On the distributional consequences of epidemics

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Abstract

We develop a tractable general theory for the study of the economic and demographic impact of epidemics, and notably its distributional consequences. To this end, we develop a three-period overlapping generations model where altruistic parents choose optimal health expenditures for their children and themselves. The survival probability of (junior) adults and children depends on such investments. Agents can be skilled or unskilled. The model emphasizes the role of orphans. Orphans are not only penalized in the face of death, they are also penalized in the access to education. Epidemics are modeled as one period exogenous shocks to the survival rates. We specifically study the consequence of a negative shock on adult survival rates in the first period. We prove that while the epidemic has no permanent effect on income distribution, it can perfectly alter it in the short and medium run. In particular, the epidemic may imply a worsening in the short and medium run of both economic performance and income distribution. Two opposite mechanisms are isolated: first, the survival rate of children at the end of the first period decreases relatively more in poor than in wealthy families. This decreases the proportion of junior adults with a low endowment of human capital in period 2. Secondly, the number of orphans in period 1 increases in both families. This decreases the proportion of junior adults with a low endowment of human capital in period 2. Therefore, the proportion of the unskilled will necessarily increase in the medium run if orphans are *too* penalized in the access to a high level of education.

Keywords

Epidemics, orphans, income distribution, endogenous survival, medium-term dynamics

JEL Classification numbers

O1, D9, I1, I2

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1. Introduction

The study of the economic effects of epidemics has always been of interest to many economists (see for example Hirshleifer, 1987). Recently, the topic has regained interest and has become an important research area due to two main factors. On one hand, the HIV/AIDS pandemic and its apparent massive demographic effects, especially in Sub-Saharan Africa, has suggested an exceptionally abundant literature, overwhelmingly empirical (see among many others, Bloom and Mahal, 1997, or McDonald and Roberts, 2006). On the other hand, the rise of a so-called ``unified growth theory'' (comprehensively surveyed by Galor, 2005), specially concerned with the understanding of the Malthusian stagnation and the determinants of the transition to the modern growth regime, has led to reconsider the role of epidemics in the development process (see Lagerlof, 2003).

Just like the Black Death has been viewed as a major engine of the transformation of the West in the Middle-Ages by prominent historians and sociologists (see Herlihy, 1997), several recent contributions are taking this avenue in the assessment of AIDS socio-economic consequences on Sub-Saharan Africa (among them, Young, 2005). While the short term effects of such pandemics are most harmful in all respects, the long-run are not that clear. As argued by Young (2005), the latter can be much less disastrous, and even favourable, if the wage effect induced by (huge) labor supply falls ends up decreasing fertility (via increased female participation in the labor market). Yet this view is not unanimously accepted. No empirical study has identified so far a sizeable wage effect in Sub-Saharan Africa although more recent papers by Young (2007) and Boucekkine, Desbordes and Latzer (2008) conclude that HIV is lowering fertility in the area. Kalemli-Ozcan (2006) defends the opposite view. She suggests that the impact of AIDS on fertility might even go the other way as a result of an insurance effect.[4]

This paper sheds light on another side of epidemics, namely their distributional consequences both in the short, medium and long-run. In the main mortality crises studied (Black Death, Spanish flu or AIDS), death affects more the adult population of working age than younger or

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[4] The same debate takes place on the Black Death disaster. Among them, Robbins (1928) argued that ``…*the English villein, lured by the prospects of high wages in neighboring towns, must sooner or later have deserted his manor. The plague …furnished him an excuse*''.

older populations. Yet, when young adults die, not only do they reduce the amount of productive labour and human capital, but they also leave orphans behind them, potentially leading to disastrous consequences: ``*… Orphaning rates above 5% worry UNICEF because they exceed the capacity of local communities to care for parentless children. So do places such as Zambia, where almost 12% of children are AIDS orphans…. Orphans tend to be poorer than non orphans, and to face a higher risk of malnutrition, stunting and death — even if they are free of HIV themselves. Orphans are less likely to attend school because they cannot afford the fees but also because step-parents tend to educate their own children first*''.[5]

As noted by Case, Paxson and Ableidinger (2004), orphans use to live in foster families who discriminate against them and in favour of the children of the family head. The probability of the school enrolment of an orphan is inversely proportional to the degree of relatedness of the child to the household head. Gertler, Levine and Martinez (2003) show that parental loss does not operate only through a reduction in household resources. Parental presence, including the loss of mentoring, the transmission of values and emotional and psychological support, plays an important role in investment in child human capital. All these findings are consistent with the broader view that the amount of human capital (education and health) embodied in a person strongly results from decisions taken by his parents, as documented by Bowles and Gentis (2002) quoting a series of empirical results for the United States. Grawe and Mulligan (2002) review cross-country evidence showing that countries with lower public provision of human capital experience smaller intergenerational mobility. The connection between the absence of intergenerational mobility and education is also well documented (see again, Bowles and Gentis and Case, Lubotsky and Paxson, 2001).

Our model is completely on this line. In order to isolate the short, medium and long-term distributional impact of orphans, we shut down the wage and fertility channels, abundantly commented in the recent AIDS literature. People live for three periods, successively as children, junior adults and senior adults. A junior adult has an exogenous number of children and is perfectly altruistic in that he only cares for the survival of his children and the social position they will get. He invests in his own health and education, and in the health and education of his children. The probabilities of survival of a child and of a junior adult depend on the amounts of money spent by the junior adult for his own human capital and for the one

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[5] The Economist (2003) – "AIDS. A mixed prognosis", November 29th, 87-89.

of his children. So, under imperfect credit markets, health and education spending and the probabilities of survival will be low if parents are poor. Moreover, if a parent dies and if his children become orphans, their probabilities of survival will be lowered. Finally, an orphan has a lower probability to reach a high level of human capital than a child brought up by living parents. Accordingly, a key feature of the paper is to consider a crucial dimension of inequality, namely inequality in the face of death. Inequality between children has several causes. First, the children of less educated parents who have survived have a higher probability of dying before growing adults because their parents spend less on their health and education. Secondly, less educated parents spend less on their own education and health and have a higher probability to die and to be unable to bring their children up.

Relation to the literature

Very few theoretical papers have been devoted so far to investigating the links between health spending, mortality and the persistence of inequality across generations. Two important contributions are Chakraborty and Das (2005) and Bell and Gersbach (2008).[6] The former base their analysis on the fact that poor parents invest less in their own health and so have a high probability of dying. Thus, they save little and leave a small bequest to their children if they survive and a still smaller bequest if they die. The paper assumes that parents only care for their children if they are themselves alive when their children grow. An extension of the paper introduces the possibility of investing, not only in the health of parents, but in the education of children too. The productivity of labour depends on both these investments. Nonetheless, these authors do not consider investments in the health of children nor their survival probability. Our model does incorporate the latter critical aspect. Moreover, the demographic and economic properties of the model are fully analytically investigated in the short, medium and long-run, which is already a contribution to the literature.

Bell and Gersbach's paper (2008) shares one of the main objectives of ours, that is the study of human capital transmission across generations under epidemics. Interestingly, these authors consider a two- parents model, which in turn allows them to distinguish between the case of full orphans (with no surviving parent) and orphans with one surviving parent. However, in contrast to Chakraborty and Das (2005) and to our model, no health investment is explicitly

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[6] Note however that some applied papers on AIDS do comment on the role of orphans and on the induced changes in the distributions of human capital and income possibly following the epidemic although they do not aim to theoretically investigate them. See for example the computable general equilibrium models elaborated by Bell, Devarajan and Gersbach (2003) and Corrigan, Glomm and Mendez (2004).

considered, the survival probabilities and epidemiological dynamics being fully exogenous. Nonetheless, within a somewhat sophisticated dynamic structure, the authors are able to bring out several useful conclusions on the distributional impact of epidemics under alternative family arrangements.

The paper is organised as follows. The second section presents the model and its short run equilibrium. The third section is devoted to the transitory dynamics and the long run equilibrium of demographic variables. The fourth section investigates the economic and demographic effects of epidemics. The fifth section concludes.

2. The model: behaviour of the agents and temporary equilibrium

We consider a discrete time, perfect foresight dynamic model of a small open economy. People live for three periods, successively as children, junior adults and senior adults. We will start by examining the choices of a junior adult in a given period denoted t. To ease the exposition and to be able to bring out a fully analytical characterization, we shall refer to a single good, health care. The latter should be taken in the much broader sense of any investment raising human capital (including education).

2.1. The choices of a junior adult

A junior adult enters period t with an endowment in human capital h. Healthcare is the only good existing in the economy. It is produced by firms, which use human capital as their unique input and which operate under constant returns. We will assume that the productivity of human capital is equal to 1 and that firms make no profit. Thus, h can also be interpreted as the earnings of the agent. The healthcare good can be stored without cost. The agent sets his saving (his storage of healthcare good) s and his investment in health l for the period, under the budget constraint

$$(1) \quad h = s + l$$

Spending on health has an effect on the lifetime of the agent. His probability of being alive in period $t+1$ (as a senior adult) is $\pi(l)$. At the end of period t the agent will have an exogenous number n of children. Senior adults receive no wages. This assumption will simplify the model in directions that we are not very interested to investigate. The agent will invest e_{+1} in the health of each of his children. The probability for each of them to be alive at the beginning of period $t+2$ will depend on this investment. If the agent is alive in period

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$t+1$ and can take care of his children, this probability will be $\lambda(e_{+1})$. If he is dead and if his children are orphans, this probability will be $c\lambda(e_{+1})$, with $0 < \underline{c} \le c < 1$. The budget constraint of the agent in period $t+1$ is:

$$(2) \quad s = ne_{+1}$$

Notice that the amount invested by the agent in the health of his children will be the same if the agent dies or stays alive at the end of period t. This investment is equal to the saving made in period t. The intertemporal budget constraint of the agent is

$$(3) \quad h = l + ne_{+1}$$

To simplify the model, we will assume that human capital can take only two values: h^1 and h^2, with: $0 < h^1 < h^2$. We will assume that a child who has living parents and who stays alive has a probability p of obtaining a human capital of h^2 and a probability $1-p$ of obtaining a human capital of h^1. An orphan who stays alive has the probability q of obtaining the high level of human capital and $1-q$ of obtaining the low level of human capital. We assume that $0 \le q < p \le 1$.

Our junior adult has the following utility function in period t

$$(4) \quad U \equiv n\lambda(e_{+1})\left\{\pi(l)v\left[p(h^2 - h^1) + h^1\right] + [1 - \pi(l)]vc\left[q(h^2 - h^1) + h^1\right]\right\}$$

The junior adult is wholly altruistic. His utility only depends on the expected human capital accumulated by his children who will reach the adult age. Our specification is in the spirit of evolutionary biology (see Galor and Moav, 2002 and 2005). Consistently with the traditional Darwinian theory, the parent should maximize the probability of survival and quality of her children. Nonetheless, in contrast to Galor and Moav (2005), we keep the number of offspring fixed. As argued in the introduction, our paper intends to isolate the role of orphans, and to this end, we shut down the wage and fertility channels abundantly commented in the literature. On the other hand, adding endogenous fertility to the model would require additional adjustments which will reduce sharply its tractability.

If the junior adult reaches the age of senior adult, he will bring his children up, which will increase their probability of survival and their expected levels of human capital. vh^2 (vh^1) represents the satisfaction a child brings to his parent when he reaches the adult age with the level of human capital h^2 (h^1), $v > 0$. When the child dies, this satisfaction is 0. We will introduce the following notations

$$(5) \quad r_1 = v\left[p(h^2 - h^1) + h^1\right], \quad r_2 = vc\left[q(h^2 - h^1) + h^1\right] \text{ and } r = r_1 / r_2 - 1.$$

The utility function of our junior adult in period t becomes, after removing a constant multiplicative term, $U \equiv \lambda(e_{+1})[\pi(l)r+1]$. r represents the satisfaction premium brought by children when their parent stays alive, or if one prefers, the utility for parents of staying alive. In this case, the probability of survival of each child is higher (by a factor $1/c$) and his expected level of human capital is higher too. r, is an increasing function of the inequality in earnings, $(h^2 - h^1)/h^1$, which is expected for the next period. Finally, our junior adult must solve in period t the program

$$(6) \quad \underset{l,e_{+1}}{Max}\,\lambda(e_{+1})[\pi(l)r+1]$$

$$h = l + ne_{+1}$$

$$l, e_{+1} \geq 0$$

Before solving this program we must give precise specifications of the survival functions:

$$(7) \quad \lambda(e_{+1}) = \min\left\{(Ae_{+1} + A')^{1-\alpha}/(1-\alpha),1\right\}$$

$$(8) \quad \pi(l) = \min\left\{(Bl + B')^{1-\beta}/(1-\beta),1\right\}$$

with: $0 < \beta, \alpha < 1$, $A, B, B' > 0$, $0 \leq A' < (1-\alpha)^{1/(1-\alpha)}$, $B' < (1-\beta)^{1/(1-\beta)}$. .

In the rest of the paper we will assume that we are always inside the intervals where both functions are strictly increasing. Some comments are in order here. Concerning the concave functional forms considered, empirical evidence is quite compelling: among others, Deaton (2003) notices that health spending, the health state and the longevity of an individual are increasing and concave functions of his income: for instance the probability of dying between the ages of 50 and 60 is a decreasing convex function of his income. This concavity is a possible explanation of the impact of inequality on the average health state in a country, and it implies that some redistribution of income can increase average health.

Second, we consider survival functions such that $\lambda(0) = A'^{1-\alpha}/(1-\alpha) \geq 0$ and $\pi(0) = B'^{1-\beta}/(1-\beta) > 0$. Chakraborty and Das (2005) assume that their survival probability drops to zero with zero investment in health. It is easy to justify why survival rates need not be zero when health investment is zero: $\lambda(0)$ or $\pi(0)$ can simply be interpreted as reflecting inherent (and exogenous) health situations, unrelated to health investments (see Finlay, 2005). This specification is not only aimed to generalize the analytical framework, it is a fundamental ingredient of our theory. To get an immediate idea of it, consider the efficiency of adults' health spending, that is the derivative of their probability of survival with respect to health

spending, $\partial \pi(l)/\partial l = B(Bl + B')^{-\beta}$. Notice that it is decreasing in the investment, which is reasonable. Moreover, we have:

$$\partial^2 \pi(l)/(\partial l \partial B) = [(1-\beta)Bl + B'](Bl + B')^{-1-\beta} > 0, \ \partial^2 \pi(l)/(\partial l \partial B') = -\beta B(Bl + B')^{-1-\beta} < 0,$$

that is the marginal efficiency of investment does not respond in the same way to shocks on B or B'. Henceforth, mortality crises have completely different consequences depending on whether they operate through B, B' or both. Boucekkine and Laffargue (2008) provide a complete characterization of the model dynamics in all these cases, and also consider child mortality crises (shocks on A and A').

In this paper, we take a more specific view. While an epidemic can be defined as a decrease in one of the parameters of the survival functions, we will focus on the epidemics which hit junior adults by shifting downward their survival function, that is by decreasing the value of parameter B'. The epidemic essentially affects inherent health, nothing can be done against the epidemic itself, although an increase in health spending will reduce the number of death toll. Though our theory allows for any age profile of mortality, we shall abstract from exogenous child mortality here for simplicity. This is consistent with the W-shaped age-profile of mortality observed for major epidemics like the Spanish flu or AIDS: the mortality impact of the epidemic is much stronger on junior adults than on children. Last, we consider that the epidemic hits people irrespectively of their endowment in human capital. This assumption is certainly debatable. There are indications that people with a relatively high schooling level are more exposed to AIDS because they have more sexual partners (Cogneau and Grimm, 2005). However these people are usually more aware of the risks of AIDS than less educated people and understand faster the usefulness of not engaging in risky behaviour.[7] In this paper, we implicitly assume that the two effects offset each other.

Hereafter, we assume $A'=0$ to simplify the algebra. With the survival functions given above, program (6) becomes

$$(9) \ \underset{l, e_{+1}}{Max} (Ae_{+1})^{1-\alpha} \left[r(Bl + B')^{1-\beta} /(1-\beta) + 1 \right]/(1-\alpha)$$

$$Rh = lR + ne_{+1}$$

$$l, e_{+1} \geq 0, \ Ae_{+1} \leq (1-\alpha)^{1/(1-\alpha)}, \ Bl + B' \leq (1-\beta)^{1/(1-\beta)}$$

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[7] For instance they are more responsive to campaigns of information, and prevention (de Walque, 2004).The United Nations (2004) quotes several studies showing that poor and uneducated people are more likely to engage in risky behaviour and to acquire HIV/AIDS

We make the following assumptions.

Assumption 1. *The parameters of the model must satisfy the constraints*

$$(10)\quad Bh^2 + B' \le (1-\beta)^{1/(1-\beta)}\left[1+\frac{1-\alpha}{1-\beta}(1+1/r)\right]$$

$$(11)\quad h^2 \le n(1-\alpha)^{1/(1-\alpha)}/A$$

$$(12)\quad \frac{1-\alpha}{1-\beta}B'+\frac{1-\alpha}{r}B'^{\beta} < Bh^1$$

These assumptions are needed for the optimization problem to make sense, as established in the following lemma. In particular, condition (12) is needed for existence: the low value of human capital should be large enough for an optimal (interior) solution to exist. Conditions (10) and (11) guarantee that optimal decisions lie inside the intervals where the survival functions are strictly increasing. They set upper bounds for $\pi(h^2)$ and $\lambda(h^2)$ respectively.

Lemma 1. *Program (9) has a unique solution defined by the two equations*

$$(13)\quad \frac{Bh+B'}{Bl+B'}-\frac{1-\alpha}{r(Bl+B')^{1-\beta}}=1+\frac{1-\alpha}{1-\beta}$$

$$(14)\quad e_{+1}=(h-l)/n$$

Proof. Equation (14) is the constraint in program (9). We use this constraint to eliminate e_{+1} from the objective function. This function is concave in l. Equation (14) is the first order conditions of the so-transformed objective function. Let us define the function $y(l)\equiv\frac{Bh+B'}{Bl+B'}-\frac{1-\alpha}{r(Bl+B')^{1-\beta}}$. We have $y(0)=1+\frac{Bh}{B'}-\frac{1-\alpha}{rB'^{1-\beta}}>1+\frac{1-\alpha}{1-\beta}$, because of inequality (12). Also $y(h)=1-\frac{1-\alpha}{r(Bh+B')^{1-\beta}}<1<1+\frac{1-\alpha}{1-\beta}$. $y(l)$ has a unique minimum, which is negative, for $(Bl+B')^{\beta}=\frac{r(Bh+B')}{(1-\alpha)(1-\beta)}$. $y(l)=0$ for $(Bl+B')^{\beta}=\frac{r(Bh+B')}{1-\alpha}$. Thus, equation (13) defines a unique value for l, which is positive and smaller than h.

We have to check that this solution satisfies $Bl+B'\le(1-\beta)^{1/(1-\beta)}$. This is equivalent to $y\left[(1-\beta)^{1/(1-\beta)}/B-B'\right]\le1+(1-\alpha)/(1-\beta)$, which results from inequality (10). We also have to check that $Ae_{+1}=A(h-l)/n\le(1-\alpha)^{1/(1-\alpha)}$ or $l\ge h-(1-\alpha)^{1/(1-\alpha)}n/A$. This condition is satisfied because of inequality (11). □

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The three following lemmas describe in detail the characteristics of optimal decisions taken by a junior adult, first concerning investment in his own health, then concerning investment in the health of his offspring.

Lemma 2. *a) A junior adult endowed with high human capital invests more in his health than a junior adult endowed with low human capital. b) The investment of a junior adult in his own health increases with the utility for parents of being alive. c) The investment of a junior adult in his own health is independent of the number of his children.*

Lemma 3. *a) A junior adult endowed with high human capital invests more in the health of his children than a junior adult endowed with low human capital. b) The investment of a junior adult in the health of his children decreases with the utility for parents of being alive. c) The total investment of a junior adult in the health of his children is independent of the number of his children.*

Lemma 4. *a) The investment of a junior adult in his own health increases in case of epidemic (when parameter B' decreases).*
b) However, his probability of survival decreases by

$$(15) \quad \frac{d\pi(l)}{\pi(l)} = \frac{(1-\beta)(Bl+B')^{-\beta}}{\left(1+\frac{1-\alpha}{1-\beta}\right)(Bl+B')^{1-\beta} + \frac{\beta(1-\alpha)}{r}} dB' = \frac{(1-\beta)}{Bh+B'-(Bl+B')^{\beta}(1-\alpha)(1-\beta)/r} dB' < 0$$

c) The probability of survival of a junior adult decreases relatively less for those endowed with a high human capital than for those endowed with a low human capital.
d) The investment of a junior adult in the health of his children decreases in case of epidemic.
e) The probability of survivals of his children decreases by

$$(16) \quad \frac{d\lambda(e_{+1})}{\lambda(e_{+1})} = \frac{1-\alpha}{B(h-l)}\left[1 - \frac{(Bl+B')^{1-\beta}}{\left(1+\frac{1-\alpha}{1-\beta}\right)(Bl+B')^{1-\beta} + \frac{\beta(1-\alpha)}{r}}\right] dB' < 0$$

f) The probability of survival of a child decreases relatively less if his parent is endowed with high human capital than if his parent is endowed with low human capital.

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Proof. We deduce from equation (14)

$$B\frac{dl}{dB'} = -1 + \frac{1}{\dfrac{Bh+B'}{Bl+B'} - \dfrac{(1-\alpha)(1-\beta)}{r(Bl+B')^{1-\beta}}} = -1 + \frac{1}{1 + \dfrac{1-\alpha}{1-\beta} + \dfrac{\beta(1-\alpha)}{r(Bl+B')^{1-\beta}}} < 0.$$ We also have

$$\frac{d\pi(l)}{dl} = \frac{\partial\pi(l)}{\partial B'} + \frac{\partial\pi(l)}{\partial l}\frac{dl}{dB'} = (Bl+B')^{-\beta}\left(1 + B\frac{dl}{dB'}\right).$$ We get

$$\frac{d\pi(l)}{dB'} = \frac{(Bl+B')^{-\beta}}{1 + \dfrac{1-\alpha}{1-\beta} + \dfrac{\beta(1-\alpha)}{r(Bl+B')^{1-\beta}}} \in \left(0, \quad \frac{\partial\pi(l)}{\partial l}\right).$$ Finally we have

$$\frac{d\pi(l)}{dB'}\Big/\pi(l) = \frac{(1-\beta)(Bl+B')^{-\beta}}{\left(1 + \dfrac{1-\alpha}{1-\beta}\right)(Bl+B')^{1-\beta} + \dfrac{\beta(1-\alpha)}{r}},$$ which is a decreasing function of l, and so of

h. Thus $d\pi(l^1)/\pi(l^1) < d\pi(l^2)/\pi(l^2)$. Then we substitute equation (13) in this expression.

We deduce from equation (7) and (14): $\dfrac{d\lambda(e_{+1})}{\lambda(e_{+1})} = (1-\alpha)\dfrac{de_{+1}}{e_{+1}} = -(1-\alpha)\dfrac{dl}{h-l}$. We substitute in

the right-hand side of this equation the expression of dl given above and get equation (15). If

we remind that $h-l = ne_{+1}$, and that l and e_{+1} increase with h (lemma 2 and 3), then, the

factor of dB' in equation (16) is a decreasing function of h. Thus

$d\lambda(e_{+1}^1)/\lambda(e_{+1}^1) < d\lambda(e_{+1}^2)/d\lambda(e_{+1}^2)$.

The model has several worth-mentioning properties. First, and as announced in the
introduction section, our model entails inequality in the face of death. Children of parents with
low human capital have a higher probability of dying before growing. Moreover, such parents
tend to spend less in their own health care, and hence face a lower survival probability with
the subsequent negative effect on the human capital of the resulting orphans. Second, the
investment decisions taken by the junior adults are sensitive to exogenous changes in their
survival function (lemma 4). Put in other words, an epidemic hitting young adults will have an
impact on the investment decisions of these individuals.

The consequences of varying life expectancy are extensively studied in the literature. Our
model has some interesting predictions regarding this issue. In the standard theory relying on
Blanchard-Yaari structures, life expectancy (or mortality rate) is exogenous. A downward
shift in life expectancy generally decreases the marginal return to investment in this

framework, implying less investment in human capital (as in Boucekkine, de la Croix and Licandro, 2002). In our model life expectancy is no longer exogenous. When an epidemic hits a generation of junior adults, these individuals increase their own health expenditures and decrease health expenditures on their children. The first decision dampens, but is insufficient to reverse the effects of the epidemic and junior adults' life expectancy decreases. The second decision reduces the probability of survival of their children.

Lemma 4 also establishes that under epidemics the probability of survival of junior adults decreases proportionally less for those endowed with high human capital than for those with low human capital. This comes from the fact that the efficiency of health spending increases in the period of the epidemic shock, and that this spending is higher for junior adults with a high endowment of human capital. However, as the probability of survival of these junior adults is also higher, we do not know if the absolute reduction of their probability of survival is smaller or larger than for junior adults with low human capital. Similarly, the probability of survival of children decreases proportionally less if their parents are endowed with high human capital than when they are endowed with low human capital.

Finally, total investment of a junior adult in the health of his children is independent of the number of his children. If this investment were to increase with the number of children, then health expenditures on parents would go down, which would decrease their survival probability and increase the number of orphans. Transferring health spending from children to parents can neither be optimal: health spending per child would decrease first because total health spending on children goes down, secondly because there are more children. In our model, the two mechanisms outlined above exactly neutralize each other.

2.2. Demographic variables

The population alive in period t includes N^{21} and N^{22} junior adults with human capital endowments respectively equal to h^1 and h^2. It also includes N^{31} and N^{32} senior adults. Finally, it includes N^{11}, N^{12} children who have parents with respective human capital h^1 and h^2, and N^{1o1}, N^{1o2} orphans with respectively low and high bequests. The parents of the two first kinds of children are the senior adults of the period. So, we have:

$$(17) \quad N^{11} = nN^{31} \text{ and } N^{12} = nN^{32}$$

The populations N^{1o1}, N^{1o2}, N^{21}, N^{22}, N^{31} and N^{32} are predetermined in period t. The number of senior adults endowed with low (high) human capital which will be alive in period

$t+1$ is equal to the number of junior adults with the same endowment who are alive in period t multiplied by their rate of survival

$$(18)\ N_{+1}^{31} = \pi(l^1)N^{21}, \ N_{+1}^{32} = \pi(l^2)N^{22},$$

If we use equation (17) in period $t+1$, we get the equations[8]

$$(19)\ N_{+1}^{lo1} = nN^{21} - nN_{+1}^{31} \text{ and } N_{+1}^{lo2} = nN^{22} - nN_{+1}^{32}$$

The numbers of junior adults with high and low human capital endowment in period $t+1$ are respectively

$$(20)\ N_{+1}^{22} = \lambda(e^1)\big(pN^{11} + qcN^{lo1}\big) + \lambda(e^2)\big(pN^{12} + qcN^{lo2}\big),$$

$$N_{+1}^{21} = \lambda(e^1)\big(N^{11} + cN^{lo1}\big) + \lambda(e^2)\big(N^{12} + cN^{lo2}\big) - N_{+1}^{22}$$

3. Dynamics and long run equilibrium

3.1. The dynamics of populations

There are N^{21} and N^{22} junior adults alive in period $t \geq 0$. They will have n children each. These children will either become N_{+2}^{21} and N_{+2}^{21} junior adults with earnings respectively equal to h^1 and h^2 in period $t+2$, or they will die at the end of period $t+1$. D_{+2} represents the supplementary number of junior adults who would exist in period t if no children die before reaching the age of junior adult, that is if the survival rate function λ were identical to 1. We will investigate the dynamics of the model for $t \geq 2$. The states of the economy in periods 0 and 1 are assumed to be given. We have the fundamental relationship:

$$(21)\ \begin{pmatrix} N_{+2}^{21} \\ N_{+2}^{22} \\ D_{+2} \end{pmatrix} = Mn \begin{pmatrix} N^{21} \\ N^{22} \\ D \end{pmatrix} = \begin{pmatrix} a_{11} & a_{12} & 0 \\ a_{21} & a_{22} & 0 \\ 1-a_{11}-a_{21} & 1-a_{12}-a_{22} & 1 \end{pmatrix} n \begin{pmatrix} N^{21} \\ N^{22} \\ D \end{pmatrix}$$

with

$$a_{11} = \lambda(e_{+1}^1)\big\{\pi(l^1)(1-p) + \big[1-\pi(l^1)\big]c(1-q)\big\}$$

$$a_{12} = \lambda(e_{+1}^2)\big\{\pi(l^2)(1-p) + \big[1-\pi(l^2)\big]c(1-q)\big\}$$

$$a_{21} = \lambda(e_{+1}^1)\big\{\pi(l^1)p + \big[1-\pi(l^1)\big]cq\big\}$$

$$a_{22} = \lambda(e_{+1}^2)\big\{\pi(l^2)p + \big[1-\pi(l^2)\big]cq\big\}$$

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[8] Notice that the total number of children in this period is equal to the number of junior adults in period t times n,

and with $N^{21}(0)$, $N^{22}(0)$ and $D(0)$ given if t is even and $N^{21}(1)$, $N^{22}(1)$ and $D(1)$ given if t is odd. Lemma 1, 2 and 3 imply that these parameters satisfy the constraints

$$0 < a_{11} < a_{12} < 1, \qquad 0 < a_{21} < a_{22} < 1, \qquad , \qquad a_{11} + a_{21} < a_{12} + a_{22} < 1 \qquad \text{and}$$

$$a_{11}a_{22} - a_{12}a_{21} = c(p-q)\lambda(e_{+1}^1)\lambda(e_{+1}^2)\left[\pi(l^2) - \pi(l^1)\right] \in \left]0,1\right[.$$

The elements of each column of M are positive and sum to 1. So they can be interpreted as proportions, or as conditional probabilities for instance for a child of a junior adult with high human capital endowment to acquire a high or low human capital, or to die two periods later. More precisely, $a_{22} - a_{21}$ is the difference between the probabilities for a child to reach a high level of human capital if his parent is endowed with high human capital versus if his parent has low human capital. $a_{12} - a_{11}$ is the difference between the probabilities for a child to reach a low level of human capital if his parent has a high human capital endowment versus if his parent has low human capital. The difference between the probabilities for a child to die if his parent is endowed with high human capital versus if his parent has low human capital is

$$-\left(a_{22} - a_{21}\right) - \left(a_{12} - a_{11}\right).$$

Matrix M in period t only depends on health spending set by junior adults, l^1, l^2, e_{+1}^1 and e_{+1}^2. These spending are functions of the values taken by a series of exogenous variables in period t: the parameters of the survival functions of children and young adults A, B, B', α and β, the incomes of the junior adults h^1 and h^2 and the number of their children n.

Equation (21) gives the dynamics of the numbers of junior adults and of the dead, N^{21}, N^{22} and D for $t \geq 2$, when the values of these variables are given in periods 0 and 1. Equation (18) gives the dynamics of the numbers of senior adults $N^{31} = \pi(l^1)N_{-1}^{21}$, $N^{32} = \pi(l^2)N_{-1}^{22}$ for $t \geq 1$. Equation (17) gives the dynamics of the number of children with surviving parents, $N^{11} = nN^{31}$ and $N^{12} = nN^{32}$ for $t \geq 1$. Finally, the numbers of orphans in period $t \geq 1$ are given by equations (19) $N_{+1}^{1o1} = nN^{21} - nN_{+1}^{31}$ and $N_{+1}^{1o2} = nN^{22} - nN_{+1}^{32}$.

We define $P = N^{21} + N^{22} + D$ as the potential population of junior adults. It would be equal to the effective population if all children reached the age of junior adult. Equation (21) shows that this potential population grows at rate n: $P_{+2} = nP$. The number of dead people is equal to the difference between the potential population and the number of junior adults:

$D = P - (N^{21} + N^{22})$. Thus, we just have to investigate the dynamics of the numbers of living

junior adults N^{21} and N^{22}, which are given by

$$(22) \begin{pmatrix} N^{21}(t+2) \\ N^{22}(t+2) \end{pmatrix} = M'n \begin{pmatrix} N^{21}(t) \\ N^{22}(t) \end{pmatrix} = \begin{pmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{pmatrix} n \begin{pmatrix} N^{21}(t) \\ N^{22}(t) \end{pmatrix}$$

with $N^{21}(0)$ and $N^{22}(0)$ given if t is even and $N^{21}(1)$ and $N^{22}(1)$ given if t is odd.

3.2. Characterization of the demographic dynamics

We will assume in this paragraph that all the parameters and exogenous variables stay

constant over time for $t \geq 0$. We will also assume that t is even. Then, matrix M' will stay

constant over time, and the dynamics of the model will be limited to the sizes of the different

components of population (including the dead). Let us introduce the new variable

(23) $\Delta \equiv (a_{11} + a_{22})^2 - 4(a_{11}a_{22} - a_{12}a_{21}) = (a_{11} - a_{22})^2 + 4a_{12}a_{21} > 0$.

We have the lemma

Lemma 5. *a) The eigenvalues of matrix M', ρ_1 and ρ_2, are real and such that*

$1 > \rho_1 > \rho_2 > 0$. *Their expressions are*

$$(24)\ \rho_1 = (a_{11} + a_{22} + \sqrt{\Delta})/2 \ \text{and} \ \rho_2 = (a_{11} + a_{22} - \sqrt{\Delta})/2$$

b) Let us denote by $V_1 = \begin{pmatrix} v_{11} \\ v_{21} \end{pmatrix}$ *and* $V_2 = \begin{pmatrix} v_{12} \\ v_{22} \end{pmatrix}$ *the right-hand column eigenvectors of M' and*

by $V = (V_1 \ \ V_2)$ *the matrix of these eigenvectors. A determination of these eigenvectors is*

$$(25)\ V = \begin{pmatrix} a_{11} - a_{22} + \sqrt{\Delta} & -a_{11} + a_{22} + \sqrt{\Delta} \\ 2a_{21} & -2a_{21} \end{pmatrix}$$

V_1 can be normed such that its components are positive and sum to 1. V_2 can be normed such

that its first component is positive, its second component is negative and the sum of both

components is equal to 1.

c) Let $W = \begin{pmatrix} w_{11} & w_{12} \\ w_{21} & w_{22} \end{pmatrix}$ *be the inverse of V :* $VW = I$ *. Then, we have*

$$(26)\ W = \frac{1}{4a_{21}\sqrt{\Delta}} \begin{pmatrix} 2a_{21} & -a_{11} + a_{22} + \sqrt{\Delta} \\ 2a_{21} & -a_{11} + a_{22} - \sqrt{\Delta} \end{pmatrix}$$

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d) The elements of matrix W satisfy the constraints

$$(27)\quad w_{12} > w_{11} > 0 \text{ and } w_{22} < 0 < w_{21}$$

The proof is in the appendix. We can now establish the following crucial proposition which neatly characterizes the demographic dynamics and the evolution of human capital (and thus income) distributions over time.

Proposition 1. *Assume, to fix the ideas that* $N^{21}(0) + N^{22}(0) = 1$. *Then:*

a) The dynamic paths followed by the sizes of the cohorts of both kinds of junior adults, are linear combinations of two geometric series with rates equal to the growth rate of potential population n *times the eigenvalues of matrix* M'.

$$(28)\quad N^{21}(t+2) = (\rho_1 n)^{t/2+1} v_{11}\big[(w_{11} - w_{12})N^{21}(0) + w_{12}\big] + (\rho_2 n)^{t/2+1} v_{12}\big[(w_{21} - w_{22})N^{21}(0) + w_{22}\big]$$

$$(29)\quad N^{22}(t+2) = (\rho_1 n)^{t/2+1} v_{21}\big[(w_{11} - w_{12})N^{21}(0) + w_{12}\big] + (\rho_2 n)^{t/2+1} v_{22}\big[(w_{21} - w_{22})N^{21}(0) + w_{22}\big]$$

In the long run the populations of both kinds of junior adults will grow at a rate equal to the growth rate of the potential population of junior adults times the largest eigenvalue of matrix M' *(which is smaller than 1). The long run size of each group depends on the initial condition,* $N^{21}(0)$. *However, the long run proportions of the two groups of junior adults are independent of the initial conditions, and are precisely proportional to the two components of the eigenvector associated to the largest eigenvalue of matrix* M'.

b) Let us assume that its share of junior adults holding a high level of human capital in the initial population is decreased. In the long run, the sizes of both groups of junior adults will drop. Along the transition path, the number of junior adults holding a high level of human capital and the total size of the population of junior adults will unambiguously go down. In contrast, the number of junior adults holding a low level of human capital may increase in the short run.

The proof is in the appendix. Proposition 1 has several important implications, which will be illustrated in our application to epidemics in the next section. First of all, Property a) shows the ability of the model to generate hysteresis. This should not be though seen as a surprising result: this is a natural outcome in demographic models: initial demographic shocks are likely to have long lasting echo effects. Such effects may be dampened after a while, for example if fertility markedly changes some generations after the initial shock, but it seems out of question that persistence is a fundamental property of demographic dynamics. Second, our

model features that an initial change in the income distribution of the population may distort this distribution in the short and medium terms but not in the long run. This is a very important property as we will thereafter.

4. The demographic and economic effects of epidemics

We shall study the impact of an epidemic shifting downward the survival probability function of young adults (a decrease in B') whatever their endowment in human capital. We shall only consider one-period long epidemics occurring in period 0. Longer epidemiological shocks would complicate tremendously the analytical treatment. As we shall see, one-period long shocks are enough to capture the main economic and demographic mechanisms at work in the model and to identify the distributional outcomes of the epidemic.

We start from a reference balanced growth path with a total population of junior adults equal to 1. If the vector of the initial values of the populations of the two kinds of junior adults is equal to the eigenvector of the transition matrix, M', associated to its largest eigenvalue $\begin{pmatrix} N^{21}(0) \\ N^{22}(0) \end{pmatrix} = V_1$, the population of junior adults will follow the balanced growth path

$$(30) \quad \begin{pmatrix} N^{21}(t+2) \\ N^{22}(t+2) \end{pmatrix} = (\rho_1 n)^{t/2+1} V_1$$

Proposition 1 shows that this steady state is relatively asymptotically stable. We now move to our analysis of epidemics. For a better understanding, recall that total domestic output in our model is given by

$$(31) \quad Y(t) = N^{21}(t)h^1 + N^{22}(t)h^2 \ .$$

The epidemic takes place in period 0 and kills a proportion of junior adults at the end of the period. The number of children alive in period 1 will be unchanged but the proportion of orphans among them will be higher. The number of senior adults alive in period 1 will be lower as a result of the epidemic.

Let us investigate the problem at a more formal level. According to lemma 4, as the epidemic hits the economy by decreasing parameter B', junior adults will increase their investment in their own health, and their survival rates at the end of the period will decrease by less than what results directly from the epidemic. Junior adults will also decrease their investment in the health of their children in period 1, which will reduce the survival rate of children in period 1, and affect the size of the population of junior adults in period 2. The relative

variations in the populations of junior adults holding a low level and a high level of human capital, in this period is given by differentiation of equation (22)

$$(32) \quad \frac{dN^{21}(2)}{N^{21}(2)} = \frac{v_{11}da_{11} + (1 - v_{11})da_{12}}{\rho_1 v_{11}}$$

$$(33) \quad \frac{dN^{22}(2)}{N^{22}(2)} = \frac{v_{11}da_{21} + (1 - v_{11})da_{22}}{\rho_1(1 - v_{11})}$$

The relative changes in the total population of junior adults and in the domestic output per worker are

$$(34) \quad \frac{dN^{21}(2) + dN^{22}(2)}{N^{21}(2) + N^{22}(2)} = \frac{v_{11}(da_{11} + da_{21}) + (1 - v_{11})(da_{12} + da_{22})}{\rho_1}$$

$$(35) \quad \begin{array}{l} \dfrac{dY(2)}{Y(2)} - \dfrac{dN^{21}(2) + dN^{22}(2)}{N^{21}(2) + N^{22}(2)} = \\[2em] \dfrac{N^{21}(2)N^{22}(2)(h^1 - h^2)}{\left[N^{21}(2)h^1 + N^{22}(2)h^2\right]\left[N^{21}(2) + N^{22}(2)\right]}\left[\dfrac{dN^{21}(2)}{N^{21}(2)} - \dfrac{dN^{22}(2)}{N^{22}(2)}\right] \end{array}$$

The following proposition summarises the distributional effects of the epidemic in period 2.

Proposition 2. *a) In period 2 the total population of junior adults decreases.*

b) The proportion of young adults holding a low level of human capital changes under the action of two opposite forces. First, the survival rate of children at the end of the first period decreases relatively more in poor than in wealthy families. This decreases the proportion of junior adults with a low endowment of human capital in period 2. Secondly, the number of orphans in period 1 increases in both families. This decreases the proportion of junior adults with a low endowment of human capital in period 2. If the first effect dominates, domestic output per worker increases, otherwise it decreases.

c) The numbers of each kind of children and senior adults are unchanged.

Proof. See the appendix.

When an epidemic takes place, parents will spend less on the health of their children. This will contribute to decreasing the proportion of children who will survive in period 2. Moreover, more children will grow as orphans whose the probability of survival is lower. Both effects lead to a decrease in the population of young adults in period 2.

The proportion of children surviving at the end of period 1 decreases by a lower percentage if their parents are wealthy than if they are poor. Children of wealthy parents have a higher probability of reaching a high level of human capital than the children of poor parents. Thus, this first mechanism leads to an increase in the proportion of young adults with a high level of human capital in period 2. In period 2, the number of junior adults who were orphans will increase and the number of those who were brought up by their parents will decrease. Orphans have a lower probability to reach a high level of human capital. Thus, this second mechanism leads to a decrease in the proportion of young adults with a high level of human capital in period 2.

Proposition 2 is a crucial characterisation of the medium term distributional effects of epidemics. The distributional consequences are significant in the medium run. If the second mechanism dominates, more young adults will get less educated two periods after the epidemic and output per worker goes down. However, the epidemic has no effect on the number of children and old adults living in period 2. Thus, the share of the active population in the total population decreases. So output per capita decreases by a higher proportion than output per worker. The economy is clearly impoverished (with respect to the reference balanced growth path) at this time horizon. If the first mechanism dominates, more young adults will get more educated two periods after the epidemic and output per worker goes up. In this case, the effect on output per capita is ambiguous.

The analysis of even periods, posterior to period 2, can easily be deduced from Proposition 1. If the composition per skill of the population of junior adults in period 2 were unchanged, then the population of junior adults and the output of the economy would follow a balanced path parallel to but lower than the original one. However, as the number of children and old adults living in these periods has not been modified by the economics, output per capita will permanently be under its value before the epidemic. If the proportion of young adults with low skill in period 2 has increased, then this proportion will progressively decreases over time and finally converge to its initial value. During this transition output per worker will be lower than if the epidemic has not taken place. In the long run, output per worker will converge to its initial value, but output per capita will be lower. If the proportion of young adults with low skill in period 2 has decreased, then this proportion will progressively increase over time and converge to its initial value. During this transition output per worker will be higher than if the epidemic had not taken place. In the long run, output per worker will converge to its initial value.

A similar analysis can be done for odd periods. In period 1, the number of old adults has decreased because of the epidemic, but the numbers of children and of young adults of both skills is unchanged. So, output per worker is unchanged but output per capita has increased. In the following odd periods, the number of old adults and of children has decreased but the number of young adults of both kinds is unchanged. So, still output per worker is unchanged but output per capita has increased.

So, in contrast to some contributions in the AIDS-related literature (like Bell et al., 2003), the model predicts a kind of corrective dynamics which will bring some key variables to the corresponding balanced growth corresponding values, although some demographic variables will be permanently affected as already mentioned in Proposition 1.

Further results

In addition to the analysis of the distributional consequences of epidemics highlighted in the previous section, the model has several predictions on other demographic and economic variables which are worth a look having in mind the recent AIDS empirical literature. We select three indicators to make the point.

a) **Population size:** Population decreases in all periods and this effect is permanent. This is consistent with empirical studies. For instance in the 2004 United Nations report, the predictions point rather at a sharp fall in total population by 2020 in Sub-Saharan Africa (38 countries), about 14% less than without AIDS.

b) **Age pyramid:** In the short run (t=0), the epidemics implies a reduction in the proportion of young adults, which is also a key economic implications since these adults are also the workers of the economy. In the medium run (period 1) it is the proportion of old adults, which decreases. This is still consistent with the available AIDS projection. The projections included in the 2004 United Nations report for Botswana show up a huge effect on the age structure of its population by 2025: more than half of the potential population aged 35-59 would have been lost to AIDS. This proportion is much lower for the older and younger populations.

c) **Output and productivity:** In period 1, output per worker is the same as if the epidemic had not taken place, but output per capita has increased. This results from the assumption that the epidemic has lasted for only one period and has not hit

children. However, in period 2, output per worker may decrease or increase. In the first case, output per capita decreases, in the second case we cannot conclude.

5. Conclusion

In this paper, we have presented a full analytical dynamic theory of income distribution under epidemics. A peculiarity of the theory with respect to the usual set-ups is the neutralization of the wage and fertility effects typically invoked, allowing for the isolation and the inspection of new transmission mechanisms of the epidemiological shocks. Within this framework, we have analytically shown several properties. First, transitory epidemiological shocks have permanent effects on the size of population and on the level of output. However and more importantly, the income distribution is shown to be unaltered in the long-run. Second, we show that this distribution can be seriously altered in the medium-term due to two clearly identified mechanisms, and in particular to the ability of orphans to access high levels of education. The sharply rising number of orphans is therefore of crucial importance: if not conveniently treated (for example by internationally funded social and specially education aid programs for orphans), this problem is likely to induce a sharp worsening of poverty in the medium run.

Of course, the mechanisms isolated in this paper are not the unique relevant in the analysis of the socio-economic impact of epidemics. We have already mentioned the possible wage and fertility effects. It is not obvious at all how these effects interact in reality, and what could be (or could have been) their relative significance in concrete epidemic episodes. We are currently working hard on this issue.

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APPENDIX

Proof of Lemma 4

a) The eigenvalues of matrix M' are the roots of the characteristic equation

$$S(\Lambda) \equiv \rho^2 - (a_{11} + a_{22})\rho + (a_{11}a_{22} - a_{12}a_{21}) = 0$$

The discriminant of this equation is $\Delta > 0$. So, the two eigenvalues of M' are distinct and real. Their product is given by $S(0) \equiv a_{11}a_{22} - a_{12}a_{21} \in \,]0,1[$. Moreover we have

$$S(1) \equiv 1 - (a_{11} + a_{22}) + (a_{11}a_{22} - a_{12}a_{21}) = (1 - a_{11})(1 - a_{22}) - a_{12}a_{21}$$

As we have $1 - a_{11} > a_{21}$ and $1 - a_{22} > a_{12}$, we can conclude that $S(1) > 0$. Thus, the two eigenvalues of matrix M' are strictly included between 0 and 1.

b) We have

$$a_{21}v_{11} + a_{22}v_{21} = \rho_1 v_{21} = \left(a_{11} + a_{22} + \sqrt{\Delta}\right)v_{21}/2 \text{, so}$$

$$2a_{21}v_{11} = \left(a_{11} - a_{22} + \sqrt{\Delta}\right)v_{21}$$

We also have

$$2a_{21}v_{12} = \left(a_{11} - a_{22} - \sqrt{\Delta}\right)v_{22}$$

So, a determination of the eigenvectors is given by equation (25). The two components of V_1 are positive and we can norm this eigenvector by setting $v_{11} + v_{21} = 1$. Moreover the sum of the two components of V_2 is positive and we can norm this eigenvector by setting $v_{12} + v_{22} = 1$

c) We deduce from $VW = I$

$$(a_{11} - a_{22})(w_{11} - w_{21}) + \sqrt{\Delta}(w_{11} + w_{21}) = 1$$

$$(a_{11} - a_{22})(w_{12} - w_{22}) + \sqrt{\Delta}(w_{12} + w_{22}) = 0$$

$$2a_{21}(w_{11} - w_{21}) = 0$$

$$2a_{21}(w_{12} - w_{22}) = 1$$

so $w_{11} = w_{21} = \dfrac{1}{2\sqrt{\Delta}} > 0$, $w_{12} = \dfrac{1}{4\sqrt{\Delta}} \dfrac{\sqrt{\Delta} - a_{11} + a_{22}}{a_{21}} > 0$ and $w_{22} = \dfrac{1}{4\sqrt{\Delta}} \dfrac{-\sqrt{\Delta} - a_{11} + a_{22}}{a_{21}} < 0$

d) The inequalities are easy to check. For example, $w_{12} > w_{11}$ is equivalent to

$\sqrt{\Delta} > 2a_{21} + (a_{11} - a_{22})$. A sufficient condition for this inequality is

$\Delta \equiv (a_{11} - a_{22})^2 + 4a_{12}a_{21} > (a_{22} - a_{11})^2 + 4a_{21}(a_{21} + a_{11} - a_{22})$, or

$a_{12} + a_{22} > a_{11} + a_{21}$, which is true. □

Proof of Proposition 1

a) Let P be the diagonal matrix with elements ρ_1 and ρ_2. Then (22) can be rewritten

$$\begin{pmatrix} N^{2+}(t+2) \\ N^{2-}(t+2) \end{pmatrix} = M'n\begin{pmatrix} N^{2+}(t) \\ N^{2-}(t) \end{pmatrix} = VPWn\begin{pmatrix} N^{2+}(t) \\ N^{2-}(t) \end{pmatrix} = V(nP)^{t/2+1}W\begin{pmatrix} N^{2+}(0) \\ N^{2-}(0) \end{pmatrix}$$

In the long run, under $N^{2+}(0) + N^{2-}(0) = 1$, we have

$$N^{21}(t+2)/(\rho_1 n)^{t/2+1} \underset{t\to\infty}{\to} v_{11}[(w_{11} - w_{12})N^{21}(0) + w_{12}]$$

$$N^{22}(t+2)/(\rho_1 n)^{t/2+1} \underset{t\to\infty}{\to} v_{21}[(w_{11} - w_{12})N^{21}(0) + w_{12}]$$

This establishes directly property a).

b) We deduce from equation (28) and (29) the dynamics of the total population of junior adults

$$N^{21}(t+2)+N^{22}(t+2)=$$

$$\left(\rho_1 n\right)^{t/2+1}(v_{11}+v_{21})\left[(w_{11}-w_{12})N^{21}(0)+w_{12}\right]+\left(\rho_2 n\right)^{t/2+1}(v_{12}+v_{22})\left[(w_{21}-w_{22})N^{21}(0)+w_{22}\right]$$

We know from Lemma 5d that $w_{12}>w_{11}>0$, and $w_{22}<0<w_{21}$. Lemma 5b establishes that $v_{11}, v_{21}, v_{12}>0$, $v_{22}<0$, and $v_{12}+v_{22}>0$ also hold.

Then, we notice that, if $N^{22}(0)$ is decreased, that is if $N^{21}(0)$ is increased, then $N^{22}(t+2)$ goes down.

As $\rho_1>\rho_2$, $N^{21}(t+2)+N^{22}(t+2)$ drops too if

$(v_{11}+v_{21})(w_{11}-w_{12})+(v_{12}+v_{22})(w_{21}-w_{22})\geq 0$. The expressions of matrices V and W given in Lemma 5 show that the left-hand side of this inequality is equal to 0.

However, we do not know if $N^{21}(t+2)$ increases or decreases. Indeed, by the same reasoning as just before, this figure would go down if $v_{11}(w_{11}-w_{12})+v_{12}(w_{21}-w_{22})\leq 0$. Unfortunately this expression turns out to be equal to 1. Therefore anything could happen in the short run as for the number of low human capital junior adults. □

Proof of Proposition 2

a) We deduce from the expressions of the elementrs of matrix M' and from lemma 4

$$d(a_{11}+a_{21})=d\left\{\lambda\left(e_{+1}^1\right)\left[\pi\left(l^1\right)(1-c)+c\right]\right\}=\left[\pi\left(l^1\right)(1-c)+c\right]d\lambda\left(e_{+1}^1\right)+\lambda\left(e_{+1}^1\right)(1-c)d\pi\left(l^1\right)<0$$

A similar computation shows that $d(a_{12}+a_{22})<0$. Then, equation (34) establishes part a of the proposition.

b) We have $\dfrac{dN^{21}(2)}{N^{21}(2)}-\dfrac{dN^{22}(2)}{N^{22}(2)}=\dfrac{v_{11}da_{11}+(1-v_{11})da_{12}}{v_{11}a_{11}+(1-v_{11})a_{12}}-\dfrac{v_{11}da_{21}+(1-v_{11})da_{22}}{v_{11}a_{21}+(1-v_{11})a_{22}}$. This

expression has the same sign as

$$v_{11}\left\{\left[v_{11}a_{21}+(1-v_{11})a_{22}\right]da_{11}-\left[v_{11}a_{11}+(1-v_{11})a_{12}\right]da_{21}\right\}$$
$$+(1-v_{11})\left\{\left[v_{11}a_{21}+(1-v_{11})a_{22}\right]da_{12}-\left[v_{11}a_{11}+(1-v_{11})a_{12}\right]da_{22}\right\}$$

We use (25) to substitute for v_{11}. This expression has the same sign as

$$\left(a_{11}-a_{22}+\sqrt{\Delta}\right)\left\{\left[\left(a_{11}-a_{22}+\sqrt{\Delta}\right)a_{21}+2a_{21}a_{22}\right]da_{11}-\left[\left(a_{11}-a_{22}+\sqrt{\Delta}\right)a_{11}+2a_{21}a_{12}\right]da_{21}\right\}$$
$$+2a_{21}\left\{\left[\left(a_{11}-a_{22}+\sqrt{\Delta}\right)a_{21}+2a_{21}a_{22}\right]da_{12}-\left[\left(a_{11}-a_{22}+\sqrt{\Delta}\right)a_{11}+2a_{21}a_{12}\right]da_{22}\right\}$$

or

$$\left(a_{11}-a_{22}+\sqrt{\Delta}\right)\left[\left(a_{11}-a_{22}+\sqrt{\Delta}\right)a_{21}a_{11}\left(\frac{da_{11}}{a_{11}}-\frac{da_{21}}{a_{21}}\right)+2a_{21}a_{22}a_{12}\left(\frac{da_{11}}{a_{12}}-\frac{da_{21}}{a_{22}}\right)\right]$$

$$+2a_{21}\left[\left(a_{11}-a_{22}+\sqrt{\Delta}\right)a_{21}a_{11}\left(\frac{da_{12}}{a_{11}}-\frac{da_{22}}{a_{21}}\right)+2a_{21}a_{22}a_{12}\left(\frac{da_{12}}{a_{12}}-\frac{da_{22}}{a_{22}}\right)\right]$$

This expression has the same sign as

$$\left(a_{11}-a_{22}+\sqrt{\Delta}\right)^2 a_{11}\left(\frac{da_{11}}{a_{11}}-\frac{da_{21}}{a_{21}}\right)+4a_{21}a_{22}a_{12}\left(\frac{da_{12}}{a_{12}}-\frac{da_{22}}{a_{22}}\right)$$

$$+2\left(a_{11}-a_{22}+\sqrt{\Delta}\right)\left[a_{22}a_{12}\left(\frac{da_{11}}{a_{12}}-\frac{da_{21}}{a_{22}}\right)+a_{21}a_{11}\left(\frac{da_{12}}{a_{11}}-\frac{da_{22}}{a_{21}}\right)\right]$$

which is equal to

$$\left(a_{11}-a_{22}+\sqrt{\Delta}\right)^2 a_{11}\left(\frac{da_{11}}{a_{11}}-\frac{da_{21}}{a_{21}}\right)+4a_{21}a_{22}a_{12}\left(\frac{da_{12}}{a_{12}}-\frac{da_{22}}{a_{22}}\right)$$

$$+2\left(a_{11}-a_{22}+\sqrt{\Delta}\right)\left[a_{11}a_{22}\left(\frac{da_{11}}{a_{11}}-\frac{da_{21}}{a_{21}}\right)+a_{21}a_{12}\left(\frac{da_{12}}{a_{12}}-\frac{da_{22}}{a_{22}}\right)+\left(a_{11}a_{22}-a_{12}a_{21}\right)\left(\frac{da_{21}}{a_{21}}-\frac{da_{22}}{a_{22}}\right)\right]$$

or

$$a_{11}\left(a_{11}-a_{22}+\sqrt{\Delta}\right)\left(a_{11}+a_{22}+\sqrt{\Delta}\right)\left(\frac{da_{11}}{a_{11}}-\frac{da_{21}}{a_{21}}\right)+2a_{21}a_{12}\left(a_{11}+a_{22}+\sqrt{\Delta}\right)\left(\frac{da_{12}}{a_{12}}-\frac{da_{22}}{a_{22}}\right)$$

$$+2\left(a_{11}-a_{22}+\sqrt{\Delta}\right)\left(a_{11}a_{22}-a_{12}a_{21}\right)\left(\frac{da_{21}}{a_{21}}-\frac{da_{22}}{a_{22}}\right)$$

We deduce from equation (21)

$$\frac{da_{11}}{a_{11}}=\frac{d\lambda\left(e_{+1}^1\right)}{\lambda\left(e_{+1}^1\right)}+\frac{\lambda\left(e_{+1}^1\right)\left[1-p-c(1-q)\right]}{a_{11}}d\pi\left(l^1\right),\quad \frac{da_{21}}{a_{21}}=\frac{d\lambda\left(e_{+1}^1\right)}{\lambda\left(e_{+1}^1\right)}+\frac{\lambda\left(e_{+1}^1\right)(p-cq)}{a_{21}}d\pi\left(l^1\right),$$

$$\frac{da_{12}}{a_{12}}=\frac{d\lambda\left(e_{+1}^2\right)}{\lambda\left(e_{+1}^2\right)}+\frac{\lambda\left(e_{+1}^2\right)\left[1-p-c(1-q)\right]}{a_{12}}d\pi\left(l^2\right),\quad \frac{da_{22}}{a_{22}}=\frac{d\lambda\left(e_{+1}^2\right)}{\lambda\left(e_{+1}^2\right)}+\frac{\lambda\left(e_{+1}^2\right)(p-cq)}{a_{22}}d\pi\left(l^2\right)$$

Hence

$$\frac{da_{11}}{a_{11}}-\frac{da_{21}}{a_{21}}=\frac{\lambda\left(e_{+1}^1\right)}{a_{11}a_{21}}\left\{\left[1-p-c(1-q)\right]a_{21}-(p-cq)a_{11}\right\}d\pi\left(l^1\right)=-c(p-q)\frac{\lambda\left(e_{+1}^1\right)^2}{a_{11}a_{21}}d\pi\left(l^1\right)$$

$$\frac{da_{12}}{a_{12}}-\frac{da_{22}}{a_{22}}=\frac{\lambda\left(e_{+1}^2\right)}{a_{12}a_{22}}\left\{\left[1-p-c(1-q)\right]a_{22}-(p-cq)a_{12}\right\}d\pi\left(l^2\right)=-c(p-q)\frac{\lambda\left(e_{+1}^2\right)^2}{a_{12}a_{22}}d\pi\left(l^2\right)$$

$$\frac{da_{21}}{a_{21}}-\frac{da_{22}}{a_{22}}=\frac{d\lambda\left(e_{+1}^1\right)}{\lambda\left(e_{+1}^1\right)}-\frac{d\lambda\left(e_{+1}^2\right)}{\lambda\left(e_{+1}^2\right)}+(p-cq)\left[\frac{\lambda\left(e_{+1}^1\right)}{a_{21}}d\pi\left(l^1\right)-\frac{\lambda\left(e_{+1}^2\right)}{a_{22}}d\pi\left(l^2\right)\right]$$

The above expression as the same sign as

$$-c(p-q)\left(a_{11}+a_{22}+\sqrt{\Delta}\right)\left[\left(a_{11}-a_{22}+\sqrt{\Delta}\right)\frac{\lambda\left(e_{+1}^1\right)^2}{a_{21}}d\pi\left(l^1\right)+2a_{21}\frac{\lambda\left(e_{+1}^2\right)^2}{a_{22}}d\pi\left(l^2\right)\right]$$

$$+2\left(a_{11}-a_{22}+\sqrt{\Delta}\right)\left(a_{11}a_{22}-a_{12}a_{21}\right)\left\{\frac{d\lambda\left(e_{+1}^1\right)}{\lambda\left(e_{+1}^1\right)}-\frac{d\lambda\left(e_{+1}^2\right)}{\lambda\left(e_{+1}^2\right)}+(p-cq)\left[\frac{\lambda\left(e_{+1}^1\right)}{a_{21}}d\pi\left(l^1\right)-\frac{\lambda\left(e_{+1}^2\right)}{a_{22}}d\pi\left(l^2\right)\right]\right\}\right]\right\}$$

We remind that $a_{11}a_{22}-a_{12}a_{21}=c(p-q)\lambda(e_{+1}^1)\lambda(e_{+1}^2)\left[\pi(l^2)-\pi(l^1)\right]$. The previous expression has the same sign as

$$\frac{a_{11}-a_{22}+\sqrt{\Delta}}{a_{21}}\lambda\left(e_{+1}^1\right)^2\left\{-\left(a_{11}+a_{22}+\sqrt{\Delta}\right)+2\lambda(e_{+1}^2)\left[\pi(l^2)-\pi(l^1)\right](p-cq)\right\}d\pi\left(l^1\right)$$

$$-2\frac{\lambda\left(e_{+1}^2\right)^2}{a_{22}}\left\{\left(a_{11}+a_{22}+\sqrt{\Delta}\right)a_{21}+(p-cq)\left(a_{11}-a_{22}+\sqrt{\Delta}\right)\lambda(e_{+1}^1)\left[\pi(l^2)-\pi(l^1)\right]\right\}d\pi\left(l^2\right)$$

$$+2\left(a_{11}-a_{22}+\sqrt{\Delta}\right)\lambda(e_{+1}^1)\lambda(e_{+1}^2)\left[\pi(l^2)-\pi(l^1)\right]\left[\frac{d\lambda\left(e_{+1}^1\right)}{\lambda\left(e_{+1}^1\right)}-\frac{d\lambda\left(e_{+1}^2\right)}{\lambda\left(e_{+1}^2\right)}\right]$$

As $d\pi\left(l^1\right)<0$, the first term is positive if

$$a_{11}+a_{22}+\sqrt{\Delta}>2\lambda(e_{+1}^2)\left[\pi(l^2)-\pi(l^1)\right](p-cq)$$
$$=2\lambda(e_{+1}^2)\left[a_{22}/\lambda(e_{+1}^2)-a_{21}/\lambda(e_{+1}^1)\right]=2a_{22}-2a_{21}\lambda(e_{+1}^2)/\lambda(e_{+1}^1)$$

or $a_{11}-a_{22}+\sqrt{\Delta}>-2a_{21}\lambda(e_{+1}^2)/\lambda(e_{+1}^1)$,

which is true because the left-hand side is positive and the right-hand side is negative.

As $d\pi\left(l^2\right)<0$, the second term of the expression is positive.

As we established in lemma 5 that $\dfrac{d\lambda\left(e_{+1}^1\right)}{\lambda\left(e_{+1}^1\right)}-\dfrac{d\lambda\left(e_{+1}^2\right)}{\lambda\left(e_{+1}^2\right)}<0$, the second term of the expression is

negative.□