Journal of Mathematical Economics 50 (2014) 34–53

Contents lists available at ScienceDirect

Journal of Mathematical Economics

journal homepage: www.elsevier.com/locate/jmateco

Infectious diseases and economic growth

Aditya Goenka [a,*], Lin Liu [b], Manh-Hung Nguyen [c]

[a] Department of Economics, National University of Singapore, AS2 Level 6, 1 Arts Link, Singapore 117570, Singapore
[b] Department of Economics, Harkness Hall, University of Rochester, Rochester, NY 14627, USA
[c] LERNA-INRA, Toulouse School of Economics, Manufacture des Tabacs, 21 Allée de Brienne, 31000 Toulouse, France

ARTICLE INFO

Article history:
Received 10 February 2012
Received in revised form
2 August 2013
Accepted 8 October 2013
Available online 16 October 2013

Keywords:
Epidemiology
Infectious diseases
Existence of equilibrium
Sufficiency in non-convex dynamic problems
Health expenditure
Economic growth

ABSTRACT

This paper develops a framework to study the economic impact of infectious diseases by integrating epidemiological dynamics into a neo-classical growth model. There is a two way interaction between the economy and the disease: the incidence of the disease affects labor supply, and investment in health capital can affect the incidence and recuperation from the disease. Thus, both the disease incidence and the income levels are endogenous. The disease dynamics make the control problem non-convex thus usual optimal control results do not apply. We establish existence of an optimal solution, continuity of state variables, show directly that the Hamiltonian inequality holds thus establishing optimality of interior paths that satisfy necessary conditions, and of the steady states. There are multiple steady states and the local dynamics of the model are fully characterized. A disease-free steady state always exists, but it could be unstable. A disease-endemic steady state may exist, in which the optimal health expenditure can be positive or zero depending on the parameters of the model. The interaction of the disease and economic variables is non-linear and can be non-monotonic.

1. Introduction

This paper develops a theoretical framework to jointly model the determination of income and disease prevalence by integrating epidemiological dynamics into a continuous time neo-classical growth model. It allows us to address the issue of what is the optimal investment in health when there is a two way interaction between the disease transmission and the economy: the incidence of diseases affects the labor force and thus, economic outcomes, while economic choices on investment in health expenditure affect the disease transmission—expenditure in health leads to accumulation of health capital which reduces infectivity to and increases recovery from the disease. In this paper we study what is the best that society can do in controlling the disease transmission by taking into account the externality associated with its spread (see Geoffard and Philipson, 1996 and Miguel and Kremer, 2004 on externalities of disease transmission). Thus, we look at the social planning problem (see Hall and Jones, 2007 which takes a similar approach for non-infectious diseases). We show a steady state with disease prevalence and zero health expenditure could be optimal as it depends on the relative magnitude of marginal product of physical capital investment and health expenditure.

The key contribution of this paper is that we endogenize both disease dynamics and accumulation of physical and health capital. The existing literature does not simultaneously model these together (see e.g. Delfino and Simmons, 2000, Geoffard and Philipson, 1996, Gersovitz and Hammer, 2004, Goenka and Liu, 2012, Kremer, 1996). In modeling the interaction between infectious diseases and the macroeconomy, we expect savings behavior to change in response to changes in disease incidence. Thus, it is important to incorporate this into the dynamic model to be able to correctly assess the impact of diseases on capital accumulation and hence, growth and income. As the prevalence of diseases is affected by health expenditure, which is an additional decision to the investment and consumption decision, this has to be modeled as well. Without modeling both physical and health capital accumulation and the evolution of diseases at the same time, it is difficult to understand the optimal response to disease incidence. As the literature does not model both disease dynamics and capital accumulation explicitly, the existing models are like a black-box: the very details of disease transmission and the capital accumulation process that are going to be crucial in understanding their effects and for the formulation of public policy, are obscured. We find that even when the strong assumption of log-linear preferences is made (which is usually invoked to justify fixed savings behavior) there can be non-linear and non-monotonic changes in steady state outcomes.

* Corresponding author. Tel.: +65 65163961.
E-mail addresses: goenka@nus.edu.sg (A. Goenka), lliu18@mail.rochester.edu (L. Liu), mhnguyen@toulouse.inra.fr (M.-H. Nguyen).

0304-4068/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.jmateco.2013.10.004

In order to model the disease transmission explicitly we integrate the epidemiology literature (see Anderson and May, 1991, Hethcote, 2009) into dynamic economic analysis. In this paper we examine the effect of the canonical epidemiological structure for recurring diseases—*SIS* dynamics—on the economy. *SIS* dynamics characterize diseases where upon recovery from the disease there is no subsequent immunity to the disease. This covers many major infectious diseases such as flu, tuberculosis, malaria, dengue, schistosomiasis, trypanosomiasis (human sleeping sickness), typhoid, meningitis, pneumonia, diarrhea, acute hemorrhagic conjunctivitis, strep throat and sexually transmitted diseases (STD) such as gonorrhea, syphilis, etc. (see Anderson and May, 1991). While this paper concentrates on *SIS* dynamics, it can be extended to incorporate other epidemiological dynamics. An easy way to understand epidemiology models is that they specify movements of individuals between different states based on some 'matching' functions or laws of motion. Thus, the modeling strategy in the paper can be applied to other contexts such as labor markets with search, diffusion of ideas (Jovanovic and Rob, 1989), etc. In particular, the joint modeling of the non-concave law of motion and capital accumulation in the current paper may be applicable to these models.

As the *SIS* dynamics are non-concave, care has to be taken in using optimal control techniques. To study optimal solutions there are two sets of problems. First, while the existence of optimal solutions relies on compactness and continuity arguments, this is subtle in continuous time models. We show, under weak assumptions, that the feasible set is weakly compact and state variables are absolutely continuous (Lemma 1). The latter rules out jumps in state and co-state variables in the interior of the feasible set as may happen in non-concave models. We show that convergent sequences are in fact feasible and using concavity of the utility function show that optimal solutions exist (Theorem 1). d'Albis et al. (2008) also have an existence result in an abstract model: our proof is more direct and constructive. Second, to characterize optimal solutions it is usual to study the associated Hamiltonian. However, while the first order conditions (and transversality conditions) of the Hamiltonian are necessary they may not be sufficient. We show directly that any path where disease are endemic and health expenditures are positive is locally optimal. In particular, the steady states are indeed optimal. This is done by showing that inequality for the maximality of the Hamiltonian holds at the interior paths where the necessary conditions hold, and thus, it also holds at the endemic steady state with positive health expenditures.[1] To check the maximality of the Hamiltonian we can decompose it into two parts: the first depends only on the control variables. As we have concavity in the objective function in control variables, using standard results, the difference between the candidate solution and any other solution is non-negative. The second part depends on the co-state and the state variables. This is helpful as the non-concavity in the problem arises from the law of evolution of labor only, and we explicitly show this term converges to zero by using a transversality type argument.

In this paper we find a disease-free steady state always exists. It is unique when the birth rate is high. The basic intuition is that healthy individuals enter the economy at a faster rate than they contract the disease so that eventually it dies out even without any intervention. As the birth rate decreases, disease-free steady state undergoes a trans-critical bifurcation and there are multiple steady states. The disease-free steady state still exists but is unstable. An endemic steady state also exists with positive or zero health expenditure depending on the relative magnitude of marginal product of physical capital investment and health expenditure. We show that in an endemic steady state it is socially optimal not to invest in health capital if the discount rate (which indexes longevity) is sufficiently high or people are very impatient, while there are positive health expenditures if it is low or people are patient. A sufficient condition is provided to guarantee the local saddle-point stability.

This paper sheds light on two strands of recent empirical literature: studies on the relationship between economic variables and disease incidence, and the relationship between income and health expenditure share. The former tries to quantify the impact of infectious diseases on the economy and one important issue is solving the endogeneity of disease prevalence (see Acemoglu and Johnson, 2007, Ashraf et al., 2009, Bleakley, 2007, Bloom et al., 2009, Weil, 2007, Young, 2005). Our model, which endogenizes both income and disease incidence, shows that reduced form estimation by assuming a linear relationship is not well justified as non-linearity is an important characteristic of models associated with the disease transmission, and this nonlinearity in disease transmission can become a source of non-linearities in economic outcomes. The latter tries to identify the cause of the changing share of health expenditures. Our findings suggest increase in longevity or decrease in the fertility rate could also generate a positive relationship between income and health expenditure share as observed in the data.

In this paper we abstract away from disease related mortality. This is a significant assumption as it shuts down the demographic interaction. This assumption is made for three reasons. First, several *SIS* diseases have low mortality so there is no significant loss by making this assumption. Secondly, from an economic modeling point of view, we can use the standard discounted utility framework with a fixed discount rate if there is no disease related mortality. Thirdly, introducing disease related mortality introduces an additional state variable, population size, and does not permit analysis in per capita terms. In the paper we, however, study the effect of changes in the discount rate on the variables of interest. As discussed in the literature, an increase in longevity reduces discounting, and thus the analysis of varying the discount rate captures some effects of change in mortality.

The paper is organized as follows: Section 2 describes the model and in Section 3 we establish existence of an optimal solution. Section 4 studies the steady state equilibria, Section 5 studies sufficiency conditions and Section 6 contains the stability and bifurcation analysis of the steady states. Section 7 studies the effect on steady states of varying the discount and birth rates, and the last section concludes.

2. The model

In this paper we study the canonical deterministic *SIS* model which divides the population into two classes: susceptible (S) and infective (I) (see Fig. 1). Individuals are born healthy but susceptible and can contract the disease—becoming infected and capable of transmitting the disease to others, i.e. infective. Upon recovery, individuals do not have any disease conferred immunity, and move back to the class of susceptible individuals. Thus, there is horizontal incidence of the disease so the individuals potentially contract the disease from their peers. This model is applicable to infectious diseases which are absent of immunity or which mutate rapidly so that people will be susceptible to the newly mutated strains of the disease even if they have immunity to the old ones.[2] There is homogeneous mixing so that the likelihood of any individual contracting the disease is the same, irrespective of age. Let S_t be the number of susceptibles at time t, I_t be the

[1] The other two steady states that may exist are essentially neoclassical steady states for which optimality is well known.

[2] As there is no disease conferred immunity, there typically do not exist robust vaccines for diseases with *SIS* dynamics.