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Analysis

Sustainable harvest of a native species and control of an invasive species: A bioeconomic model of a commercial fishery invaded by a space competitor

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ABSTRACT

Biological invasions are nowadays an important challenge to biodiversity and human welfare. This paper deals with the control of an invasive species, void of market value, and acting as a space competitor for a valuable native harvested species. It presents a theoretical bioeconomic model describing the interacting dynamics of the two species and accounting for the undesirable consequences of native stock harvesters' behaviour on the spread of invasion. Dynamic optimisation of the model displays the existence of a time-path leading to an optimal stationary steady-state solution where the native species is sustainably harvested and the invasive species is kept under control, provided unit costs of native species harvesting and of invaded areas cleaning are quite low, natural and anthropogenic dispersal coefficients of invasion, and time-discount rate are moderate. Moreover, the problem should be addressed early enough. The model is applied to the Bay of Saint-Brieuc scallop fishery invaded by slipper-limpet. We show that it is nearly always optimal to control the invasion in that case study.

1. Introduction

Biological invasions are nowadays an important challenge to biodiversity and human welfare (Convention on Biological Diversity, article 8h, 1992). The worldwide spread of invasive alien species has increased in the second part of the 20th century (Mack et al., 2000; Mooney and Cleland, 2001; Williamson, 1996) and is now considered as one of the most serious threats to biodiversity (Didham et al., 2005; Lövei, 1997; Wilcove et al., 1998). This evolution is mainly due to human activities (Carlton, 1987; Carlton and Geller, 1993; Vitousek et al., 1997), particularly trade (Carlton, 1989; Krcmar-Nozic et al., 2000; Ruiz and Carlton, 2003), and human-induced disturbance of ecosystems (Dalmazzone, 2000; Williamson, 1996, 1999). By altering biodiversity and the services it supports, biological invasions may impose significant cost in terms of forgone output and ecosystem services (Perrings et al., 2000, 2002). Thus, in the Black Sea the cost of *Mnemiopsis leidyi* invasion has been estimated at about $16.8 million per year (Knowler, 2005; Knowler and Barbier, 2000), and biological invasion damage and control costs in the USA have been evaluated to $128 billion per year (Pimentel et al., 2005).

Mostly, biological invasions management, which encompasses both prevention and control, is considered as a public good (Perrings et al., 2002) and thus may requires public policies. In this paper, we focus on the control aspect of such policies in the case of a particular interspecific competition, exerted by an invasive alien species on a native one, explicitly modelled. This paper deals with the control of an invasive species, void of market value, and acting as a space competitor for a native valuable harvested species. It presents a theoretical bioeconomic model describing the interacting dynamics of the two species and accounting for the undesirable consequences of native stock harvesters' behaviour on the spread of invasion. The aim of the paper is to describe the impact of invasion on the native species harvest, through space competition, and to display the possibilities of sustainable harvest of the native species by controlling the invaded areas. The analysis is derived from a real case study: the invasion of the Bay of Saint-Brieuc scallop fishery by slipper limpets.

Most optimal control models of biological invasions usually relate the damage caused by the invasion to the invasive stock size (Eiswerth and Johnson, 2002; Junqueira-Lopes et al., 1996; and others). In those models, the state variable is the invasive stock. The control variable is the effort of control applied to the invasive species. The objective of the social planner is to minimise the discounted flow of damage and control costs. Wilman (1996) studies explicitly the interaction between native and invasive species dynamics by combining the dynamics of a

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native untargeted valuable species and an invasive species, acting as a predator. In her model, state variables are the native and invasive stocks, and control variables and target-functions are the same as previous. Our model adopts the same approach with two state variables (the native and invasive species), but (i) we assume a space competition relationship between species, (ii) the control variables are the levels of harvesting effort of each species, and (iii) the target-function maximises the resource rent provided by harvesting the native stock, minus the cost of controlling the invasive species. Perrings (2002) analyses biological invasion in aquatic system, and shows that the dynamical characteristics of the invasion depends on the costs and benefits both of native and invasive species as well as population dynamics. His model used measures of the space occupied by invasive and native species for the state variables rather than population or biomass, assuming the total space to be constant. Like Perrings, we use a measure of space, but only for the invasive species state variable. Our model derives from Flaaten's (1991) competing species bioeconomic model. While competing species terrestrial models could also be relevant, Flaaten's model of a fishery is closed to our interspecific competition problem. It is based on a simple analytical model (Gordon-Schaefer), classically used in fisheries economics, and it has already been applied to the Bay of Saint-Brieuc scallop fishery to deal with management issues (Frésard and Boncoeur, 2006; Guyader et al., 2004; Mahé and Ropars, 2001). Unlike Flaaten's model, we consider (i) an asymmetric competition between species, (ii) a competition influencing the ecosystem's carrying capacity for the native species, (iii) an invasive species void of market value, and (iv) an invasive species dispersal coefficient depending on a natural component and on an anthropogenic one. Following Macpherson et al. (2006), our model considers the unintentional effects of native stock fishers' behaviour on the spread of invasion. The differences between our model and Macpherson et al.'s (2006) model are the following: in our model, (i) the invasion dispersal depends on natural and anthropogenic components, (ii) the fishers' behaviour is exogenous as regards invasion and its control, and (iii) a logistic growth plurispecies bioeconomic model is used (a two-species case of the standard Gordon-Schaefer model; Gordon, 1954; Schaefer, 1954, 1957).

The paper is organized as follows. Section 2 presents the bioeconomic model. Section 3 exposes the dynamic optimisation model. In Section 4, we illustrate our model numerically with reference to the Bay of Saint-Brieuc scallop fishery invaded by slipper-limpet. Section 5 concludes.

2. Bioeconomic Model of the Invaded Fishery

2.1. Assumptions

- We study a bay where a fishing fleet harvests a benthic native stock.
- The native stock is negatively affected by the spread of an invasive alien species, void of market value. This invasion is the only environmental disturbance in the fishery and only the consequences of the invasion on the fishery are studied.
- The invasive species is a benthic species and acts as a space competitor for the native species: the invasion of the bay decreases the size of the suitable area for native species recruitment. The whole square meterage of the bay area can therefore be divided into two parts: the unharmed ones and the invaded ones.
- The space competition between species is asymmetric: the presence of any number of native individuals on a square metre of benthos does not hinder the establishment and the development of invasive individuals.
- The dispersal of the invasion has two components: a natural one and an anthropogenic one, linked to fishers' behaviour.
- The natural dynamics of native stock biomass is represented by a logistic model, where the carrying capacity of the ecosystem for the native stock is proportional to the unharmed areas of the bay. Catch per unit of effort (CPUE) is assumed to be proportional to stock abundance.
- The dynamics of invaded areas is represented by a logistic model, where the intrinsic growth rate of dispersal has two components: an exogenous natural one and an anthropogenic one, which is proportional to the native stock harvesting effort. The dispersal of invaded areas can be controlled by cleaning operations. We assume that the average productivity of cleaning operations (the number of square metres cleaned per unit of cleaning effort) is proportional to the whole number of square metres of invaded areas.
- Ex-vessel unit price of native species catch, unit cost of native species harvesting effort, and unit cost of invaded areas cleaning effort are exogenous.
- There is no technical progress.

2.2. Equations

We consider the combined dynamics of two harvested species, a native valuable one ($i = 1$) and an invasive one ($i = 2$), void of commercial value and acting as a space competitor. Then, there are two state variables: the native stock biomass X_1 and the invaded share of the whole area of the bay X_2, and two control variables: the harvesting effort of the native stock E_1 and the cleaning effort of the invaded areas E_2. All these variables are subject to a non-negativity constraint and $X_2 \leq 1$.

The two equations of motion describing the dynamics of X_1 and X_2 respectively are written as:

$$\frac{dX_1}{dt} = rX_1\left(1-\frac{X_1}{K(1-X_2)}\right)-q_1E_1X_1 \tag{1}$$

$$\frac{dX_2}{dt} = (s+gE_1)X_2(1-X_2)-q_2E_2X_2 \tag{2}$$

where r is the intrinsic growth rate of native stock, K is the carrying capacity of the non-invaded ecosystem for the native stock, q_1 is the catchability coefficient, i.e. the relationship between CPUE and native stock biomass, s is the natural dispersal coefficient of invasion, g is the anthropogenic dispersal coefficient of invasion, and q_2 is the productivity of cleaning operations, i.e. the ratio between the number of square metres cleaned per unit of effort and the whole invaded areas. All theses parameters are constant and positive.

The immediate global surplus GS which is the sum of the profit π of harvesting the native stock minus the cost of cleaning invaded areas is given by:

$$GS = \pi-C_2E_2 = Pq_1E_1X_1-C_1E_1-C_2E_2 \tag{3}$$

where P, C_1 and C_2 are respectively the ex-vessel unit price of native species catch, the unit cost of effort devoted to harvesting the native stock, and the unit cost of cleaning effort, assumed constant.[1]

3. Sustainable Harvest of the Native Species and Control of the Invasive Species

The damage imposed by the proliferation of the invasive species has public "goods" characteristics since the community pay for the cleaning cost of the invaded areas. Then the problem for the regulator of the invaded fishery is to determine[2] the effort levels E_1 and E_2 maximising

[1] The total cost of cleaning effort depends implicitly of the invaded areas size. Indeed, at equilibrium the cleaning effort, defined in Eq. (12), is increasing as this invaded areas size decreases. The marginal cost of cleaning effort is constant, but the marginal cost of cleaning the invaded areas is increasing as the invaded areas size decreases. Indeed, the total cost function can be expressed as $C_2Y_2(q_2X_2)^{-1}$, with the invaded areas cleaned being $Y_2 = q_2E_2X_2$.

[2] We drop the subscript t in the following equations to simplify notations.