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Interactive dynamics between natural and man-made assets: The impact of external shocks ☆

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ABSTRACT

This paper studies a two-sector economy in which one of the sectors (the "commodity sector") depends in part on the exploitation of a renewable natural resource and examines the issue in an economy-wide context where both natural resources and a man-made asset change endogenously over time. We show that under an open access resource regime: i) a resource-rich, capital-poor economy may experience a "natural resource curse" phase and under certain conditions, may even follow a non-sustainable path leading to complete natural resource depletion; ii) a labor inflow results in a *higher* steady-state per capita income, with unchanged natural resources, though it makes the economy more prone to reach a path that converges to resource collapse; iii) the introduction of a small import tariff or export tax results in larger steady-state natural resources and commodity output and renders the economy less vulnerable to resource collapse. We also contrast the open access case with the other polar case of perfect property rights, showing that in this case the economy experiences neither a resource curse nor a resource collapse.

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1. Introduction

Many developing countries obtain a large share of their income from the exploitation of common-property renewable natural resources, including fisheries, forests, grazing grounds, and water resources (Larson and Nash, 2010). The degradation of natural resources has typically been associated with activities such as agriculture, fisheries, logging, and several others (López, 2010). Natural resource degradation has also been associated with the process of extraction of exhaustible resources. For instance, it is estimated that nearly one third of all active mines and exploration sites are located within areas of ecosystems of high conservation value (Miranda et al., 2003); mining and oil extraction has led to the depletion of water supplies, water contamination, deforestation, and more. Lack of property rights to natural resources generates negative externalities, resulting in excessive use of labor and other variable factors as compared with the social optimum, and thus in a higher rate of natural resources depletion and a smaller long-run or steady-state natural resource stock, and in some cases in its total depletion.

López (1998b) estimates the losses from non-cooperative behavior on common-property lands and lack of internalization of the external costs of biomass use in land allocation decisions in Côte d'Ivoire to be as high as 14 percent of the total village income. He finds that the degree of internalization of the negative externalities is less than 30 percent and declines with community size. López (1997a) obtains similar estimates for the income loss in Ghana. These and other studies make it clear that the problem of imperfect property rights is of crucial importance for many countries (Barbier, 2005).

A large number of studies have examined communities that had been stable for long periods but then started a process of impoverishment that worsened over time (López, 1998a; Pearce, 2005). These communities typically experienced important changes over time – such as an increase in community size, in market size for their output (and increase in its price), or in labor mobility – but failed to develop adequate institutions to deal with them. This resulted in a decline in the degree of internalization of the negative externalities and led to increased pressure on renewable resources. Often located in tropical areas, land quality in such communities has typically been poor, with natural resource depletion impeding regeneration of soil fertility. This has led to further decline in soil quality by hampering nutrients deeper in the soil to rise to the surface. The ensuing deforestation has, in extreme cases, led to the disappearance of entire communities. For instance, deforestation in low-lying areas in the Philippines has led in recent years to the movement of some four million people from low-lying to high-lying areas (Washington Post, February 23, 2009,

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pp. 1–2). The classic case of natural resource depletion is that of fisheries. The depletion of fisheries has affected a large number of countries over time and early studies of natural resource depletion focused on this issue (e.g., Gordon, 1954; Scott, 1955).[1]

This paper examines the welfare consequences of commodity production under lack of property rights for natural resources. In general, most renewable natural resources of great economic importance are inherently open access. The fact that the resource-dependent sector is typically composed of many small producers makes it almost impossible to regulate. Also, as Partha Dasgupta has often emphasized, the fact that most natural resources such as animals, insects, rivers, ground water, fish resources and the atmosphere are often mobile renders it almost impossible to establish or enforce property rights (Dasgupta, 2005).[2] This justifies our maintained assumption of open access resource exploitation throughout most of the text. However, for the sake of completeness, we do compare some of our results for the open access case with a benchmark case of perfect property rights.

The present study considers the impact of important shocks that often affect developing countries, including reduction in trade barriers and labor migration. Unlike most previous studies that are based on static equilibrium analysis, allowing only for endogenous changes of the renewable natural resources, we focus on the dynamics of the economy's adjustment, explicitly allowing endogenous changes not only in natural resources but also in man-made assets ("capital"). We consider a multi-sector economy where one of the productive sectors, the primary commodity-producing sector, is directly dependent on renewable natural resources. The economy uses three assets, labor, capital and the renewable natural resource. The first two are allocated competitively across the various sectors while the natural resource stock is exclusively used in the commodity-producing sector. The economy can save and invest such savings in expanding the stock of man-made capital. We highlight the interactive dynamics of two assets, natural capital and man-made capital, as a key factor determining the nature of economic development.

The links between trade and the environment have received great attention in the literature.[3] A common argument is that international trade may exacerbate environmental externalities and result in welfare losses in (developing) countries where imperfect property rights prevent the internalization of such externalities. Early studies focused on the long-run equilibrium effects of trade, using static models that assume a constant stock of both natural resources and man-made capital, thus neglecting any dynamic adjustment to changes in the trade regime (Chichilnisky, 1994). More recent literature has continued to focus on long-run equilibrium but has explicitly recognized that the underlying natural resource stocks do change over time (Brander and Taylor, 1998; Copeland and Taylor, 1994; Jinji, 2006; Smulders et al., 2004).

We are not aware of any study that considers the dynamic adjustment to external shocks and allows for dynamic adjustments of both natural and man-made assets. This is a significant problem, because changes in investment in man-made assets are likely to be an important component of the response to external shocks and because the evolution of the natural resource may be heavily dependent on the changes in man-made assets. In addition, the fact that shocks occur frequently and that the economy rarely has time to reach its long-run equilibrium but rather tends to adjust to the various shocks when in a disequilibrium situation, renders the analysis under disequilibrium highly relevant. In fact, as the analysis in this paper reveals, incorporating the dynamic interaction of natural and man-made assets leads to potential outcomes that are not obtainable with the above-mentioned models, including some rather unexpected results.

This paper also links to the vast literature on the so-called "resource curse" which emphasizes the fact that many resource-rich low income countries tend to experience low or even negative growth rates (Sachs and Warner, 1995, 2001). As shown by Barbier (2005) and, more recently, by the comprehensive survey by Frankel (2010), this literature explains the resource curse by using a variety of super-imposed special assumptions regarding governance, political conditions, social conflicts, Dutch disease and many others. We show that the resource curse is inherent to the out-of-steady state dynamics of a resource-rich economy, and it cannot be satisfactorily explained by models that focus only on long-run equilibrium or in the neighborhood of the steady state. Our analysis of the out-of-steady state dynamics allows us to uncover a mechanism that causes resource curse for a poor and resource-rich economy arising naturally from the fundamental neoclassical growth model without requiring any other super-imposed assumptions.

This paper is a first effort to fill these important gaps in the literature. We examine out-of-steady-state adjustments to changes in policy as well as their impact on the steady state, explicitly recognizing the interactive dynamics between man-made and natural assets. An analysis that emphasizes conditions outside the long-run equilibrium in a context of two state variables (physical capital and natural resources) can be exceedingly complex. In order to keep the problem tractable, we provide a basic dynamic model with the minimum level of complexity needed to yield important insights on the behavior of the economy when subjected to a variety of shocks.

The remainder of the paper is organized as follows. Part II presents the benchmark model, Part III looks at the transition path of a resource-rich, capital-poor economy, and Part IV examines the impact of trade and factor movement policies. Part V concludes.

2. The model

The economy consists of two sectors, a resource-dependent commodity sector and the rest of the economy (encompassing mainly services and manufacturing), which we henceforth call "the manufacturing sector", that does not depend on the natural resource as an input. Each sector uses labor (l) and capital (k). The commodity sector also uses a renewable natural resource input, n, in addition to capital and labor. The production functions are:

$$y_s = Ak_s^{\alpha} l_s^{1-\alpha} \tag{1}$$

$$y_c = nDk_c^{\beta} l_c^{1-\beta} \tag{2}$$

where y_s and y_c are the output levels of the manufacturing and commodity goods, respectively ($0 < \alpha < 1$, $0 < \beta < 1$) and A and D are fixed parameters reflecting total factor productivity (*TFP*) in each industry. The natural resource enters the production of the commodity (Eq. (2)) in the way it is conventionally done in the literature (Copeland and Taylor, 1994; Gordon, 1954; Schaefer, 1957).

We assume that the manufacturing sector is more capital intensive than the rural commodity sector, i.e., we assume that $\alpha > \beta$. This assumption is likely to be valid for most poor countries where resource extraction is comprised mainly of semi-subsistence activities.

[1] An example of such depletion is Peruvian anchovies whose world price increased dramatically in the late 1970s and early 1980s. This raised the incentive to invest in fishing boats. Moreover, the government of Peru subsidized investment in these boats when imposing a tax would have been optimal. The higher prices as well as the subsidies led to a dramatic increase in the fishing fleet. The result was that the stock of anchovies disappeared for several years, leading to a decline in the use of these boats and thus in fishing. This enabled the anchovy stock to replenish over time.

[2] Two studies in Sub-Saharan Africa have empirically shown that even in cases where resources are not mobile (such as forests and woodlands) and are used by a restricted number of producers, the management of these resources appears to reflect the internalization of only a negligible fraction of their true economic value (López, 1997, 1998b). Common property in these cases is indistinguishable from open access from the point of view of resource management.

[3] For a good review and analysis of trade's environmental impact, see Copeland and Gulati (2006).

Throughout the text we highlight results that are dependent on this assumption and discuss how they may differ when the opposite assumption holds.

The dynamics of the natural resource stock is given by

$$\dot{n} = g(n) - \phi n D k_c^{\beta} l_c^{1-\beta} \tag{3}$$

The term $g(n)$ is the intrinsic growth function of the renewable natural resource.[4] The second term represents the reduction of the natural resource stock due to production of the commodity good. The parameter $0 < \varphi < 1$ measures the intensity of the environmental demands per unit of commodity output. We follow much of the literature and assume that the intrinsic growth of the natural resource takes the logistic form

$$g(n) = \gamma n (1 - (n/\overline{n})) \tag{4}$$

where $\overline{n}$ is the maximum carrying capacity and $\gamma > 0$ is a parameter.

The aggregate stock of man-made capital (K) grows according to:

$$\dot{K} = A k_s^{\alpha} l_s^{1-\alpha} + pnD k_c^{\beta} l_c^{1-\beta} - \delta K - c \tag{5}$$

where p is the world commodity price (the price of the manufactured good is normalized to 1), δ is a parameter representing the rate of capital depreciation, and $c \equiv c_s + pc_c$ are the total real consumption expenditures measured in units of the manufactured good. The sum of the first two terms on the right-hand-side of Eq. (5) is the total real income of the economy, y, also measured in units of the manufactured good, so that gross capital accumulation is equal to net savings $y - c$.[5]

Eq. (5) also represents the budget constraint of the economy. It reflects, in the context of an open economy, the trade balance equilibrium or, equivalently, the situation where the total value of domestic output is equal to the value of expenditures in consumption of the two goods plus investment, with differences between production and consumption exported (imported) for the commodity (service) at a fixed price.

Eq. (5) is valid if there are no initial trade distortions. If trade is restricted say by an export tax or import tariff we would need to include the tax or tariff revenues in Eq. (5) as part of the total income of the economy. For simplicity we assume that initially the economy is not distorted (and hence export taxes and tariffs are initially zero). The comparative dynamics analysis of trade policy below considers the effects of *introducing* a small trade tax.[6]

Labor and capital markets are assumed perfectly competitive so that at any moment in time the economy is in full employment and the stock of man-made capital is fully utilized. We assume that the total labor force L is fixed:

$$l_c + l_s = L \tag{6}$$

$$k_c + k_s = K \tag{7}$$

The behavior of a competitive economy can be replicated by a constrained optimum for the economy that maximizes the present value of welfare, subject to the parameters and institutional constraints (Stiglitz, 1991). Among the institutional constraints we assume that property rights on the natural resource are non-existent.[7]

We assume that the economy's indirect utility function is,

$$u = u(c/e(1,p)), \tag{8}$$

where $e(1,p)$ is the unit expenditure function. The indirect utility function in Eq. (8) implies that the underlying direct utility function is homothetic. Also, u is assumed to be increasing and strictly concave in c. The indirect utility function implies that the consumer has already solved the static consumer problem by picking the optimal combination of c_s (consumption of the manufactured good) and c_c (consumption of the commodity good) conditional on the price, p, and on a level of total consumption expenditure, c.[8] The optimal level of c (and hence of capital accumulation) is determined by the inter-temporal constrained optimization.

A competitive economy behaves "as if" it maximizes the present discounted value of the utility function, $\int_0^{\infty} u(c/e(1,p))\{\exp \rho t\} dt$ (ρ is the time discount rate), subject to the relevant economic and institutional constraints. It does so by choosing the levels of c, l_c, l_s, k_c, k_s and investment $I \equiv \dot{K} + \delta K$ at each point in time subject to Eqs. (5), (6) and (7), and subject to the initial conditions $K(0) = K_0$ and $n(0) = n_0$, both given. As a consequence of the institutional failure the economy ignores the impact of its choices on the environmental dynamic represented by Eq. (3). However, the above choices do impinge upon the dynamics of the natural resource according to Eq. (3), which in turn carries implications for future choices. Thus, despite the assumption of competitive markets the existence of the institutional constraint associated with imperfect property rights on the natural resource implies that the solution to the optimization problem should be interpreted as the best path possible *given* the institutional imperfection.

This problem can be solved by maximizing the current value Hamiltonian

$$H = u(c/e(1,p)) + \lambda \left[A k_s^{\alpha} l_s^{1-\alpha} + pnD k_c^{\beta} l_c^{1-\beta} - \delta K - c \right] \tag{9}$$

where λ is the co-state variable of the capital stock. Assuming interior solutions, the first-order conditions are[9]:

$$u_c(c/e(1,p)) = \lambda \tag{10}$$

$$pnD(1-\beta)(k_c/l_c)^{\beta} = A(1-\alpha)(k_s/l_s)^{\alpha} \equiv w \tag{11}$$

$$pnD\beta(k_c/l_c)^{\beta-1} = A\alpha(k_s/l_s)^{\alpha-1} \equiv r \tag{12}$$

$$\dot{\lambda} = \lambda\left(\rho + \delta - A\alpha(k_s/l_s)^{\alpha-1}\right) \tag{13}$$

$$\lim_{t\to\infty} e^{-\rho t} \lambda K = 0 \tag{14}$$

where w and r are the market wage rate (in units of the manufactured good) and the rental price of capital or interest rate, respectively.[10] In addition we have the equation of motion of capital Eq. (5) and the initial conditions for K and n.

[4] From Eq. (3) it follows that n is measured in the same units as y_c.

[5] We assume that K is irreversible; that is, once the economy builds capital, it cannot be transformed back into consumption goods. Hence, the stock K can only be reduced through time by allowing it to depreciate.

[6] Focusing on the introduction of small trade distortions has been prominent in the trade literature as a way of illustrating first-order effects of trade policy without having to be concerned about second-order effects associated with changes in tax or tariff revenues (Bhagwati et al., 1998).

[7] But see below for a comparison with the case of property rights.

[8] In fact, by Roy's identity, one can retrieve the optimal conditional consumption bundle from the indirect utility function.

[9] An interior solution implies that the economy produces both final goods. There are extreme conditions regarding the initial asset endowments under which this may not be the case. We discuss this possibility below.

[10] An optimal path with perfect property rights on the natural resource would require that the choosing of the control variables give full consideration to their effect on the changes of the natural resource stock (valued at its shadow price) in the optimization problem. An unrestricted optimum would thus need to consider an additional term, $\mu\dot{n}$ (where μ is the optimal shadow value of the stock of natural resources), in Eq. (9). Lack of property rights on the resource means that the economy behaves myopically with respect to the natural resource stock, as if $\mu = 0$.

Eqs. (11) and (12) are a central feature of any model that assumes competitive factor markets, not just the particular model that we have assumed. They indicate that factor returns in competitive markets are equal to their respective marginal value products and, given factor mobility, such returns are equalized across the sectors.

Eq. (10) shows the equalization between the marginal utility of current consumption and the shadow price of capital (or the present value of the utility derived from an extra unit of capital created by reducing consumption today). Again, this condition applies as long as the capital market is perfect, in which case consumers select the consumption and saving levels optimally by equalizing the marginal value of consumption to the present value of increases in future consumption represented by the asset value of capital (λ). This value is of course endogenous.

Eq. (13) is the classical no-arbitrage condition reflecting temporary competitive equilibrium in the stock market (that is, for a given stock of capital which is fixed in the short run). It states that the expected returns to holding one unit of capital (the interest rate, r, plus the expected capital gain, $\dot{\lambda}/\lambda$) should be equal to the marginal cost of holding it (the capital depreciation rate, δ, plus the opportunity cost, ρ). That is, an efficient stock market leads to an instantaneous temporary equilibrium where traders are exactly happy with the existing capital holdings which are fixed in the short run. Thus, all the above conditions are simply the result of assuming competitive equilibrium and perfect capital markets together with current account equilibrium (Eq. (5)), not of the particular inter-temporal optimization model that we use mainly to organize the presentation.

Dividing Eq. (11) by Eq. (12), we obtain:

$$\frac{k_c}{l_c}=\frac{\beta(1-\alpha)}{\alpha(1-\beta)}\frac{k_s}{l_s}\equiv\Psi\frac{k_s}{l_s} \tag{15}$$

Given the assumption that $\alpha>\beta$, it follows that $0<\psi<1$. Substituting Eq. (15) in Eq. (12), we can obtain an expression for the capital/labor ratio in the commodity sector as a function of the stock of natural resources and various parameters, i.e.:

$$\frac{k_c}{l_c}=\nu(pn)^{\frac{1}{\alpha-\beta}}\equiv Z_c(pn) \tag{16}$$

where $\nu\equiv\left[\left(\frac{1-\beta}{1-\alpha}\right)^{1-\alpha}\left(\frac{\beta}{\alpha}\right)^{\alpha}\frac{D}{A}\right]^{\frac{1}{\alpha-\beta}}$. The assumption $\alpha>\beta$ implies that the function $Z_c(pn)$ is increasing in pn. Thus, Eqs. (15) and (16) solve for the capital–labor ratios in each industry as a function of the relative commodity price, fixed parameters and the stock of natural resources, n. The fact that the capital–labor ratios are functions of $n(t)$ dictates the time dynamics of these ratios which change as n is constantly changing outside the steady state. The capital–labor ratios in both industries are increasing in n, the commodity price p and the total factor productivity (TFP) level in the commodity sector (D), and decreasing in the TFP level in the service sector (A).

The intuitive reason that the capital–labor ratios are increasing in n is as follows. An increase in the resource stock raises the economy's demand for labor more than that for capital because the commodity sector is labor-intensive relative to the service sector ($\alpha>\beta$). This causes the wage rate to increase relative to the rental rate of capital which, in turn, makes the economy more capital intensive. The increase in the capital–labor intensities in both sectors is compatible with the fact that the total stocks of capital and labor are fixed in the short run due to changes in the output composition; competitive pressures force the contraction of the capital-intensive service sector and allow for an expansion of the labor-intensive commodity sector.

2.1. Diversification or specialization

Using Eqs. (6), (7), (15) and (16) allows us to solve for the levels of labor and man-made capital used in each sector as a function of the (fixed) aggregate level of labor in the economy, as well as of the stock of man-made capital and of natural resources given at a point in time,

$$(a)\quad l_c=\frac{\psi}{(1-\psi)Z_c}\left(\frac{Z_c}{\psi}L-K\right);\quad (b)\quad k_c=\frac{\psi}{(1-\psi)}\left(\frac{Z_c}{\psi}L-K\right) \tag{15'}$$

$$(a)\quad l_s=\frac{\psi}{(1-\psi)}\left(\frac{1}{Z_c}K-L\right);\quad (b)\quad k_s=\frac{Z_c}{(1-\psi)}\left(\frac{1}{Z_c}K-L\right) \tag{16'}$$

Eqs. (15') and (16') yield the conditions for the economy to remain diversified over time (that is, the conditions for an interior solution),

$$\frac{Z_c(pn)}{\psi}>K/L>Z_c(pn) \tag{16''}$$

Eq. (16") defines the cone of diversification of the economy. The cone of diversification is much broader, and hence specialization is less likely, the more diverse the sectors are, i.e., the smaller the value of ψ. For example if $\alpha=0.6$ and $\beta=0.1$ (values that are probably realistic in the context of a poor economy), then $\psi=0.07$, implying a very wide range for the K/L ratio for which diversification remains in place. Another important aspect to note from Eq. (16") is that the cone of diversification is affected by the natural resource stock; as we show below, this implies that the boundaries of the cone of diversification are likely to broaden when the economy specializes in a way that makes the persistence of specialization less permanent.

Specialization in the manufacturing sector implies that $K/L>Z_c(pn)/\psi$. This is possible when the economy is capital rich and resource poor (remember that Z_c is increasing in n). However, this condition may not persist over time because the stock of the resource must grow quite fast given that it is not used at all. That is, n would grow rapidly, causing $Z_c(pn)$ to increase and eventually becoming large enough to allow for diversification. In particular, a specialized steady state where n is constant despite the fact that the resource is not used, is not feasible as long as $g(n)>0$. Thus, under specialization $\dot{n}=0$ only if $n=0$, i.e., if the resource has become extinct. We do consider specialization under resource extinction below.

Specialization in the commodity sector occurs if the economy is very poor in capital and rich in natural resources and/or labor, i.e., if $K/L<Z_c(pn)$. In this case $l_c=L$ and $k_c=K$. But specialization has implications for the evolution of the stock of natural resources. Equation of motion (3) under specialization in the commodity industry is now,

$$\dot{n}/n=g(n)/n-\phi DK^{\beta}L^{1-\beta} \tag{3'}$$

We note that when the resource level is very high, the condition for specialization requires $g(n)/n$ to be very low (in fact, using Eq. (4), it follows that $g(n)/n\to 0$ as n gets closer to the maximum carrying capacity, $\overline{n}$). On the other hand, Z_c is always increasing in n and hence, given that the maximum level of n is $\overline{n}$, its maximum feasible level is $Z_c(p\overline{n})$. Thus, we rule out specialization in the commodity output by assuming that,

$$K_0/L\geq Z_c(p\overline{n}),$$

where the subscript 0 indicates initial levels. That is, the initial capital/labor ratio is not lower than the maximum level of Z_c.

2.2. Factor prices

Using the definition of factor prices w and r given by Eqs. (11) and (12), and using Eqs. (15) and (16), we can now obtain explicit expressions for the factor prices:

$$w=(1-\alpha)A\left(\frac{\nu}{\psi}\right)^{\alpha}(pn)^{\frac{\alpha}{\alpha-\beta}} \tag{17}$$

$$r=\alpha A\left(\frac{\nu}{\psi}\right)^{\alpha-1}(pn)^{\frac{\alpha-1}{\alpha-\beta}} \tag{18}$$

More succinctly, we can write the factor prices as

$$(i)\ \ w = w(pn), \quad (ii)\ \ r = r(pn) \tag{19}$$

ith first derivatives, $w'(pn) > 0$, and $r'(pn) < 0$. Factor prices also follow a dynamic path over time as they are functions of the evolution of the natural resource stock.

Thus, the wage rate (interest rate) is increasing (decreasing) in $n(t)$ and p. These comparative static effects are directly associated with the assumption that $\alpha > \beta$. The fact that the commodity sector is less intensive in K than the service sector means that the price of capital r is decreasing in n. A higher level of the natural resource shifts the composition of output in the economy towards the labor-intensive commodity output and against the capital-intensive manufacturing sector. This shift in production reduces the total demand for K which causes a reduction of its rental price. If the commodity sector were more capital intensive than the manufacturing sector then the above comparative static effects would be exactly opposite.

As is well known, the total level of income in the economy (in units of the service output) can be expressed either in terms of the value of outputs ($y_s + py_c$) or, equivalently, of the total factor returns. Thus, using Eq. (19), and considering that under an open access regime rents are fully dissipated, income is just equal to the total returns to capital and labor. Thus, the economy's total income (y) is

$$y(w(pn), r(pn), K; L) = w(pn)L + r(pn)K \tag{20}$$

where the income or (dual) revenue function, y, is of course increasing in K and L. This leads us to an important remark and corollary,

Remark 1. The fact that rents are fully dissipated implies that the stock of natural resources affect income only through its effect on factor prices.

In addition, this remark implies the following corollary,

Corollary to Remark 1. *For an individual household under perfect competition (being therefore a price-taker in all markets), the economy's resource stock is a parameter.*

Remark 1 and its corollary are extremely important because they imply that each household in the economy chooses its optimal consumption and investment level focusing only on factor prices and output prices. The effect of the stock of natural resources does not play any role in those choices except to the extent that they affect factor prices. The full impact of the resource stock on an individual household decision is condensed in the level of factor prices.

We now characterize the revenue function defined in Eq. (20). It has been shown that the dual revenue function must be increasing and convex in p and the first derivative of the income function with respect to p is equal to the commodity output level, by the so-called Hotelling lemma (Diewert, 1981); that is, $\partial y/\partial p = y_c$. This means that the net effect of p on national income must be positive. Since the effects of p and n in the income function are symmetric and of the same sign, this implies that the national income function is also increasing in n. That is, the positive wage effect necessarily dominates the negative capital price effect (both of which are associated with a higher level of n). Also, the convexity of the national income function in the commodity price means that $\partial y_c/\partial p > 0$; that is, the production of the commodity must be increasing in its price. This also means that y_c is increasing in the resource stock, n. Specifically, we can write y_c as the first derivative of Eq. (20) with respect to p,

$$y_c = w'(pn)nL + r'(pn)nK. \tag{21}$$

From Eq. (21) it follows that we can define the commodity output per unit of the resource as entirely a function of pn, K and L and not directly of n; that is, the average product of the commodity output is,

$$y_c/n = w'(pn)L + r'(pn)K \tag{21'}$$

where the average product y_c/n is increasing in pn. Since $w'(pn) > 0$ and $r'(pn) < 0$, it follows that y_c *increases* in the labor force and *decreases* in the total stock of capital (K). The following lemma summarizes these results.

Lemma 1. *The economy's income function is increasing and convex in n and p. Further if the manufacturing sector is more capital intensive than the commodity sector then: (i) the economy's wage rate is increasing in the stock of natural resources and in the commodity output price while the interest rate falls in the same variables, and (ii) the production of primary commodities (manufacturing) is increasing (decreasing) in the resource stock and in the labor force and decreasing (increasing) in the stock of man-made capital.*

If the manufacturing sector is less capital intensive than the commodity sector then results (i) in Lemma 1 would be reversed so that production of commodities in this case would be increasing in the capital stock. As we show below this implies that while in the case where $\alpha > \beta$ man-made capital and the natural resource are complements (in the sense that capital accumulation is associated with an increasing resource stock), in the case where $\alpha < \beta$, capital and natural resources become substitutes.

Rewrite Eq. (13) using (19.ii),

$$\dot{\lambda}/\lambda = \rho + \delta - r(pn) \tag{13'}$$

and the equation of motion of the natural resource in terms of rate of change obtained from Eq. (4), using Eq.(21'), and by dividing both sides by n, as

$$\dot{n}/n = g(n)/n - \phi\left[w'(pn)L + r'(pn)K\right] \tag{4'}$$

Since both capital and natural resource stocks change endogenously over time, it follows that both factor prices and the level and composition of national income must also adjust over time. Before analyzing the dynamics of the system, it is convenient to consider its long-run equilibrium or steady state.

2.2.1. Steady state

We define the steady state using two conditions: the shadow value of consumption is constant, which means that $\dot{\lambda} = 0$, and the stock of natural resources must be constant. That is, in steady state we have that $\dot{\lambda} = \dot{n} = 0$. The first equality means,

$$r(pn^*) = \rho + \delta \tag{22}$$

That is, there is a unique level of the natural resource stock, n^*, that allows for the equalization of the rate of return to capital and its opportunity cost. Moreover, by setting $\dot{n} = 0$, we can solve Eq. (4') for the steady state level of capital, K^*:

$$\phi\left[w'(pn^*)L + r'(pn^*)K\right] = g(n^*)/n^* \tag{23}$$

The steady state requires simultaneous satisfaction of Eqs. (22) and (23) which uniquely determine the levels of capital and natural resources that are compatible with steady state equilibrium. In steady state, the levels of K^* and n^* are thus determined.

Moreover, the fact that $\dot{\lambda} = 0$ implies that consumption is also constant in steady state, that is $\dot{c} = 0$. This follows directly by differentiating Eq. (10) with respect to time. The constancy of c and n implies that in steady state there is no net investment in capital. Clearly by Eq. (22) it follows that the rate of interest is just equal to the opportunity cost of capital which means that there are no incentives for increasing the stock of capital or for consumption growth. Also, by Eq. (23) the consumption of natural resources is just equal to its natural renewal. The following lemma follows.

Lemma 2. *The steady state level of the stock of natural resources n^* is decreasing in the commodity price p and is not affected by the size of the labor force L.*

Proof. Substituting Eq. (18) in Eq. (22), we obtain an explicit solution for n^*, namely:

$$n^* = \frac{1}{p}\left[\frac{\alpha A}{\rho+\delta}\right]^{\frac{\alpha-\beta}{1-\alpha}}\left(\frac{\beta}{\alpha}\right)^{\beta}\left(\frac{1-\beta}{1-\alpha}\right)^{1-\beta}, \tag{24}$$

The steady state level of the stock of natural resources n^* is decreasing in the commodity price and independent of L. ⊗

The value of K^* is implicitly defined by substituting Eq. (24) into Eq. (23). Finally, substituting Eq. (24) into Eq. (17), we obtain an explicit solution for the steady-state level of the wage rate:

$$w^* = (1-\alpha)A^{\frac{1}{1-\alpha}}\left[\frac{\alpha}{\rho+\delta}\right]^{\frac{\alpha}{1-\alpha}} \tag{25}$$

2.2.2. Dynamics

Rewriting Eqs. (3), (5) and (13) and differentiating Eq. (10) with respect to time using the results in Lemma 1, we have:

$$\dot{n}/n = g(n)/n - \phi\left[w'(pn)L + r'(pn)K\right] \tag{26}$$

$$\dot{K} = w(pn)L + r(pn)K - \delta K - c(\lambda; p) \tag{27}$$

$$\dot{c}/c = -(1/a)\dot{\lambda}/\lambda = (1/a)(r(pn) - (\rho+\delta)) \tag{28}$$

where $a \equiv -cu_{cc}/u_c > 0$ is the elasticity of the marginal utility which is assumed constant. The function $c(\lambda;p)$ follows from Eq. (10). Given strict concavity of the utility function in c, it follows that c is decreasing in λ.

From Eq. (18) we know that given p, the level of r is dictated exclusively by the value of n. Thus, whether or not the economy is in steady state depends entirely on the level of the initial stock of natural resources vis-à-vis its steady state level. Thus we have the following lemma,

Lemma 3. *If $n > n^*(n < n^*)$ then $r < \delta + \rho$ $(r > \delta + \rho)$ and hence the rate of growth of consumption is negative (positive), $\dot{c}/c<0$ $(\dot{c}/c > 0)$.*

Proof. Using Eq. (18) it follows that r is decreasing in n. Next use this in Eqs. (22) and (28) to obtain the result ⊗.

From Lemma 4 below we derive insights into the out-of-steady state dynamics,

Lemma 4. *There are two possible out-of-steady state conditions:*

- **(i)** *if $n > n^* \Leftrightarrow r<\delta+\rho \Leftrightarrow \dot{K}<0$, households have no incentive to invest in capital; that is, $\dot{K} = -\delta K<0$. In addition, the fact that there is no investment and therefore no savings implies that $c = y(pn, K, \overline{L})$.*
- **(ii)** *if $n<n^* \Leftrightarrow r > \rho+\delta \Leftrightarrow \dot{K} > 0$. In this case $c<y(pn, K, \overline{L})$.*

Proof. See Appendix.

Thus, while we cannot pinpoint exactly the dynamic of $\dot{K}$ which, as can be seen in Eq. (28), depends on λ whose out-of-steady-state values are difficult to define precisely, we do know the direction of change of K over time: it must be increasing (decreasing) whenever the rate of return to capital (r) is higher (lower) than the opportunity cost of capital ($\rho + \delta$) and K is constant if the return to capital is equal to its opportunity cost. This result is eminently intuitive: if the marginal return to capital is above its marginal cost, potential investors tend to invest in it, expecting to earn a net profit; similarly, if the rate of return to capital is below its opportunity cost, investors are unhappy with the stock and abstain from investing so that the stock falls. Only if the marginal return to capital equals its marginal cost, which corresponds to a long-run equilibrium condition, will investors be happy with the stock level and will want to maintain it at the same level.

As shown in the appendix, Lemma 4 follows because investment decisions are made by individual household-producers which take factor prices as *given*. An important assumption is that households do not have perfect foresight regarding the evolution of factor prices; it is assumed instead that at the time of making their investment decisions households do not consider the dynamics of the natural resource stock which in turn determines the evolution of factor prices. This is a reasonable assumption in the context of poor producers where natural resources have open access as assumed here.

Even if producers had perfect foresight regarding factor prices it would be unreasonable to expect that the direction of their investment decisions would be dominated by their expectations regarding the evolution of factor prices. For example, suppose that $r > \rho + \delta$; according to Lemma 4 producers would choose positive levels of net investment. Suppose that producers have perfect foresight and n is increasing implying that r will be expected to fall in the future towards r^*.[11] Would the predicted future fall of r reverse the outcome presented in Lemma 4 and make them to disinvest instead of investing? The answer is no because they would forego a profit during the adjustment process during which the return to capital is higher than its opportunity cost. The return to capital, while falling, will still remain above the opportunity cost of capital given that throughout the adjustment $r \geq \delta + \rho = r^*$. Perfect foresight would merely cause slower rate of investment but it would not reverse the result. It may simply lower the rate of investment compared to the case of static expectations regarding factor prices, but net investments would still be positive.

3. Transition path of a resource-rich, capital-poor economy

We now turn to the transitional dynamics of a prototype poor economy that is rich in natural resources and poor in capital, and where the manufacturing sector is more capital intensive than the primary commodity sector. Fig. 1 shows this case. The formal mathematical derivation of the phase diagram in Fig. 1 is presented in the Appendix. The top panel depicts the relationship between the rate of return on capital (or interest rate) r and the stock of natural resources n. The second panel in Fig. 1 is a phase diagram depicting the dynamics of the system in the $\{K, n\}$ space. The third panel shows the dynamics of the adjustment in the $\{\phi y_c, n\}$ space. We have divided the area in this second panel into four phases on the basis of the dynamic forces affecting $K(t)$ and $n(t)$. The following analysis deals directly with three of these phases (Phases I, II and III) that are the most relevant for the analysis of out-of-steady state dynamics.

Consider the case of an economy that is initially rich in natural resources ($n(0) > n^*$) and poor in capital ($K(0) < K^*$). This initial condition is illustrated by a point such as M in the second panel of Fig. 1, given by coordinates $\{K(0);n(0)\}$ and by coordinates $\{y_c(0),n(0)\}$ in the bottom panel. In the top panel this situation is depicted by coordinates $\{n(0);r(0)\}$. Since $n(0) > n^*$, it follows that $r(0) < \delta + \rho$, which by Lemma 4 implies that initially there is no investment in capital and, therefore, that $\dot{K}<0$.

Also, the initial level of the commodity output $y_c(0)$ must be above its equilibrium level because $K(0) < K^*$ and $n(0) > n^*$, as shown by point M in the bottom panel (remember that by Lemma 1, y_c is increasing in n and decreasing in K). Intuitively, at point M, the declining level of capital causes the output of the capital-intensive industry

[11] Of course if n is instead expected to decrease the investment effect is reinforced because in this case r increases in the future, and hence the incentives to invest today become even stronger.

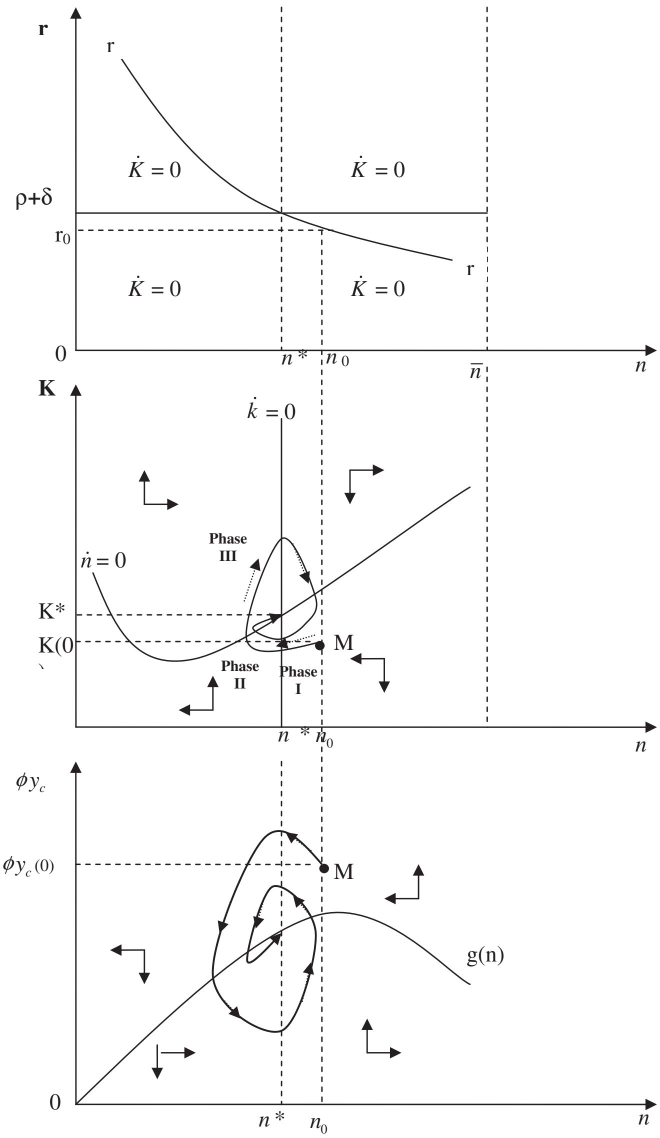

Fig. 1. Adjustments by a resource-rich capital-poor economy (case when $\alpha > \beta$).

to fall, thereby making more labor available for the commodity sector. Moreover, the fact that the stock of the natural resource is above equilibrium also contributes to enhance the ability of the commodity sector to attract more labor. Hence, we have that $y(0) > y^*$. Thus, we can describe the three phases along the adjustment process as shown in the middle panel of Fig. 1.

3.1. Phase I: The "resource curse"

An economy in Phase I evolves according to the dynamics depicted by the arrows in Fig. 1. The economy disinvests in capital which causes K to fall. The reason K falls is that in this phase the natural resource is overabundant which, as discussed earlier, causes the rate of return to capital to fall below its opportunity cost. The stock of n falls as well; this is due to the fact that the low level of K causes the economy to produce too much commodities, and hence to exert too much pressure on the natural resource.

Given that both productive assets fall, the economy experiences negative growth of output. Also, since $r < \rho + \delta$ consumption (which in this case of no investment is equal to the total output level) is falling. This is consistent with the observation that many resource-rich low income countries tend to experience negative growth rates (Sachs and Warner 1995, 2001). That is, Phase I provides a natural explanation for the so-called "resource curse" that does not require the use of super-imposed assumptions concerning potential connections between governance, political conditions, conflicts, Dutch disease, and so forth.[12] The resource curse is inherent to the out-of-steady state dynamics of a natural resource-rich, capital-poor economy where property rights on the natural resource are non-existent.

3.2. Phase II: Economic growth with resource degradation

As can be seen in Fig. 1, in this phase the natural resource continues to degrade despite the fact that the economy becomes resource poor (i.e., the stock of the resource becomes smaller than its steady state level), though it starts experiencing an increase in the capital stock. In this phase, $\dot{\lambda}$ is negative which, by Eq. (10), means that consumption starts growing from a low initial level.

Intuitively, once the economy has reduced the stock of natural resources sufficiently the rate of return to capital ($r(pn)$) has increased enough to become above the marginal cost of capital (this is by construction of the figure where the boundary between the two phases is defined by the level of n at which $r(pn) = \delta + \rho$). Hence, in Phase II there are economic incentives to invest in K which allows it to start growing. But as K increases concavity of the optimal value function (see Appendix A) implies that the shadow price of capital ($J_K = \lambda$) must decrease. This, in turn, implies that the opportunity cost of consumption falls and hence that consumption must be increasing. The stock of natural resource continues to fall; the reason is that K in this phase is still low which means that the commodity output is still too high, above the natural renewal capacity of the resource.

3.3. Phase III: Economic growth with resource recovery

Phase III in Fig. 1 is characterized by positive growth of capital as well as by a recovery of the stock of natural resources. All this implies that consumption is also growing over time along this phase. In this phase, the natural resource has become sufficiently low to make the opportunity costs of capital and labor in the manufacturing sector sufficiently high and the level of commodity output sufficiently low to allow the natural resource stock to start recovering.

At this phase the system may converge directly to the steady state equilibrium; however, as shown in Fig. 1, the capital stock and the natural resource stock may both overshoot. The economy would find itself moving in cycles around the equilibrium, experiencing periods of positive growth followed by contraction of assets and consumption before eventually converging to long-run equilibrium. That is, economies with imperfect property rights are prone to exhibit economic instability.

3.4. Bifurcation and specialization

Phase II is the critical one because the adjustment path of an economy lying in this phase may bifurcate: It either may reach Phase III with a positive level of the resource if the adjustment path (indicated in the figure by the arrow arising from point M) is sufficiently steep or, alternatively, it may be unable to reach Phase III if the adjustment path is too flat in which case the natural resource may converge towards its complete collapse.

The slope of the adjustment path depends on the speed of adjustment of man-made capital and of the natural resource; more precisely, $dK(t)/dn(t) = \dot{K}(t)/\dot{n}(t)$. Intuitively, the faster is the increase of capital and the slower is the decline in natural capital along Phase II, the steeper is the slope (which is negative) of the adjustment path and

[12] See Frankel (2010) for a detailed survey of the large number of hypotheses that have been used to explain why the resource curse prevails in many cases and why it does not in others.

vice-versa. In this case the economy specializes in the manufacturing good on a permanent basis. As indicated earlier, resource extinction is the only case in which specialization in the manufacturing sector can be persistent over time.

The following proposition summarizes the adjustment path of an economy that is initially resource-rich and capital-poor.

Proposition 1. On "resource curses" and resource depletion traps

Assume an economy that is initially resource-rich and capital-poor and exhibits imperfect property rights on the resource. (i) The first phase of the out-of-steady-state equilibrium is a "resource curse" where both natural and man-made assets as well as consumption decline. However, this may be merely a transitory phase and the economy may extricate itself from the resource curse and eventually grow its way towards the steady state. (ii) The adjustment towards long-run equilibrium is in general non-monotonic and the economy may exhibit instability with boom and bust cycles before eventually converging towards its long-run equilibrium. (iii) However, under certain conditions the economy may not be able to sustain a diversified equilibrium and end up specialized in the manufacturing sector if the resource becomes extinct. The economy is more vulnerable to fall into an irreversible resource depletion trap the higher is its environmental impact (the higher is ϕ), the higher is the commodity price, p, and the lower is its initial capital endowment.

Proof. See Appendix.

While there are no obvious examples of resource extinction for entire countries, examples of resource extinction as a consequence of negative shocks causing the disappearance of local communities in many areas of the world have been reported in the literature; these studies have been summarized by López (1998a). Moreover, several studies have discussed the apparent collapse of entire civilization in earlier times including the Mayan and Easter Island cases (Basener et al., 2008; Brander and Taylor, 1998; Croix and Dottori, 2008; Reuveny and Decker, 2000).

One final comment about resource collapse: the studies just cited and several others have considered natural resource extinction as a Malthusian phenomenon where resource collapse is the result of excessive growth triggered by population growth. Our analysis, which assumes a constant level of population, shows that population growth is not a necessary source of resource collapse. Neither is too much economic growth. On the contrary, the main source of resource extinction in our analysis is a low rate of capital accumulation. The main reason for the difference in results is that existing studies on resource depletion have invariably assumed a one-sector economy and have considered only two factors of production, the natural resource and labor. This precludes the possibility of output composition change as a mechanism for preventing resource collapse, a mechanism that is central in our analysis but that might be too weak to prevent it, namely in the case where the economy is not accumulating capital fast enough.

4. Applications

We consider three important further applications of the analysis: The effects of immigration, capital inflows and trade policy.

4.1. Immigration

Assume two proximate countries, both small and initially open to trade. The home (H) and foreign (F) countries are identical except for the fact that total factor productivity in manufacturing (A) is higher in the former. Assume first an internal equilibrium. Then, as shown by Eqs. (24) and (25), the steady-state level of the stock of natural resources and the wage rate are higher in H than in F. The wage differential provides an incentive to migrate from F to H. Suppose now that H can effectively control its borders and decides to allow a limited number of immigrants.

4.2. Long run effects

In the long run, neither the level of the stock of natural resource nor the wage rate are affected by the size of the labor force (see Eqs. (24) and (25)) and hence are not affected by immigration.[13] Since the steady-state level of the natural resource is unchanged, the same holds for the commodity's output because there is a unique level of commodity production that can be supported by the resource stock level n^* (see Eq. (23)). Rewriting Eq. (21) and evaluating it at the steady-state level of the resource, we have:

$$y_c = n^* f(pn^*, K; L) = L\left[w'(pn^*)n^* + r'(pn^*)n^*(K/L)\right] \tag{21'}$$

Since immigration causes the labor force to increase, long-run commodity output can only remain constant if the capital–labor ratio of the economy increases (recall that $w'(pn) > 0$ and $r'(pn) < 0$). Thus, along the adjustment path, the economy must invest sufficient resources to raise the long-run level of capital by a greater proportion than that of the labor force. This is shown in Fig. 2. The solid upward-sloping line shows the combinations of K and L that are consistent with a fixed level of $y_c = g(n^*)/\phi$. Given $w'(pn) > 0$ and $r'(pn) < 0$, this line must originate at a positive level of L. Thus, since immigration raises L, the K/L ratio must increase, as shown in the Fig. 2.[14]

Using Eq. (20), the total level of per capita income is

$$y(pn^*, K; L)/L = w(pn^*) + r(pn^*)K/L. \tag{20'}$$

Since immigration raises the K/L ratio, it follows from Eq. (20') that the per capita income of the economy increases in the long-run as a consequence of immigration. Finally, from Eq. (23) it follows that long-run commodity output is equal to $g(n^*)/\phi$ where n^*, as given by Eq. (24), is independent of L. Thus, immigration has no impact on long-run commodity output. Total output rises and commodity output is unchanged, so that manufacturing must expand. This result may seem paradoxical in view of the Rybczynski Theorem whereby an increase in a factor's endowment raises output of the industry using that factor intensively. The reason for the difference is that the commodity sector uses a third factor, the natural resource, which imposes a long-run constraint on the level of output of the labor-intensive sector but not on that of the other sector. Also, as explained above and shown in Fig. 3, K increases in the long run.

The following proposition summarizes the previous results.

Proposition 2. On the immigration paradox

Assume the economy is able to converge to a new interior sustainable steady state after a one-time inflow of a given number of immigrants. Such an inflow (i) raises its per capita income in the new long-run equilibrium, (ii) the long-run stock of natural resources is not affected while the stock of per capita stock of capital increases; (iii) the wage rate is unchanged; and (iv) the level of output of the manufacturing (commodity) sector increases (is unaffected).

Thus, two important and surprising results obtain for an economy converging towards a new interior (sustainable) steady state. First, contrary to popular fears, (limited) immigration leads to higher, not lower

[13] The intuition behind this result is similar to that in the standard Hecksher–Ohlin model. Labor or capital endowments do not affect factor prices as long as the economy remains diversified. An increase in the labor supply caused by immigration causes an incipient wage decrease which in turn instantaneously causes an expansion of the labor-intensive industry (in this case the commodity) because it becomes more profitable. This results in a contraction of the capital-intensive industry, and the change in the composition of output – with labor moving from the capital to the labor-intensive sector – raises the demand for labor until the increase in the labor force is absorbed without any wage increase.

[14] A constant capital/labor ratio implies an increase in the output of both manufacturing and the commodity (Rybczynski Theorem), which cannot be the steady state since commodity output is unchanged in steady state. Thus, capital must increase proportionately more than labor for commodity output to be unchanged in steady state.

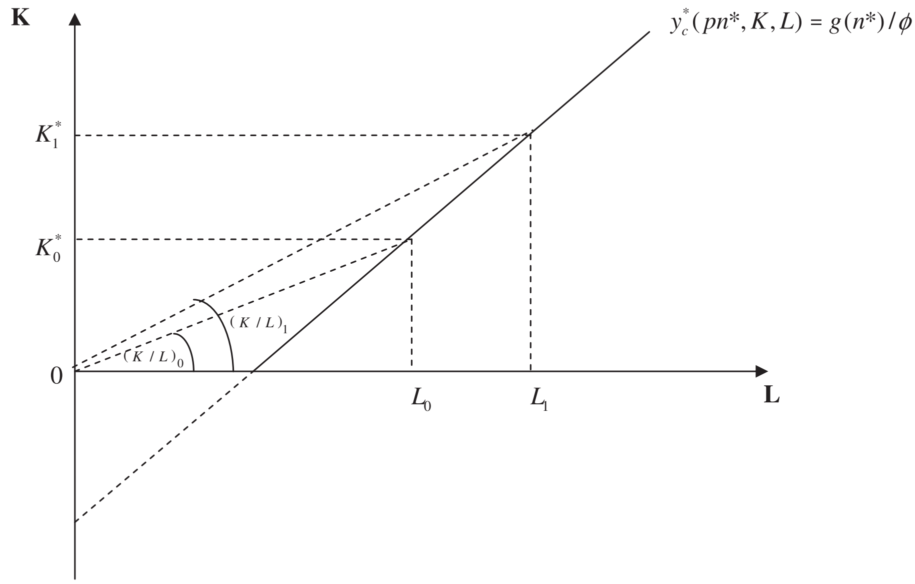

Fig. 2. The effect of immigration: an increase in L leads to an increase in the capital–labor ratio from $(K/L)_0$ to $(K/L)_1$.

per capita income in the long run and causes no natural resource degradation. Second, immigration leads to an increase in the output of the capital-intensive sector (in this case manufacturing), not of the most labor intensive one as the Rybczynski Theorem predicts. Note that the results in Proposition 2 are valid, whether manufacturing is more or less capital intensive than commodity production.

4.3. The adjustment process

The transitional dynamics caused by a one-time inflow of immigrants is shown in Fig. 3. We consider two initial cases, with the economy i) in long-run equilibrium or ii) in Phase II.

(i) *Steady-state equilibrium*: The economy starts at point M in Fig. 3. Immigration raises commodity output, y_c, and shifts the $\dot{n} = 0$ schedule upwards, causing natural resources to fall and the return to capital to rise. This stimulates investment ($r > \rho + \delta$), resulting in a move up and to the left of M. The capital stock keeps rising and, while y_c starts declining from the higher level caused by immigration's initial impact, n continues to fall until the process reaches the new $\dot{n}' = 0$ schedule. Capital accumulation is still positive but the natural resource stock start recovering as the higher capital level reduces the level of y_c to the point where the stock starts recovering. When the new steady state, N, is finally reached, there is no incentive to continue to raise the capital stock.

(ii) *Immigration triggers a trap*. The rise in the $\dot{n} = 0$ schedule may increase the vulnerability of the natural resource to an irreversible collapse. Immigration may lead an economy in Phase II to shift from a sustainable path such as MN in Fig. 4 to an unsustainable path such as MF. The reason is that at a given initial point (i.e., at given initial values of K and n) along Phase II, an increase in L raises y_c, making the $\dot{n}(t)$ function more negative in Phase II (see Eq. (26)). Since L has no effect on the rate of return of capital, it does not affect the $\dot{K}(t)$ function. Hence the adjustment path $dK(t)/dn(t) = K(t)/n(t)$ becomes more flat as a consequence of the inflow of labor. Thus, given that the $\dot{n} = 0$ shifts upwards and that the adjustment path $dK(t)/dn(t)$ becomes more flat, it follows that bifurcation towards unsustainable development becomes possible (see Fig. 4).

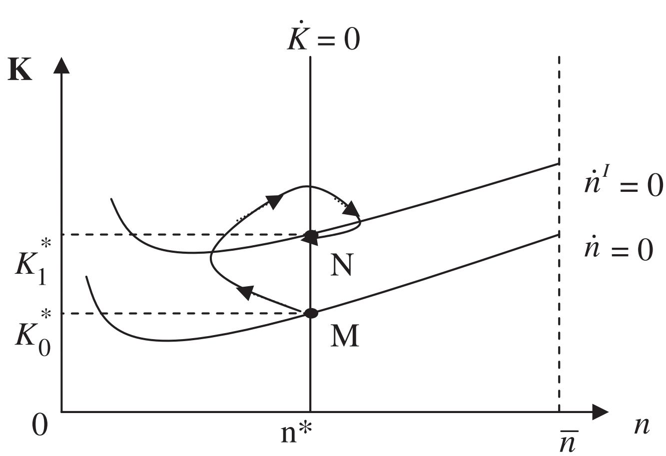

Fig. 3. The effect of an increase in the labor force (immigration).

The following proposition summarizes these results

Proposition 3. On the dynamic effects of immigration

A one-time increase in the number of immigrants makes the economy more vulnerable to bifurcation towards a path that converges to irreversible natural resource depletion.

Thus, taken together, Propositions 2 and 3 show an immigration paradox that illustrates the importance of a dynamic analysis and the potential pitfalls of ignoring the adjustment process. On the one hand, limited immigration may be viewed as quite desirable because it appears to raise per capita income in the long run without a negative impact on natural resources. However, this result is based on the presumption of an interior solution for the new long-run equilibrium. What our results show is that this need not be the case and that the pressure the larger labor force exerts on the natural resource over the transition raises the likelihood of a corner solution, with the new long-run equilibrium characterized by complete and irreversible resource degradation.[15] Thus, popular belief

[15] As $n \to 0$, the economy can no longer produce the commodity and given that the stock of capital is positive and growing, the economy specializes in the manufacturing industry. Given the assumed functional form for $g(n)$, the natural resource stock cannot recover even though the commodity is not produced because $g(n) = \gamma n(1-(n/\overline{n}))\to 0$, as $n \to 0$, i.e., the natural resource is unable to grow. This would necessarily occur for any function $g(n)$ if a minimum level of n is needed for the resource to reproduce itself.

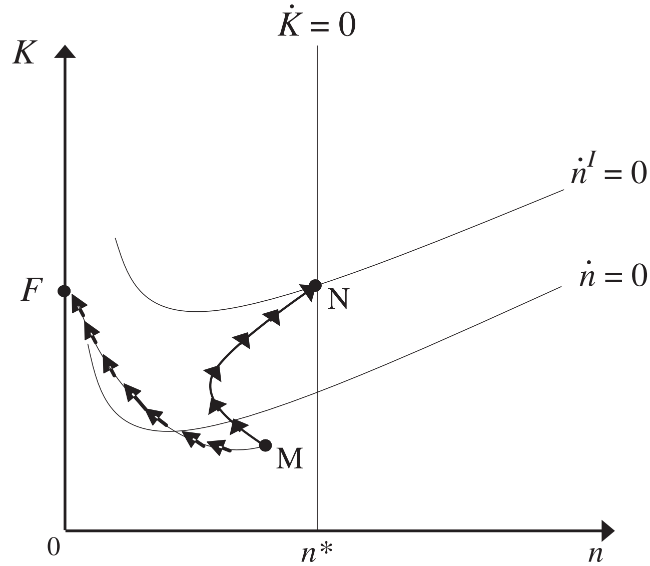

Fig. 4. Bifurcation: the possible effects of immigration in Phase II.

might in fact be correct after all in its apprehension towards accepting more immigrants.

If there were property rights or optimal resource access regulations, a path to extinction would be corrected through, for example, an increasing access fee for resource use. The lack of corrective policy suggests that complete resource depletion is associated with institutional failure and correcting it would raise welfare and prevent depletion.

4.4. Capital inflows (foreign aid)

Consider now the effect of an exogenous capital inflow, say, in the form of foreign aid. Its long-run impact is null if bifurcation is not relevant as the steady state is by definition not path dependent in this case. If capital is initially below its long-run equilibrium level, a capital inflow will simply help the economy reach its steady state sooner.

However, capital inflows can have dramatic long-run effects for an economy in Phase II that is on an adjustment path that converges towards a complete resource collapse. Foreign aid in this case can prevent such an outcome. As shown in Proposition 1, an exogenous increase in capital causes the economy to get closer to Phase III or to actually enter Phase III directly, thus allowing it to take a sustainable development path towards an interior solution. Even if the capital inflow is not of sufficient size for the economy to enter Phase III directly, Proposition 1 shows that it raises the steepness of the adjustment path and sets it closer to the $\dot{n} = 0$ schedule, thereby reducing the economy's vulnerability to unsustainable development.

4.5. Trade policy

Consider now the introduction of a small tax on primary commodity exports or a small import tariff. This causes a fall in the domestic commodity price, which lowers (raises) the wage (interest) rate and raises (reduces) manufacturing (commodity) output, causing the long-run natural resource stock to increase. With $r > \rho + \delta$, the interest rate above the cost of capital in the short run, the economy invests and the capital stock increases.

The adjustment process works as follows: The lower level of the commodity price raises the interest rate, with $r > \rho + \delta$. This induces the economy to invest more and hence the stock of capital increases faster over time. Commodity output falls, causing the stock of natural resources to increase over time or to fall at a slower rate. That is, the lower price moves the economy closer to Phase III. Thus, using Proposition 1, we have that the likelihood of bifurcation towards a long-run equilibrium characterized by resource extinction is reduced.

This is a second-best result: given a distortion, in this case an environmental one, the activity that causes it (primary commodity production in this case) must be taxed. The level of the "optimal" tax is a priori unknown but we do know that it is positive. Thus, introducing such tax at a sufficiently low level mitigates the distortion and raises welfare. A further tax increase would generate a classical second-best ambiguity.

In summary, the introduction of a small commodity export tax or of a small import tariff not only increases the likelihood that the economy will converge towards a sustainable interior long-run equilibrium but that the equilibrium will be characterized by a higher stock of natural resources and higher per capita consumption.

5. V. extensions

Here we discuss two alternative polar scenarios as a way of shedding more light on the reasons behind some of the previous results; (a) the case of perfect property rights instead of the open access case that we have considered; (b) the case of an autarkic economy instead of an open one.

5.1. Property rights on the natural resource

When the natural resource is subject to property rights, resource owners charge a rent for its use. The rental price of n is endogenous and generally changing over the adjustment process. When property rights exist the planning problem has to take explicit consideration of the resource dynamics (Eq. (3)). Hence the Hamiltonian function in (9) now changes to

$$H = u(c/e(1,p)) + \lambda\left[Ak_s^{\alpha}l_s^{1-\alpha} + pnDk_c^{\beta}l_c^{1-\beta} - \delta K - c\right] + \mu\left[g(n) - \phi nDk_c^{\beta}l_c^{1-\beta}\right] \quad (9')$$

where μ is the shadow rental price of the natural resource expressed in units of utility.

The first-order conditions now are,

$$u_c(c/e(1,p)) = \lambda \quad (10')$$

$$qnD(1-\beta)Z_c^{\beta} = A(1-\alpha)Z_s^{\alpha} \quad (11')$$

$$qnD\beta Z_c^{\beta-1} = A\alpha Z_s^{\alpha-1} \quad (12')$$

$$\dot{\lambda}/\lambda = \rho + \delta - \alpha AZ_s^{\alpha-1} \quad (13')$$

$$\dot{\mu}/\mu = \rho - g'(n) + \phi\left(\frac{q}{p-q}\right)DZ_c^{\beta}l_c \quad (29)$$

where $Z_c \equiv k_c/l_c, Z_s \equiv k_s/l_s$ and $q \equiv p - \phi(\mu/\lambda)$ is the commodity price net of the rental payment that producers have to pay to the resource owners, $\phi(\mu/\lambda)$. This rental price is in dollar value and fully captures the resource damage caused by each unit of commodity output produced. The conditions are completed with Eqs. (3), (5), (6) and (7), which remain valid.

Equilibrium conditions (11'), (12') and (13') are identical to Eqs. (11), (12) and (13) for the open access case, except for the fact that these equations are evaluated using the net price q instead to p. This implies that Z_c and Z_s are now functions of qn instead of pn as in Eqs. (15) and (16) but they are nonetheless identical functions. That is, $Z_c(qn)$ and $Z_s = \frac{1}{\psi}Z_c(qn)$. This also implies that factor prices are given by Eqs. (17) and (18) except that they are now evaluated at qn instead of pn. That is,

$$w = (1-\alpha)A\left(\frac{\nu}{\psi}\right)^{\alpha}(qn)^{\frac{\alpha}{\alpha-\beta}} \quad (17')$$

$$r = \alpha A\left(\frac{\nu}{\psi}\right)^{\alpha-1}(qn)^{\frac{\alpha-1}{\alpha-\beta}} \tag{18'}$$

Thus, the assumption $\alpha > \beta$ implies that w is increasing in qn and r is a decreasing function of qn.

Finally, the factor demands from each industry are identical to Eqs. (15') and (16') except that they are functions of qn instead of pn,

$$(a)\ \ l_c = \frac{\psi}{(1-\psi)Z_c(qn)}\left(\frac{Z_c(qn)}{\psi}L-K\right);\ \ (b)\ \ k_c = \frac{\psi}{(1-\psi)}\left(\frac{Z_c(qn)}{\psi}L-K\right) \tag{15'}$$

$$(a)\ \ l_s = \frac{\psi}{(1-\psi)}\left(\frac{1}{Z_c(qn)}K-L\right);\ \ (b)\ \ k_s = \frac{Z_c(qn)}{(1-\psi)}\left(\frac{1}{Z_c(qn)}K-L\right) \tag{16'}$$

Thus, all industry factor demands are also functions of qn,K and L. In particular, $l_c = l_c(qn,K,L)$. This function is increasing in qn and decreasing in K. Hence, we can write the average product of the commodity $DZ_c^{\beta}l_c = f(qn,K;L)$ which implies that Eq. (29) can be written as,

$$\dot{\mu}/\mu = \rho - g'(n) + \phi\left(\frac{q}{p-q}\right)f(qn,K;L) \tag{29'}$$

Also since $\alpha A Z_s^{\alpha-1} = r(qn)$ we can rewrite Eq. (13) as

$$\dot{\lambda}/\lambda = \rho + \delta - r(qn) \tag{13'}$$

We can now derive the dynamics of the net commodity price. Differentiating $q \equiv p - \phi(\mu/\lambda)$ with respect to time we obtain that $\dot{q} = \phi\left(\dot{\lambda}/\lambda - \dot{\mu}/\mu\right)$. Hence, using Eqs. (29') and (13') we obtain,

$$\dot{q}/q = \left[\frac{p-q}{q}\right]\left(g'(n) - r(qn)\right) + \phi f(qn,K;L) \tag{30}$$

The rate of change of the resource is also analogous to the open access case in Eq. (26) except that the function f is evaluated at qn instead of pn,

$$\dot{n}/n = g(n)/n - \phi f(qn,K;L) \tag{26'}$$

Given that most of the key variables depend on qn it is important deriving its dynamics over time. Using Eqs. (30) and (26') we obtain the rate of change of qn,

$$\frac{(qn)^{\bullet}}{qn} \equiv \frac{\dot{q}}{q} + \frac{\dot{n}}{n} = \left[\frac{p-q}{q}\right]\left(g'(n) - r(qn)\right) + \frac{g(n)}{n} \tag{31}$$

We note that qn is increasing over time as long as $g'(n) \geq r(qn)$, that is, as long as the "marginal product" of nature is not lower than the rate of interest. Finally we note that the rate of growth of consumption per capita is given by,

$$\dot{c}/c = \frac{1}{a}(r(qn) - (\rho + \delta)) \tag{32}$$

5.2. Steady state

In steady state Eqs. (13'), (30) and (26) reach stationary levels, $\dot{\lambda}/\lambda = \dot{q}/q = \dot{n}/n = 0$, which allows us to solve the three equations for the steady state levels of the three endogenous variables, n^{**}, K^{**} and q^{**} (where the double (single) star denotes steady state equilibrium under property rights (open access)). In particular, in steady state equilibrium, we have from (13'):

$$r(qn)^{**} = \rho + \delta \tag{22'}$$

Comparing Eqs. (22') and (22), it is easy to see that $(qn)^{**} = pn^{*}$. This makes intuitive sense: Given that with property rights the rental price of the resource $\phi\mu/\lambda > 0$, it it follows that $q^{**} < p$ and hence $n^{**} > n^{*}$; that is, the long-run equilibrium level of the resource stock is higher when property rights exist than when they do not.

Similarly, setting Eq. (26') equal to zero, recalling that $f(qn,K;L)$ is decreasing in K and noting that $g(n)/n$ is also decreasing in n, it follows that $K^{**} > K^{*}$.[16] That is, long-run equilibrium with property rights yields a higher level not only of the resource stock but also of the capital stock, compared to open access. The long run levels of factor prices, however, are identical under both regimes. Moreover, we note from Eq. (31) that in steady state $g'(n^{**}) - r((qn)^{**}) < 0$. We also note that outside the steady state $g' - r < 0$ as long as $n > n^{**}$ and $(qn) < (qn)^{**}$. Thus we have the following lemma,

Lemma 5. *Property rights on the natural resource induce higher long run stock levels of both natural resources as well as of physical capital. That is, the effects of property rights are pervasive in the economy, influencing not only the management of natural resources but also causing greater incentives to invest in man-made capital.*

5.3. Out-of-steady state dynamics

The dynamics of the system is given by Eqs. (13'), (26') and (31). By multiplying numerator and denominator of the first term in square brackets by n, it is clear that the dynamics of qn is entirely determined by n and qn. Using the quadratic functional form for $g(n)$ (see Eq. (4)) we have that the slope of the $\frac{(qn)^{\bullet}}{qn} = 0$ schedule is,

$$\frac{d(qn)}{dn}\Big|_{(qn)^{\bullet}} = 0 = \frac{r - \gamma\left(1 - 4n\frac{=}{n} + \frac{q}{p}\right)}{r + \gamma n\frac{=}{n}} - (p-q)nr'(qn)$$

Since $r'(qn) < 0$ the denominator is positive. Thus, the slope of the $\frac{d(qn)}{dn}\big|_{(qn)^{\bullet}} = 0$ schedule is positive if $n \geq \frac{1}{4}\left(1 + \frac{q}{p}\right)\overline{n}$. Noting that $q/p < 1$ it follows that the slope of the schedule might be negative only at very low levels of n (also note that if n is very low then r is high, so even at low levels of n the numerator above may still be positive). Fig. 5 shows the $\frac{d(qn)}{dn}\big|_{(qn)^{\bullet}} = 0$ schedule in the qn and n space.

The $\dot{n} = 0$ schedule is derived by differentiating Eq. (26') with respect to qn and n. That is, we derived the slope of this schedule conditional on a given level of K,

$$\frac{d(qn)}{dn}\Big|_{\dot{n}} = o = \frac{\partial(g/n)/\partial n}{\phi\partial f/\partial(qn)} < 0.$$

Thus, the slope of this schedule is negative. Fig. 5 shows this schedule as well. In Fig. 5, the intersection of these two schedules shows the equilibrium levels of qn and n for a given arbitrary level of K. The arrows show the dynamics at each of the four sectors. Clearly the adjustment path should be upward sloping and this adjustment is monotonic (without cycles) because qn is a choice variable. At a level of the state variable n_0, for example, the planner will pick a level of q (or, equivalently the markets will set the resource rental rate, $\phi\mu/\lambda$) at a level such that $(qn)_0$ is along the indicated adjustment path shown in the Fig. 5. However, as mentioned above, this adjustment path is conditional on a level of K.

Assume that the initial level of K is low, well below K^{**}, and that initially n is very large (as in point M in Fig. 6). That is, we assume the economy in Phase I has great resource abundance and little capital. In the case of open access, we showed that the economy is subject to the resource curse in Phase I because both K and n decline, and so do income and consumption per capita. In the case of property rights,

[16] In steady state we have that $g(n^{**})/n^{**} = \phi f((qn)^{**},K^{**};L)$. Since $g(n^{**})/n^{**} < g(n^{*})/n^{*}$ due to the fact that $g(n)/n$ is decreasing in n it follows that $f^{**} < f^{*}$, which given that $(qn)^{**} = pn^{*}$ and that f is decreasing in K it implies that $K^{**} > K^{*}$.

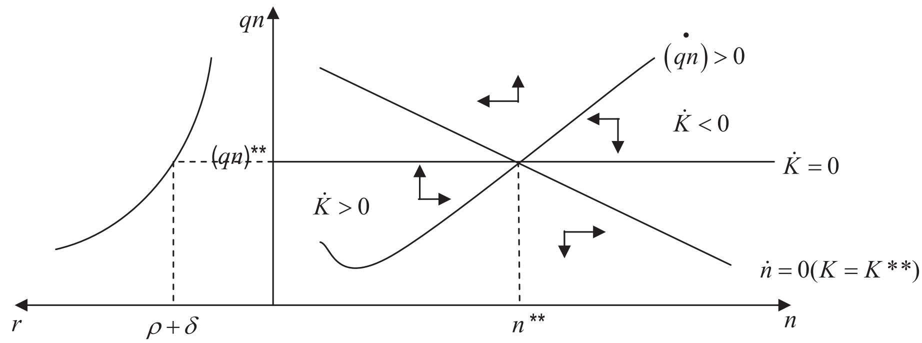

Fig. 5. Dynamics with property rights.

this does not happen; as seen in Fig. 6, at first the economy picks $(qn)_0 < (qn)^{**}$, which implies that $r((qn)_0) > \rho + \delta$. This is a signal for the economy to expand K. Increasing K shifts the $\dot{n} = 0$ schedule upwards. Using this new schedule as a reference, qn must increase. The $\dot{n} = 0$ schedule continues shifting up as K increases towards its steady state level, K^{**}, showing an adjustment path as the one indicated in the Fig. 6. The highest $\dot{n} = 0$ schedule in Fig. 6 shows the steady state equilibrium. As can be seen, throughout the adjustment path, $(qn) < (qn)^{**}$ which means that $r > \rho + \delta$ and hence, using Eq. (10'), it is clear that consumption per capita is growing throughout the full adjustment period. That is, the existence of property rights precludes the existence of the resource curse. Proposition 4 below summarizes these results.

Proposition 4. On property rights and the resource curse

Resource-rich and capital-poor economies tend to be affected by the resource curse if property rights for the resource are imperfect. However, if property rights are perfect, a resource-rich and capital-poor economy escapes the resource curse. While the resource stock declines, capital and per capita income continuously increase towards long-run equilibrium. Unlike the case of open access, under perfect property rights, the economy does not exhibit a cyclical adjustment path and instead monotonically converges towards its long-run equilibrium thus preventing the collapse of the resource.

The intuitive reason for the absence of resource curse when property rights are perfect is that the planner has in this case an additional important control variable to use, the resource rental price or tax. Thus, even if the resource is abundant as in phase I in the case of open access there is a positive tax on the resource use which is translated in a lower incentive to produce the commodity. Also, the resource tax increases the interest rate sufficiently to allow capital investments to be positive and thus for the scarce asset (capital) to expand. The intuition for the absence of cyclical behavior and for precluding in this case resource collapse is that when the resource becomes too scarce to risk extinction the resource rent increase whatever is necessary to allow the resource to recover.

5.4. Autarky

Assume that the country suffers from the "natural resource curse," with both the capital stock and the natural resource stock declining over time along the Phase I, and the government decides to change its trade policy from free trade to autarky. Also assume that in free trade the economy exports part of the commodity output and imports the manufactured good. Hence, the autarky relative commodity price must be lower than the free trade one; that is p falls.

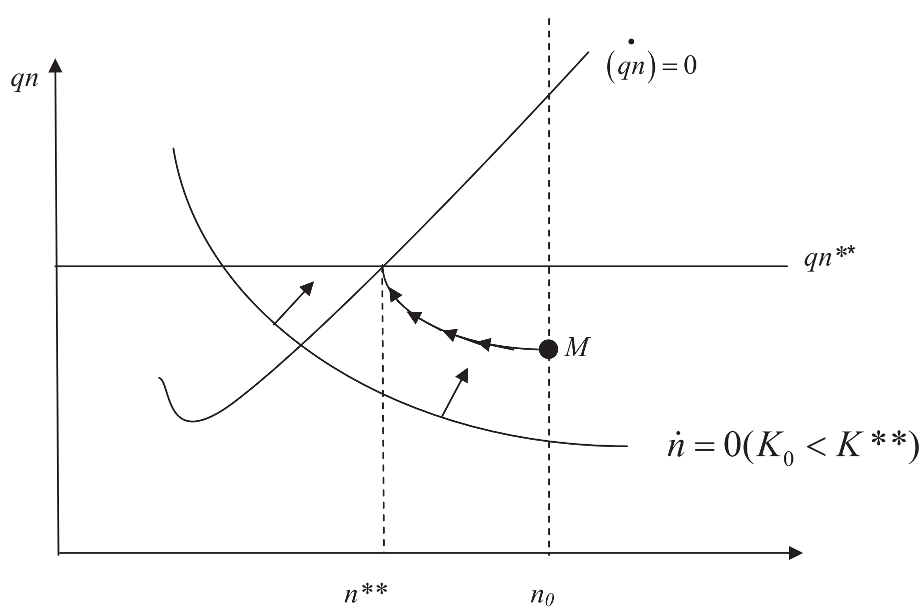

Fig. 6. Adjustment towards long-run equilibrium of an initially resource-rich and capital-poor economy with property rights.

The increase in the relative price of the capital-intensive manufactured output must raise the return to capital, r, and leads to an increase in investment, thereby reducing the rate of decline of the capital stock, or even resulting in a positive rate of growth if the reduction in the relative commodity price is sufficiently large. The decline in p also leads to a decrease in commodity output and in the rate of depletion of the natural resource, n. In other words, a move to autarky reduces the extent of the natural resource curse and the amount of time until the phase where the capital stock start increasing is reached. If the autarky level of p is sufficiently lower than the free trade price, the shift to autarky may even allow the economy to abandon Phase I at once, thus extricating itself from the resource curse.

Recall that the return to capital is a function of pn. In steady-state equilibrium, the capital stock is constant, with the return to capital equal to its cost. In other words, $r(pn) = \rho + \delta$, which uniquely determines the value of pn. Thus, the steady-state value of pn is identical under autarky and under free trade. Assume plausibly that there is no trade reversal, i.e., that if the country reverted to free trade after reaching the autarkic steady state, it would export the commodity. This implies that the autarkic steady state is characterized by a smaller relative commodity price p than under the initial free trade case and is therefore characterized by a larger natural resource stock. Moreover, since investment raises the capital stock during the transition, the autarkic steady state is characterized by both a larger natural resource stock and a larger capital stock.

Free trade is clearly sub-optimal or second best under imperfect property rights. As noted earlier in the paper, an import tariff (or export tax) exists whose value changes over the transition period and which would improve resource allocation by reducing p. Beyond the optimum, an increase in the tariff rate reduces the intervention's benefit, which becomes negative once a critical rate is reached, denoted by $\tau(t)$ at time t. Autarky reduces p as well. In the absence of trade reversal, as long as the relative commodity price under autarky is larger than the one at $\tau(t)$, a policy change from free trade to autarky may be beneficial.

6. Conclusion

This paper has provided an analysis of the transition path and steady state outcome of a small open economy that obtains a large share of its income from the exploitation of a renewable natural resource. It examined alternatively the case where resources are exploited under open access and under perfect property rights. We have shown that the out-of-steady state dynamics is fundamentally different, depending on whether the resources are under perfect property rights or open access. Under open resource access the resource curse is unavoidable for resource-rich and capital-poor economies at least as a transitory period. If property rights are perfect, the resource curse is not relevant even in economies that are initially very poor in man-made capital and rich in natural resources. We have also shown that the adjustment path of such an economy is a monotonic approach towards the long-run equilibrium. This is in sharp contrast with the case of the open access economy which exhibits wasteful cyclical behavior, with both assets passing through expansion and declining phases before approaching the steady state. Moreover, the long-run equilibrium of an economy under perfect property rights is characterized by a higher level of not only the resource stock but also of the man-made capital stock, compared to the open access economy. The long run per capita consumption is also higher.

An important contribution of the paper is its examination of the impacts of various shocks to which economies are often subjected, in the steady state *as well as* outside of the steady-state, explicitly incorporating the endogenous dynamics of both natural and man-made assets. The importance of such a framework is reflected in the fact that path bifurcation and state dependence tend to be prominent features when the resource is exploited without property rights. The dynamic forces may lead the economy to dramatically different steady states, one of which is characterized by a complete and irreversible depletion of the natural resource.

In this case, foreign aid may reduce the risks of unsustainable development if primary commodity production is less capital intensive than the rest of the economy. Unsustainable growth is also less likely under a lower relative commodity price. The introduction of a small import tariff or commodity export tax results in a larger steady-state commodity output and natural resource stock, a smaller capital stock and manufacturing output, higher welfare, and it may prevent complete natural resource depletion.

We have shown the existence of an immigration paradox that illustrates the importance of out-of-steady-state dynamic analysis. It shows the pitfalls of comparative analyses of exogenous shocks that compare steady states without examining whether such a change will allow the economy to reach a steady state that is qualitatively similar to the original one. For instance, limited immigration can be seen as quite desirable under the assumption that the new steady state is similar in nature to the initial one because it raises per capita income over the long-run without having a negative impact on natural resources. However, this result is based on the (hitherto unexamined) presumption that an interior solution is attained in the long run. This need not be the case and the new long-run equilibrium could consist of a corner solution characterized by complete and irreversible resource degradation. Even more importantly, immigration itself raises the likelihood of such a corner solution.

These results yield a fundamental policy implication: Overemphasizing trade liberalization in poor countries with imperfect property rights for natural resources may be much riskier than in wealthier countries as the latter benefit from a much larger endowment of capital and more complete property rights and natural resource management. While increasing globalization that leads to higher commodity prices may only cause a marginal reduction in the long-run state of natural resources in middle-income countries, globalization may trigger a qualitative shift in a poor economy and result in a devastating and irreversible impact on its natural resources, an outcome hardly consistent with welfare improvement.

Appendix AI. *Derivation of Fig. 1 and Proof of Lemma 4*

Since capital investment decisions are made by each individual household we focus on the representative household-producer decision model underlying the aggregate market equilibrium analysis of the text. We assume that all households are identical and that each household takes factor prices as given. Factor prices are determined at the economy-wide equilibrium as shown in the text (see Eqs. (17) and (18)). Also, consistent with the aggregate model in the text, we assume that leisure is fixed and hence that the representative household has a fixed labor endowment. Finally, we assume open resource access.

1. Proof of Lemma 4

Consider the budget constraint of a representative household i,

$$\dot{K}^i = wL^i + rK^i + \mu n/N - \delta K^i - c^i \tag{A1}$$

where μ is the rental value of the natural resource, N is the total number of households exploiting the resource, and L^i,K^i, and c^i represent the labor endowment, the capital stock and the consumption of the household, respectively, and w and r are the market wage rate and rental price of capital. The first two right-hand terms in (A1) correspond to the labor and capital income of the household. The third right-hand term is the share of the total rents derived from the natural resource which is obtained by the household i. Thus, the total income of the household, represented by the sum of its labor, capital and natural resource income, is spent in consumption plus its gross investment ($\dot{K}^i + \delta K^i$), both of which are endogenous.

Open access to natural resources means that rents are completely dissipated. That is, the rental price of the natural resource (μ) is driven to zero as a consequence of free entry, which means that the third right-hand side term in (A1) vanishes (also, N may approach infinite in the case of open access). Hence, the budget constraint for the representative household reduces to,

$$\dot{K}^i = wL^i + rK^i - \delta K^i - c^i \tag{A2}$$

Open access means that the stock of the natural resource, n, does not have an independent effect on the household income. As shown in Eq. (20) in the text, n affects aggregate income and hence income of each household only via its effect on factor prices, $w(pn)$ and $r(pn)$. Thus, investment decisions are made by each household independently from each other taking factor prices, and hence n, as given. Then the representative household i inter-temporal optimization is,

$$\max_{c^i} \int_0^\infty u\left(c^i/e(1,p)\right)\{\exp - \rho t\}dt, \tag{A3}$$

subject to:

(i)

$$\dot{K}^i = wL^i + rK^i - \delta K^i - c^i$$

(ii)

$$K^i(0) = K_0^i$$

The Hamiltonian function of household i is (Kamien and Shwartz, 1991; Cooper and McLaren, 1980),

$$H^i = u\left(c^i/e(1,p)\right) + \lambda^i\left[wL^i + rK^i - \delta K^i - c^i\right] \tag{A4}$$

where λ^i is the co-state variable of K^i. Among the first-order conditions we focus on the following,

$$(i)\quad u_c^i\left(c^i/e(1,p)\right) = \lambda^i, \quad (ii)\quad \dot{\lambda}^i = \lambda^i(\rho + \delta - r) \quad (iii)\quad \lim_{t\to\infty} e^{-\rho t}\lambda^i K^i = 0 \tag{A5}$$

where u_c^i denotes first partial derivative with respect to c^i. Differentiating expression (i) with respect to time and then using (ii) we obtain,

$$\dot{c}^i/c^i = -(1/a)\dot{\lambda}^i/\lambda^i = (1/a)(r - (\rho + \delta)) \tag{A6}$$

where $a \equiv -cu_{cc}^i/u_c^i > 0$ is the elasticity of the marginal utility which is assumed constant.

Thus, the household takes the rate of growth of consumption as fixed. From (A6) it follows that,

$$c^i = c_0^i e^{(1/a)(r - \delta - \rho)t} \tag{A7}$$

where c_0^i is the initial level of consumption which is the key endogenous variable. Now we can rewrite (A2) as,

$$\dot{K}^i = wL^i + rK^i - \delta K^i - c_0^i e^{(1/a)(r - \delta - \rho)t}$$

(i) Suppose that $r - \rho - \delta > 0$ and the household picks c_0 large enough so that $\dot{K}<0$. The household would be making a suboptimal decision: Since c^i is continuously growing $\dot{K}$ would remain negative over time which eventually would cause income to be low enough to become inconsistent with $\dot{c}^i > 0$. That is, $\lim K^i_{t\to\infty} = -\infty$, which of course cannot be optimal (the transversality condition, A5(iii), would be violated). Hence, if the household maximizes its welfare it must choose the initial level of consumption low enough to allow capital to grow. Hence it must be that,

$$r - \rho - \delta > 0 \Rightarrow \dot{K}^i > 0$$

(ii) Assume that $r - \rho - \delta < 0$. Suppose the household picks c_0^i low enough so that at time zero $\dot{K} > 0$. In this case since c^i falls continuously it must be the case that capital and hence income would increase continuously. That is, $\lim K^i_{t\to\infty} = \infty$, which violates A5(iii) and hence is not consistent with utility maximization. Hence, it must be that

$$r - \rho - \delta < 0 \Rightarrow \dot{K}^i < 0$$

Through a similar thought process it is easy to see that if $r - \rho - \delta = 0$ then $\dot{K}$ cannot be either positive or negative. In this case, $\dot{K}$ must be zero to be consistent with utility maximization. Hence, we must conclude that a welfare-maximizing household that takes factor prices as given in a context of open resource access must take the following investment pattern,

$$\dot{K}^i > 0 \leftrightarrow r - \rho - \delta > 0$$

$$\dot{K}^i < 0 \leftrightarrow r - \rho - \delta < 0$$

$$\dot{K}^i = 0 \leftrightarrow r - \rho - \delta = 0$$

Since $K \equiv \sum K^i$, then K follows the same dynamics as K^i. ⊗

2. On the relationship between the capital dynamics and the stock level of n

From Eq. (18) it follows that $r(pn)$ is decreasing in n, and that $r(pn^*) - \rho - \delta = 0$. That is, for $n < n^* \leftrightarrow r(n) - \rho - \delta > 0$; $n > n^* \leftrightarrow r(n) - \rho - \delta < 0$. This and Lemma 5 show that $n < n^* \leftrightarrow \dot{K}^i > 0$; $n > n^* \leftrightarrow \dot{K}^i < 0$, and $n = n^* \leftrightarrow \dot{K}^i = 0$. All this is true for all households in the economy, meaning that the aggregate stock of capital, $K \equiv \sum K^i$, follows the same dynamics as K^i. Thus, as shown in the top and central panels in Fig. 1, the $\dot{K} = 0$ schedule is vertical at $n = n^*$ and that K is increasing (decreasing) at the left (right) of the $\dot{K} = 0$ schedule.

3. The $\dot{n} = 0$ schedule is increasing in the (n,K) space

Since n and K represent aggregate variables for the economy as a whole, we focus on the aggregate analysis presented in the text instead of the household one. From Eq. (3) we have that if $\dot{n} = 0$ then

$$g(n)/\phi n = DZ_c^\beta l_c \tag{A8}$$

Using Eqs. (16) and (15'a), it follows that the right-hand side of (A8) is increasing in n and decreasing in K. Using the standard quadratic specification for $g(n)$ as in Eq. (4), it follows that $g(n)/n$ in the left-hand side of (A8) must be decreasing in n. Hence, we have that the slope of the $\dot{n} = 0$ schedule must be upward sloping, that is, $dK/dn|_{\dot{n}} = 0 > 0$.

Moreover, for levels of K above (below) the $\dot{n} = 0$ schedule the stock n must be increasing (decreasing).

This completes the formal derivation of the top and central panels of Fig. 1. The bottom panel is self-explanatory. ⊗

II. Proof of Proposition 1

Parts (*i*) and (*ii*) have been shown in the text.

Proof to part (*iii*): The slope of the adjustment path is

$$dK(t)/dn(t) = \dot{K}(t)/\dot{n}(t), \tag{A8}$$

where $\dot{K}(t) = \Omega(r(pn(t) - (\delta + \rho))$ (Ω is an increasing function) and $\dot{n}(t) = g(n(t)) - \phi y_c(p, n(t), K(t); L)$. Whether or not the economy converges towards a specialization with resource extinction is defined in Phase II. In Phase II we have that $\dot{K}(t) > 0$ and $\dot{n}(t) < 0$ which means that $dK(t)/dn(t) < 0$. As can be seen in Fig. 1, vulnerability to extinction is greater the higher is the $\dot{n} = 0$ schedule and the more flat is the adjustment function (the higher is $dK(t)/dn(t)$). We show here that both higher ϕ and/or p contribute to shift the $\dot{n} = 0$ schedule upwards and increase the value of $dK(t)/dn(t)$. That is, higher ϕ and/or p increase vulnerability to extinction. By inspecting Eq. (26) it is clear that for a given level of n the $\dot{n} = 0$ schedule will require a higher level of K if ϕ is higher. Also given that y_c is increasing in p it follows that the required level of K is also increasing in p. That is, the $\dot{n} = 0$ schedule shifts upwards if ϕ and/or p increase. Differentiating (A8) it follows that $dK(t)/dn(t)$ in Phase II is increasing in ϕ and, given that $r'(pn) < 0$, is also increasing in p. The slope of the adjustment path becomes more flat. Therefore, the economy becomes more vulnerable to specialization with extinction the higher is ϕ or p. Also, if the economy reaches Phase II with a low level of K it will be far below the schedule $\dot{n} = 0$. That is, the fall of n will need to be greater before reaching the turning point at which this trend is reverted (reaching the $\dot{n} = 0$ schedule and crossing into Phase III). This also increases vulnerability to resource extinction.

Finally, we show that a specialized steady state equilibrium with $n = 0$ is stable: This follows from the assumption that $g(0) = 0$, an assumption that is satisfied by the commonly used logistic model in Eq. (4). In this case once n reaches a zero level the resource cannot grow again and hence the commodity sector disappears irreversibly ⊗.

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