win–win optimal solution that achieves higher harvest, higher steady state equilibrium, and higher economic value than annual harvesting. These results can be explained by the combined effects of the actualization of the growth rates of the stock, decrease of harvesting costs, and more frequent discounting, which all take place if the stock is harvested seasonally (quarterly or monthly).

Third, we show that the discrete-time solution quickly converges to that obtained in continuous-time. In particular, convergence is achieved if the stock is harvested quarterly, which seems to confirm the robustness of the discretization method.

It should be noted that, by the arguments provided above, it is not the aim of this paper to solve a continuous-time bioeconomic model through an appropriate discrete-time numerical procedure, and hence the case of unrealistic infinitesimal short seasons is not the focus of this paper. It has to do with developing a discrete finite-time bioeconomic model, corresponding to bioeconomic models with continuous-time growth function, but allowing for some form of seasonality and hence controllability taking such complex phenomenon into account, as closing fisheries in certain periods (seasonal closures) or utilizing some kind of economic/operational/ecological seasonal benefits or merely mimic the fact that certain fleets take part in several fisheries and allocate effort in a particular fishery only in special favorable periods (seasons) during the year.

2. Method

2.1. Discretization method of continuous-time bioeconomic models

In this section we describe the discretization method that takes a standard continuous-time model as a starting point, given by:

$$\begin{aligned} &\max_h \int_0^{\infty} e^{-\beta t}\Pi(h,x)dt \\ &\text{s.t.}\dot{x}(t) = F_C(x) - h \\ &x(0) = x_0, \end{aligned} \tag{1}$$

where x represents the fish stock biomass, h the harvest rate, Π net revenues, β the discount rate, and $\dot{x}(t) = dx/dt$ the population dynamics where $F_C(x)$ represents the natural growth function.

The discretization method consists of several stages:

i) In contrast to the standard continuous-time model, the natural growth function

$$\dot{x}(t) = F_C(x), \tag{2}$$