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An economic model of metapopulation dynamics

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ABSTRACT

In this paper, we aim to model the impact of human activities on the wildlife habitat in a general equilibrium framework by embedding the Levins model (1969) of metapopulation dynamics into a Ramsey model (1928) with a pollution externality. In the long run, as in Levins (1969), two steady states coexist: a zero one with mass extinction and another one with positive wildlife when the migration rate of the metapopulation exceeds the rate of extinction. A green tax always increases the wildlife and lowers the consumption demand. It is welfare-improving if and only if agents overweight the wildlife. In the short run, we show that a sufficiently negative effect of wildlife habitat on consumption demand can lead to the emergence of a limit cycle near the positive steady state through a Hopf bifurcation. We show also that the negative pollution effect on wildlife habitat works as a destabilizing force in the economy by promoting limit cycles.

1. Introduction

In ecology, a metapopulation represents a spatially fragmented population of the same species. The concept of metapopulation was introduced in the cological literature in 1969 by Levins and reconsidered by Hanski and Gilpin in 1991. In his seminal contribution, Levins represents the natural space as a partition of patches of the same size, homogeneous inside, that can be occupied or not by a metapopulation. The share of occupied patches changes over time. Dynamics are driven by two exogenous forces: the migration rate and the extinction rate. According to Levins' (1969) formulation, there are two steady states: a zero share means a massive extinction while a positive share a preserved wildlife. Dynamics are quite simple: the zero steady state is unstable while the positive one is stable and positive if and only if the migration rate exceeds the extinction rate.

Since the emergence of life, planet Earth has experienced five mass extinctions. A mass extinction is conventionally defined as a change where more than three-quarters of species disappear in a geologically short interval of time (Barnosky et al., 2011). Following Ceballos et al. (2015), a sixth mass extinction is under way due to human activities because of deforestation and pollution that imply climate change. Evidence suggests that both the migration and the extinction rate in the Levins' model (1969) depend on the pollution coming from human activities.[1]

Today, a plausible representation of metapopulation dynamics has to take in account the interplay between economic activities and pollution, and the effects of pollution on both the extinction rate and the migration rate. To the best of our knowledge, such an integrated framework does not yet exist in the literature. In this respect, we aim to fill the gap between economics and ecology. More simply and precisely, we embed the Levins' model (1969) into the Ramsey model (1928) augmented with a pollution externality resulting from production and affecting both the migration and the extinction rates.

Evidence suggests also that the consumption behavior is influenced by environmental quality. For instance, the literature has pointed out that consumers have a higher willingness to pay for green products (Roe et al., 2001; Kim and Han, 2010; Biswas, 2016). Even if, to the best of our knowledge, there is no empirical evidence on the effects of wildlife habitat on consumption demand, the common sense suggests that a link exists. If the household likes to consume in a pleasant environment, a drop in wildlife entails a lower consumption. Conversely, a decrease in wildlife implies a drop in utility to be compensated by the household with a higher consumption demand. The ambiguous environmental effects on consumption demand have been already studied in the literature. Theorists have considered pollution or natural capital instead of wildlife in the utility function. For instance, Bosi and Desmarchelier (2018) have focused on the occurrence of limit cycles in a Ramsey economy

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[1] The reader interested in the impact of global warming on species migration and extinction, is referred to Chen et al. (2011), Loehle (2018) and Rinnan (2018).

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where an Environmental Kuznets Curve (EKC)[2] appears at the steady state.[3] The present paper is not about the EKC, but one can expect that the effect of wildlife habitat on consumption demand affects the transitional dynamics of the Levins' model (1969).

In this paper, we study a continuous-time Ramsey model where a pollution externality, coming from production, impacts the evolution of a metapopulation. To simplify, we assimilate wildlife to a single metapopulation and we assume that the fraction of occupied patches (a measure of environmental health) affects the marginal utility of consumption. In addition, a green tax is introduced and levied on production at the firm level in order to finance depollution according to a balanced budget rule.

As in Levins (1969), two steady states coexist in the long run with and without wildlife. Wildlife is positive when the rate of migration exceeds the extinction rate. From an economic point of view, even if the green tax lowers both the capital intensity and the consumption demand at the steady state, the green tax always increases the wildlife with an ambiguous effect on welfare. The tax is welfare-improving if households overweight wildlife with respect to consumption.

In the short run, because of the pollution effects, the interplay between the wildlife habitat and consumption demand leads to richer dynamics around the positive steady state than those observed by Levins (1969). Indeed, a sufficiently large impact of wildlife on consumption demand can promote the emergence of a limit cycle near the steady state through a Hopf bifurcation. Moreover, the larger the (negative) impact of pollution on wildlife habitat, the lower the effect of wildlife on consumption demand, at the origin of the limit cycle. In other terms, the negative pollution effect on wildlife undoubtedly plays a destabilizing role.

In the spirit of the socio-ecological model proposed by Lafuite and Loreau (2017), we consider the coupled evolution between economy and biodiversity. In their paper, Lafuite and Loreau (2017) observe the coevolution of human population dynamics and biodiversity. They point out that convergence toward the steady state can be non-monotonic because of biodiversity feedbacks on agricultural production. In our model, because of the possibility of limit cycles, we arguably reach a similar conclusion. However, the consumers' behavior are based on different assumptions: in Lafuite and Loreau (2017), the consumer chooses the amounts of two consumption goods to maximizes a static utility function but biodiversity does not enter this utility function and, so, plays no direct role. Differently, our consumer decides a consumption path to maximize her intertemporal utility function which depends also on biodiversity. In other words, biodiversity directly affects the marginal utility of consumption changing the consumption profile at the end. While in Lafuite and Loreau (2017) the occurrence of cycles rests on the biodiversity feedbacks on production, cycles arise in our framework because of the biodiversity effects on consumption demand. In this respect, non-monotonic convergence to the steady state of a socio-ecological system seems to be a pervasive feature once biodiversity feedbacks on the economy are considered.

The rest of the paper is organized as follows. Section 2 introduces the model. Sections 3 and 4 focus on the equilibrium system and its steady state. Section 5 studies the local dynamics. An example with isoelastic preferences is considered in Section 6, while a numerical illustration is provided in Section 7. Section 8 concludes. All the proofs are gathered in Appendix (A).

[2] The EKC is an inverted U-shaped relation between income and pollution.

[3] More precisely, they have shown that a positive effect of pollution on consumption demand promotes the occurrence of a limit cycle through a Hopf bifurcation when the steady state lies on the upward-sloping branch of the EKC, while, along the downward-sloping branch, limit cycles arise if and only if pollution lowers consumption.

2. Model

We consider an economy with households, firms and a government. Households work, consume and enjoy the nature, firms produce and pollutes, the government taxes the firms to maintain the environment. Let us introduce the three ingredients of the model: a metapopulation dynamics à la Levins (1969), the economic fundamentals à la Ramsey (1928) and a simple pollution process.

2.1. Metapopulation

In ecology, a metapopulation represents a spatially fragmented population of the same species. To simplify the model, we assimilate wildlife to a single metapopulation. Following Levins (1969), we consider that space is represented by a partition of patches occupied or unoccupied by the metapopulation. Let q denotes the fraction of patches occupied at a given time. As in Levins (1969), the evolution of this share is simply given by[4]:

$$\dot{q} = \varphi q(1 - q) - \beta q \tag{1}$$

At each time, any occupied patch can become unoccupied at the extinction rate β. The contribution to the change in the share of occupied patches is given by βq. Conversely, any unoccupied patch can become occupied at the migration rate φ. The migration pressure on the share $1 - q$ of unoccupied patches is given by φq. A simple analysis of (1) allow us to point out that there exist two distinct steady states:

$$q_0 = 0 \quad \text{and} \quad q^* = 1 - \beta/\varphi$$

It follows that q_0 leads to wildlife mass extinction while q^* represents an equilibrium where wildlife is positive. Interestingly, $q^* > 0$ if and only if the migration rate φ exceeds the extinction rate β.

Human activities pollute and stress the wildlife habitat mainly through the climate change. To put it in other way, pollution accelerates the extinction rate. We also consider that a degraded environment renders more difficult the wildlife migration. In the sequel, P will denote the aggregate stock of pollution.

Assumption 1. Pollution has a positive impact on the extinction rate and a negative impact on the migration rate:

$$\beta \equiv \beta(P) \quad \text{and} \quad \varphi \equiv \varphi(P) \tag{2}$$

such that $\beta'(P) > 0$ and $\varphi'(P) < 0$.

Assumption (1) captures the pressure put by humans on wildlife. The role of pollution is summed up by the following elasticities and their difference.

Definition 1. The colonization rate is the difference between the migration and the extinction rate: $s = s(P) \equiv \varphi(P) - \beta(P)$. We introduce also the pollution elasticities of migration and extinction:

$$\varepsilon_\varphi(P) \equiv \frac{P\varphi'(P)}{\varphi(P)} \quad \text{and} \quad \varepsilon_\beta(P) \equiv \frac{P\beta'(P)}{\beta(P)}$$

and the pollution impact on colonization

$$d(P) \equiv \varepsilon_\varphi(P) - \varepsilon_\beta(P) < 0$$

Notice that the pollution impact on colonization is negative because, according to Assumption (1), $\varepsilon_\varphi(P) < \varepsilon_\beta(P)$.

2.2. Firms

Firms behave competitively. The firm j chooses the amount of capital K_j and labor L_j to maximize the profit. In addition, the government

[4] The reader interested in an economic model considering a non-renewable resource is referred to Dasgupta and Heal (1974) or Benchekroun and Withagen (2011) among the others.