Will Technological Change Save the World? The Rebound Effect in International Transfers of Technology

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Abstract

Technological change and its transfer to developing countries is often portrayed by policy-makers as a critical part of the solution to a resource problem such as climate change, based on the assumption that the transfer of resource-conserving technologies to developing countries will result in reduced use of natural capital by those countries. We demonstrate here, in a capital conversion based model of development, that the free transfer of resource-conserving technologies to developing countries will increase the options available to those countries, but that the way that they expend these options need not be in the direction of conserving resources. This is another example of the potential for a rebound effect to determine ultimate outcomes, here in the context of international technology transfer policy. The transfer of technologies is as likely to simply move developing countries more rapidly down the same development path as it is to alter the choices they make along that path. For this reason, the transfer of resource-conserving technologies, without incentives provided to alter development priorities, may not result in any resource-conservation at all.

Keywords: Technological change; Rebound Effect; Development Path

JEL Classification: O33; O39; O44; Q55; Q56

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1 Introduction

There is a substantial literature that documents the expected paths of resource use under various technological assumptions (Yang, 1999; Grubb, 2000; Löschel, 2002; Jaffe et al., 2003; Aronsson et al., 2010). One important implication of such models concerns the impact of the spillover of resource-conserving technologies to countries within the frontier.[1] And an important application of these issues concerns the expected path and aggregate amount of global carbon emissions under various assumptions concerning technological change and spillover (Yang, 1999; Löschel, 2002). In this context it is reasonably assumed that the costless transfer of resource-conserving technologies will reduce resource use in the non-frontier economies as well as those on the frontier.[2] Then the transfer of resource-conserving technological change is sometimes seen to be able to reduce overall resource use and hence potentially "save the world".

As noted by Smulders and Di Maria (2012), policy-makers have seized upon these simple conclusions to advocate straightforward policy prescriptions, such as "the importance of technology improvements, advanced technologies, and....induced technological change for achieving the stabilization targets...." (citing IPCC. Metz et al., 2007). The problem is of course that the interaction between technological choices and environmental policy is something that is already long-examined and the conclusions are not at all as simple or straightforward as this. The existing literature finds that the manner in which the regulated agents (consumers or industries) might respond to technological change ranges substantially, even "backfire" is a possibility (Saunders, 2000). For this reason the ultimate outcome of technology-focused policies is highly indeterminate.

In this paper we view the policy of international technology transfer from the perspective of the rebound effect literature.[3] This seems pertinent within a symposium considering the pursuit of technological innovation as an instrument for green growth. We find that the policy implications derived in the rebound literature apply equally in the context of free transfers of technology to developing states and societies.[4] The application of international policies focused on technological change does not necessarily determine the path forward for developing countries, with regard to the way in which those technologies are used or the manner in which the

[1]We are distinguishing the term "resource-conserving" technology from the term "resource-saving" technology, which has been used to describe technologies whose net effect is to generate less resource usage. Since we are examining the question of rebound effects, we look at technologies where the net effect is not necessarily pre-determined. See Smulders and Di Maria (2012) for a clear discussion on the use of terminology regarding technologies in this area of enquiry.

[2]The literature on this question is vast. There has been a general recognition that estimates concerning climate change mitigation are sensitive to assumptions concerning the rates of technical change. The extant literature often assumes that increased technological efficiency in resource usage will in general result in reduced resource use (Dowlatabadi, 1998). This result has been claimed or assumed across relatively general conditions and specifications (Fisher-Vanden, 2008a; Gillingham et al., 2008; Fisher-Vanden, 2008b; Vollebergh and Kemfert, 2005). This is seen as a means by which reduced resource use may be compatible with development (Jin and Zhang, 2015; Bosetti et al., 2008). As a case in point, it is often assumed that the diffusion of technological change may be an essential part of the solution to the problem of climate change (Aronsson et al., 2010; Gerlagh and Kuik, 2014; Grubb, 2000; Hübler et al., 2012).

[3]Although the discussion is framed in terms of *technology transfer*, it could also be framed in terms of *free technology adoption* by the developing country. That is, we are assuming throughout that the policy examined here consists solely of the free transfer of a resource-conserving technology to a developing country, without other incentives or constraints for how that technology will be employed.

[4]The rebound literature primarily focuses on the question of the impacts of domestic energy policy when mediated through the responses of consumers and industries. Our paper focuses instead on the question of the impact of international policy of technology transfer when mediated through the responses of developing states. See our discussion of the specific nature of our contribution to the literature in Section 2 below.

implicit wealth transfer is applied. More fundamental preferences and institutions of the society concerned are at work to determine these things. Thus, to pursue international policies of technological change and transfer, without providing additional incentives for using them in the desired manner, will not necessarily "save the world".[5]

We proceed as follows. In section 2 we provide a brief review of the rebound effect literature, as it has been applied in considering domestic energy policy, and as we will consider it within international energy policy. In section 3 we provide our model, and a brief discussion of its implications for thinking about the impacts of international technology transfer. In section 4 we provide simulations of our results, analyzing how the free transfer of a technology might impact on a developing country's choices. In section 5 we conclude.

2 Literature Review: The Rebound Effect and International Technology Transfer Policy

Since the time of Jevons, the idea of a *rebound effect* in the context of consumer or industry responses to improvements in energy efficiency has been well-known. The modern proponents of the rebound idea once again argued that technological change in energy efficiency raises complicated problems regarding ultimate outcomes (Saunders, 2000).[6] It was recognized then that the impacts on the economy of induced technical changes might be something other than the simple advance of energy efficiency and reduced energy use.[7]

Why might technological change (and policies driving it) induce outcomes other than simple advancement in the efficiency of resource use? There have been many contributors to the resource and energy economics literature that have addressed this point in the context of the microeconomic analysis of policy impacts.[8,9] We are more interested in how this microeconomic phenomenon can be extended to the macroeconomic context. Again, others have considered this issue explicitly. Saunders (2000) discusses the wide range of

[5] Our analysis is limited to the point separating out between the issues of income transfer and incentives. We do not address how these incentives might be instilled within an international transfer mechanism, but leave this to the very substantial literature on international agreements regarding the environment.

[6] We are very grateful to Sjak Smulders for providing us with many of the ideas underlying this section, the role of the rebound effect, and how its application varies between domestic and international contexts.

[7] Much of the modern rebound literature originated in analyzing the OPEC impacts on oil prices in the 1970s (Saunders, 2000).

[8] First, some authors examine how technological change shifts the marginal abatement cost (MAC) function within firms responsible for pollution control, and determine that the shift need not necessarily be downward (i.e. a reduction in MAC). When MAC shifts upward with technological change - a "brown technology" - there will be incentives for lower expenditures on abatement by the firms subjected to the change (Smulders and Di Maria, 2012). Even if the shift in the MAC function is not ambiguously upward with the change (so that the new function perhaps intersects with the old one), the outcome for the industry will not necessarily be increased abatement expenditures (Perino and Requate, 2012). So, one important point is that the responsiveness of the abatement cost to technological change is not a given, and may drive future energy use (or polluting emissions) in very different directions.

[9] A second important question regarding the rebound effect concerns the response of consumers rather than firms. When technological change results in greater energy efficiency, the consumer-oriented literature analyses the combined substitution and income effects of the policy-induced change (Binswanger, 2001). The substitution effect resulting from greater energy efficiency induces consumers to economize on the resource concerned; however, the income effect may counteract at least a portion of the substitution effect. For example, the introduction of more energy-efficient appliances by reason of the policy change will represent an income improvement for consumers, some of which may then be expended on the expansion of energy use. It is the net effect of substitution and income effects that determines the extent of the rebound. Saunders (2000) termed a rebound effect of a scale sufficient to cancel out the positive substitution effects a "backfire". There are numerous empirical papers that look at this issue of the net effect of policy change, by looking at the elasticities of demand for energy use in certain goods as their efficiency changes (Gillingham et al., 2015; Chan and Gillingham, 2015).

potential macroeconomic impacts that might flow from domestic energy policy. Others have considered the range of macroeconomic impacts potentially deriving from international energy policies.[10]

We are less interested in the impact of general climate or energy-related policies, and more in the impact of a particular policy, i.e. the free transfer of a resource-conserving technology between nations. Also, we are trying to understand what factors determine the response of a developing country in this circumstance. In doing so, we model the developing country's policy response as a *social choice*, and the issue then devolves to how developing countries will make choices when technological endowments are increased. Since more advanced technologies represent a larger set of options for the developing country, these questions are then related to the analysis of how countries make choices in the context of increased income and development.[11]

There is a related literature on the general equilibrium effects of energy policy that addresses some of these questions (Smulders and De Nooij, 2003; Di Maria and Smulders, 2004). These papers look in part at how environmental policy might induce technological change and thus result in income shifts - and thereby impact the composition of demand for goods and services. Most of this literature is looking at how regulation reduces output and so impacts demand, and so is looking at the reverse situation to ours. Perhaps the closest one of these papers to our own finds that the impact of environmental policy depends on the assumptions concerning "the substitution pattern between environmental quality and consumption goods" (Carbone and Smith, 2008). This points to the importance of the issue of how societies choose between environmental and consumption goods, as their incomes and technologies change and advance.

Perhaps most pertinently, Smulders and Di Maria (2012) examine precisely the question of how societal preferences for environment might change relative to standard consumption with technological change, but they assume that environmental quality is a *normal good* at all levels of income - and so they are focused on the issue of increased demand for environmental quality with increased income. We examine a different case, in which developing countries have preferences over environmental and consumption goods that are normal, but are also faced with a trade-off in their choices between the underlying capital stocks that produce these goods and services. When developing countries are making choices that simultaneously impact both the capital base and the consumption portfolio, the outcome of that choice (for natural-capital sourced goods and services) is not necessarily determined by reason of the normality of preferences for the goods alone.[12]

So, our precise question is: will the transfer of advanced technologies to *developing countries* also embed

[10] Barker et al. (2009) assesses the scale of a macroeconomic rebound effect in the context of climate policies applied to the global economy. They assess three different types of rebound effects: direct rebound effects, indirect rebound effects; economy wide rebound effects. *Direct rebound effects* refer to the overall increased consumption of the energy service following a reduction in the effective price of the service as a result of policy-induced technological change. *Indirect rebound effects* refer to the consumers' income effect on other energy-using goods and services from the above-mentioned changed price. *Economy-wide effects* refer to the general equilibrium effect from the increase in energy efficiency on energy-using intermediate and final goods throughout the economy. The authors find that all of these effects exist under a range of climate policies, and estimate that the aggregate indirect and economy-wide rebound effect results in a loss of about 50% of the direct positive impact of the policies investigated (Barker et al., 2009). So, in the context of one macroeconomic model, it has been argued that the rebound effect exists at the level of international policy effects, and that its magnitude is of some consequence.

[11] We return more to the question of the appropriate conceptualization of pathways of development below, but suffice it to say here that we are focusing on how countries with given preferences allocate growth between the objectives of environmentally-supplied goods and services and other goods and services, and how this alters across development.

[12] In this setting, environmental goods may end up declining (despite increased income) as the result of a conversion process in which the developing society moves away from reliance on primarily natural capital and toward a more mixed portfolio of natural/physical capital (Stokey, 1998).

incentives in those societies to use them as would developed countries, or will transfers simply encourage the society concerned to pursue more rapidly a standard development path (using up resources even more rapidly)? To address this question, we make use of the framework of resource-based development to explain how developing countries alter their choices between natural and consumption goods as they develop (the so-called Environmental Kuznets Curve (EKC) hypothesis) (Stokey, 1998; López and Yoon, 2014).[13] Another way to phrase our enquiry is to ask whether the free transfer of technology will result in "tunneling through" the EKC or simply in a more rapid movement along the pre-existing pathway. Technology optimists would hope for the former, while believers in the salience of the rebound effect would contend that the latter outcome is more likely.[14]

Will developing countries expend these sudden gains by expanding the stock of natural capital and its services, or will they simply continue (more rapidly) along the same development path that they were already following? Our conclusion is that a policy of free technology transfer will result in two distinct and potentially countervailing effects in a developing country. As a direct result, the benefits from technological change will result in the adoption of more efficient technologies, and substitution away from the use of the natural resource. The indirect - or rebound - effect is that the transfer of such technologies will create a larger set of options for such countries, that may be expended in any way that the recipient of the technology views as welfare-improving. This means that, if the country is at an early stage of development at the time of the transfer, technology transfer may result in enhanced rates of resource utilization given the available technologies, rather than reduced rates of use. Technologies mainly expand the set of options, but do not necessarily determine how those options need be expended.[15]

In short, our contribution to the rebound literature is relatively modest, but very specific. We shed light on how a policy of free transfer of a resource-conserving technology to a developing country might impact upon its use of resources. We find that the primary factor determinative of the manner in which the transfer is expended will be the pre-existing preferences of the country regarding its development path. The technology will of course encourage some direct substitution on account of the change in relative prices, but the main question is how the income effect of the transfer is expended. We demonstrate that this is primarily a matter that concerns the country's elasticity of marginal utility with regard to consumption goods as well as the capacity for management to be effective in maintaining natural capital stocks.

In the remainder of this paper we explore the way in which development paths are chosen, and the ways in

[13] López and Yoon (2014) use a more general model incorporating the scale-composition-technique effects to confirm the findings of Stokey (1998) that the EKC is a potential consumption path for developing countries, depending primarily on the elasticity of marginal utility with regard to consumption as the critical parameter determining the existence of an EKC (i.e. a path that ultimately turns toward higher environmental quality).

[14] Our contribution is simply to demonstrate that the free transfer of technologies operates very much in the same way as a transfer of income or wealth (See e.g. Munasinghe, 1999). Although voluminous, it would seem fair to say that the EKC literature broadly concludes that the EKC can be tunneled through rather than traversed, to the extent that the subject countries elect to engage in enhanced regulation, i.e. implement policies to alter their balance of flows of goods and services (Dasgupta et al., 2002). As detailed below, we concur with this conclusion in the context of technology transfer, and demonstrate that changes in relative conversion rates need not provide much more in the way of incentives to alter flows of goods and services, than does a direct transfer of wealth or income.

[15] The difference between a simple income transfer and a technology transfer lies in the change in the "conversion rate" that technology implies (as will be defined in the next section). A contribution of this paper is to demonstrate the limited difference that such changes in conversion rates make relative to income transfers under certain conditions.

which technology transfer might alter those choices (if at all). In the next section we set out our modeling of a development process as capital conversion, and a general description of the manner in which the free transfer of enhanced technologies alters choices by developing countries. And following that we use simulations of this model to demonstrate the manner in which these choices are made under varying parametric assumptions.

3 Modeling Development Paths with Technology Transfer

In this section, we describe the basic model of capital-based development (à la Stokey, 1998), with a country in an early phase of development selecting its desired portfolio of goods and services (consumption goods, natural-capital services such as health) based on fixed preferences but changing capital stocks. We subsequently examine the manner in which technology transfers impact the timing of these choices.

3.1 A Model of Development with Resource Conversion

We will start with the assumption that a given country's stage of development is represented by the state of its capital portfolio. High levels of natural capital (and relatively low levels of physical capital) are indicative of generally undeveloped countries. The converse is true for the more developed. Here, we focus on developing countries. Each developing country is represented by a social planner whose objective function is a discounted flow of utility U derived from the consumption of a private consumption good c and from the stock of environmental quality or natural capital N (e.g. in the form of a flow of health benefits).[16] The planner's problem is to maximize the discounted social welfare function subject to the dynamics of both capital stocks, initial conditions and a non-negativity constraint. This problem can be written as follows:

$$
\begin{aligned}
W(k(0),N(0)) &= \max_{c(t),m(t)} \mathbb{E}_0 \int_0^{\infty} [U(c(t),N(t))]e^{-\rho t}dt \\
\text{s.t. } \dot{k}(t) &= f(k(t)) - c(t) - m(t) \\
\dot{N}(t) &= \Psi(m(t)) - \phi f(k(t)) \\
m(t) &\geq 0 \\
k(0) &= k_0 \\
N(0) &= N_0
\end{aligned}
$$

$f(k(t))$ is an increasing and concave production function;[17] $m(t)$ represents environmental management and

[16]We think of the flow of goods and services from N as being of the nature of health benefits, and so a relatively concrete but distinctive set of goods and services from those flowing from k, but we model the problem as being a direct flow from the natural capital base for purposes of simplifying the exposition. For similar modelling, see e.g. Bovenberg and Smulders (1996) and Fullerton and Kim (2008).

[17]We acknowledge that including N as a second input could make the production function more general. In such a case, the outcome would depend on the degree of substitutability between the two inputs. In case of high substitutability between k and N, the social planner may decrease natural capital while increasing the stock of physical capital and get more consumption (although she

raises the level of natural capital through environmental protection function $\Psi(m(t))$. For simplicity of the exposition, we assume that the depreciation rate of physical capital stock is 0.[18]

The utility function is specified as:

$$U(c(t),N(t)) = \frac{c(t)^{1-\sigma}-1}{1-\sigma} + \chi\frac{N(t)^{1-\eta}-1}{1-\eta}$$

where σ and η are the curvature parameters or the inverse of the elasticity of intertemporal substitution, respectively and χ is the weight placed on natural capital.[19] This specification enables us to capture non-homotheticity of preferences to model the fact that as the country grows wealthier, it spends relatively more on some goods than on others (e.g., Deaton and Muellbauer, 1980; Ait-Sahalia et al., 2004;Wachter and Yogo, 2010). We assume that $\sigma < \eta$, i.e. the country prefers an increasing share of flows of consumption goods c relative to flows from natural capital N as it becomes wealthier (Ait-Sahalia et al., 2004; and, Wachter and Yogo, 2010). This is probably likely the case for a developing country in the early stages of its development.

Most fundamentally, this is a model that describes how a society might value flows of services deriving from two different types of capital: physical and natural. Physical capital k is used to produce the consumption good. Natural capital N generates basic health and environmental services. The model provides that society has given parameters (elasticities of marginal utility with regard to consumption and with regard to natural capital-based services) that determine how it values the relative flows of such services. One fundamental object of society is to achieve a portfolio of capital that achieves the optimal balance of flows from the two forms of capital.

Given the initial conditions placed on the capital stocks, the process of development may be represented as a move from one particular portfolio toward the parametrically-determined optimal portfolio. We define a *developing country* as a society that commences with a large natural capital stock N_0 and a very low physical capital stock k_0. The *process of development* then occurs through capital conversion, by which a country converts its natural capital stock into physical capital (or consumption services) at a technologically-determined conversion rate of ϕ (Xepapadeas, 2005). We now describe this development process, and how it relates to capital conversion, in greater detail.

We view the exchange rate or resource intensity ϕ as a measure of technologically-determined efficiency within the production process, where an increased level of technology (which translates into a reduction in ϕ) enables the same level of production to occur at a reduced rate of natural capital conversion.[20] Conversion

faces a trade-off between c and N). By contrast, in case of low substitutability, the social planner is likely to pursue a more balanced path. In either case, a decrease in ϕ is likely to strengthen our results by inducing an increase in physical capital accumulation and consumption as well as a decrease in natural capital (albeit at a higher level). The outcomes will be similar to what we already have, the only difference being the pace and magnitude at which physical capital accumulation, consumption growth and depletion of natural capital take place.

[18] With some abuse of notations, we will liberally drop the time argument of our time-variant variables when there is no risk of confusion.

[19] One could use a more general specification such as a CES function to feature a non-separable utility function (implying a positive cross-derivative $U_{cN} > 0$). However, for ease and simplicity of exposition and clarity of the results, we have opted for a utility function that is separable in its arguments so that $U_{cN} = 0$. We follow closely Stokey (1998) who relies on a similar separability assumption.

[20] To fix the meaning of ϕ: Consider it to be represented by the amount of N consumed in the production of a unit of GDP. It

is occasioned through the production process, by assuming that the level of natural capital is reduced by a factor ϕ for each unit of production. This means that a reduction of natural capital amounting to $\phi f(k)$ occurs at each point in time.[21]

In accord with our definition above, a developing country is one continuing within the capital-conversion process, i.e. one for which the ratio of physical capital over natural capital $\kappa \equiv k/N$ is below the steady-state level $\kappa^{\infty} \equiv k^{\infty}/N^{\infty}$, i.e. $\kappa < \kappa^{\infty}$, (where the steady state will be characterized later). Because of the initial imbalance between the two stocks of capital (excess of natural capital and scarcity of physical capital), a developing country starting with large stock of natural capital (N_0) and low stock of physical capital (k_0) might simply elect at the outset to make use of the existing technological relationships in order to deplete natural capital and alter its capital portfolio in this way - a natural resource extracting economy building a new capital-based economy. This is the way in which capital conversion may be used to drive the development of the country, holding technology constant.[22]

In order to enhance its control over the changing vector of services from physical and natural capital, the developing country may also elect at some point in time to invest in management services. *Management* attempts to control directly the composition of the vector of services enjoyed by the economy through institutional investments and efforts. This is accomplished by investing an amount m of forgone consumption into management, through which the country produces an amount of natural capital equal to $\Psi(m)$. This environmental protection function can be interpreted more broadly than a typical emissions abatement function. Not only does it incorporate typical end-of-pipe technologies such as carbon capture and storage (CCS), but it may also include less conventional technologies such as geo-engineering, or restoration of degraded environment.[23]

Assumption A1: *Let Ψ be an strictly increasing and strictly concave function, i.e. ($\Psi'(m) > 0$ and $\Psi''(m) < 0$) such that $\Psi(0) = 0$ and $\Psi'(0) = 1$ (normalization). We postulate that $0 < \phi \leq \Psi'(0)$.*

The concavity of Ψ helps clarify Assumption A1. Since Ψ' is decreasing in its domain, we have $\Psi'(0) = \max_m \Psi'(m)$. There exists a management level $\overline{m}$ defined by $\Psi'(\overline{m}) \equiv \phi$ such that $\Psi'(m) \geq \phi$ for $m \leq \overline{m}$.[24] In other words, it is assumed that the marginal productivity of environmental management is greater than the marginal emissions per unit of output ϕ. If we interpret $\Psi'(m)$ as reflecting the effectiveness of governance

also represents the rate of capital conversion because the loss of a unit of natural capital represents the reduction in the flow of natural-capital services (e.g. a reduction in health preserving services on account of an increase in pollution that results from the reduction of natural capital stocks). That is, increased k is used to generate increased consumption goods $f(k)$, and ϕ is the rate at which N is reduced in the face of increased production $f(k)$ and so implicitly declines with increased capital k. In this manner, increased physical capital stocks (and production) draw down on natural capital stocks (and their services); equivalently, the natural capital is being converted into physical capital at the exchange rate (or resource intensity) ϕ.

[21] Equivalently, the technological conversion coefficient may be termed the pollution or emission intensity rate of production. We focus on capital conversion (and resource intensity) because the object of our enquiry is to assess how this development path is altered by changes in technology, and our focus is on developing countries as we define them below.

[22] We view this as an explication of the development process as capital conversion, as described by Stokey (1998).

[23] The choice of such a broadly defined environmental remedial function enables us to show even with non-conventional mitigation technologies, the possibility of a rebound effect may exist on a macro level, highlighting the possible limits of relying solely on technology improvement such as reduced resource intensity to alter the priorities of developing countries towards maintaining the natural capital stock.

[24] Note that beyond $\overline{m}$, it would make more sense to reduce output than to invest in management.

with regard to natural capital management, this assumption implies that ϕ is a lower bound for environmental governance effectiveness.

To distinguish the effects of management from natural capital-saving technological change, we will assume that the control variable corresponds to management expenditures that restrict access to the natural resource (through prices or quantity controls), and so reduces the amount of natural capital depletion occurring at a given level of production.[25]

We are concerned with two questions: *(i)* how does a change in natural capital-saving technology impact the development/conversion process within this economy? and *(ii)* when does a developing country elect to engage in the management of its own natural capital depletion process?

3.2 Optimal Development with Resource Conversion and Environmental Management

The above model may be used to demonstrate the manner in which countries will use capital conversion and portfolio development as a standard development strategy. The first order conditions provide the basic engine for the way in which a country pursues development within this model, and are given by:

$$\begin{aligned} U_c &= \lambda && (1) \\ 0 &\geq -\lambda + \mu \Psi'(m) \text{ with equality if } m > 0 && (2) \\ \frac{\dot{\lambda}}{\lambda} &= \rho - \left(1 - \frac{\mu}{\lambda}\phi\right) f'(k) && (3) \\ \frac{\dot{\mu}}{\mu} &= \rho - \frac{U_N(c,N)}{\mu} && (4) \end{aligned}$$

where λ and μ represent the co-state variables associated with k and N respectively. The transversality conditions read as:

$$\begin{aligned} \lim_{t\to\infty} e^{-\rho t}\lambda(t)k(t) &= 0 \\ \lim_{t\to\infty} e^{-\rho t}\mu(t)N(t) &= 0 \end{aligned}$$

Assumption A.2: *Initial capital stocks* (k_0, N_0) *are such that* $k_0 < f'^{-1}\left(\frac{\rho}{1-\frac{\mu_0}{\lambda_0}\phi}\right)$ and $\frac{U_c(c_0,N_0)}{U_N(c_0,N_0)} > \frac{1}{\rho}$.

where the variables with subscript 0, denote the value of the variables at time $t = 0$. These initial conditions establish only that the initial portfolio is "out of balance" and so the developing country is one that optimally will pursue capital conversion.

[25] The modeling of the dynamics of natural capital is the environmental quality version of the pollution stock model presented by Xepapadeas (2005, 1239).

Proposition 1:

Given the technical capital conversion rate (or resource intensity) ϕ, a developing country with initial conditions (k_0, N_0) will pursue capital-conversion based development in the following manner:

a) The developing country will refrain from undertaking environmental management (i.e. $m(t) = 0$) so long as $t \leq \tilde{t}$ where the optimal time $\tilde{t}$ is implicitly defined by $\lambda(\tilde{t}) = \mu(\tilde{t})$.

b) For $t \leq \tilde{t}$, the developing country will reduce the stock of natural capital N from the initial level N_0 and increase the stock of physical capital and the amount of consumption.

c) For $t > \tilde{t}$, the developing country uses management $m(t) > 0$ to achieve the optimal balance of flows from c and N by reducing the rate of growth of consumption and physical capital while reducing (and possibly countering) the depletion of natural capital.

d) Reduced ϕ leads the social planner to delay the time at which environmental management is undertaken, that is, $\partial\tilde{t}/\partial\phi < 0$.

Proof: See Appendix.

Equation (1) is the static efficiency condition that requires that the *marginal value of the flow of services* from physical capital (flow of consumption) be equal to the *marginal value of the stock* of this asset. In the short run, an interior solution for the flow of management is implicitly defined by the equality $\lambda = \mu\Psi'(m)$, i.e., the marginal value of the stock of physical capital equals the marginal value of natural capital regeneration due to management. This ensures that the marginal value of physical capital is the same in all of its uses. Similar to Selden and Song (1995), the non-negativity restriction $m \geq 0$ brings the possibility of a corner solution. Indeed, when the marginal utility of consumption is greater than the benefit from management, i.e. when $\lambda \geq \mu$, the non-negativity constraint binds resulting in $m = 0$.

The dynamic efficiency conditions (3) and (4) require that the rate of return to each asset, including its own rate of return and any increase in its value, is equal to the rate of discount, and so each asset earns the same social return. So, the returns from the two forms of capital are equalized. The dynamics (for the developing country) in this model is one in which assets in the form of natural capital are divested in order to secure increased levels of physical capital assets in order to bring their returns into balance.

In the case of interior solutions (region where $m > 0$ and $\lambda = \mu\Psi'(m)$), the dynamics of the co-state variables, consumption and environmental management obtain:

$$\frac{\dot{\lambda}}{\lambda} = \rho - \left(1 - \frac{\phi}{\Psi'(m)}\right) f'(k) \quad (5)$$

$$\frac{\dot{\mu}}{\mu} = \rho - \frac{U_N}{U_c}\Psi'(m) \quad (6)$$

$$\frac{\dot{c}}{c} = \frac{1}{\sigma}\left[\left(1 - \frac{\phi}{\Psi'(m)}\right) f'(k) - \rho\right] \quad (7)$$

$$\dot{m} = \frac{\Psi'(m)}{\Psi''(m)}\left\{\frac{U_N}{U_c}\Psi'(m) - \sigma\frac{\dot{c}}{c} - \rho\right\} \quad (8)$$

There are two interesting points to be mentioned regarding the dynamics of consumption. First, the fundamental factor determining the trajectory of consumption will be the elasticity of marginal utility with regard to consumption, σ, as its value determines the degree to which the relative interest in increased consumption slows with increasing levels of consumption. Secondly, the path of consumption continues to increase only so long as there continues to be a relatively positive return to increased levels of physical capital. Management is seen to be a factor that only comes into play once sufficient capital conversion has been undertaken.

In sum, this capital-conversion model of development demonstrates how a developing country might move from an initial capital portfolio (of maximum levels of natural capital, low levels of physical capital) towards one more balanced between physical and natural capital. The objective of balancing consumption services and natural-capital based services drives the process. It comes to rest once the capital portfolio is in balance relative to utility-based preferences.

Finally, we have characterized how the critical timing $(\tilde{t})$ of environmental management is impacted by technology transfer. Reduced ϕ induces the developing country to delay the time of initiating environmental management. The reason is that a fall in ϕ has the direct effect of increasing the physical capital stock and therefore shifts its shadow value curve $(\lambda(t))$ upwards. There is however no direct effect on the scarcity value of natural capital, $\mu(t)$. In fact, as improved technology is adopted by the developing country (fall in ϕ), output becomes less harmful, so that there are greater social returns to investing in production capacity. This results in delayed expenditure on management, faster consumption growth and physical capital accumulation. So, increasing technical efficiency delays the date of introduction of environmental management.

3.3 Impact of Technology Transfer on Capital Stocks and their Management (the Steady State)

Given that the technology change is embedded within resource-based technologies, it is often assumed that such transfers will create incentives to make use of these technologies to increase the amount of management undertaken or the amounts of natural capital maintained. However, the rebound effect literature suggests that this might not necessarily be the case. This leaves open the question of whether the adoption of improved technology by the developing country will ultimately result in greater environmental performance? In order to investigate this issue, we will now characterize the effect of technology transfer (reduced ϕ) on the steady states of our key variables.

Suppose the steady state lies beyond the threshold $\tilde{\kappa}$ where $\tilde{\kappa} < \kappa^{\infty}$, and the steady-state levels $(k^{\infty}, N^{\infty}, c^{\infty}, m^{\infty})$ satisfy the usual conditions $\dot{k} = \dot{N} = \dot{c} = \dot{\lambda} = \dot{\mu} = 0$. Then, the first order conditions for the optimal steady state are as follows:[26]

[26] We can see that the steady state $(k^{\infty}, N^{\infty}, c^{\infty}, m^{\infty})$ exists in this problem. Indeed, solving the system of equations (9) and (12) yields implicitly k^{∞} and m^{∞}. It is then straightforward to obtain c^{∞} from equation (11), and subsequently N^{∞} from equation (10).

$$\begin{aligned}
\left(1-\frac{\phi}{\Psi'(m^{\infty})}\right)f'(k^{\infty}) &= \rho \quad (9)\\
\frac{U_N}{U_c}\Psi'(m^{\infty}) &= \rho \quad (10)\\
f(k^{\infty})-c^{\infty}-m^{\infty} &= 0 \quad (11)\\
\Psi(m^{\infty})-\phi f(k^{\infty}) &= 0 \quad (12)
\end{aligned}$$

Proposition 2:

a) A reduction in ϕ unambiguously increases the steady-state level of physical capital and consumption; i.e. $dk^{\infty}/d\phi<0$ and $dc^{\infty}/d\phi<0$.

b) A reduction in ϕ reduces the management level m^{∞} $(dm^{\infty}/d\phi>0)$ if $\Psi'(m^{\infty})>\phi\left(1-\frac{f'(k^{\infty})^2}{f(k^{\infty})f''(k^{\infty})}\right)$ is satisfied, and increases m^{∞} $(dm^{\infty}/d\phi<0)$ if $\Psi'(m^{\infty})<\phi\left(1-\frac{f'(k^{\infty})^2}{f(k^{\infty})f''(k^{\infty})}\right)$ is satisfied.

c) A reduction in ϕ increases the stock of natural capital N^{∞} $(dN^{\infty}/d\phi<0)$ if and only if :

- *(i) $\Psi'(m^{\infty})>\phi\left(1-\frac{f'(k^{\infty})^2}{f(k^{\infty})f''(k^{\infty})}\right)$, or*[27]
- *(ii) $\Psi'(m^{\infty})<\phi\left(1-\frac{f'(k^{\infty})^2}{f(k^{\infty})f''(k^{\infty})}\right)$ and $\left[-\frac{U_{cc}}{U_c}>-\frac{\Psi''(m^{\infty})}{\Psi'(m^{\infty})}\frac{dm^{\infty}/d\phi}{dc^{\infty}/d\phi}\ \text{or}\ \sigma>\varepsilon\frac{\theta_m}{\theta_c}\right]$*
  where $\sigma=-\frac{U_{cc}}{U_c}c$, $\varepsilon=-\frac{\Psi''(m)}{\Psi'(m)}m$, $\theta_c=\frac{dc}{d\phi}\frac{\phi}{c}$ and *$\theta_m=\frac{dm}{d\phi}\frac{\phi}{m}$.*

d) The effect of a reduction in ϕ on the steady-state stocks of natural capital increases with aversion to intertemporal elasticity of substitution σ, i.e. $\frac{\partial}{\partial\sigma}\left(\frac{dN^{\infty}}{d\phi}\right)<0$ if and only if $c^{\infty}<e^{1/\sigma}$.

Proof: See Appendix.

Part *a)* of the Proposition confirms that in the steady state there will be an unambiguous increase in physical capital and consumption goods resulting from improved technology. This increase in physical capital and consumption can be generated from the initial endowment of natural capital N_0, simply because more output can be produced per unit of natural capital. This means that, for any level of natural capital retained in the final portfolio, higher levels of consumption goods are feasible.

Parts *b)* and *c)* of the Proposition pertain to the developing country's incentive to maintain a greater proportion of natural capital in the final portfolio, given the free availability of the higher level of technical

[27] This is seen most clearly if the production function is specified; for example, if $f(k)=Ak^{\alpha}$, then this condition becomes $\Psi'(m)<\phi/(1-\alpha)$.

efficiency ϕ. The transfer of technology acts primarily as a wealth transfer because of its effect on increased physical capital accumulation k and therefore increased total output $f(k)$. Then this wealth effect in turn generates two countervailing effects. The first effect pertains to the rise in the consumption of both c and N as a result of increased total output and the normality of the assumed preferences. We term this the standard *normality-based consumption* of goods c and N given the social planner's preferences.[28] The second effect pertains to what we term the *natural capital natural capital accumulation effect, i.e.,* the potential expansion or reduction of the natural capital stock along the development path (or the natural capital state equation). *Ceteris paribus,* natural capital reduces as a direct result of the demand for increased output of standard consumption goods (as per state equation $\dot{N} = \Psi(m) - \phi f(k)$). In general however all things are not equal, in that environmental management m can be used as an instrument to control for the stock of natural capital along this path.[29] Therefore, whether the stock of natural capital decreases or increases depends in part on the effectiveness of the environmental protection function $\Psi(m)$, which we will refer to as a question of institutional efficiency.[30]

When environmental management is so effective that its impact on natural capital expansion outweighs the natural capital reduction originating from increased output, there is an overall increase in the amount of natural capital within the final portfolio. This is because, in the case of management effectiveness, the income effect resulting from the *normality* of N and the *natural capital accumulation effect* reinforce one another.

However, when environmental management is somewhat less effective (the more usual case), then an increase in the optimal stock of natural capital depends on other factors as well. The reduced effectiveness of management (which is reflected in the concavity of Ψ) may then result in an optimal path in which there is a reduced stock of natural capital. This is the the case when expenditures on m are an extremely ineffective means of providing natural capital stocks. When this is the case, then the more effective means of providing enhanced stocks of physical capital may be the conversion of natural capital.

This may result in a *rebound effect* if the decrease in the stock of natural capital resulting from the high cost of providing N via conversion (*natural capital accumulation effect)* exceeds the increase in N from the *normality* of consumption.[31] And, in particular, this rebound effect occurs whenever the curvature of the

[28] In this case, the assumed non-homothetic preferences characterized by $\eta > \sigma$ lead to a bias in favour of private consumption goods c because c increases at a faster rate than N.

[29] Note that we established in equation (10), that in the steady state, the optimal provision of natural capital is given by $\frac{U_N}{U_c}\frac{1}{\rho} = \frac{1}{\Psi'(m^\infty)}$. In other words, the social planner's discounted marginal rate of substitution of natural capital for consumption goods is equal to the marginal cost of providing N, i.e., $\frac{1}{\Psi'(m^\infty)}$. This relationship is equivalent to the optimal provision of a public good by the social planner assuming that the population of the country is normalized and equal to 1.

[30] The important point here is to distinguish between the effects of technological and institutional endowments. We do so by restricting technological change to those changes that alter the rate of conversion between capital stocks, while restricting institutional change to those changes that alter the rate at which foregone consumption is able to translate directly into increased natural capital stocks. Obviously, the two concepts are closely related in that they both represent alternate methods for enhancing natural capital stocks, at a given level of physical capital, and we separate out between them simply to indicate that we believe that there are two distinct techiques for doing so. For example, a technological change could represent a new form of physical capital that produces the desired output with reduced natural capital input (e.g. a more fuel efficient automobile), whereas an institutional change could represent an expenditure of national income on management to reduce inefficient usage of natural capital (e.g. a tax on air pollution that internalises an externality and thus causes a firm to reduce its production to a more efficient level).

[31] The increase in N through the income effect is bound to be moderate because of the non-homotheticity of the preferences where

utility of consumption goods is smaller than the curvature of the environmental management function given the response of c and m to a change in ϕ, i.e., $\sigma < \varepsilon \frac{\theta_m}{\theta_c}$. In other words, rebound occurs when the elasticity of intertemporal substitution of consumption goods $(1/\sigma)$ is large enough (low satiation) and consumption grows fast enough that it makes sense to reduce the level of natural capital given the cost of providing N.

Finally, part *d)* of Proposition 2 suggests that for sufficiently low consumption, the gain in natural capital from technology transfer is greater for countries that are more sensitive to consumption smoothing. As a result, countries that are not sensitive to large swings in consumption (smaller σ) are likely to enjoy very little gain in natural capital stock because they prefer to deplete their resource stock following technology transfer in order to hasten their accumulation of physical capital.

Hence, the conclusion from Proposition 2 is that the ultimate impact of a free transfer of technology depends upon both the preferences and the institutions within the recipient society concerned - in that these preferences and institutions then determine the society's choices of the forms and stocks of capital along its optimal development path. It is not a given that a policy of technology transfer necessarily confers incentives upon the society for the retention of increased stocks of natural capital.

3.4 Discussion: assessing the potential impact of international technology transfer policies

As in the rebound literature on macroeconomic impacts, we have shown that the net effect of a policy of free technology transfer may move in any direction, even "backfire" is feasible (Saunders, 2000). In the microeconomic rebound effect literature, the reason for this ambiguity is the net outcome of substitution and income effects, which occur at the consumer level (Binswanger, 2001). The substitution effect results from the reduced price of goods that rely on the more efficient technology, while the income effect results from the general change in policy and the transfer it implies.

In our analysis, we transpose this microeconomic framework into a macro and developmental perspective. The question of how a society makes its choice within this increased opportunity set depends significantly on how the society values flows from c relative to N as the consumption set expands, as well as the relative costs of providing the two different types of goods. If natural capital goods N are indeed *normal goods*, then the endowment effect results in an increased demand for their goods and services. This is often the case, and it implies that the technology spillovers will have positive impacts on the environment (Smulders and Di Maria, 2012). However, this need not be the case along the entire development path when natural capital is also able to be converted into physical capital. As demonstrated in the general literature on growth, environment and development, natural-resource based goods and services may follow very different paths depending on the state of development of the country concerned (López and Yoon, 2014). Countries at low levels of development will usually have a preference for consumption goods relative to nature-supplied goods and services (even though both are normal), and may sometimes convert natural capital to physical capital in order to pursue higher levels of consumption goods (Stokey, 1998).

This will be the case only when management is not an effective means of preserving natural capital stocks. If a country has relatively ineffective management institutions (in the sense that expenditures do not result in

$\eta > \sigma$.

substantial conservation of natural capital), then the sole means of providing higher levels of consumption goods may come at the expense of the conversion of natural capital. If management institutions present a relatively efficient alternative, then the additional technique will render feasible the combined pursuit of natural and consumption goods; however, the presence of such institutions is not a given within developing countries (and in fact may be endogenously determined).[32]

Thus, we would argue that the composition of consumption is indeterminate given the fact of transfer of technology alone, unless it is known how the society wishes to use that particular transfer at that particular point in its development. This preference-based effect is well-known in the EKC literature, and is subject to some debate concerning how societies do in fact allocate income gains across time (Barbier, 1997; Millimet et al., 2003; Stern, 2004). For our purposes, the only necessary point is that this is an empirical question, and not a given. The impact of technology transfer on a country's balance of natural goods and consumption goods is fundamentally determined by the country's preferences as well as the effectiveness of the institutions it has for managing natural capital.

This means that technological change and transfer does not *in itself* transfer the incentives to use that resource-conserving technology to conserve resources. A transfer of technology does little more than a pure wealth transfer in determining the path that the country will elect to follow. For this reason, our model demonstrates the idea that, if you believe in the existence of an EKC-charted path of trade-offs between environment and consumption goods (à la Stokey, 1998), technology transfer then has the effect of moving a country more rapidly along its EKC path rather than moving directly to another point on the EKC (i.e. tunneling through the EKC). In short, the technology used by more developed countries to achieve a particular balance of environment/consumption goods will not necessarily, when transferred to less developed countries, transfer the developed country's preferences for a particular set of goods and services to the developing country. In this view, the transfer does not provide incentives to alter the developing country's fundamental choices, but instead enhances the rate at which a country pursues its existing pathway. Incentives must be supplied in addition to the technology.

4 Numerical simulation of the model

Our discussion to date has been meant to demonstrate that technological change in a standard development model with natural resources has the effect of generally increasing the options available to a developing country, not necessarily altering its priorities along that path. The change in the conversion rate will result in the capacity for the country to reach higher levels of welfare in the steady state, but the enhanced retention of natural capital in the final portfolio depends instead on: a) the capacity for consumption goods to continue to produce welfare flows, and b) the incapacity of environmental management to restrict losses of natural capital. In short, technological change (and transfer) without other interventions, may do little to impact the underlying problem of natural resource depletion. Under some conditions, technological progress could even backfire and cause increased natural capital depletion.

[32]One of the principal points of the Stokey analysis of the EKC is that expenditures on management are endogenous to the country's preferences concerning natural and standard consumption.

The propositions and arguments developed above are explored here in the context of simulations of the same model of capital-based development. We calibrate our model for parameters taken from the general literature relating to development and technology. We first explore the model by varying the level of technological efficiency (i.e. ϕ) made freely available to the developing country. We use this to explore the impact of technology transfer policy on the chosen development path, in terms of the affected society's election of stocks of physical and natural capital, consumption goods, and the timing of environmental management.

Then we explore the model further to ascertain how institutions and preferences influence these outcomes. We first explore the role of the effectiveness of environmental management institutions in the impact of technology transfer. We find that less-effective management institutions results in a proclivity for the use of natural capital conversion. This means that lower rates of capital accumulation and consumption occur in general, and less natural-capital accumulation occurs in relative terms, and hence less welfare. In our simulation this effect is so pronounced that "backfire" occurs, i.e. the rebound is so severe that increased technical efficiency actually results in reduced levels of natural capital.

Finally we examine how the elasticity of marginal utility with regard to consumption goods shapes the impact of technology transfer policy. We show that a reduced elasticity of utility with regard to consumption results in a much-enhanced rate of physical capital accumulation and reduced rate of natural capital retention.

4.1 Baseline Calibration

Functional specifications:

$U(c,N) = \dfrac{c^{1-\sigma}-1}{1-\sigma} + \chi \dfrac{N^{1-\eta}-1}{1-\eta}$.

$f(k) = Ak^{\alpha}$

$\Psi(m) = \dfrac{1}{\gamma}\left[(1+m)^{\gamma}-1\right]$. This specification satisfies $\Psi(0) = 0$ and $\Psi'(0) = 1$.

As shown in Table 1, we calibrate our model using values found in the literature (Aronsson et al., 2010; Stokey, 1998; Lemoine and Traeger, 2014; Fullerton and Kim, 2008). The calibration of pollution intensity or conversion rate ϕ is critical to our paper. We use the emission (pollution) intensity calibrated by Aronsson et al. (2010) for the South in their baseline scenario. In that study, the parameter values range from an emission/output ratio of 0.546 to 0.149 over a period of 130 years. We restrict our simulation exercise to the values $\{0.546; 0.390; 0.290\}$.[33] Otherwise, we vary the parameter values for the efficiency of management and the elasticity of utility for consumption - in order to demonstrate the importance of these parameters in determining the path of consumption, given technology transfer.

[33]That is, for a developing country that has currently a pollution intensity of 0.546, what would be the effect of adopting a foreign technology that enables it to benefit from a technology improvement of 30 years ($\phi = 0.390$), or 60 years ($\phi = 0.290$).

Table 1: Baseline Calibration

Parameter	Value	Description	Source
Preferences parameters			
σ	1.5	Aversion to intertemporal elasticities of substitution of c	Bovenberg and Smulders (1996)
η	1.7	Aversion to intertemporal elasticities of substitution of N	
χ	0.7	Share of natural capital in utility	Fullerton and Kim, 2008
ρ	0.015	Discount rate	Lemoine and Traeger, 2014
Production parameters			
A	1.6	Production technology	Stokey, 1998
α	0.3	Capital share	Lemoine and Traeger, 2014
Environmental parameters			
γ	0.8	Efficiency of management	
ϕ	$\{0.29; 0.39; 0.546\}$	Pollution/resource intensity	Aronsson et al. 2010

4.2 Simulation of Changes in Development Path Given Free Transfer of Technology

We now turn to the results of our simulations under the calibration set out in Table 1.[34] In accord with our discussion above, we are interested in the extent to which the transfer of resource-conserving technologies generates incentives (or not) for conserving resources (i.e. more natural capital in the portfolio). We are also interested in the characteristics of the country (preferences or institutions) that contribute to the impact of technology transfers.

4.2.1 The Impact of Technology Transfer Policies on the Steady State

We model the transfer of technology as a free transfer of improved resource efficiency to the developing country. Figure 1 demonstrates the impact of improved technological efficiency (i.e. as efficiency shifts from $\phi = 0.546$ to $\phi = 0.29$) on the developing country's steady-state levels of capital, consumption and management. This shift to greater resource efficiency results in a doubling in the physical capital stock over 100 years. Over the same time period, the amount of natural capital retained within the capital portfolio has increased by about 80%. The incentives to engage in environmental management have actually been deferred into the future, commencing in ten years under the least efficient technology but only in 25 years under the more efficient one. The long term response to the technology transfer is to considerably enhance the rate of accumulation of physical capital relative to the retention of natural capital, and to defer management, indicating that the reduced resource intensity ϕ is being expended on moving more rapidly through the same development path. The enhanced welfare resulting from the technology transfer is demonstrated by the increase in standard consumption by more than 100% in addition to the expansion in natural capital.

4.2.2 What determines the Impact of Technology Transfer?

As discussed in Proposition 2, one of the main factors determining the impact of technology transfer is the quality of the environmental management institutions in the recipient country. This is demonstrated in Figure 2, where the reduced efficiency of management institutions is represented by a shift from $\gamma = 0.8$ to $\gamma = 0.27$. In this instance the reduced efficiency of management institutions renders it less feasible for management to substitute for conversion (of N) in the maintenance of the stock of natural capital. This means that it is less likely to simultaneously attain *both* higher levels of physical capital and higher levels of natural capital. So, we see in Figure 2 that physical capital stocks are much lower than those in Figure 1 while natural capital stocks are actually falling relative to Figure 1 and are no longer monotonic with respect to technical change. Environmental management is deferred with increasing technical efficiency, shifting out from 5 to 20 years in the future. The overall outcome of the reduced institutional efficiency is that both natural and physical capital stocks are decreased, but the decrease is relatively greater for natural capital than for physical. The rebound effect occurs because the relatively ineffective management renders conversion a more likely instrument for generating physical capital stocks. There is a trebling of consumption goods with

[34]The optimal control problem for the simulation was solved using GPOPS-II (Patterson and Rao, 2014). We thank Antony Millner for sharing code and tricks.

increased technical efficiency, because the level of consumption is remarkably low under the combination of low technical efficiency and low management efficiency.

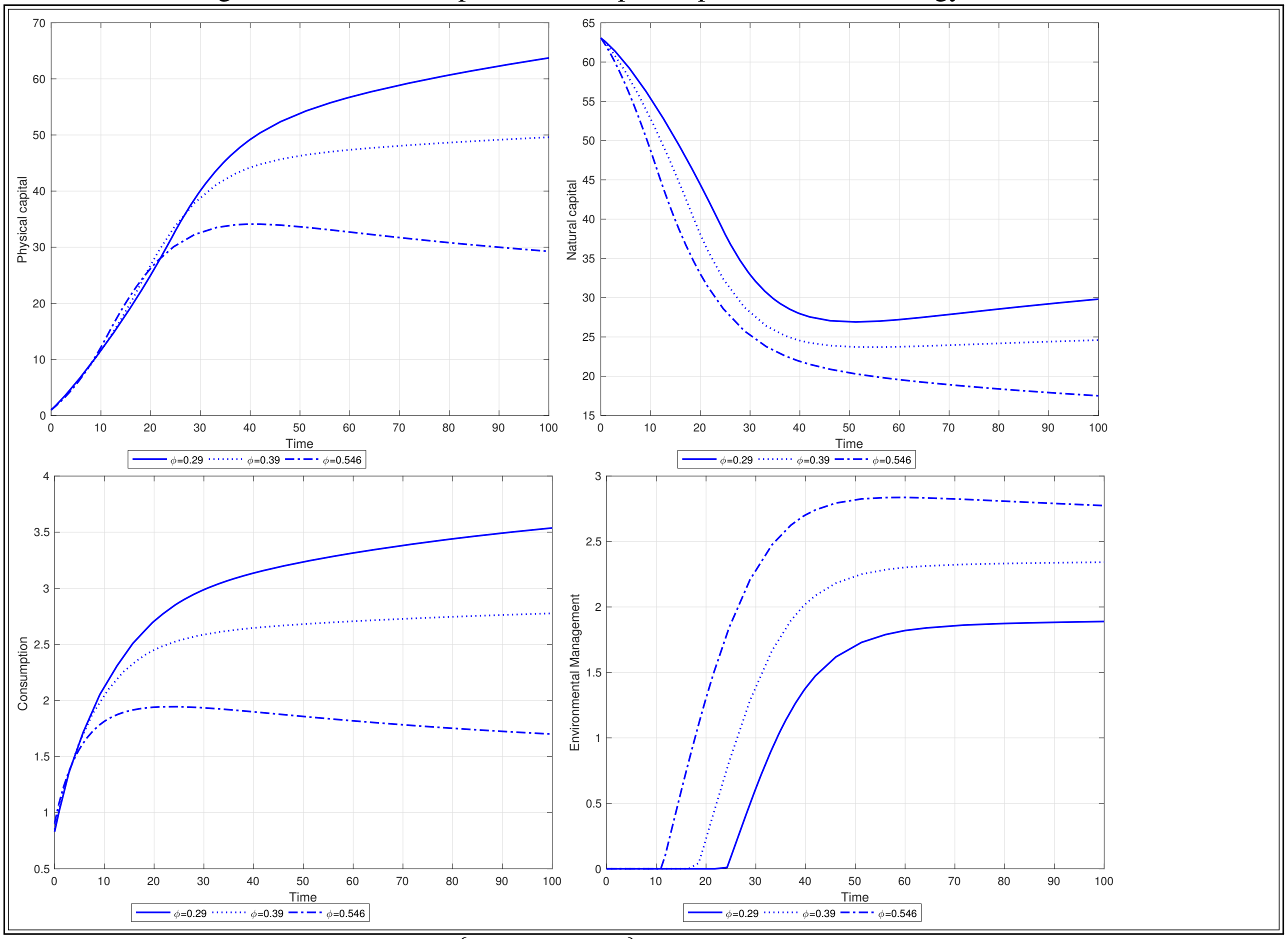
We also showed in Proposition 2 that one of the main factors determining the ultimate impacts of technology transfer is the intertemporal elasticity of consumption of goods and services derived from physical capital. In our modelling, it is the capacity of a society to become satiated with such consumption goods that drives the substitution toward natural-resource based goods and services at the highest levels of income, and so this factor matters most when the primary impact of technological improvement is to change incomes in the very long run. Figure 3 demonstrates how the impact of technology transfer depends on the satiation effect regarding physical capital-based consumption goods. With a reduced elasticity of marginal utility regarding consumption goods (i.e., $\sigma = 0.5$, a case of low satiation), both physical capital accumulation, and consequent consumption, increase.[35] Moreover, the level of natural capital reduces drastically in the steady state as a proportion of the total capital retained in the portfolio, from *approximately* 50% to *roughly* 20%.[36]

Therefore it is the combination of management institutions and societal preferences that together determine how the wealth effect of a technology transfer will be expended. Management institution efficiency determines whether the most effective means of accumulating physical capital stocks is via management or via conversion (of natural capital). Societal preferences determine the extent to which society is willing to continue to accumulate consumption goods and services rather than natural capital based goods and services. The weight of these forces determines the direction of change resulting from a technology transfer.

[35] See the discussion about the rebound effect in Section 3.3 (page 14).

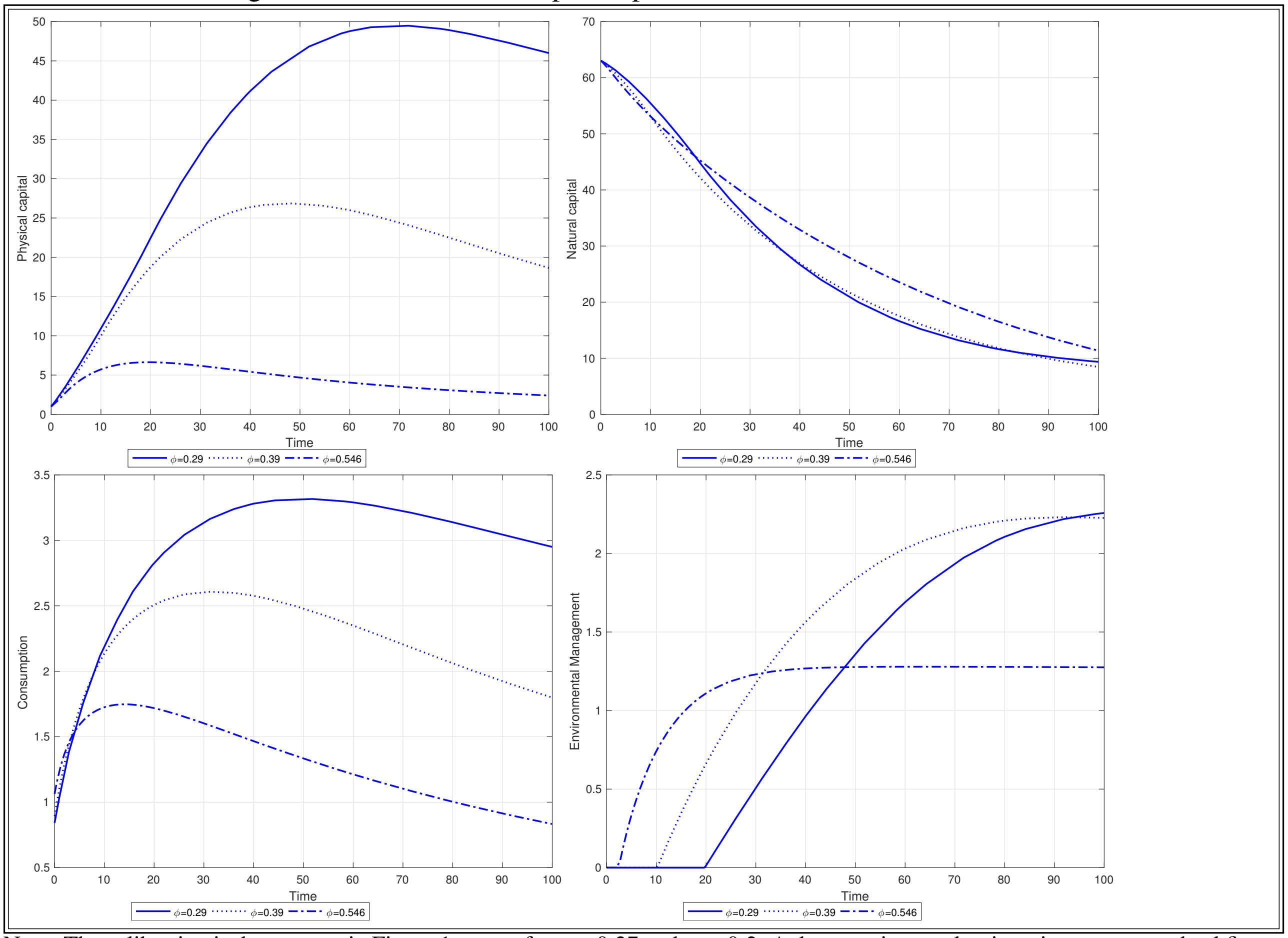
[36] This is due in part to the fact that physical capital accumulation increases while natural capital stock decreases with reduced σ.

Figure 1: Baseline: Expected development path due to technology transfer



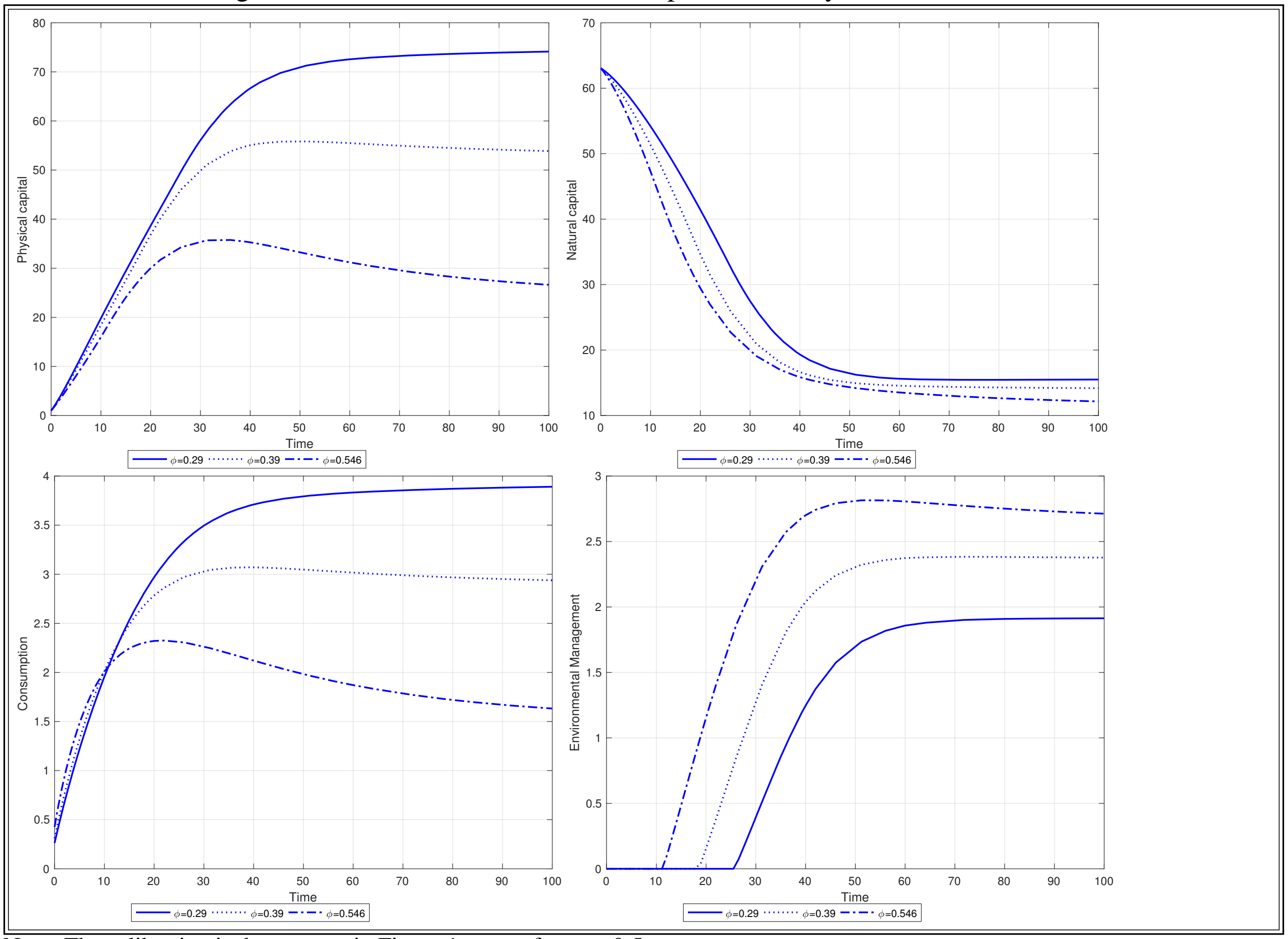
Note: The baseline calibration is used and $\phi = \{0.29; 0.39; 0.546\}$.

Figure 2: Alternative development path: Rebound effect with backfire



Note: The calibration is the same as in Figure 1 except for $\gamma = 0.27$ and $\chi = 0.2$. A decrease in χ makes it easier to generate backfire by violating condition $\sigma > \varepsilon \dfrac{\theta_m}{\theta_c}$ because it reduces concerns for N and therefore reduces m. As a result the RHS would increase through increased elasticity θ_m.

Figure 3: Effect of aversion to intertemporal elasticity of substitution σ



Note: The calibration is the same as in Figure 1 except for $\sigma = 0.5$

5 Conclusion

Our paper has been meant to demonstrate that technology transfer in a standard development model with natural resources has the primary effect of increasing the options of the developing country subject to the change or transfer. Technological change (or transfer) does not necessarily change the incentives of the developing country regarding its choice of development path, even if that change alters the rate of conversion between fundamental assets determining that process. In fact this change increases the aggregate wealth of that developing country, making it easier for that country to pursue its existing path at a more rapid pace. In short, the free transfer of resource-conserving technologies will have the direct effect of increasing the rate of a country's development, and a less direct impact on the choice of the assets on which that development will be based.[37]

[37]This places our paper at odds with the "tunneling through" camp of the EKC debate. Our findings indicate that countries will use transfers of technology to move more rapidly (and further) along the same path, rather than to alter that path or jump forward along it. If there is a silver lining to our findings, it is that the rapid movement along the EKC path might reach a point much further along the same path in a shorter amount of time, meaning that the country concerned might target a very different portfolio of capital at a much earlier point in time. However, the passage along the same path to get there implies substantial levels of resource use - at

We readily admit that our results are driven both by the development model that we have selected (Stokey, 1998) and the nature of the technology transfer we have modeled.[38] This is because the fundamental determinant of the country's development path in this model is the society's interest in balancing its flow of services (as between consumption goods and natural resource services), and hence to balance the underlying capital stocks from which these flows derive. A transfer of more efficient conversion technology then does not alter this objective, but simply makes it possible to pursue the same path more effectively. When technology transfer is thought of in this way, then it is possible to see that the countries receiving such transfers are not necessarily incentives to save resources. Then the free transfer of resource-conserving technologies has more of an impact through enhancing the general wealth of the developing country, than it does in regard to the saving of resources. Such transfers may very well result in the targeting of different portfolios, but mainly when countries have objectives that change with wealth rather than with technology.

There are three caveats to this general point that we wish to note. First, an important factor in this is the intertemporal elasticity of consumption. Ironically, the potential for satiation with regard to standard consumption goods is the other reason that increased income might shift portfolios towards natural capital. As higher ultimate development levels are attained, the developing country may become uninterested in further consumption-based welfare and is left with no other goods or services on which to spend its increased income. In this case, the wealth transfer inherent in technology transfer might be more important to changing ultimate incentives than is the technology itself.

Secondly, whether the developing country might target an enhanced natural resource component within its capital portfolio may depend on the effectiveness of environmental management combined with a large elasticity of marginal utility of consumption goods. Under such circumstances, it may be feasible to use effective management as a means of maintaining natural capital within the societal portfolio. That is, increasingly effective management institutions render natural capital conversion a decreasingly attractive means of producing physical capital.

Third, our point here is a narrow one - i.e., that the transfer of resource-conserving technologies does not necessarily confer incentives o use them to save resources. This does not mean that technology transfer is unable to provide an impetus for developing countries to preserve environmental quality; it only means that it is not in itself a complete solution. It remains necessary to engage in contracting with developing states to incentivize them to alter the balance of services targeted within their objectives. Free technology transfers may be seen as wealth transfers that complement and compensate for changed objectives, but probably not as substitutes for these contracts.

So, the diffusion of resource-conserving technologies does not in itself provide much prospect for saving the world. This is because a transfer of resource-conserving technology does not automatically transfer the incentives to use it to save resources. Hence, the primary function of any technology transfer is to make the recipient a richer country, with all of the possible options and choices that greater wealth implies. This is simply another application of the well-known rebound effect in energy policy, now in the context of international technology-transfer policy. It is crucial to focus on creating effective and efficient institutions

earlier points in time - than would have occurred in the absence of the transfer.

[38] We have elected to model it as disembodied technical change that decreases the polluting effect of physical capital.

for managing resources, and the incentives (or information) that would cause developing countries to want to make use of these institutions, just as much as it is to find the technologies that can save the world.

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Appendix

Proof Proposition 1

Proof: The Hamiltonian of this problem $\mathscr{H} = U(c,N) + \lambda\left[f(k) - c - m\right] + \mu\left[\Psi(m) - \phi f(k)\right]$ yields the following first order conditions:

$$U_c = \lambda \tag{13}$$

$$-\lambda + \mu\Psi'(m) \leq 0 \qquad \text{with equality if } m > 0$$

$$m = \begin{cases} 0 & \text{if } \lambda \geq \mu \\ m^* = \Psi'^{-1}(\lambda/\mu) > 0 & \text{if } \lambda = \mu\Psi'(m) \end{cases} \tag{14}$$

$$\frac{\dot{\lambda}}{\lambda} = \begin{cases} \rho - \left(1 - \frac{\mu}{\lambda}\phi\right) f'(k) & \text{if } \lambda \geq \mu \\ \rho - \left(1 - \frac{\phi}{\Psi'(m)}\right) f'(k) & \text{if } \lambda = \mu\Psi'(m) \end{cases} \tag{15}$$

$$\frac{\dot{\mu}}{\mu} = \begin{cases} \rho - \frac{U_N(c,N)}{\mu} & \text{if } \lambda \geq \mu \\ \rho - \frac{U_N(c,N)}{U_c}\Psi'(m) & \text{if } \lambda = \mu\Psi'(m) \end{cases} \tag{16}$$

The dynamics of consumption and environmental management obtain following time differentiation of (13) and $\lambda = \mu\Psi'(m)$ for $m > 0$:

$$\frac{\dot{c}}{c} = \begin{cases} \frac{1}{\sigma}\left[\left(1 - \frac{\mu}{\lambda}\phi\right) f'(k) - \rho\right] & \text{if } \lambda \geq \mu \\ \\ \frac{1}{\sigma}\left[\left(1 - \frac{\phi}{\Psi'(m)}\right) f'(k) - \rho\right] & \text{if } \lambda = \mu\Psi'(m) \end{cases} \tag{17}$$

$$\dot{m} = \begin{cases} 0 & \text{if } \lambda \geq \mu \\ \frac{\Psi'(m)}{\Psi''(m)}\left\{\frac{U_N}{U_c}\Psi'(m) - \sigma\frac{\dot{c}}{c} - \rho\right\} & \text{if } \lambda = \mu\Psi'(m) \end{cases} \tag{18}$$

Part a) Consider a developing country that is initially endowed with low physical capital stock k_0 and large natural capital stock N_0. So long as the shadow value of physical capital is high relative to the shadow value of natural capital so that $\lambda \geq \mu$, the social planner will optimally choose not to manage the environment and set $m^* = 0$. To see that there is an optimal time at which environmental management is undertaken, we resort to the same argument as Stokey (1998). Since λ is decreasing while μ is increasing , so that the ratio λ/μ

declines monotonically, there exists a finite time period $\tilde{t}$ (i.e. $\tilde{t} < \infty$) that satisfies $\lambda(\tilde{t}) = \mu(\tilde{t})$ (with $\dot{\lambda}(\tilde{t}) < 0$ and $\dot{\mu}(\tilde{t}) > 0$) so that for $t < \tilde{t}$, $\lambda(t) \geq \mu(t)$ and therefore $m(t) = 0$.

Now for $t \leq \tilde{t}$, $\dot{\lambda}(t) < 0$ if and only if $f'(k(t)) > \dfrac{\rho}{1 - \dfrac{\mu(t)}{\lambda(t)}\phi}$ *i.e.* $k(t) < f'^{-1}\left(\dfrac{\rho}{1 - \dfrac{\mu(t)}{\lambda(t)}\phi}\right)$. In particular for $t = 0$, we have $k_0 < f'^{-1}\left(\dfrac{\rho}{1 - \dfrac{\mu_0}{\lambda_0}\phi}\right)$. In addition, from (16), for $t \leq \tilde{t}$, $\dot{\mu} > 0$ if and only if $U_N < \rho\mu \leq \rho\lambda = \rho U_c$ or equivalently $\dfrac{U_c}{U_N} > \dfrac{1}{\rho}$, i.e. if the marginal rate of N for c is large enough. In other words if N is large enough. In particular for $t = 0$, we have $\dfrac{U_c(c_0, N_0)}{U_N(c_0, N_0)} > \dfrac{1}{\rho}$.

Part b) For $t \leq \tilde{t}$, it is straightforward to see that $\dot{N} = -\phi f(k) < 0$ and $\dot{m} = 0$. By definition of $\tilde{t}$, when $t \leq \tilde{t}$, $\dot{\lambda} < 0$ and $\dot{\mu} > 0$. By the dynamics of c (equation 17), $\dot{c} > 0$ if and only if $\dot{\lambda} < 0$. This in turn implies that $\dot{k} = f(k) - c > 0$.

Part c) *Part a)* implies that the developing country will use management $m(t) > 0$ for $t > \tilde{t}$. In the transition phase towards $\tilde{t}$, we know that $\lambda \geq \mu\Psi'(m)$, which implies that $1 - \dfrac{\mu}{\lambda}\phi \geq 1 - \dfrac{\phi}{\Psi'(m)}$. In addition, since $f'(k(t \leq \tilde{t})) > f'(k(t > \tilde{t}))$, it follows that:

$$\begin{aligned}\frac{1}{\sigma}\left[\left(1 - \frac{\mu}{\lambda}\phi\right) f'(k(t \leq \tilde{t})) - \rho\right] &> \frac{1}{\sigma}\left[\left(1 - \frac{\phi}{\Psi'(m)}\right) f'(k(t > \tilde{t})) - \rho\right] \\ \frac{\dot{c}(t \leq \tilde{t})}{c(t \leq \tilde{t})} &> \frac{\dot{c}(t > \tilde{t})}{c(t > \tilde{t})}\end{aligned} \tag{19}$$

That is, consumption growth slows down beyond the optimal date $\tilde{t}$. In addition, multiplying (19) by $-\sigma$ yields:

$$\begin{aligned}\rho - \left(1 - \frac{\mu}{\lambda}\phi\right) f'(k(t \leq \tilde{t})) &< \rho - \left(1 - \frac{\phi}{\Psi'(m)}\right) f'(k(t > \tilde{t})) \\ \frac{\dot{\lambda}(t \leq \tilde{t})}{\lambda(t \leq \tilde{t})} &< \frac{\dot{\lambda}(t > \tilde{t})}{\lambda(t > \tilde{t})}\end{aligned} \tag{20}$$

Inequality (20) suggests that the shadow value of physical capital decelerates at a slower rate beyond $\tilde{t}$. It must be the case that the growth in the stock of physical capital slows down relative to the earlier phase before $\tilde{t}$. [39]

In addition, since for $t > \tilde{t}$, $\dot{N} = \Psi(m) - \phi f(k)$, the depletion of natural capital decelerates due to the investment in environmental management. Note that for sufficiently small $\phi < \Psi(m)/f(k)$, $\dot{N} > 0$, i.e. the natural

[39] Note that since $\dot{\lambda} < 0$, inequality (20) suggests that the LHS has a steeper slope than the RHS. This is confirmed by the fact the

capital is regenerated.

Part *d)* We established earlier that at $\tilde{t}$, $\lambda(\tilde{t}) = \mu(\tilde{t})$. This is implies that:

$$\int_{\tilde{t}}^{\infty} \dot{\lambda}(s)ds = \int_{\tilde{t}}^{\infty} \dot{\mu}(s)ds$$

$$\int_{\tilde{t}}^{\infty} \left[\left(\rho - f'(k(s)) \right) \lambda(s) + \phi \mu(s) f'(k(s)) \right] ds = \int_{\tilde{t}}^{\infty} \left[\rho \mu(s) - U_N(c(s), N(s)) \right] ds$$

$$\int_{\tilde{t}}^{\infty} \left[\left(\rho - f'(k(s)) \right) \lambda(s) + \phi \mu(s) f'(k(s)) \right] - \left[\rho \mu(s) - U_N(c(s), N(s)) \right] ds = 0 \tag{21}$$

Consider $J(\beta) = \int_a^b h(x, \beta)\, \mathrm{d}x$, Leibniz rule states that $\frac{\mathrm{d}J}{\mathrm{d}\beta} = \int_a^b h_\beta(x, \beta)\, \mathrm{d}x + h(b, \beta) \frac{\mathrm{d}b}{\mathrm{d}\beta} - h(a, \beta) \frac{\mathrm{d}a}{\mathrm{d}\beta}$. Applying Leibniz rule to equation (21), we obtain:

$$\left\{ \begin{array}{l} \int_{\tilde{t}}^{\infty} \mu(s) f'(k(s))\, ds \\ - \left[\underbrace{\left(\rho - f'(k(\tilde{t})) \right) \lambda(\tilde{t}) + \phi \mu(\tilde{t}) f'(k(\tilde{t}))}_{\dot{\lambda}(\tilde{t})} - \underbrace{\left(\rho \mu(\tilde{t}) - U_N(c(\tilde{t}), N(\tilde{t})) \right)}_{\dot{\mu}(\tilde{t})} \right] \frac{d\tilde{t}}{d\phi} \end{array} \right\} = 0 \tag{22}$$

$$\frac{d\tilde{t}}{d\phi} = \frac{\int_{\tilde{t}}^{\infty} \mu(s) f'(k(s))\, ds}{\dot{\lambda}(\tilde{t}) - \dot{\mu}(\tilde{t})} < 0 \tag{23}$$

This is true because $\dot{\lambda}(\tilde{t}) < 0$ and $\dot{\mu}(\tilde{t}) > 0$ by Part *a)* of this proof (see above). □

Proof Proposition 2

The system of equations (9) - (12) that defines the steady state after total differentiation can be written in matrix form as:

fact that λ is decreasing and convex $\ddot{\lambda} = \underbrace{\left(\underbrace{\delta + \rho - f'(k)}_{<0} \right) \underbrace{\dot{\lambda}}_{<0}}_{>0} + \underbrace{\dot{\mu} f'(k)}_{>0} - \underbrace{\underbrace{(\lambda - \mu\phi)}_{>0 \text{ since } \lambda - \mu > 0} \underbrace{f''(k)}_{<0}}_{>0} > 0.$

$$\begin{pmatrix} 0 & a_1 & a_2 & 0 \\ a_3 & a_4 & 0 & a_5 \\ -1 & -1 & f'(k) & 0 \\ 0 & \Psi'(m) & -\phi f'(k) & 0 \end{pmatrix} \times \begin{pmatrix} dc \\ dm \\ dk \\ dN \end{pmatrix} = \begin{pmatrix} \frac{f'(k)}{\Psi'(m)} d\phi \\ 0 d\phi \\ 0 d\phi \\ f(k)\, d\phi \end{pmatrix}$$

where the matrix is denoted Ξ; $a_1 \equiv \dfrac{\Psi''(m)}{\Psi'(m)^2} \phi f'(k) < 0$; $a_2 \equiv \left(1 - \dfrac{\phi}{\Psi'(m)}\right) f''(k) < 0$; $a_3 \equiv -\rho U_{cc} > 0$; $a_4 \equiv U_N \Psi''(m) < 0$; $a_5 \equiv U_{NN} \Psi'(m) < 0$.

Define $\Xi = \begin{pmatrix} 0 & a_1 & a_2 & 0 \\ a_3 & a_4 & 0 & a_5 \\ -1 & -1 & f'(k) & 0 \\ 0 & \Psi'(m) & -\phi f'(k) & 0 \end{pmatrix}$; $M_c = \begin{pmatrix} \frac{f'(k)}{\Psi'(m)} & a_1 & a_2 & 0 \\ 0 & a_4 & 0 & a_5 \\ 0 & -1 & f'(k) & 0 \\ f(k) & \Psi'(m) & -\phi f'(k) & 0 \end{pmatrix}$;

$M_m = \begin{pmatrix} 0 & \frac{f'(k)}{\Psi'(m)} & a_2 & 0 \\ a_3 & 0 & 0 & a_5 \\ -1 & 0 & f'(k) & 0 \\ 0 & f(k) & -\phi f'(k) & 0 \end{pmatrix}$; $M_k = \begin{pmatrix} 0 & a_1 & \frac{f'(k)}{\Psi'(m)} & 0 \\ a_3 & a_4 & 0 & a_5 \\ -1 & -1 & 0 & 0 \\ 0 & \Psi'(m) & f(k) & 0 \end{pmatrix}$

$M_N = \begin{pmatrix} 0 & a_1 & a_2 & \frac{f'(k)}{\Psi'(m)} \\ a_3 & a_4 & 0 & 0 \\ -1 & -1 & f'(k) & 0 \\ 0 & \Psi'(m) & -\phi f'(k) & f(k) \end{pmatrix}$

Using Cramer's rule, we can derive the comparative statics:

$$\frac{dc^\infty}{d\phi} = \frac{\det M_c}{\det \Xi}; \quad \frac{dm^\infty}{d\phi} = \frac{\det M_m}{\det \Xi}; \quad \frac{dk^\infty}{d\phi} = \frac{\det M_k}{\det \Xi}; \quad \frac{dN^\infty}{d\phi} = \frac{\det M_N}{\det \Xi}$$

The determinant of Ξ is negative and given by:

$$\det \Xi = -a_5 \left[a_1 \phi f'(k) + a_2 \Psi'(m) \right] < 0$$

The direction of the four effects is therefore given by the sign of the determinants $\det M_c$, $\det M_m$, $\det M_k$ and $\det M_N$.

Part *a)* we have:

$$\det M_c = \frac{a_5 \left[-\left(\Psi'(m) - \phi\right) f'(k)^2 + \left(a_2 + a_1 f'(k)\right) f(k) \Psi'(m) \right]}{\Psi'(m)} > 0$$

$$\det M_k = a_5 \left[a_1 f(k) - f'(k) \right] > 0$$

It follows that $dc^\infty / d\phi < 0$; and $dk^\infty / d\phi < 0$.

Part *b) & c)*

$$\det M_m = -a_5\left[\frac{\phi f'(k)^2}{\Psi'(m)} + a_2 f(k)\right]$$

As a result, $\mathrm{sgn}(\det M_m) = \mathrm{sgn}(\Delta)$ where $\Delta \equiv \frac{\phi f'(k)^2}{\Psi'(m)} + a_2 f(k) = \left[\phi + \left(\Psi'(m) - \phi\right)\frac{f(k) f''(k)}{f'(k)^2}\right]\frac{f'(k)^2}{\Psi'(m)}$.
$\Delta < 0$ if and only if $\Psi'(m) > \left(1 - \frac{f'(k)^2}{f(k) f''(k)}\right)\phi$. Then $\det M_m < 0$ and consequently we always have $dm^\infty/d\phi > 0$.

$\Delta > 0$ if and only if $\Psi'(m) < \left(1 - \frac{f'(k)^2}{f(k) f''(k)}\right)\phi$. Then $\det M_m > 0$ and consequently we always have $dm^\infty/d\phi < 0$.

In addition, we have:

$$\det M_N = \underbrace{-\frac{f'(k)^2}{\Psi'(m)}\rho U_{cc}\Gamma}_{>0} + \underbrace{\Psi''(m) U_N}_{<0}\underbrace{\Delta}_{\lesseqgtr 0}$$

where $\Gamma \equiv \left[1 - \frac{f(k) f''(k)}{f'(k)^2}\right]\left(\Psi'(m) - \phi\right) - \frac{\Psi''(m)}{\Psi'(m)}\phi f(k) > 0$.
If $\Delta < 0$ then $\det M_N > 0$ and consequently we always have $dN^\infty/d\phi < 0$.

If $\Delta > 0$ then the sign of $\det M_N > 0$ if and only if:

$$-\rho U_{cc} > -\Psi''(m) U_N \frac{\Psi'(m)}{f'(k)^2}\frac{\Delta}{\Gamma} \tag{24}$$

Now $\det M_c$ and $\det M_m$ can be written as a function of Γ and Δ respectively so that $\det M_c = -U_{NN} f'(k)^2\Gamma$ and $\det M_m = -U_{NN}\Psi'(m)\Delta$. As a result, the necessary and sufficient condition (24) can be written:

$$-\rho U_{cc} > -\Psi''(m) U_N \frac{\det M_m}{\det M_c}$$

This is equivalent to

$$-\frac{U_{cc}}{U_c} \quad > \quad -\Psi''(m)\frac{U_N}{U_c}\frac{1}{\rho}\frac{dm^\infty/d\phi}{dc^\infty/d\phi}$$

By equation (10), we established that $\frac{U_N}{U_c}\frac{1}{\rho} = \frac{1}{\Psi'(m^\infty)}$, i.e., the discounted marginal rate of substitution between natural capital (as a public good) and consumption goods is equal to the marginal cost of providing N. This implies that:

$$-\frac{U_{cc}}{U_c} \quad > \quad -\frac{\Psi''(m)}{\Psi'(m^\infty)}\frac{dm^\infty/d\phi}{dc^\infty/d\phi}$$

After simple calculation and re-interpretation of the expression in terms of elasticities, we obtain:

$$\sigma \quad > \quad \varepsilon\frac{\theta_m}{\theta_c} \tag{25}$$

where $\sigma = -\frac{U_{cc}}{U_c}c$ and $\varepsilon = -\frac{\Psi''(m)}{\Psi'(m)}m$ represent the elasticity of marginal utility of consumption and the elasticity of marginal product of management, respectively; $\theta_c = \frac{dc}{d\phi}\frac{\phi}{c}$ and $\theta_m = \frac{dm}{d\phi}\frac{\phi}{m}$ denote the elasticity of consumption and management with respect to ϕ.

Part *d)* From the expressions of $\det M_N$ and $\det\Xi$, we can write:

$$\frac{dN^\infty}{d\phi} = \frac{\det M_N}{\det\Xi} = \frac{-\frac{f'(k)^2}{\Psi'(m)}\rho U_{cc}\left\{\left[1-\frac{f(k)f''(k)}{f'(k)^2}\right]\left(\Psi'(m)-\phi\right)-\frac{\Psi''(m)}{\Psi'(m)}\phi f(k)\right\}+\Psi''(m)U_N\Delta}{-U_{NN}\Psi'(m)\left\{\frac{\Psi''(m)}{\Psi'(m)}\phi^2 f'(k)^2+\left(1-\frac{\phi}{\Psi'(m)}\right)f''(k)\Psi'(m)\right\}}$$

After some tedious though simple computation, we obtain:

$$\frac{dN^\infty}{d\phi} = \frac{\rho\sigma c^{-1-\sigma}\left\{\left[f'(k)^2-f(k)f''(k)\right]\left(\Psi'(m)-\phi\right)-\frac{\Psi''(m)}{\Psi'(m)}\phi f(k)f(k)f'(k)^2\right\}+\Psi''(m)U_N\Delta}{\chi\eta N^{-1-\eta}\left\{\Psi''(m)\phi^2 f'(k)^2+\left(\Psi'(m)-\phi\right)f''(k)\Psi'(m)^2\right\}}$$

Now $c^{-1-\sigma} = e^{(-1-\sigma)\ln c}$ so that for $g(\sigma) = \sigma c^{-1-\sigma} = \sigma e^{(-1-\sigma)\ln c}$, we have $g'(\sigma) = c^{-1-\sigma}+\sigma(-1)\ln(c)e^{(-1-\sigma)\ln c} = c^{-1-\sigma}\left[1-\sigma\ln(c)\right]$,

$$\frac{\partial}{\partial\sigma}\left(\frac{dN^\infty}{d\phi}\right) = \rho c^{-\sigma-1}\left[1-\sigma\ln(c)\right]\Omega$$

where $\Omega \equiv \frac{\left[f'(k)^2 - f(k) f''(k)\right]\left(\Psi'(m) - \phi\right) - \frac{\Psi''(m)}{\Psi'(m)} \phi f(k) f(k) f'(k)^2}{\chi \eta N^{-1-\eta}\left[\Psi''(m) \phi^2 f'(k)^2 + \left(\Psi'(m) - \phi\right) f''(k) \Psi'(m)^2\right]} < 0$ since both the numerator is positive and the denominator is negative.

$$\frac{\partial}{\partial \sigma}\left(\frac{dN^{\infty}}{d\phi}\right) < 0 \iff 1 - \sigma \ln\left(c^{\infty}\right) > 0 \iff c^{\infty} < e^{1/\sigma}$$

□