Endogenous Population and Environmental Quality*

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Abstract

This paper provides with empirical and theoretical studies of the relationship between population, economic growth and environmental quality. Using a simple endogenous growth model we obtain results close to empirical findings. We show existence of a sustainable balanced growth path (BGP) equilibrium in which perpetual economic growth goes in parallel with environmental quality preservation. At the BGP equilibrium, when all exogenous factors are controlled, a negative relationship between fertility rate and economic growth (termed neo-Malthusian relationship) and a negative relationship between population growth rate and environmental quality emerge.

Key words: Environmental quality; Endogenous population; Endogenous growth; Deforestation

JEL classification: C14; C21; J13; O13

1 Introduction

Following Ehrlich and Ehrlich [1981], environmental quality is determined by three main factors: consumption, technology and population pressure. These factors are extensively studied in the literature, particularly after the emergence of endogenous growth theory. Endogenous population, modelled by fertility choice, is highlighted in theoretical studies of several authors – see, e.g., Razin and Ben-Zion [1975] and Becker and Barro [1988]. Intuitively, fertility choice will have an impact on environmental quality. But in the endogenous growth literature, endogenous population and the environment have analysed independently. On one hand, endogenous population is studied in Becker, Murphy, and Tamura [1990], Iyigun [2000] and Yip and Zhang [1996, 1997], among others. There may exist two different equilibrium regimes, one is generally corresponding to high fertility and low economic growth and the other one to low fertility and high economic growth. On the other hand, the natural environment has been included into endogenous growth models to study the question of sustainability and policy – see, e.g., Aghion and Howitt [1998], Bovenberg and de Mooij [1997] and Byrne [1997]. It has been shown that sustainable growth is possible and government intervention is Pareto improving.

In this paper, firstly we investigate empirically the relationship between population, economic growth and environmental quality. Secondly, we use a simple endogenous growth model to study theoretically the interaction between these three variables.[1] We show existence of a sustainable balanced

[1] The relationship between population and the environment was studied in an exogenous

growth path (BGP) equilibrium in which perpetual economic growth goes in parallel with environmental quality preservation. At the BGP equilibrium, when all exogenous factors are controlled, a negative relationship between fertility rate and economic growth (termed neo-Malthusian relationship) and a negative relationship between population growth rate and environmental quality emerge.

The paper is organized as follows. Section 2 presents the empirical analysis of deforestation in developing countries. The theoretical model and an equilibrium analysis are presented in Sections 3 and 4 respectively. Some conclusions are given in Section 5.

2 Empirical analysis of deforestation

Environmental quality is a large concept. It might be represented by several indicators of air quality, water quality, and deforestation, etc. In this section, being aware of the narrowness of the use of an individual indicator and because of the unavailability of other environmental indicators in our data sample, we use the rate of deforestation (= minus the percentage change in forest area) as a measure of environmental quality. An improve in environmental quality is then represented by a reforestation (or a negative rate of deforestation).

We use a cross-section of countries to investigate the reduced form of the

growth framework by, e.g., Jöst, Quaas, and Schiller [2001] and Makdissi [2001] (with endogenous fertility choice), and Cronshaw and Requate [1997] (with exogenous population). For an overview see Nerlove and Raut [1997] and Robinson and Srinivasan [1997].

long run relationship between population, economic growth and the rate of deforestation. The use of cross-section regressions (variables are averaged) to investigate a long-run relationship between variables is a classical method in growth empirics (see, e.g., Dinopoulos and Thompson [2000], Liu and Stengos [1999] and Mankiw, Romer, and Weil [1992]) whereas other authors use a panel data approach (see, e.g., Islam [1995] and Caselli, Esquivel, and Lefort [1996]). Advantages and inconvenients of cross-sectional approach comparing to panel data approach are underlined in Temple [1999].

The relationship between deforestation, economic growth and population in developing countries is empirically studied by Cropper and Griffiths [1994] and Koop and Tole [1999], among others. Cropper and Griffiths [1994] used a fixed effects panel data model on a panel of 64 developing countries during 1961-1988. They suggested that, on one hand, there exist environmental Kuznets curves (EKC) for Africa and Latin America and on the other hand, population density in Africa has a positive effect on deforestation holding income per capita constant. Using a larger dataset (76 developing countries over the period 1961-1992), Koop and Tole [1999] specified a more flexible model (panel data model with random coefficients). They argued that there is little evidence of an EKC and population seems to have a positive effect on deforestation (however, all estimated coefficients are not significant).

We use a balanced panel data over the period 1961-1994 on deforestation, income and population of 85 developing countries in Africa (43 countries), Asia-Oceania (16 countries) and Latin America (26 countries). We limit our study to developing countries because deforestation is seen there as an important problem. Series on deforestation and population are extracted from the World Resources 1998-1999 Database of the World Resources Institute. Series on income (real GDP per capita in constant dollars at international prices, base year 1985) is obtained from the Penn World Table 5.6 (see Summers and Heston [1991]). As the Penn World Table 5.6 only provides data until 1992, economic data from 1993 and missing values are completed from 1985 GDP per capita and GDP per capita growth rates of Global Development Finance and World Development Indicators.

Variables used in estimation are the rate of deforestation ($\triangle$FOREST, dependent variable), GDP per capita (noted as GDP), the percentage change (or the growth rate) of GDP per capita ($\triangle$GDP), population density (PDENS) and the growth rate of population ($\triangle$POP). All variables are averaged over three time periods 1962-1972, 1973-1983 and 1984-1994.[2] Then, 3 observations are made for each country in order to obtain 255 observations in total. Dummy variables indicating region (AFR for Africa, AS_OC for Asia and Oceania and LAT_AM for Latin America) are also included into the estimation to capture the regional heterogeneity. As there are only two countries from Oceania (Fiji and Papua-New Guinea), we group them with Asian countries. The group AFR is the largest in the data and used as the reference. Descriptive statistics are given in Table 1. A summary of definition of variables and the list of countries used in this paper are given in Appendix 1.

[2]As the data on surface of forests and GDP per capita are available between 1961 and 1994, the data on the rate of deforestation and the percentage of change of GDP per capita start only from 1962.

Insert Table 1 here

Table 1 shows that, in average, 0.1% of forest are cleared each year from 1962 to 1994. In some countries, this proportion accounts more than 3% (e.g., Thailand, El Salvador, Paraguay and Costa Rica, where Costa Rica has the highest average annual rate of deforestation over 1973-1983, 3.7%), whereas some countries present a high reforestation rate (e.g., Pakistan and Belize, where the latter has the highest average annual reforestation rate during the period 1973-1983, deforestation rate $= -0.098$).

To investigate relationship between deforestation, economic growth and population, let us assume the following parametric specification:

$$\begin{aligned}\triangle\text{FOREST} = \beta_1\text{GDP} + \beta_2 \triangle \text{GDP} + \beta_3\text{PDENS} + \beta_4 \triangle \text{POP} +\\ d_1\text{AS\_OC} + d_2\text{LAT\_AM} + \text{intercept} + \varepsilon,\end{aligned} \tag{P1}$$

where ε is an idiosyncratic error. Specification (P1) can be estimated by the method of Ordinary Least Squares. Estimation results are given in Table 2.[3]

Insert Table 2 here

Table 2 shows that GDP per capita has a small negative effect on the rate of deforestation. However, this effect is not significant. The results show that demographic pressure (population density and population growth) has positive and significant effect on deforestation. The effect of the growth rate of population on deforestation is very high (equal to 0.1803), comparing

[3]STATA 6.0 is used to implement the calculations.

to population density. Countries of Latin America have significantly higher deforestation than other countries (estimated coefficient equal to 0.0046).

Now we want to analyse whether economic variables have significant effect on deforestation. A F-statistic is then used to test the restriction H_0 : $\beta_1 = \beta_2 = 0$. It is computed equal to 0.80, widely smaller than 3.03 – the table value of $F_{(2,248)}$ at the 5% level. Therefore, we can conclude that the restriction is not rejected by the data. That means that economic variables have insignificant effect on the rate of deforestation.

We turn now to the study of the robustness of relation (P1). It is reasonable to think that there are some non-linearities in the relationship between deforestation, economic growth and demographic pressure. Linear functional forms in specification (P1) might turn out to be very restrictive. In order to avoid this problem, we suggest the following additive semiparametric partially linear specification:

$$\begin{aligned}\triangle\text{FOREST} = f_1(\text{GDP}) + f_2(\triangle\text{GDP}) + f_3(\text{PDENS}) + f_4(\triangle\text{POP}) + \\ d_1\text{AS\_OC} + d_2\text{LAT\_AM} + \text{intercept} + \varepsilon, \qquad \text{(P2)}\end{aligned}$$

where $f_i(.)$, $i = 1, \ldots, 4$, are one-dimensional unknown functions to be estimated. For identification purpose, the data is normalized so that $f_i(.)$ has a zero mean.

Specification (P2) uses more flexible functional forms than specification (P1). Its additive structure of one-dimensional unknown functions also allows us to avoid the so-called "curse of dimensionality" often met in nonparametric and semiparametric applications (see Hastie and Tibshirani [1990]). In estimation, we implement nonparametric smoothing techniques to estimate functions f. Estimation method, based on Hastie and Tibshirani [1990], is described in Appendix 2.[4] Estimators of linear coefficients in (P2) – d_1, d_2 and the intercept – are given in Table 2.

In specification (P2), individual degrees of freedom – or effective number of parameters, which might be fractional – of GDP, $\triangle$GDP, PDENS and $\triangle$POP are respectively equal to 2.88, 6, 1.97 and 2.[5] Table 2 also reports, for each variable, a statistic called the "gain", which is the difference in normalized deviances between specification (P2) and a specification with a linear term for this variable. This statistic follows approximately a $\chi^2\left(df_i - 1\right)$, where 1 is the degree of freedom of the corresponding variable in specification (P1) and df_i represents the individual degrees of freedom in (P2). All statistics are not significant at the 5% level, that means that individual gains from nonparametric fits are not significant.

Figures 1–4 present the estimated nonparametric curve, $\hat{f}\left(.\right)$, the 95% pointwise confidence interval of $\hat{f}\left(.\right)$ and the linear curve obtained from parametric estimation corresponding respectively to GDP, $\triangle$GDP, PDENS and $\triangle$POP. We observe that the parametric curve fits as well as the nonparametric curve. In Figure 1, although the nonparametric relationship between deforestation and income per capita displays a U shape, we can conclude that

[4] Estimation of (P2) is based on a procedure noted "backfitting algorithm". The structure of (P2) is similar to that of Liu and Stengos [1999], which is used to study effects of intinial output and schooling levels on economic growth rates in a cross-section of countries. However, the method of estimation in Liu and Stengos [1999] is based on marginal integration.

[5] See Appendix 2 for details on the calculation of the degrees of freedom.

the parametric linear functional form is not rejected by the data against the nonparametric form. This is because the gain obtained from using nonparametric function compared to parametric function is too small. Furthermore, the 95% pointwise confidence interval of the nonparametric estimator is too large, especially for GDP per capita higher than 6,000$. We can obtain similar results for other variables: parametric forms perform quite well the data. In Figures 3 and 4, both parametric and nonparametric curves show a monotonic increasing relationship between deforestation and population density, and deforestation and population pressure, respectively.

Insert Figures 1–4 here

To compare (P1) and (P2) as a whole, we can perform an approximate specification test. This is an overall gain statistic which is equal to the sum of the individual gains. This statistic follows approximately a $\chi^2\,(df - 7)$. df is total degrees of freedom of specification (P2), equal to the sum of individual degrees of freedom ($df = 15.84$). The total degrees of freedom of specification (P1), which is just the number of coefficients to estimate, are equal to 7. The value of the overall gain statistic is equal to 10.40, smaller than the 5% level value of $\chi^2\,(8.84)$, 16.69. Therefore, we can conclude that the parametric specification is not rejected by the data against the semiparametric one.

The main conclusions of the empirical analysis above are that: (i) economic growth has insignificant effect on deforestation and (ii) population pressure exerts a positive effect on the rate of deforestation. In the next section, we provide with a simple theoretical model which gives us the results close to these empirical findings.

3 The theoretical model

We use a closed economy with a continuum of identical infinitely-lived individuals. As in Palivos [1995], Razin and Ben-Zion [1975] and Yip and Zhang [1996, 1997], we use an instantaneous utility function of each agent, u, depending on consumption, c_t, and on the number of children or on the fertility rate, n_t. We introduce an additional variable representing environmental quality, E_t, into this function. Then the utility function at the time 0 is

$$U = \int_0^\infty e^{-\rho t} u \left(c_t, n_t, E_t\right) dt, \tag{1}$$

where $\rho > 0$ is the constant rate of time preference. The fertility rate may be considered as the net rate, i.e. $n_t = \tilde{n}_t - d$ where $\tilde{n}_t$ and d are respectively the gross fertility rate and the mortality rate, the latter is assumed exogenous.

In each period, the household divides its available time, normalized to 1, between child bearing, $\gamma\left(n\right)$, and work, $1 - \gamma\left(n\right)$.[6] In general, the function $\gamma\left(.\right)$ is assumed twice differentiable, increasing and with the second order derivative of either sign, but here we assume that $\gamma\left(n\right) = \gamma n$, where $\gamma > 0$. The household's budget constraint is

$$\dot{a} = \left(r - n\right) a + w \left(1 - \gamma n\right) - c \tag{2}$$

where a, r and w are respectively the stock of assets held by the household, the interest rate and the wage rate.

On the production side, a Cobb-Douglas production function is employed, $y = Ak^{\psi} \left(1 - \gamma n\right)^{1-\psi} \bar{k}^{1-\psi}$, $\psi \in \left]0, 1\right[$. y is production per capita, A is the

[6] Index t is suppressed to simplify the notation.

level of technology which is treated as exogenous. The average stock of physical capital of the economy, $\bar{k} > 0$, which is equal to capital per capita k at equilibrium, is used to generate perpetual growth (Romer [1986]). This kind of function will imply the non-optimality of the decentralized equilibrium. By replacing $a = k$, $r = \psi A k^{\psi-1} (1 - \gamma n)^{1-\psi} \bar{k}^{1-\psi}$ ($\equiv$ marginal product of capital) and $w = (1 - \psi) A k^{\psi} (1 - \gamma n)^{-\psi} \bar{k}^{1-\psi}$ ($\equiv$ marginal product of labour), we obtain

$$\dot{k} = A k^{\psi} (1 - \gamma n)^{1-\psi} \bar{k}^{1-\psi} - nk - c. \tag{3}$$

Environmental quality is considered as a physical good. Suppose that environmental quality has a finite upper bound, $E_{\max}$. Environmental quality, E, is measured by the difference between the actual level and this upper limit. Thus, E is always negative. E comprises the quality of soil or groundwater, the cleanliness of rivers, the air quality, or the rate of deforestation.

As we focus on population and environmental quality, we suppose that the evolution of environmental quality takes the form

$$\dot{E} = -\eta E - \theta n \tag{4}$$

where $\eta \in \,]0, 1[$ characterizes the capacity of natural regeneration of the environment and $\theta > 0$ measures the importance of the environmental destruction due to demographic pressures. Equation (4) does not take into account effects of consumption, production or technology. Note also that (4) does not imply the non-optimality of the decentralized equilibrium because externalities of household's fertility choice on environmental quality are entirely internalized. Moreover, as in Aghion and Howitt [1998], we assume that there is a finite lower limit, $E_{\min}$, for environmental quality under which there will be a catastrophe. With the non-positivity of E, we have the following constraint

$$E_{\min} \leq E \leq 0 \tag{5}$$

To simplify the analysis, we use a separable utility function

$$u(c,n,E) = \ln c + \alpha \ln n - \frac{(-E)^{1+\beta}}{1+\beta}$$

with α, $\beta > 0$. A separable utility function with consumption and the fertility rate is commonly used in Iyigun [2000], Jöst, Quaas, and Schiller [2001], Tamura [1996] and Yip and Zhang [1996, 1997], among others. A separable utility function with consumption and environmental quality was studied in, e.g., Aghion and Howitt [1998] and Michel and Rotillon [1996].

The problem of the representative agent is to maximize (1) under (3), (4), (5) and k, c, $n \geq 0$ by applying the Pontryagin's maximum principle. The current-value Hamiltonian is given by:

$$\begin{aligned} H(c,n,k,E,\lambda,\mu) &= u(c,n,E) + \lambda\left[Ak^{\psi}(1-\gamma n)^{1-\psi}\bar{k}^{1-\psi} - nk - c\right] + \\ &\quad \mu\left[-\eta E - \theta n\right]. \end{aligned}$$

The necessary conditions are

$$\lambda = \frac{1}{c}, \tag{6}$$

$$\frac{\alpha}{n} = \lambda(1-\psi)\gamma Ak^{\psi}(1-\gamma n)^{-\psi}\bar{k}^{1-\psi} + \lambda k + \mu\theta, \tag{7}$$

$$\dot{\lambda} = \rho\lambda - \lambda\psi Ak^{\psi-1}(1-\gamma n)^{1-\psi}\bar{k}^{1-\psi} + \lambda n, \tag{8}$$

$$\dot{\mu} = \rho\mu - (-E)^{\beta} + \mu\eta, \tag{9}$$

and also (3), (4) and (5). Transversality conditions are

$$\lim_{t\to\infty} e^{-\rho t}\lambda_t k_t = \lim_{t\to\infty} e^{-\rho t}\mu_t E_t = 0.$$

Define $H_0(k, E, \lambda, \mu) = \max_{c,n} H(c, n, k, E, \lambda, \mu)$. Since the Hessian of H with respect to c and n is negative definite, conditions (6) and (7) are sufficient for $\max_{c,n} H(c, n, k, E, \lambda, \mu)$.

Assumption 1 *H_0 is concave with regard to k, given λ and μ.*

Proposition 1 *If Assumption 1 is satisfied, conditions (3)-(9) are sufficient for a maximum of H.*

Proof. As the cross-derivative of H_0 with regard to k and E is zero and H_0 is concave with regard to E, Assumption 1 allows then to obtain a Hessian of H_0 negative definite with regard to k and E. Therefore, an application of the Arrow Sufficiency Theorem brings us directly to these results (see Arrow and Kurz [1970]). ■

4 Equilibrium analysis

Hereafter we suppose that Assumption 1 is fulfilled. At equilibrium, $k = \bar{k}$, let $X \equiv k/c$, condition (7) can be written as

$$\frac{\alpha}{n} = (1-\psi)\gamma A(1-\gamma n)^{-\psi} X + X + \mu\theta,$$

thus $n = \Gamma(X, \mu)$. We can verify that $n_\mu \equiv \partial\Gamma/\partial\mu < 0$ and $n_X \equiv \partial\Gamma/\partial X < 0$. The following dynamic system governs the economy:

$$\dot{X} = \rho X + (1-\psi) A [1 - \gamma\Gamma(X, \mu)]^{1-\psi} X - 1, \tag{10}$$

$$\dot{E} = -\eta E - \theta\Gamma(X, \mu), \tag{11}$$

$$\dot{\mu} = (\rho + \eta)\mu - (-E)^\beta. \tag{12}$$

Definition 1 *A balanced-growth path (BGP) equilibrium is a set* $\{c_t^*, k_t^*, n_t^*, E_t^*, \mu_t^*\}$ *so that* c *and* k *grow at the same constant rate,* E *and* μ *are constant and* $n^* = \Gamma(X^*, \mu^*)$ *where* $X^* = k^*/c^*$.

Hereafter we only focus on the nontrivial equilibrium. From Definition 1, at the BGP equilibrium, the economy grows perpetually. The BGP equilibrium is given by

$$X^* = \frac{1}{\rho + (1-\psi) A [1 - \gamma n^*]^{1-\psi}}, \tag{13}$$

$$E^* = -\frac{\theta}{\eta} n^*, \tag{14}$$

$$\mu^* = \frac{(\theta n^*)^\beta}{(\rho + \eta)\eta^\beta}, \tag{15}$$

and $n^* = \Gamma(X^*, \mu^*)$.

The Jacobian matrix of the system (10)-(12) at the equilibrium is given by

$$\begin{pmatrix} \rho + (1-\psi) A (1-\gamma n^*)^{1-\psi} - D (1-\gamma n^*)^{-\psi} X^* n_X & 0 & -D (1-\gamma n^*)^{-\psi} X^* n_\mu \\ -\theta n_X & -\eta & -\theta n_\mu \\ 0 & \beta (-E^*)^{\beta-1} & \rho + \eta \end{pmatrix},$$

where $D = \gamma A (1-\psi)^2$. Straightforward application of the Routh theorem (see, e.g., Marti [1997], p. 59-60) implies that this matrix has either one or two eigenvalues with negative real parts. Then the equilibrium is saddle-path stable. These results are summarized in the following proposition

Proposition 2 *Under Assumption 1, there exists a unique and saddle-path stable BGP equilibrium.*

We can see that, in the economy, there exists a sustainable growth equilibrium for which consumption and capital per capita grow indefinitely and environmental quality is preserved.

To study the long run relationship between fertility and growth we proceed as in Yip and Zhang [1996]. In this section we assume that all exogenous factors are controlled. Along the BGP path, c and k grow at the same rate. This is given, from (6) et (8), by:

$$g^* = \psi A (1-\gamma n^*)^{1-\psi} - n^* - \rho. \tag{16}$$

A straightforward differentiation of (16) yields

$$\frac{\partial g^*}{\partial n^*} = -\left[1 + \psi (1-\psi) \gamma A (1-\gamma n^*)^{-\psi}\right] < 0.$$

Then there exists a negative relationship between population growth and economic growth. As in Yip and Zhang [1996], this is the evidence of a neo-Malthusian relationship between population growth and economic growth when all exogenous factors are controlled.

At the BGP equilibrium, $E^* = -\theta n^*/\eta$, an increase in population growth will damage environmental quality. In the absence of population control, there will be a low growth (neo-Malthusian relationship) and environmental degradation. If the equilibrium growth rate of population is very high, E^* will reach its lower limit $E_{\min}$, leading to an environmental catastrophe.

Now we analyse the effects of the technological parameter A on economic growth, population growth and environmental quality. To do this, let us derive g^* from the budget constraint (3):

$$g^* = A\left(1 - \gamma n^*\right)^{1-\psi} - n^* - \frac{1}{\Omega\left(n^*\right)} \tag{17}$$

where $\Omega\left(n^*\right) \equiv X^*$ is obtained from $n^* = \Gamma\left(X^*, \mu^*\right)$ and μ is replaced by its equilibrium value. Explicitly,

$$\Omega\left(n^*\right) = \frac{\alpha/n^* - \theta^{1+\beta} n^{\beta} / \left[\left(\rho + \eta\right) \eta^{\beta}\right]}{1 + \left(1 - \psi\right) \gamma A \left(1 - \gamma n^*\right)^{-\psi}}.$$

By the non-negative constraint of X the numerator of this expression is always positive. This implies that $\Omega' < 0$.

It can be shown, from (16) and (17), that

$$\begin{aligned}
\frac{\partial n^*}{\partial A} &= \frac{\left(1 - \psi\right)\left(1 - \gamma n^*\right)^{1-\psi}}{\left(1 - \psi\right)^2 \gamma A \left(1 - \gamma n^*\right)^{-\psi} - \Omega'/\Omega^2} > 0, \\
\frac{\partial g^*}{\partial A} &= \psi\left(1 - \gamma n^*\right)^{1-\psi} - \left[1 + \left(1 - \psi\right) \gamma A \left(1 - \gamma n^*\right)^{-\psi}\right] \frac{\partial n^*}{\partial A}.
\end{aligned}$$

The expression $\partial g^*/\partial A$ is generally indeterminate. Exogenous technological progress induces an increase in the fertility rate but has an ambiguous effect on economic growth.

Concerning environmental quality, it is decreasing with A because

$$\frac{\partial E^*}{\partial A} = -\frac{\theta}{\eta}\frac{\partial n^*}{\partial A} < 0.$$

Since in our model there are no incentives to innovate in new green technology, technological progress does not have any direct effect on environmental quality, but has an indirect effect through the growth rate of population. It implies an increase in population growth rate and then a degradation of environmental quality.

5 Concluding remarks

This paper uses a simple endogenous growth model to analyse the interaction between endogenous population, economic growth and environmental quality. This simple model allows us to obtain results close to empirical findings: economic growth has no effect whereas population pressure has a negative effect on environmental quality. In the theoretical modelling, we show that there exists a sustainable growth equilibrium in the economy. We also find that when the economy is on the BGP path and all exogenous factors are controlled, a neo-Malthusian relationship between the fertility rate and economic growth emerges.

It should be noticed that several theoretical models may give the same conclusion. The theoretical model presented in the paper is simple and gives the results compatible with empirical findings. It should be also noticed that our theoretical model matches much more with developing countries than with developed countries.

In this paper, we treat the rate of deforestation as a measure of environmental quality. Of course, environmental quality is a large concept, but we can always consider the rate of deforestation as one of various possible indicators of environmental quality. Another drawback is that we were unable to treat the endogeneity bias in parameters which might appear in the empirical analysis. Furthermore, since equation (4) does not take into account the impacts of consumption, production, or technology on environmental quality but only takes into consideration the impacts of population, environmental externalities are entirely internalized in the model. Public interventions to internalize externalities are therefore not necessary in our model. These problems will be analysed in future studies.

Appendix 1

1. List of countries

Africa (43 countries): Algeria, Angola, Benin, Botswana, Burkina Faso, Burundi, Cameroon, Cape Verde, Central Africa Rep., Chad, Comoro, Congo Dem. Rep. (former Zaire), Congo, Ivory Coast, Ethiopia, Gabon, Gambia, Ghana, Guinea, Guinea-Bissau, Kenya, Madagascar, Malawi, Mali, Mauritania, Mauritius, Morocco, Mozambique, Niger, Nigeria, Rwanda, Senegal, Seychelles, Sierra Leone, South Africa, Sudan, Swaziland, Tanzania, Togo, Tunisia, Uganda, Zambia and Zimbabwe.

Asia-Oceania (16 countries): Bangladesh, China, Fiji, India, Indonesia, Iran, Jordan, Malaysia, Nepal, Pakistan, Papua-New Guinea, Philippines, Saudi Arabia, Sri Lanka, Syria and Thailand.

Latin America (South America and Central America, 26 countries): Argentina, Barbados, Belize, Bermuda, Bolivia, Brazil, Chili, Colombia, Costa Rica, Dominican Rep., El Salvador, Ecuador, Guatemala, Guyana, Haiti, Honduras, Jamaica, Mexico, Nicaragua, Panama, Paraguay, Peru, Suriname, Trinidad and Tobago, Uruguay and Venezuela.

2. Definition of variables

All variables are averaged over three times periods 1962-1972, 1973-1983 and 1984-1994.

$\triangle$FOREST: the average rate of deforestation. For each country, it is defined as $(F_{it} - F_{it-1})/F_{it-1}$, where F_{it} is the forest and woodland of the country i in the year t. Forests and woodland refer to natural or planted forests and land that will be reforested in the near future. Further details on definition and problems of measurement of forests and woodland are discussed in Allen and Barnes [1985] and Koop and Tole [1999].

GDP: average real GDP per capita in thousands 1985$.

$\triangle$GDP: average percentage change of GDP per capita.

PDENS: average density of population (people/ha).

$\triangle$POP: average growth rate of population.

AFR, AS_OC and LAT_AM: regional dummies taking values of 0, 1 (e.g., an African country has AFR=1). We group Asia and Oceania together to form the group AS_OC as far as there are only two countries from Oceania (Fiji and Papua-New Guinea). LAT_AM (Latin America) represent countries from South and Central America (including Mexico).

Appendix 2: Estimation method

In this appendix, we describe the procedure "backfitting algorithm" and the gain statistic used in the paper. The estimation method of (P2) is based on Hastie and Tibshirani [1990]. Given the semiparametric model of the form (bold characters represent matrix notations)

$$y = c + \mathbf{d}'\mathbf{z} + \sum_{j=1}^{p} f_j\left(x_j\right) + \varepsilon,\ \ E\left[f_j\left(x_j\right)\right] = 0,$$

where $\mathbf{z}$ contains regional dummies and $x_j, j = 1, ..., p$, are GDP, $\triangle$GDP, PDENS and $\triangle$POP, the backfitting algorithm can be implemented as follows:

- Initialization: $\hat{f}_j = f_j^0$ (we can use a linear fit, i.e. $f_j^0 = \hat{\beta}_j x_j$) $\forall x$ and $\forall j$, $\hat{c} = \bar{y}$.
- Cycle $j = 1, 2, ..., p, 1, ..., p, ...$

  $$\hat{f}_j = E\left[y - \hat{c} - \hat{\mathbf{d}}'\mathbf{z} - \sum_{k \neq j} \hat{f}_k \mid x_j\right],$$

  and $\hat{\mathbf{d}}$ is obtained by linear regression of $y - \sum_j \hat{f}_j$ on $\mathbf{z}$. Each cycle in this step resembles the method of Robinson [1988]. The process continues until the functions $\hat{f}_j$ converge.

The degree of freedom of the fit $\hat{f}_j$, df_j – considered as the effective number of parameters – might be approximated by the trace of $2\mathbf{S}_j - \mathbf{S}_j\mathbf{S}_j'$, where $\mathbf{S}_j$ is the smoothing matrix so that $\hat{\mathbf{f}}_j = \mathbf{S}_j\mathbf{y}$ (note that $\hat{\mathbf{f}}_j$ is the vector of $\hat{f}_j$). Therefore, df_j might be fractional. In case of linear estimator (Ordinary Least Squares), we have $\mathbf{S}_j = \mathbf{X}\left(\mathbf{X}'\mathbf{X}\right)^{-1}\mathbf{X}'$, where $\mathbf{X}$ is the matrix of regressors, and $df_j = 1$.

To compare two individual smooths $\hat{\mathbf{f}}_{j,1} = \mathbf{S}_{j,1}\mathbf{y}$ and $\hat{\mathbf{f}}_{j,2} = \mathbf{S}_{j,2}\mathbf{y}$, for example $\hat{\mathbf{f}}_{j,1}$ is linear, we can use the following approximative statistic (see Hastie and Tibshirani [1990]):

$$G = \frac{\left(RSS_1 - RSS_2\right) / \left(df_2 - df_1\right)}{RSS_2 / \left(n - df_2\right)} \sim F_{df_2 - df_1, n - df_2},$$

where RSS_1 and RSS_2 are respectively the deviance (or the residual sum of squares) of the models corresponding to $\hat{f}_{j,1}$ and $\hat{f}_{j,2}$. This distribution of the statistic "gain" might be approximated by $\chi^2_{df_2 - df_1} / \left(df_2 - df_1\right)$.

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Table 1: Descriptive statistics

variable	$\triangle$FOREST	GDP	$\triangle$GDP	PDENS	$\triangle$POP	#obs.
mean	0.001	2.116	0.013	0.685	0.025	
std.dev.	0.011	1.994	0.026	1.139	0.008	255
min.	−0.098	0.290	−0.064	0.010	−0.005	
max.	0.037	12.426	0.081	8.249	0.056	

Table 2: Estimation results

specification	P1		P2		
variable	coef.	t-stat$^{(a)}$	coef.	t-stat	gain$^{(b)}$
GDP	-0.475×10^{-3}	-1.21	–	–	2.34
$\triangle$GDP	-0.0040	-0.19	–	–	7.41
PDENS	**0.0013**	2.39	–	–	0.19
$\triangle$POP	**0.1803**	2.50	–	–	0.45
AS_OC	-0.0012	-0.49	-0.0011	-0.53	
LAT_AM	**0.0046**	2.14	**0.0054**	2.87	
intercept	$-$**0.0045**	-2.12	-0.475×10^{-3}	-0.45	
df	7		15.84		

Notes: dependent variable is the average rate of deforestation; P1 corresponds to the parametric specification which is estimated by OLS; P2 corresponds to the semiparametric additive specification which is estimated by "backfitting algorithm"; significant coefficients at 5% level are in boldface; *df* is total degrees of freedom, which might be fractional in specification P2, (see Hastie and Tibshirani [1990]); (a) the asymptotic t-statistics reported are based on the robust estimate of the variance (see White [1980]); (b) gain corresponding to a variable is a statistic representing the difference in normalized deviance between specification P2 and a specification with a linear term for this variable.

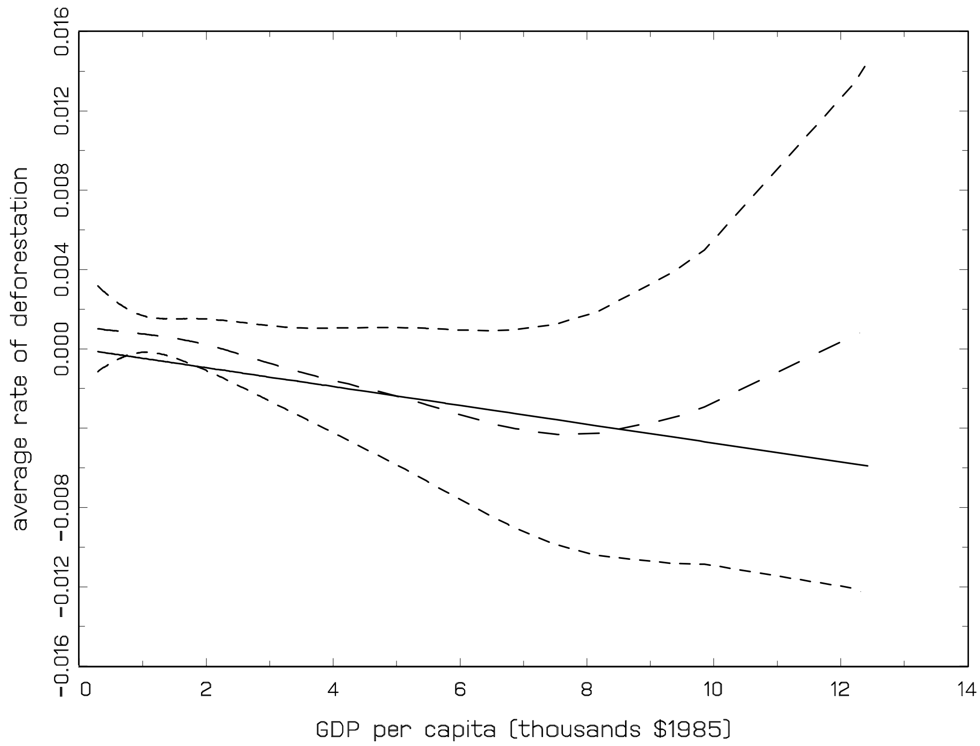

Figure 1: Relation between the avegare rate of deforestation and GDP per capita. The solid line is the parametric linear fit $\hat{\beta}_1$GDP. The dashed curve is the estimated nonparametric fit $\hat{f}_1\left(\mathrm{GDP}\right)$. The short dashed curves represents the 95% pointwise confidence interval $\hat{f}_1 \pm 1.96SD\left(\hat{f}_1\right)$, where SD is the standard deviation. In nonparametric estimation, the data are normalized so that $\hat{f}_1$ has a zero mean.

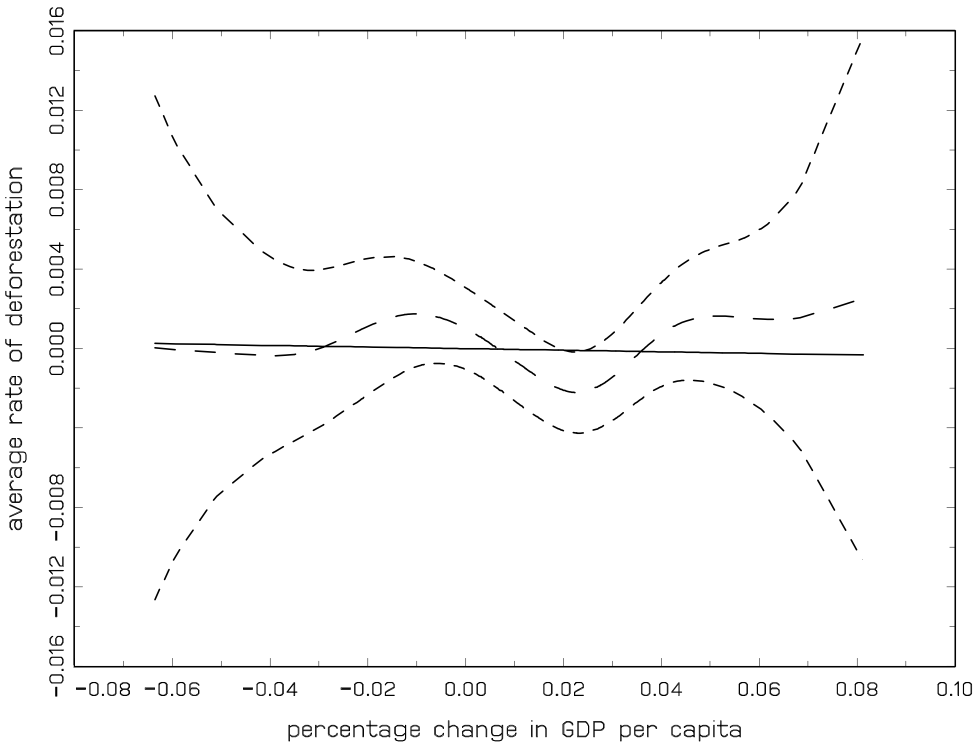

Figure 2: Relation between the avegare rate of deforestation and percentage change in GDP per capita. The solid line is the parametric linear fit $\hat{\beta}_2 \triangle \text{GDP}$. The dashed curve is the estimated nonparametric fit $\hat{f}_2 (\triangle \text{GDP})$. The short dashed curves represents the 95% pointwise confidence interval $\hat{f}_2 \pm 1.96 SD \left(\hat{f}_2 \right)$, where SD is the standard deviation. The data are normalized so that $\hat{f}_2$ has a zero mean.

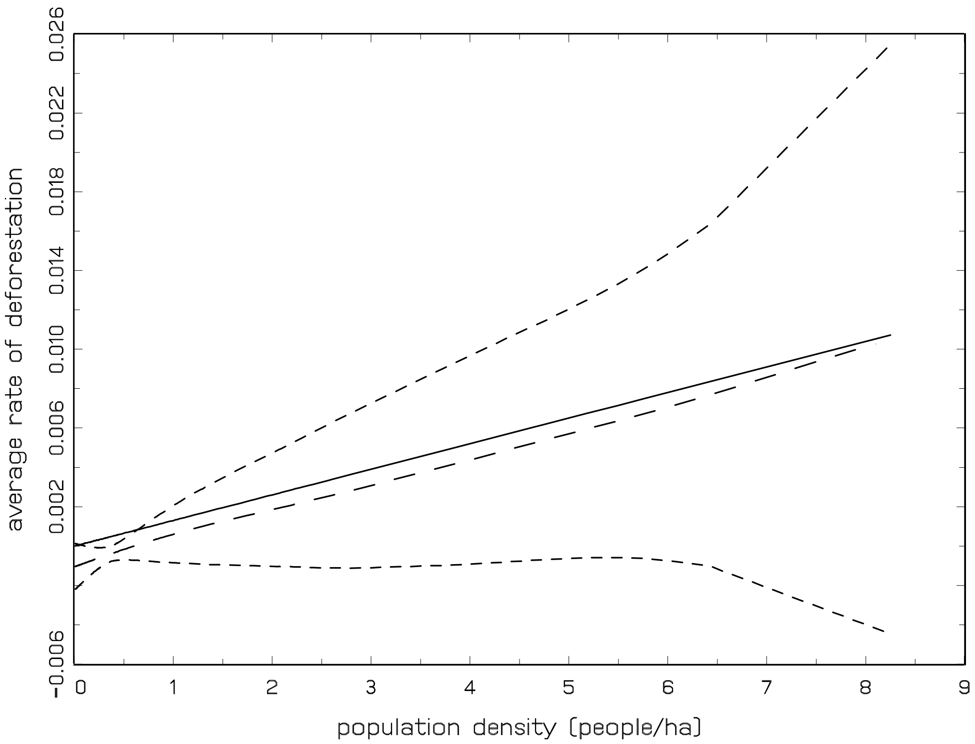

Figure 3: Relationship between the average rate of deforestation and population density. The solid line is the parametric linear fit $\hat{\beta}_3$PDENS. The dashed curve is the estimated nonparametric fit $\hat{f}_3\,(\text{PDENS})$. The short dashed curves represents the 95% pointwise confidence interval $\hat{f}_3 \pm 1.96SD\left(\hat{f}_3\right)$, where SD is the standard deviation. The data are normalized so that $\hat{f}_3$ has a zero mean.

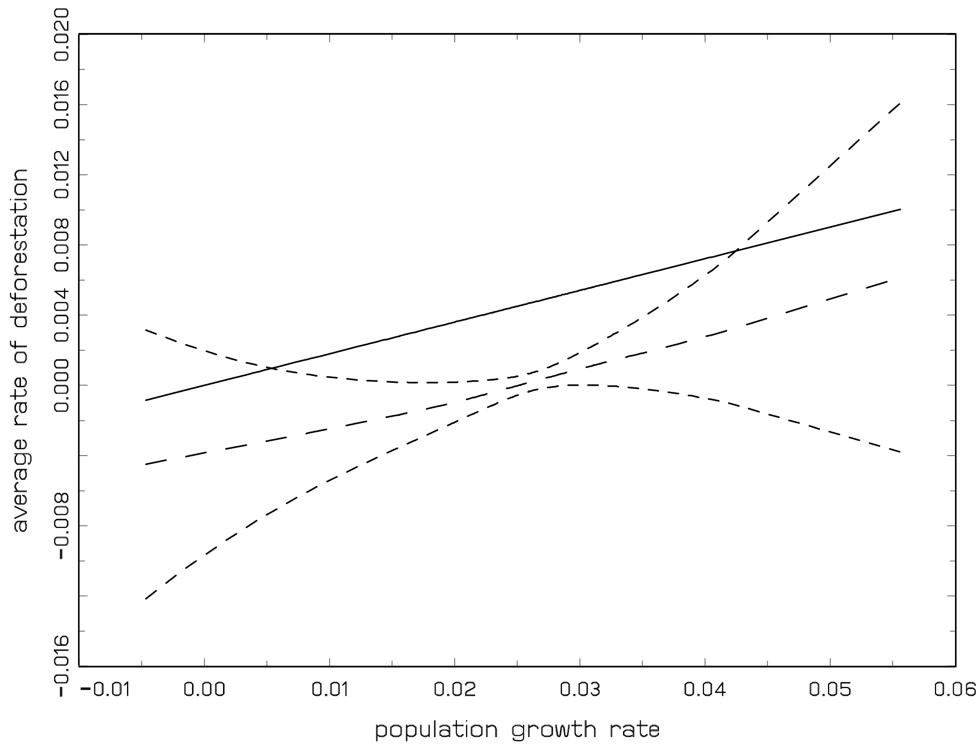

Figure 4: Relationship between the average rate of deforestation and the population growth rate. The solid line is the parametric linear fit $\hat{\beta}_4 \triangle \mathrm{POP}$. The dashed curve is the estimated nonparametric fit $\hat{f}_4 (\triangle \mathrm{POP})$. The short dashed curves represents the 95% pointwise confidence interval $\hat{f}_4 \pm 1.96 SD \left(\hat{f}_4\right)$, where SD is the standard deviation. The data are normalized so that $\hat{f}_4$ has a zero mean.