ELSEVIER

Agricultural Economics 19 (1998) 99–112

AGRICULTURAL
ECONOMICS

Population growth, agricultural intensification, induced innovation and natural resource sustainability: An application of neoclassical growth theory

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Abstract

Using a simple neoclassical type growth model including both man-made and natural capital as inputs to production, the theoretical basis for a U-shaped relationship between agricultural intensification and farm household investment in renewable resource capital is established. As development of technology, infrastructure, or markets increase the relative return to investment in man-made capital over natural capital, resource depletion occurs as man-made capital is substituted for lower return natural capital. Once returns are equalized, both man-made and natural capital are accumulated. If labor and these forms of capital are complementary, the output effects outweigh the substitution effects in the long run, leading to net accumulation of natural as well as man-made capital as a result of such technological or market development. Population growth also induces investment in both man-made and natural resource capital in the long run by increasing their marginal products. However, population growth causes declining per capita levels of both natural and man-made capital and production per capita in the long run, if technology is fixed and decreasing returns to scale. The model thus supports the Boserupian argument of induced intensification and resource improvement, as well as the Malthusian argument of the impoverishing effects of population growth. However, population growth may also induce development of infrastructure, markets, and technological or institutional innovation by reducing the fixed costs per capita of these changes, though these developments may not occur automatically. Government policies can play a large role in affecting whether these potential benefits of population growth are realized. In addition, credit policies may reduce resource degradation caused by substitution of man-made for natural capital, by allowing farmers to accumulate man-made capital (such as fertilizers) without depleting their natural capital. Policies to internalize the external environmental costs of using man-made capital will reduce both types of capital and production, indicating a clear trade-off between addressing environmental concerns on the one hand and reducing poverty and promoting resource conservation investments on the other. By contrast, internalizing the external benefits of investments in resources increases wealth and production per capita in the long run. The 'intertemporal externality' due to a higher private than social rate of time preference does not justify interventions to promote investments in resource capital; rather it argues for the promotion of savings and investment in general.

Keywords: Population growth; Agricultural intensification; Induced innovation; Economic growth; Natural resource sustainability

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0169-5150/98/$19.00
PII S0169-5150(98)00024-3

1. Introduction

The impacts of population growth on agricultural productivity and the sustainability of natural resources have been debated, at least since the time of Malthus. In the past few decades, there has been a resurgence of pessimism about the impacts of population growth, particularly in rapidly growing developing countries (Club of Rome, 1972; Brown, 1974; Ehrlich and Ehrlich, 1990). Slowing the growth of population in developing countries is widely regarded as critical to achieving sustainable development in poor countries (e.g. World Commission on Environment and Development, 1987).

At the same time, a more optimistic perspective has emerged. Boserup (1965) and many others have argued that population pressure induces agricultural intensification, development of infrastructure and markets, and technological and/or institutional innovation (Ruthenberg, 1980; Darity, 1980; Pryor and Maurer, 1982; Robinson and Schutjer, 1984; Hayami and Ruttan, 1985; Binswanger and McIntire, 1987; Salehi-Isfahani, 1988). There has been debate, however, about whether this process improves or reduces labor productivity and human welfare (e.g. Robinson and Schutjer vs. Salehi-Isfahani). The impacts on natural resources and the environment are also debated (Lele and Stone, 1989; Panayotou, 1993).

The evidence on the impacts of population growth is mixed. Numerous studies have shown a positive relationship between population densities or growth and deforestation, overgrazing, soil erosion, declining soil fertility, and other resource and environmental problems[1]. However, there are also many examples showing that population growth and very high population densities can be consistent with sustainable agricultural practices (Templeton and Scherr, 1997). In an often cited study of land management in the Machakos District of Kenya, substantial rehabilitation and improvement of previously degraded land resources (including investments in terraces, tree planting, and adoption of new technologies) was observed to occur between 1930's and 1990, despite (or perhaps because of) a five-fold increase in population (Tiffen et al., 1994).

Such observations have contributed to the hypothesis of a 'U-curve' type of relationship between population growth and the condition of natural resources and the environment in developing countries (Scherr and Hazell, 1994). Others have postulated an inverted U-shaped relationship between economic growth and environmental degradation (World Bank, 1992). Several statistical studies have examined the relationship between various indicators of environmental or resource degradation (mainly measures of pollution and deforestation) and economic growth, and some have found support for an inverted U-shaped relationship between income per capita and environmental degradation[2].

The main purpose of this paper is to consider the theoretical basis for a U-shaped relationship between the condition of natural resources used in agricultural production and population or economic growth, and to consider the implications of this theory. The emphasis is on productive natural resources rather than amenities; thus, the argument is not based upon assuming a high income elasticity of demand for environmental amenities, which may be a dubious assumption[3].

The argument is a simple application of neoclassical theory. At low levels of population density and economic development, households are well endowed with natural resource capital in the form of forests, soil fertility, etc., relative to their stock of human produced capital. As economic development proceeds, development of infrastructure, markets and technology tend to reduce the price and/or increase the marginal value product of investments in human produced capital. This induces substitution of human produced capital for natural capital, resulting in depletion of natural capital in the near term. Once the rate of return to these different types of capital have equalized, however, output effects take over and accumulation of both natural and man-made capital will occur. If man-made

[1] See, for example, the studies cited by Panayotou (1993), Stern et al. (1996) and Templeton and Scherr (1997).

[2] See Stern et al. (1996) for citations. The validity and generality of these results has been questioned on theoretical and empirical grounds (Stern et al., 1996; Arrow et al., 1995).

[3] One recent study found that the income elasticity of demand for environmental amenities is less than one in several European countries, contradicting some arguments for the inverted U-curve hypothesis (Kriström and Riera, 1996). Evidence on this issue is still very limited, however, and virtually non-existent for developing countries.

capital and natural capital are complementary, output effects will outweigh substitution effects in the long run[4]. If labor supply is complementary to both types of capital, then population growth induces investment in both types of capital after their rates of return are equalized.

This argument emphasizes the positive role of complementarity between renewable natural resource capital and man-made capital in promoting sustainable development. This contrasts sharply with the situation for exhaustible resources. Economic growth is unsustainable, if the elasticity of substitution between exhaustible resources and reproducible capital is less than unity (Hamilton, 1995). This is because the rising price of the exhaustible resources over time reduces use of both resources and man-made capital due to their complementarity.

The model presented in this paper could be characterized as 'Boserupian' given its optimistic predictions about the impacts of population growth on investment in renewable resources and other forms of capital. However, it also shares the Malthusian pessimism regarding the impacts of population growth on per capita production and consumption (holding technology and market development fixed). This is based on the assumption that agricultural production technology exhibits constant or decreasing returns to scale. If there are nonconvexities in the production function (such as, fixed costs), population growth may have positive effects on production per capita by reducing the per capita level of such fixed costs (Krautkraemer, 1994). However, with imperfect capital markets, the presence of such nonconvexities may lead to a 'poverty trap', in which poorer households are 'locked-in' to a low-level equilibrium path (Pender, 1992; Barro and Sala-I-Martin, 1995; Fafchamps and Pender, 1997).

Similar arguments apply to nonconvexities that exist more generally in the economy, such as fixed costs of infrastructure development, technological and institutional innovation. Population growth reduces these costs per capita and thus may induce this form of development, as argued by Boserup. However, the ability to take advantage of these declining costs is not automatic, since it depends on the ability to achieve collective action (including government action) to share these costs, or the development of institutions allowing private agents to internalize the external benefits of paying these fixed costs. In the case of collective action, rent seeking and transactions costs may undermine the ability to achieve collective action, particularly as population grows. In the case of private agents, monopoly power can become a constraint to economic efficiency and growth. Thus, the implications of population growth are more uncertain when such nonconvexities are taken into account; and are more strongly conditioned by the cultural norms, institutions, and government policies that influence transactions costs and monopoly power.

In addition to the effects of population growth, I consider the implications of other factors affecting agricultural intensification, including changes in market prices, technology (whether or not induced by population growth), the rate of time preference, and externalities. Reductions in the market price of man-made capital relative to the output price or technological improvement lead to higher long-run levels of both man-made and resource capital and higher levels of per capita production and consumption. A lower rate of time preference has similar qualitative long run implications, although it does not favor accumulating more of one type of capital than another. Thus, there is no rationale for promoting investments in natural resource capital relative to other investments to address the so-called 'intertemporal externality' due to a high private rate of time preference. What is needed is promotion of savings and investment more generally. Where environmental externalities exist, the implications of internalizing them depends upon whether they are external costs or benefits. For example, internalizing the external costs of water pollution associated with man-made capital will reduce the long run level of both man-made and resource capital, and production and consumption per capita. In contrast, internalizing the external benefits of planting trees or other conservation activities will lead to higher long run levels of resource and man-made capital, production and consumption. Thus, the use of 'stick' approaches to environmental problems in developing countries, such as, taxes and regulations, face serious

[4]These adjustments occur sequentially, rather than instantaneously as in the standard static theory of production, if the changes involved are large, credit markets are not well functioning, and natural capital is non-marketable.

trade-offs with goals of reducing poverty and even conserving natural resources; while 'carrot' approaches such as, subsidies for planting trees, may serve all of these objectives.

2. Theory and comparative statics

Suppose households seek to maximize the intertemporal utility function

$$\int_0^{\infty} \mathrm{e}^{-pt} u(c_t)\,\mathrm{d}t \tag{1}$$

where $u()$ is strictly concave. c_t is per capita consumption, equal to

$$c_t = \frac{F(L_t, K_t, R_t) - p_K I_{K_t} - p_R I_{R_t}}{L_t} \tag{2}$$

where $F()$ is the production function, L_t is the population of the household[5], K_t is the stock of man-made (marketable) capital, R_t is the stock of resource (non-marketable) capital[6], I_{K_t} is investment in purchased capital, I_{R_t} is investment in resource capital, p_K is the price (in units of the output) of purchased capital, and p_R is a technical coefficient (not a market price) representing the amount of output used up to increase the resource stock by 1 unit. For example, p_R may represent the amount of crop residue the farmer would need to leave on his land to increase soil organic matter by 1 ton per hectare. Land is taken to be fixed and tenure secure.

The production function is assumed to be concave, twice differentiable, and increasing the stock of any input is assumed not to decrease the marginal product of other inputs

$$F_{LK} \geq 0,\ F_{LR} \geq 0,\ F_{KR} \geq 0 \tag{3}$$

In the case of a constant elasticity of substitution production function, these assumptions are met if the elasticity of substitution is less than or equal to 1. Estimates from numerous studies using data from different countries and different methods suggests complementarity or unitary elasticity between labor and capital, labor and fertilizer, or labor and a composite of other inputs (e.g. Ruttan and Hayami, 1988; Antle and Aitah, 1983; Yotopolous et al., 1976; Binswanger, 1974; Srivistava and Heady, 1973). Of course there are exceptions to this; e.g. Ray (1982) and Brown and Christensen (1981) estimated greater than unitary elasticity between labor and fertilizer using US data, and Lopez (1980) estimated greater than unitary elasticity between labor and capital using data from Canada. Estimates of the complementarity or substitutability between human produced capital and natural capital are more rare. One study of wheat production in the Punjab found a positive relationship between organic soil carbon and labor and fertilizer demand, suggesting complementarity; though the relationship was not statistically significant (Sidhu and Baanante, 1981). More research is needed on this issue.

The decision variables at any moment are I_{K_t} and I_{R_t}. The non-marketability of resource capital implies the constraint

$$I_{R_t} \geq 0 \tag{4}$$

Some of the man-made capital and resource capital are assumed to be consumed in production in each period. For example, man-made capital may represent inorganic nutrients and resource capital may represent organic matter in the soil, both of which are consumed in crop production. The amount of each type of capital consumed is assumed to be proportional to production (though the proportionality constants may differ)

$$\dot{K}_t = I_{K_t} - \delta_K F(L_t, K_t, R_t) \tag{5}$$

$$\dot{R}_t = I_{R_t} - \delta_R F(L_t, K_t, R_t) \tag{6}$$

Household population grows at an exogenously determined rate n (≥ 0)

$$\dot{L}_t = nL_t \tag{7}$$

The maximization of Eq. (1), subject to the non-marketability constraint on resource capital Eq. (4) and the equations of motion for the state variables Eqs. (5)–(7), defines the household's optimization problem.

[5] This assumes that all household members are laborers, in effect setting the dependency ratio to zero. Nothing in the qualitative results will be changed if there is a positive dependency ratio, as long as the ratio stays constant.

[6] Alternatively, production could be determined by the flow of services from L, K, and R. If such flows are functions only of these stocks, there is no loss in generality in writing production as a function of these stocks.

The Appendix shows that, if the non-marketability constraint is non-binding, two Euler equations must be satisfied:

$$\frac{\dot{\mu}_t}{\mu_t} = \rho + n - (1 - p_K\delta_K - p_R\delta_R)\frac{F_K}{p_K} \quad (8)$$

$$\frac{\dot{\mu}_t}{\mu_t} = \rho + n - (1 - p_K\delta_K - p_R\delta_R)\frac{F_R}{p_R} \quad (9)$$

where μ_t is the marginal utility of consumption at time t ($u'(c_t)$). Both Eqs. (8) and (9) can be satisfied if and only if:

$$\frac{F_K}{p_K} = \frac{F_R}{p_R} \quad (10)$$

Eq. (10) is the usual requirement for technical efficiency. It states that the marginal rate of return for investment in man-made capital must be equal to the marginal rate of return for investment in natural capital. In Eq. (10), p_R plays the role of a price, even though it is a technical coefficient. If $F_K/p_K > F_R/p_R$, then the non-marketability constraint on resource capital will be binding ($I_{K_t} = 0$)[7] and

$$\dot{R}_t = -\delta_R F(L_t, K_t, R_t) < 0 \quad (11)$$

In words, if the initial rate of return to man-made capital is higher than the rate of return to resource capital, resource capital will be depleted until these rates of return are equalized. The initial disequilibrium (defined as a violation of Eq. (10)) may be a result of a technological or market development that significantly increases the marginal return of man-made capital or reduces its price. If that is the case, this resource degradation is not 'population induced' (unless the technological or market changes were population induced), although it may coincide with population growth. I consider the comparative statics of the model and such temporary disequilibria further below.

Once the returns to marketable and resource capital are equalized, population growth will induce net investment in both types of capital. Intuitively, this is because increasing labor supply increases the marginal return to investment in both types of capital (as a result of Eq. (3)). I illustrate this and other results below for two cases: (1) constant returns to scale technology, and (2) diminishing returns to scale technology.

2.1. Constant returns to scale

If the production function is constant returns to scale, production per worker (y_t) is a concave function of man-made capital per worker ($K_t/L_t = k_t$) and resource capital per worker ($R_t/L_t = r_t$)

$$y_t = \frac{F(L_t, K_t, R_t)}{L_t} = f(k_t, r_t) \quad (12)$$

It is straightforward to show that

$$F_K = f_k,\ F_R = f_r \quad (13)$$

Thus, we can replace F_K and F_R by f_k and f_r in the Euler Eqs. (8) and (9). In the steady state, consumption and the marginal utility of consumption are constant, which implies from Eqs. (8) and (9):

$$f_k(k,r) = \frac{p_K(\rho + n)}{1 - p_K\delta_K - P_R\delta_R} \quad (14)$$

$$f_r(k,r) = \frac{P_R(\rho + n)}{1 - p_K\delta_K - p_R\delta_R} \quad (15)$$

If f_k and f_r are greater than these values, c_t, k_t and r_t will be rising towards their steady-state values, as in the standard Ramsey growth model with only one capital stock; conversely, if f_k and f_r are less than these values, c_t, k_t and r_t will be falling[8].

Since K_t/L_t and R_t/L_t approach is a steady state, K_t and R_t both eventually grow as population grows[9]. This is population induced intensification. Note that, if k_t and r_t are initially below their steady- state levels, K_t and R_t will grow faster than population, until the steady state is reached. This additional intensification is induced by the relatively high initial returns to investment.

[7]This is proved in the Appendix.

[8]This problem can be readily converted to a growth problem with a single capital stock. Since the production function is homogeneous, the locus of points satisfying Eq. (10) is a straight line through the origin in r,k space. Thus $r=ak$ on this locus for some $a>0$, and we can define $g(k)=(1-p_K\delta_K-p_R\delta_R)f(k,ak)$ as the new production function. The problem is then a standard Ramsey growth model, and all of the standard results apply.

[9]If k_t and r_t are initially above their steady-state levels, K_t and R_t may decline for some time as k_t and r_t decline.

Table 1
Comparative statics of the steady state–constant returns to scale case

	Endogenous variable		
Exogenous variable	k	r	y
n	–	–	–
ρ	–	–	–
p_K	–	–	–
p_R	–	–	–
δ_K	–	–	–
δ_R	–	–	–
A (neutral technical change)	+	+	+
A_K (capital augmenting technical change)	+	+/0	+
A_R (resource augmenting technical change)	+/0	+	+

Table 2
Comparative statics of the steady state–decreasing returns to scale case

	Endogenous variable		
Exogenous variable	K	R	y
L	+/0	+/0	–
ρ	–	–	–
p_K	–	–	–
p_R	–	–	–
δ_K	–	–	–
δ_R	–	–	–
A (neutral technical change)	+	+	+
A_K (capital augmenting techical change)	+	+/0	+
A_R (resource augmenting techical change)	+/0	+	+

The comparative statics of the steady state are shown in Table 1[10]. Increasing any of the exogenous factors (ρ, n, p_K, p_R, δ_K, δ_R) increases f_k and f_r in the steady state, resulting in lower steady state k, r, and y. The effect of neutral technical change can be modeled by replacing $f(k_t, r_t)$ by $Af(k_t, r_t)$. Then f_k and f_r in Eqs. (14) and (15) are replaced by Af_k and Af_r, implying that an increase in A leads to a reduction in f_k and f_r in the steady state, and an increase in steady state k, r, and y. The effect of capital or resource augmenting technical change can be modeled using $f(A_k k_t, A_r r_t)$ as the production function. An increase in A_k or A_r also increases steady state k, r, and y.

2.2. Diminishing returns to scale

It might reasonably be objected that the assumption of constant returns to scale is highly restrictive and probably unrealistic in many circumstances. Given the fact that land area (not quality) is assumed to be fixed (or the ability to expand area is limited), it may be more realistic to assume diminishing returns to scale. In this case, there is no steady-state level of production or consumption per capita as population grows; instead these will continually fall as population rises (unless offset by other changes such as improvements in technology)[11]. This is the classical Malthusian scenario.

For a steady state to exist in this case, the population growth rate must be zero. Unlike the constant returns to scale case, in which only the growth rate and not the level of population is important, the level of population is a critical factor with diminishing returns to scale. Thus, I assume that the population growth rate is zero, but examine the impact of changing the level of population.

The equations determining the steady state in this case are very similar to Eqs. (14) and (15)

$$F_K(L,K,R) = \frac{p_K \rho}{1 - p_K\delta_K - p_R\delta_R} \tag{16}$$

$$F_R(L,K,R) = \frac{p_R \rho}{1 - p_K\delta_K - p_R\delta_R} \tag{17}$$

The comparative statics of the steady state are shown in Table 2. If L increases, this tends to increase F_K and F_R, so K and R increase[12]. Thus, population

[10]The comparative statics results are derived in the Appendix.

[11]This is most readily seen by considering the case of only one type of capital and assuming that, the production function $F(L,K)$ is homogeneous of degree t, where $t<1$. Then F_L, and F_K are homogeneous of degree $t-1$. Suppose that a steady state did exist in which production per capita remained constant after population increased by a factor of x. Then K would have to have increased by more than x. But that would imply that F_K had declined, since this function is homogeneous to a negative degree. This would cause Eq. (14) to be violated, contradicting the assumption of a steady state.

[12]This result is proved in the Appendix.

growth induces investment in both man-made capital and resources even in the Malthusian scenario with decreasing returns. This runs counter to the common perception that a Malthusian perspective implies resource degradation as population grows. It also suggests that there is not necessarily a contradiction between the Malthusian perspective and the Boserupian 'induced intensification' perspective. Consistent with Boserup's logic, population pressure induces investments to improve the productivity of the land, once frontier expansion is no longer an option. But consistent with Malthus, production and consumption per capita fall as a result of population growth[13]. Thus, although population growth may eventually be good news for resource conservation, it is a bad news for human welfare.

The other comparative statics results are identical to those for the constant returns to scale case. This should not be surprising, since Eqs. (16) and (17) are essentially identical to Eqs. (14) and (15), if L is constant (ignoring the population growth rate (n)). The production function $F(L,K,R)$ can be redefined as $g(K,R)$ (since L is constant), and g has the same properties as $f(k,r)$ (i.e. concavity, positive cross partial derivatives).

3. Implications

These results imply that the population growth may not be responsible for resource degradation in developing countries, when degradation is due to substitution of more profitable forms of capital for resource capital. Indeed, population growth eventually induces investments in resource improvements, where land is becoming scarce and tenure is relatively secure. Nevertheless, reducing the growth of population can increase (or reduce the decline in) per capita income and consumption. The case for population control, thus, may hinge more on considerations of poverty than on considerations of resource degradation or improvement.

Other causal factors demonstrate a complementarity between reducing poverty and improving resource conditions. For example, technological improvements (whether neutral or biased towards augmenting one of the factors of production) tend to increase investments in both man-made and resource capital and per capita income. Technological improvements in the production of man-made capital may reduce p_K, also increasing resource and other investments and per capita income in the long run. Improvements in transportation infrastructure or other factors causing an increase in output relative to input prices also may be reflected by a reduction in p_K.

Although such changes lead to resource improvements in the long run, they cause resource degradation in the short run by increasing the rate of return to man-made capital relative to resource capital. This process is illustrated in Fig. 1. An initial steady state at point O becomes inefficient after a reduction in p_K, which rotates the efficiency locus clockwise. If resource stocks were marketable, they would be immediately sold and converted to man-made capital stocks, until point P in Fig. 1 was reached. Given the marketability constraint, resource depletion will occur more slowly, as man-made capital is being accumulated, until the rates of return are equalized at a point like Q in the figure. After this point, investment in both resources and man-made capital occur until the new steady state (S) is reached. The results in Tables 1 and 2 imply that this new steady state will be at a higher stock of resources per capita than in the initial steady state. Because increasing man-made capital increases the marginal return to resource capital, the output effects outweigh the substitution effects in the long run.

This example demonstrates that it is important not to interpret resource depletion *per se* as a problem. From the farmer's point of view, the initial depletion of resources in Fig. 1 represents the most efficient way to take advantage of the new opportunities afforded by the reduction in p_K, and to increase both man-made capital and resource stocks in the long run. Policy makers could try to halt or slow the initial depletion of resources by promoting investments in resource conservation and improvement, but farmer adoption of such investments is likely to be low due to their lower

[13] An argument very similar to that in Footnote 11 demonstrates that steady-state capital and resource stocks per capita and production per capita falls after an increase in population, even though total capital and resource stocks rise. If the production function is homogeneous of degree $t<1$, then increasing or holding constant K/L and R/L would reduce F_K and F_R, thus violating Eqs. (16) and (17). Thus, K/L and R/L fall, implying that $F(L,K,R)/L$ falls (since decreasing returns would require K/L and R/L to rise if F/L were to be held constant or increase as L increases).

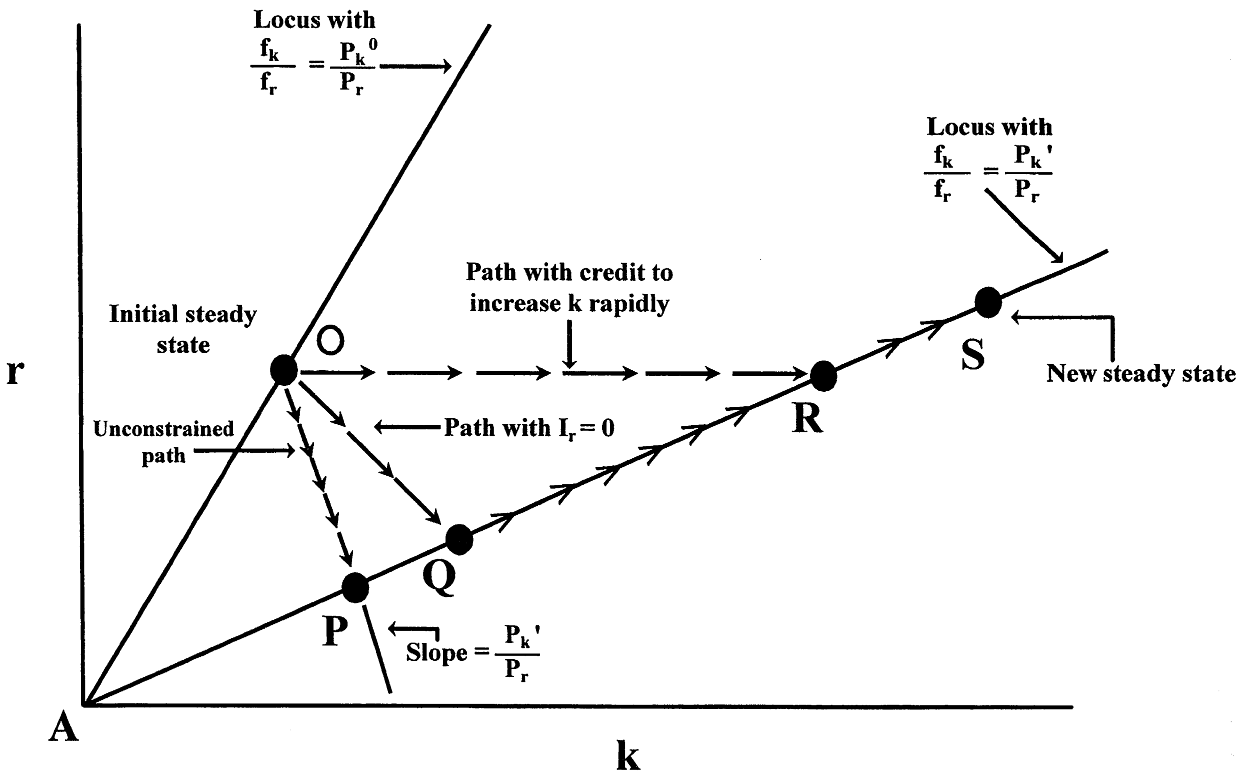

Fig. 1. Effect of a reduction in p_K.

rate of return than other investments (unless substantial subsidies are provided). For example, it is not uncommon for returns to capital invested in fertilizers to exceed 100% in poor countries (e.g. Gandhi et al., 1995; Larson and Frisvold, 1996), while rates of return on conservation practices are often much less than this (Cleaver and Schreiber, 1994; Lutz et al., 1994; Kumwenda et al., 1996). It is not surprising that farmers often show little interest in such practices, even though they may be profitable, if they have other much more profitable ways to use their scarce labor and savings.

Some development programs have sought to overcome the reluctance of farmers to invest in lower return conservation technologies by bundling these technologies with higher return investments in fertilizer, seeds, etc. Fig. 1 suggests that such an approach may be most beneficial and successful if it is combined with sufficient credit to enable the farmer to 'jump' to a higher level of man-made capital close to the final steady state (thus equalizing the rates of return at a point such as R in Fig. 1), rather than tracing out the entire depletion/accumulation path. Then the farmer will have incentive to invest immediately in resource capital as well as man-made capital. Without such an ability to accumulate capital quickly, the farmer would be better off shifting his assets towards those having higher returns initially, and this would enable him to accumulate savings and approach the long run steady state more quickly. Notice that this is true even if, as we have assumed, increasing resource capital increases the marginal product of man-made capital.

Of course, farmers' optimal decisions may not be optimal from a social point of view if there are externalities associated with their decisions. For example, use of fertilizers or other purchased capital may generate external costs on others that they do not take into account, such as water pollution caused by runoff and leaching of inorganic nutrients, or the contribution of the fertilizer production and transportation system to buildup of carbon dioxide and global warming[14]. If farmers were take these costs into account, the result would be (not surprisingly), less investment in fertilizers or other forms of capital causing external costs, less investment in resource capital (more surprising), and lower steady-state production and consumption per capita.

To show this result, suppose that each person's utility is reduced by the per capita use of man-made capital

$$u(c_t, k_t) = u(c_t - \alpha k_t) \tag{18}$$

Then, Eq. (14) is replaced by:

$$f_k(k, r) = \frac{p_K(\rho + n) + \alpha}{1 - p_K\delta_K - p_R\delta_R} \tag{19}$$

while Eq. (15) remains the same. It is straightforward to show that an increase in α leads to a reduction in the steady-state level of k, r, and y, similar to the effect of an increase in p_K[15]. Conversely, if there are external benefits of investment (e.g. if investing in planting trees generates external benefits by reducing carbon dioxide in the atmosphere), the steady-state levels of k, r, and y would be increased if these benefits were internalized, similar to the effect of a reduction in p_R.

These results suggest that there may be no conflict among the objectives of increasing agricultural productivity, improving resource conditions, reducing rural poverty, and addressing environmental concerns, if subsidies are used to internalize external benefits of improving resource conditions. On the other hand, there are clear trade-offs involved if taxes or regulations are used to internalize the external costs associated with agricultural production. Although an optimal intervention will increase aggregate social welfare and reduce environmental costs, it will reduce investment in resource capital as well as other capital, reduce agricultural production and income per capita. There may also be adverse distributional consequences since farmers in poor countries are often poorer than their urban neighbors (and certainly poorer than those in advanced countries), who benefit from reducing the external costs of developing country agriculture.

Another key issue from the standpoint of social welfare is the so-called 'intertemporal externality'; i.e. the fact that decisions made by farmers today affect the welfare of future generations, which they may not adequately account for in their decisions[16]. This issue may be reflected in the private rate of time preference (ρ) being greater than the social rate of time preference. If the social rate of time preference were applied to investment decisions instead of the private rate, there would be a higher level of all types of capital and higher per capita incomes in the long run. Note that this 'externality' affects all types of investments, not only investments in resource capital, and does not argue in favor of accepting a lower rate of return on investments in resource conservation than investments in other forms of capital. Thus, it does not change the implication that it can be socially optimal to let resources degrade in the near term; rather, it changes the steady state that will be approached after resources have degraded sufficiently to equalize the rates of return to different investments.

This issue is sometimes poorly understood in policy (and even academic) discussions. The 'intertemporal externality' is sometimes used to justify regulations or subsidies to prevent resource degradation or increase investment in resource conservation. As I hope this discussion makes clear, a high private rate of time preference does not justify interventions targeted specifically to resources, although it may justify efforts to promote savings and investment more generally.

4. Extensions

It is important to emphasize the key assumptions driving these predictions, to avoid over-generalizing them. Of critical importance are the assumptions that

[14] This assumes that market prices of fertilizer do not reflect these costs, which is likely to be true today, but could be remedied if a global agreement to limit carbon dioxide emissions is reached and this leads to higher prices of fossil fuels. This also assumes that, fertilizer production and use creates a net addition to atmospheric carbon dioxide. This may not be true however, since fertilizer use can contribute to the stock of living plant material, which acts to reduce atmospheric carbon dioxide.

[15] The effects are similar in the case of decreasing returns to scale.

[16] I prefer not to refer to this as an externality, because I think it leads to confusion. As argued by Solow (1993), this can be seen as an issue of inter-generational equity.

land area is fixed, that land tenure is secure and private, that the returns to capital increase with labor supply, and that man-made capital and resource capital are not substitutes. These assumptions imply that the private returns to investment rise as population grows, eventually inducing investment in both types of capital. If land area is not fixed and frontier land is available at relatively low cost, investment may not be profitable until available frontier land has been settled. A great deal of resource degradation, induced or amplified by population growth, may occur in the process of clearing and settling frontier land. The theory presented here does not address this aspect of the population-resource degradation nexus.

Lack of secure tenure to land also changes the story, in that the incentive to invest is reduced by insecure tenure. This does not necessarily change the basic predictions of the theory, however. Suppose, for example, that there is a given probability of eviction during each period, that this probability is independent of the farmer's decisions and statistically independent over time, and that if evicted the farmer receives his reservation utility of 0 from then on. The effect of the probability of eviction can be represented by an increase in the rate of time preference, and thus, results in lower investment and income per capita in the long run[17]. Where the probability of eviction depends upon the investment behavior of the farmer, this needs to be modeled explicitly. If resource degrading activities (such as, clearing trees) enhance tenure security, factors that promote investment (such as, lower time preference, increasing output prices, land titling and credit programs) may increase degradation (Angelsen, 1996). On the other hand, if planting trees enhances tenure security, more trees will be planted, though this may not be socially optimal (Otsuka et al., 1997).

If tenure is secure but communal rather than private, the model predictions will hold at the community level, if optimal collective decisions are made by the community. There is ample evidence that communities have been able to manage common property productively in many developing country settings (Baland and Platteau, 1996). However, the ability to maintain effective collective action may decline as population grows, because the private benefits from deviant behavior may rise while the costs of monitoring and enforcement increase. Thus, population growth may cause resource degradation in the near term by contributing to the breakdown of traditional systems of communal resource management.

In the longer term, population growth may contribute to the development of more private and specific property rights as the benefits of establishing such rights increases (Boserup, 1965; Demsetz, 1967; Binswanger and McIntire, 1987). In addition, the per capita costs of establishing and enforcing private property rights may fall as population grows, since a substantial component of these costs may be fixed. However, whether and how such institutional innovation will occur in response to changing incentives is more difficult to predict than the responses of households under a given institutional framework. Given the presence of high fixed costs, collective action requirements, and the possibility of coordination failures, institutional innovation may be a path dependent process having multiple equilibria, with no assurance that socially optimal outcomes will occur (North, 1990).

Similar arguments apply to technological innovation. The process of technological innovation typically involves substantial fixed costs (Romer, 1990), and the per capita level of these costs are reduced by population growth[18]. In addition, population growth may increase the returns to innovation, as argued in the induced innovation literature (Boserup, 1965; Hayami and Ruttan, 1985). As with institutional innovation, this process may be path dependent (David, 1985; Arthur, 1989).

Government policies may have large impacts (for good or ill) at certain critical times on which path of institutional or technological change occurs; however, at other times, the technology or institutional framework may be 'locked-in' and policies relatively ineffective in changing them. Understanding such pathways of change and the role of government poli-

[17]In the context of infinitely repeated games, Kreps (1990), chapter 14) points out that the commonly used exponential discount factor may result from a positive probability that the game will not continue.

[18]Romer argued, however, that population growth does not necessarily induce innovation because he assumed that labor supply is not an important input in the innovative sector.

cies in affecting them is an important area for future research.

The assumption that man-made and natural capital are not substitutes ($F_{KR} \geq 0$) is a critical one. If they are substitutes, the prediction that resource capital will rise in the long run after a reduction in the price of man-made capital or technological change increasing the marginal product of man-made capital could be reversed. Note, however, that the condition $F_{KR} \geq 0$ is a sufficient and not a necessary condition for the comparative statics results. The predictions of the theory will still hold if the degree of substitutability is not too large.

The model considered here also has the limitation that risk is not incorporated. Consideration of risk and risk aversion would qualify the conclusion that households seek to equate marginal rates of return. Instead, farmers would be expected to hold a diversified portfolio of assets to reduce their exposure to risk, with some perhaps having lower expected returns. Households also would likely hold precautionary savings as a hedge against future income shortfalls. These extensions do not alter the basic insight of the deterministic theory, however; i.e. large changes in prices or technology induce substitution of man-made for natural capital in the near term and accumulation of both types of capital in the long term.

It is also important to emphasize what is not assumed in the theory presented here. I have not assumed that perfect markets exist, although I assume the existence of markets for the output and man-made capital. No land, labor, or credit markets are assumed to exist. If a perfect set of markets exists within communities (no transaction costs and property rights fully specified and enforced) and external markets for output and man-made capital exist, the theory presented here would apply at the community level. The functioning of local factor markets (even if not perfect) tends to reduce the impact on production decisions of differences among households in factor endowments or preferences, since the marginal products of production factors tend to equalize across households.

However, these markets can also exacerbate distributional differences over time. For example, households with lower rates of time preference will tend to save and invest more over time, and if land sales markets are functioning, they will also acquire more land. Local credit markets facilitate this process by encouraging 'patient' households (those whose rate of time preference is lower than the local interest rate) to become net lenders and accumulate assets, while impatient households become net borrowers and divest of assets over time[19]. If labor markets are functioning, these impatient households will become landless laborers. While this process may be desirable from the standpoint of efficiency and sustainability (since the lower rate of time preference of more patient households will determine the long run level of asset accumulation), it is not desirable from the standpoint of eliminating poverty.

5. Conclusion

The theory developed in this paper supports both the Boserupian optimism about the improvements in resource management induced by population growth and the Malthusian pessimism about the impact of population growth on incomes and welfare. The Malthusian pessimism is mitigated to the extent that population growth induces infrastructure and market development, and technological and institutional innovation. However, these responses are not automatic and likely depend to a substantial extent upon the initial institutional framework, cultural norms, and government policies. Thus, governments have a critical role to play in facilitating the process of market development and technological and institutional innovation.

Governments likely have much less impact on the long run implications of intensification, given the state of technology and institutions; although they can affect the path towards the long run steady state. In particular, they can accelerate the accumulation of man-made capital by helping to make credit more widely available (this does not imply the use of subsidies), and thus reduce the incentive to deplete natural resources in the near term. Policies to subsidize the accumulation of natural capital are not justified simply because people have a short time perspective; this will simply result in lower production

[19]Barro and Sala-I-Martin (1995) p. 99) discuss this problem in open economy growth models with variations in time preference. In the limit, patient households acquire all of the marketable assets.

and consumption in the near and long term. However, if there are external environmental costs associated with man-made capital accumulation, taxes or regulation can increase aggregate welfare and reduce these costs, but there will be a trade-off with goals of reducing poverty and conserving natural resource capital (if man-made and natural resource capital are complements). In contrast, if conserving natural capital has external benefits, subsidies can increase production and consumption as well as environmental quality in the long term.

The possibility of jointly serving environmental, economic, and social objectives by subsidizing investments in resource capital is an attractive prospect. For example, it suggests that attempts to address global warming by promoting tree planting (when this is complementary to income and production objectives) might involve much fewer trade-offs than more regulatory or tax-based approaches. However, realizing such a win-win solution depends critically upon whether natural capital and man-made capital are complements or substitutes, and this is not yet well understood. Technical research identifying possible complementarities between different forms of natural and man-made capital could thus have a very high potential payoff.

Appendix

Derivation of optimal path and comparative statics results

A.1 Optimal Path

The current value Hamiltonian for the household's optimization problem is

$$H \equiv u\left[\frac{F(L_t,K_t,R_t) - p_K I_{K_t} - p_R I_{R_t}}{L_t}\right] + \lambda_K[I_{K_t} - \delta_K F(L_t,K_t,R_t)] + \lambda_R[I_{R_t} - \delta_R F(L_t,K_t,R_t)] + \lambda_L n L_t + \gamma I_{R_t} \quad \text{(A1)}$$

where γ is the Lagrangian multiplier associated with the non-marketability constraint of resource capital Eq. (4).

To show that $F_K/p_K > F_R/p_R$ implies that $I_R=0$, use the envelope theorem to compute the effect on the value function at time t ($V(L_t, K_t, R_t)$) of an increase in either K or R:

$$\frac{\partial V}{\partial K} = \frac{\partial H}{\partial K}\Big|_{\text{optimal}I_K,I_R} = \left(\frac{u'(c_t)}{L_t} - \lambda_K\delta_K - \lambda_R\delta_R\right)F_K \quad \text{(A2)}$$

$$\frac{\partial V}{\partial K} = \frac{\partial H}{\partial K}\Big|_{\text{optimal}I_K,I_R} = \left(\frac{u'(c_t)}{L_t} - \lambda_K\delta_K - \lambda_R\delta_R\right)F_R \quad \text{(A3)}$$

These derivatives represent the marginal benefit (in utility terms) of an increase in K or R. Since F_K and F_R are positive, these will be positive if the term in parentheses is positive, which can be shown to be true if $(1 - p_K\delta_K - p_R\delta_R > 0)$[20]. The marginal utility cost of an increase in K is $p_K u'(c_t)/L_t$ and the marginal cost of an increase in R is $p_R u'(c_t)/L_t$. If the marginal benefit/cost ratio for investments in R is less than the marginal benefit cost ratio for investments in K, investment in R will be zero. Eqs. (A2) and (A3) imply this if $F_K/p_K > F_R/p_R$. Investment in R will be zero as long as this holds, causing R to fall Eq. (11) until $F_K/p_K = F_R/p_R$.

Assume that the rates of return to K and R have equalized (thus $\gamma=0$). Differentiating the Hamiltonian with respect to I_{K_t} and I_{R_t} and setting these equal to 0, we obtain

$$\lambda_K = \frac{p_K u'(c_t)}{L_t} \quad \text{(A4)}$$

$$\lambda_R = \frac{p_R u'(c_t)}{L_t} \quad \text{(A5)}$$

The costate equations are

$$\dot{\lambda}_K = \rho\lambda_K - \frac{\partial H}{\partial K} = \rho\lambda_K - \left[\frac{u'(c_t)}{L_t} - \lambda_K\delta_K - \lambda_R\delta_R\right]F_K \quad \text{(A6)}$$

$$\dot{\lambda}_R = \rho\lambda_R - \frac{\partial H}{\partial K} = \rho\lambda_R - \left[\frac{u'(c_t)}{L_t} - \lambda_K\delta_K - \lambda_R\delta_R\right]F_R \quad \text{(A7)}$$

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[20] When the non-marketability constraint is binding, Eq. (A5) below is replaced by

$$\lambda_R + \gamma = \frac{p_R u'(c_t)}{L_t}$$

This equation and Eq. (A4) imply that

$$\frac{u'(c_t)}{L_t} - \lambda_K\delta_K - \lambda_R\delta_R = \frac{u'(c_t)}{L_t}(1 - p_K\delta_K - p_R\delta_R) + \gamma\delta_R$$

Defining: $\mu_t = u'(c_t)$, solving Eqs. (A4) and (A5) for λ_K and λ_R, and substituting these into Eqs. (A6) and (A7) and simplifying, we obtain Eqs. (8) and (9).

5.2. Comparative statics of the steady state (constant returns case)

Eqs. (14) and (15) are of the form

$$f_k = A \tag{A8}$$

$$f_r = B \tag{A9}$$

where both A and B are increasing functions of ρ, n, p_K, p_R, δ_K, and δ_R. Let z represent any of these exogenous variables. Applying the implicit function theorem we obtain

$$\frac{\mathrm{d}k}{\mathrm{d}z} = \frac{(\mathrm{d}A/\mathrm{d}z)f_{rr} - (\mathrm{d}B/\mathrm{d}z)f_{kr}}{f_{kk}f_{rr} - f_{rk}^2} \tag{A10}$$

$$\frac{\mathrm{d}r}{\mathrm{d}z} = \frac{(\mathrm{d}B/\mathrm{d}z)f_{kk} - (\mathrm{d}A/\mathrm{d}z)f_{kr}}{f_{kk}f_{rr} - f_{rk}^2} \tag{A11}$$

Strict concavity of $f(k,r)$ implies that the denominator in Eqs. (A10) and (A11) are positive, and that f_{kk} and f_{rr} are negative. By assumption $f_{kr} \geq 0$. These results, together with the facts that $\mathrm{d}A/\mathrm{d}z$ and $\mathrm{d}B/\mathrm{d}z$ are positive, imply that $\mathrm{d}k/\mathrm{d}z<0$ and $\mathrm{d}r/\mathrm{d}z<0$. This in turn implies that $\mathrm{d}y/\mathrm{d}z<0$.

5.3. Comparative statics (decreasing returns case)

I consider only the effect of increasing L. The effects of the other variables are exactly the same as in the constant returns to scale case.

We have equations of the form

$$F_K(L,K,R) = C \tag{A12}$$

$$F_R(L,K,R) = D \tag{A13}$$

Applying the implicit function theorem, we obtain

$$\frac{\mathrm{d}K}{\mathrm{d}L} = -\frac{F_{KL}F_{RR} - F_{RL}F_{KR}}{F_{KK}F_{RR} - F_{KR}^2} \tag{A14}$$

$$\frac{\mathrm{d}R}{\mathrm{d}L} = -\frac{F_{KK}F_{RL} - F_{RK}F_{KL}}{F_{KK}F_{RR} - F_{KR}^2} \tag{A15}$$

The strict concavity of the production function and relations Eq. (3) imply that $\mathrm{d}K/\mathrm{d}L$ and $\mathrm{d}R/\mathrm{d}L \geq 0$.

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