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Growth Theory and “Green Growth”

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Abstract

The relatively new and still amorphous concept of “Green Growth” can be understood as a call for balancing longer-term investments in sustaining environmental wealth with nearer-term income growth to reduce poverty. We draw on a large body of economic theory available for providing insights on such balancing of income growth and environmental sustainability. We show that there is no *a priori* assurance of substantial positive spillovers from environmental policies to income growth, or for a monotonic transition to a “green steady state” along an optimal path. The greenness of an optimal growth path can depend heavily on initial conditions, with a variety of different adjustments occurring concurrently along an optimal path. Factor-augmenting technical change targeting at offsetting resource depletion is critical to sustaining long-term growth within natural limits on the availability of natural resources and environmental services.

Key words: growth; environment; natural resources; innovation; R&D spillovers; sustainable development; natural capital.

JEL codes: O1, O3, O4, Q2, Q3, Q4

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GROWTH THEORY AND “GREEN GROWTH”

1. Introduction

In this paper we draw on literature analyzing economic growth and the environment over the past several decades in order to shed light on the relatively new and still somewhat amorphous concept of “Green Growth.” In very general terms, Green Growth can be understood as a call for balancing longer-term investments in sustaining environmental wealth with nearer-term needs for growth to reduce poverty. It builds on the central concerns for sustainable development that became formalized from the 1970s through the 1990s,² while also emphasizing the importance of increases in conventionally measured income for reducing poverty and inequality.

Consideration of these ideas in the literature is not new. The literature that looks at resource scarcity and the dynamics of environmental policy through the lens of economic growth theory is directly relevant to green growth. We review selected portions of this literature to highlight its implications in terms of both long-run dynamics (how much can we sustainably grow?) and transitional dynamics (how will the nature of the growth process change over time?). From this review, a sharper picture emerges as to what can be said conceptually about prospects for green growth. Of particular interest is consideration of what can and cannot be said about factors that may soften the tradeoffs between income growth and depletion of natural capital, or even lead to positive spillovers between environmental and growth policies.

2. The Concept of Green Growth

As noted, proponents of green growth emphasize the need to protect various forms of natural capital to contribute to and sustain improved living standards over time. A stronger argument put forward by some green growth proponents is that policies for reducing natural resource and

² See WCED (1987), and Toman (1994). A survey of how economic analysis of sustainable development evolved over this period is found in Pezzey and Toman (2003).

environmental degradation can achieve environmental sustainability without large sacrifices of economic growth, and may even help stimulate growth.

Statements from two recent reports on green growth illustrate a range of views. One, from the OECD, states that:

“Green growth ... is about fostering economic growth and development while ensuring that natural assets continue to provide the resources and environmental services on which our well-being relies. It is also about fostering investment and innovation which will underpin sustained growth and give rise to new economic opportunities.....policy action requires looking across a very wide range of policies, not just explicitly ‘green’ (*i.e.* environmental) policies” (OECD 2011, page 18).... “the success of a green growth strategy will rest on addressing political obstacles and distributional concerns about the costs of change” (OECD 2011, page 20)....”a number of companies seek competitiveness gains through clean technology investment. Environmental action also generates new business opportunities. For instance, firms see the search for environmental performance as an opportunity to gain advantage over less technologically advanced rivals and to capture market shares.” (OECD 2011, pages 24-25)

UNEP defines a “green economy” as one that results in “improved human well-being and social equity, while significantly reducing environmental risks and ecological scarcities” (UNEP 2011, page 16). The UNEP report continues,

“In its simplest expression, a green economy is low carbon, resource efficient, and socially inclusive. In a green economy, growth in income and employment should be driven by public and private investments that reduce carbon emissions and pollution, enhance energy and resource efficiency, and prevent the loss of biodiversity and ecosystem services. These investments need to be catalyzed and supported by targeted public expenditure, policy reforms and regulation changes. The development path should maintain, enhance and, where necessary, rebuild natural capital as a critical economic asset and as a source of public benefits. This is especially important for poor people whose livelihoods and security depend on nature. The key aim for a transition to a green economy is to eliminate the trade-offs between economic growth and investment and

gains in environmental quality and social inclusiveness...the environmental and social goals of a green economy can also generate increases in income, growth, and enhanced well-being”... (UNEP 2011, page 16).

We can label the OECD view as “weak green growth,” and the UNEP view as “strong green growth,” by analogy with the distinction between weak and strong sustainability. The weak view holds that typically there are tradeoffs between income growth and the environment, but that appropriate policies can soften this tradeoff while taking advantage of those win-win opportunities that do exist. This is a well-established perspective in neoclassical environmental economics (see, *e.g.* Perman et al., 2011).

Further insights along these lines are provided by Sterner and Damon (2011) and Damon and Sterner (2012), who spotlight institutional and perceptual/political economy aspects. In the context of climate change, Sterner and Damon (2011) argue that achieving needed reductions in global greenhouse gas emissions ultimately requires tough targets and efficient policy instruments; but because such instruments are onerous to many consumer and producer interests, and the imposition of tough targets raises huge challenges related to cost-sharing and growth prospects for developing countries, it is also important to encourage innovation and technology-oriented approaches to reducing emissions (*e.g.* a “green car”). Similar observations lead Damon and Sterner (2012) to emphasize the importance of a holistic approach to environmental policy (and research on environmental policy), with attention paid to institutional capacities and political economy as well as cost-effectiveness in policy design.

The strong view sees complementarities between maintaining natural capital and increasing income growth as more the norm. An important example would be environmental policy that has as a side effect an improvement in productivity in parts of the economy other than the resource sector. Perhaps the best-known of the arguments for such spillover effects is the “Porter hypothesis,” which holds that stricter and more prescriptive environmental regulation also can increase productivity and thus enhance growth (Porter and van der Linde 1995). The basic idea is that tougher environmental regulation also motivates greater attention to previously

unrecognized opportunities for general improvements in productivity.³ However, this view is not so widely accepted, and to date very little statistical evidence in support of this hypothesis (Ambec et al. 2011).

As noted, the focus in Green Growth is on growth in conventional income, versus a broader concept of consumption utility or overall economic welfare.⁴ This focus reflects in part a “Realpolitik” about the importance of income growth (i.e., a typical focus for many finance ministers), and concern about potential negative impacts on income growth from maintaining and recuperating environmental and ecological services. It also reflects practical limitations on consumption smoothing when longer-term output benefits from natural capital improvement require many years to be realized.

3. The lens of growth theory

Theories of economic growth identify the sources of growth and the mechanisms by which policies that affect economic growth. In the neoclassical growth theories, accumulation of capital and technical change drive growth, which in turn are driven by the rewards to investment and innovation. The crucial assumptions in the theory are about substitution, diminishing return, and technical change. The theory’s results stem from the assumption that in the economy’s production process capital can substitute for labor inputs and thus augment labor productivity and per capita income. However, accumulation of capital without technical change runs into diminishing returns. Only if steady technical change continuously creates new investment opportunities, per capita income growth can be sustained. Higher rates of return to investment create incentives for households to save more so that firms have access to more resources for investment and the economy grows faster. Externalities and policies affect the rate of return.

³ What we state here is the “strong version” of the Porter hypothesis. The “weak version,” which attracts much less controversy, is simply that more market-oriented environmental measures do more to stimulate innovation than more prescriptive policies – something entirely consistent with conventional theory (and weak Green Growth).

⁴ Clearly the existence of any intertemporal externality implies that correction of that externality can increase overall well-being. Moreover, if correction of an environmental externality increases long-term tangible wealth (e.g., reversal of fishery over-depletion), then it would be possible in principle to borrow against future wealth increases to smooth consumption over time (i.e. invest less in traditional capital and consume more in the short run), even if conventional income and output declined in the near term.

Growth theory can say something about Green Growth if we can point out the connections between environmental degradation and environmental policies on the one hand and the sources of growth and the rates of return to investment on the other hand. The theory can show how trade-offs that reflect the growth and environment tension are the result of general theoretical forces like substitution, diminishing returns, externalities, and preferences; it can show how different trade-offs are possibly connected and it can derive through which processes and policies trade-offs might be mitigated. Of course theory alone can only inform the Green Growth policies by presenting possibilities, while empirics and experiments should in the end complement the theory, but the theory brings consistency and coherence into the debate. Growth theory is also the basis of Computable General Equilibrium (CGE) models with more complexity and numerically calibrated to realistic trends and features of the world or regional economy. These models are used in particular to inform climate change policies. Understanding growth theory helps understanding the structure and outcomes of these models.

Below we review the insights from growth theory by focusing on small analytical models that highlight certain mechanisms and policy options. This has several advantages. Since growth theory is inherently dynamic we can identify trade-offs between short run and long run. Since we study growth at the aggregate, macroeconomic, level, we take on board that effects in one sector might offset effects in other sector. The main insight we get from growth theory is that environmental policies affect and interact with the sources of growth, investment and innovation. In general, environmental policy can be expected to slow down capital accumulation and growth, but if it stimulates innovation, the trade-off would be softened. We can also expect various externalities to be present so that the actual investments in the economy deviated from desired investments. Growth theory can link these externalities and derive implications for policies and growth.

4. How do Economic Growth and Environment Interact?

4.1 A basic neoclassical model

Is Green Growth possible in the long run, what policies will it require, and how different will it be from growth without Green Growth policies? Growth theory gives answers to these questions by analyzing models and checking, respectively, (i) whether the necessary investments for GDP growth can be sustained in case long-run environmental quality is required to be maintained at certain levels, (ii) what externalities play a role and (iii) how investment incentives differ with and without environmental policies. The crucial trade-off to study is therefore the one between investment in GDP and investment in environmental quality. In this section we present the basic (neoclassical) growth framework in which these two variables are the capital stocks from which production and welfare is derived.

We denote the stock of man-made capital by K , and the labor force by L , taken to be constant for the ease of exposition. Let N denote a stylized measure of the stock of capacity that “nature” possesses for providing various kinds of goods and services. Denote by R a measure of resources extracted from the natural environment (*e.g.*, oil, fish, and timber).

Nature as a stock provides direct benefits to consumers. A high quality forest has amenity value, the existence of a stock of whales has a value per se, the accumulated stock of CO₂ poses a negative value or a negative externality, etc. Both N , through flows of naturally provided ecosystem services, and resources extracted from nature, R , affect production. Pollution, for example, may hurt the productivity of workers, and environmental stress from climate change will harm total factor productivity in agriculture in particular, whereas clean water is beneficial for the production process

The maximal output Y that can be obtained with given factor inputs is described by the production function F with standard neoclassical properties (quasi-concavity, positive but decreasing marginal products of inputs, unbounded marginal product as an input use goes to zero). Omitting reference to the assumed-constant labor force to simplify the exposition, a useful model of production with natural capital and extractive resources as well as physical capital can be written as:

$$(1) \quad Y = F(K, R, N)$$

Both the man-made capital stock and then environmental stock may change over time. The former increases with net investment, which is the amount of output that is not used for

consumption, C , for the cost of extracting resources, μR (where μ is the unit extraction cost), and for replacement of worn out capital, δK (where δ is the depreciation rate):⁵

$$(2) \quad \dot{K} = F(K, R, N) - C - \mu R - \delta K .$$

Environmental quality improves if resource use is less than natural regeneration:

$$(3) \quad \dot{N} = E(N) - R .$$

The function E in (3) describes how nature regenerates. Resource stocks have a capacity to grow, but cannot grow infinitely large. This implies that E is a function of the stock N and becomes zero for if the stock approaches its bio-physical maximum size. Because there is a limit to investing in environmental quality, a trade-off arises in green growth policies. It is impossible to let resource inputs grow without eventually depleting the resource.⁶ In an extreme case, the stock is truly nonrenewable; then $E(N) = 0$ for all resource stocks and regeneration doesn't take place. This is a strong and not especially realistic assumption for natural capital as a whole, though it certainly applies to some parts of natural capital and even renewable natural capital (e.g. a fishery) can be depleted beyond the point of recovery.

4.2. Feasible Green Growth

Our first question, whether Green Growth is feasible, can already be answered in this setting. The answer is affirmative if production relies on renewable resources, i.e. if $E > 0$. The reason is that man-made capital substitutes for resource inputs: an economy that expands its man-made capital can increase GDP even when it refrains from simultaneously expanding its energy and resource inputs. This economy can restrict the intensity of resource use to keep environmental quality constant, in particular $R = E(N)$. Moreover, this economy can restrict goods consumption,

⁵ The dot denotes the change over time: for any variable X , we write $\dot{X} \equiv dX / dt$.

⁶ It would be completely misleading to make E always increasing with N , because then N could grow without bounds and so would R .

C , to ensure that net investments in man-made capital are positive, in particular $C < F(K, E(N), N) - \delta K - \mu R$.

If an economy depends heavily on nonrenewable extracted resources, then the inevitable ultimate decline of the resource's economic availability will exert a significant drag on total output, consumption, and capital accumulation. This does not necessarily mean that production will ultimately decline. Increased investment in productive capital could offset the decline in resource availability so that consumption never needs to decline. However, it is unlikely that a market economy is willing to invest in the capital needed for such a growth path if the returns to investment fall with the declining availability of the necessary non-renewable energy inputs. Indeed, growth models suggest that without increasing returns in capital investment or technical change, consumers and investors ultimately see consumption and production shrink to zero, though growing consumption is possible in the nearer term (e.g. Benckroun and Withagen, 2011). Overall this scenario seems too pessimistic, unless we believe that technical change cannot be sustained and non-renewable resources can never be replaced by renewable ones.

If an economy depends on renewable (rather than just non-renewable) resources, a constant flow of extracted resource inputs can be used in production (at the level that is equal to regeneration capacity) in principle, so that the resource drag on growth mentioned above can be avoided. Nevertheless, when an economy starts from an unsustainably high level of extraction because of neglect of environmental issues in the past - e.g. extraction above the maximum sustainable harvest defined by the maximum regeneration rate, $E(N)$ - resource use necessarily has to be reduced and this implies a growth drag in the short run, even though the long-run growth rate becomes sustainable.

The rationale for shifting toward investment in a larger renewable resource stock is that it generates production benefits over the longer term. In the case of a fishery, for example, natural regeneration increases relative to a highly depleted stock, catching cost falls, and this enhances surplus in the sector. More generally, reduced pressure on renewable resources can increase ecosystem services and improve the productivity of ecosystems and ultimately also the productivity of the economic sectors that depend on the ecosystems. The improved longer-term productivity will offset the economic cost of reduced production that follows from reducing

harvesting (assuming the previously unsustainable extraction profile also was economically inefficient). The increase in the long-run rate of return from extraction eventually stimulates investment and growth. But in the framework under consideration here, the intertemporal tradeoff faced in recovering from inefficient, unsustainable past over-use of natural capital is unavoidable.

Similar considerations are in place in the case of stock pollution. Reduced emission flows come at a direct mitigation cost, but lower concentrations of pollutants in the atmosphere, water bodies or soil generate longer-term productivity effects. These productivity gains could stem from health effects (healthier workers are more productive and fewer resources are expended on medical care), or ecosystem services (a cleaner environment produces more valuable services, such as more abundant fish stocks, lower costs of water treatment), or tourism income if tourists are attracted by natural amenities.⁷ The DICE model that Nordhaus (1994, 2008) has developed to study the economics of climate change policies relies on a very similar assumption, since in this Ramsey-type model the avoidance of climate change improves economy-wide productivity.⁸

Whenever resource use policies affect the rate of return, i.e., the marginal productivity of man-made capital, there is an indirect effect on growth through induced changes in capital investment. The cost of environmental policy is magnified (the policy lowers output directly, and through reducing the marginal product of capital it also reduces investment indirectly), but the benefits are magnified as well. How big these general equilibrium or interaction effects are depends on how important man-made capital inputs are relative to resource inputs and how strong the diminishing returns are (Smulders, 2000).

Environmental improvements also can spur growth through alternative mechanisms, which are surveyed by Ricci (2007a). First, pollution taxes make consumption more expensive

⁷ It is certainly true in principle that the nearer-term effects on total output of reducing pollution flow, or of reducing pollution stock just a little, could more than offset the nearer-term costs of emissions mitigation. However, the evidence on health effects for example suggests that while the monetized increase in utility from reduced health risks can offset mitigation costs, direct productivity benefits are smaller or take longer to accumulate.

⁸ When it comes to the design of an optimal carbon tax, it is important to realize that the tax level as well as its time path may crucially depend of having damages incorporated in a multiplicative or an additive way in instantaneous welfare (e.g. Weitzman 2010) or in technology (e.g., Rezai et al. 2013).

and reduce the marginal value product of production labor; this can lead households to reallocate time toward education, in addition to leisure (e.g., Hettich, 1998). Second, the prospect of a cleaner environment might induce households to save more and postpone consumption to the future if consumption and amenities are complements (Michel and Rotillon, 1995; Mohtadi, 1996). Third, pollution taxes might fall disproportionately on old goods if new generations of products become cleaner. Thus a pollution tax could speed up obsolescence and stimulates innovation in new products (Hart, 2004; Ricci, 2007b).

4.3 Optimal growth and policy

Which of the many feasible growth paths is most desirable depends on preferences. Growth theory typically assumes a representative household whose preferences guide society's preferred growth path. This household cares about direct benefits from the state of nature as well as conventional consumption, as summarized in the instantaneous utility function $U(C, N)$. It has the usual properties: it is increasing and concave and has unbounded marginal utility as consumption goes to zero. Since the household cares about consumption and environment at present as well as in the future, the relevant criterion for society's choice is the intertemporal welfare, which in the simplest case is the discounted stream of utilities:

$$(4) \quad \max W_u = \int_0^{\infty} e^{-\rho t} U(C, N) dt,$$

where ρ is constant the utility discount rate, which measures how quickly the weight of future consumption and environmental quality diminish. The maximization of (4) subject to (2) and (3), a problem which can be referred to as the utilitarian version of the Ramsey problem, gives the optimal growth trajectory for the economy, including natural capital management.⁹ Along this trajectory the trade-off between consumption and growth and the trade-off between consumption and environment are optimally balanced. To maximize welfare, consumption should be chosen such that its marginal contribution to welfare equals the capital stock's marginal contribution to welfare (i.e. its shadow price); resource extraction should be chosen such that its marginal

⁹ An egalitarian version of the framework also has been explored, in which welfare is determined by the instantaneous utility of the generation that is worst off: $W_e = \min_t U(C(t))$. See in particular Solow (1974) and Asheim (2007).

contribution to welfare equals the environmental stock's marginal contribution to welfare (i.e. the shadow price of natural capital). In the long run, the latter condition can be written as:

$$(5) \quad F_R = \mu + \frac{F_N + U_N / U_C}{\rho - E_N},$$

where the left-hand side is the value of resource use in production and the right-hand side represents the direct extraction cost (μ) plus the marginal value of natural capital as the sum of all future marginal benefits in utility and production, discounted with the utility discount rate corrected for the marginal regeneration of the natural capital stock (E_N). This expression teaches us something about the optimal trade-off between resource-based production and environmental quality: a high preference for environmental quality and a big sensitivity of output to environmental change optimally call for conservative resource use.

For the economy to grow optimally, the marginal cost of postponing consumption to the future should equal the marginal benefits of doing so, such that society is indifferent between investing now and investing later. This optimality condition, the so-called (Keynes-)Ramsey rule, can be written as:

$$(6) \quad \frac{\dot{C}}{C} = \sigma[F_K(K, R, N) - \delta - \rho] + \sigma \frac{U_{CN}}{U_C} \dot{N},$$

where $\sigma = -U_C / CU_{CC} > 0$ is the elasticity of intertemporal utility substitution. Economic growth, as measured by the growth rate of consumption \dot{C}/C , should according to this Ramsey rule be positive if the net return to investment, $F_K - \delta$, is sufficiently large to overcome the impatience of consumers (as measured by ρ) and if changes in environmental quality increase the demand for consumption (i.e. if $U_{CN}\dot{N} > 0$).

The former effect is the standard growth policy prescription to take advantage of investment opportunities. It also frames the well-known debate over the implications of what discount rate(s) are used in practice for evaluating e.g. climate change mitigation policies. If individuals are more impatient (larger ρ), this implies – other things equal – a slower growth rate in consumption. In terms of adjustment of optimal path, we would expect higher consumption

initially and slower growth over time, with less provision for investing in environmental or regular capital (as is confirmed by equation (5) where a higher discount rate reduces the net present value of benefits from environmental quality).

The latter effect is more specific and highly relevant for the Green Growth setting. We interpret its policy implication under the assumption that environmental quality is a “normal good”, so that its demand increases – *ceteris paribus* – with income and consumption ($U_{CN} > 0$). Then faster environmental quality improvements call for faster economic growth.

The Ramsey rule also informs us about how optimal growth should develop over time. If the economy initially has a low capital stock, then the return to investment is high, other things being equal, and savings will be high; this capital “deepening” in turn increases the output potential of the economy for the given labor force, permitting consumption growth as well. However, as the capital stock grows over time, the return to investment falls (because of diminishing returns to capital). Similarly improvements in environmental quality must stop because of the boundedness of natural assets. As a result consumption growth also falls to zero and a stationary steady state arises. It should be noted however that growth vanishes only in the long run, which might take several decades or centuries to be reached. Moreover, the conclusion becomes less pessimistic in the presence of ongoing technical change as discussed in Section 6 below. This underlines that technical change is an important factor to consider in policy.

We can now give an answer to our question, how Green Growth differs from other patterns of growth. It is natural to start from a situation in which economic growth is desirable, in the sense that - given its stocks of man-made and natural capital – the welfare-maximizing path would involve growing consumption and output, as well as increasing environmental quality. It is also natural to compare green growth to a situation of “Brown Growth”, in which resource inputs grow and environmental quality deteriorates – the situation that Green Growth proponents see as the current trend that we need to reverse. Brown Growth arises in an economy if natural resource inputs and polluting inputs are priced below their social cost. In a growing economy, producers tend to demand more resources – technically because resource inputs and capital are imperfect substitutes, i.e. complements to some degree – unless market resource prices grow fast. If the market price reflects extraction costs (μ) but not the effects that pollution and extraction have through environmental quality, which acts as a public good, price growth may be too low to

adequately curb resource use.¹⁰ Brown Growth is likely to be faster initially, since it benefits from growing resource inputs, but this fast growth is unlikely to be maintained if the resource stock gets depleted.

Another example of the role of externalities in creating Brown Growth is analyzed by Lopez (2011). He considers a competitive economy with open access to a biologically renewable resource. The resource develops according to a natural growth function with harvest, but there is an additional factor that causes depletion of the resource stock. This is activity in another sector of the economy, the industrial sector. It may have a negative impact on the growth of the resource through, for example, oil spills as a consequence of nonrenewable resource use. Man-made capital accumulates through savings from profits in the industrial sector (workers don't save). In the long run the equilibrium in this economy can be of two types. If the negative impact of industrialization on the natural resource is not too large, then industrialization will produce both growth and a non-declining resource stock, even if, as is assumed in the model, no property rights are defined on the natural resource. However, in less favorable circumstances that are identified in the analysis, expansion of the industrial sector will make result in resource degradation.

5 Trade-offs in Clean Technology Transitions

A key element in a Green Growth policy, for developed economies at present and all industrialized economies going forward, is a reduced reliance on fossil energy and a transition to clean energy sources, for reasons of climate change and local air pollution. This is an inherently dynamic problem, for which policy questions arise with respect to timing, speed, and nature of the transition. Since fossil energy is an important input in most sectors of the economy, the policy analysis requires an economy-wide focus. This makes growth theory, which accounts for dynamics as well as general equilibrium effects, a useful tool to think through the trade-offs in transition.

¹⁰ Resource use in the market would be characterized by equality of marginal product of resource use and the market price, so that $Y_R(K,R,N) = \mu$, rather than by the optimality condition in (5).

Fossil resources, from oil, coal and gas, provide energy services with highly desirable properties at low production cost. Alternative cleaner sources of energy, from renewable sources like solar and wind energy, are relatively more expensive in terms of production costs, and less convenient due to intermittency and storage problems. The trade-off in the energy transition is therefore nearer-term energy supply costs versus longer-term environmental benefits.

To analyze the implications of this trade-off for green growth, we need to study the interaction between two types of energy in production: fossil versus clean. Fossil energy is non-renewable, but it is unlikely that eventually all fossil resource stocks will be profitably depleted. We base our discussion therefore not on the textbook Hotelling model with full depletion of the non-renewable resource stock, but on the Heal (1976) model in which a large non-renewable resource stock is available at extraction costs that rise with depletion and become larger than the cost of substitute energy sources before the full stock is exhausted. We denote extracted fossil resources by R and the non-renewable fossil stock by S , so that $\dot{S} = -R$. We denote unit mining costs for fossil fuel by the decreasing function $M(S)$. As a substitute for fossil fuels, we consider energy generated from renewable sources such as solar and wind, denoted by B . We first focus on the implications of the fact that the cost of generating this alternative energy is typically above the cost of fossil energy at present, in some cases substantially so, and we model an unlimited supply of alternative energy at unit cost β , which exceeds the initial fossil extraction cost, $M(S_0)$, but is below the extraction cost of the last fossil reserves, $\beta < M(0)$. This way we treat alternative energy as a “backstop” and we consider the case in which fossil is always replaced eventually by this backstop.

Gross production now depends on capital and the two types of energy, R and B , while GDP is gross production minus the cost of energy production. The part of GDP that is not consumed is invested in the physical capital stock:

$$(7) \quad \dot{K} = F(K, R + B, N) - [M(S)R + \beta B] - \delta K - C,$$

where F is gross production (as in the previous section, labor as an input in production is suppressed) and the term in brackets is energy production cost.¹¹

The essence of climate change and stock pollution is that fossil emissions cumulate in the air and atmosphere, and that greater cumulative emissions degrade environmental quality in a persistent way. If decay (absorption) of CO₂ and pollutants from the atmosphere is negligible we find that environmental quality and the preserved fossil stock are positively related: the less fuel is extracted the fewer carbon particles are cumulate in the atmosphere. In the model this implies:

$$(8) \quad N = S - S_0 + N_0$$

and

$$(9) \quad \dot{N} = -R.$$

Comparing (9) to (3), we see that this formulation implies $E(N) = 0$, i.e. the economy depends on non-renewable rather than renewable resources and irreversible pollution stocks. This allows us to bring out sharply the implications of non-renewability and irreversibility associated with the climate change problem.

Without environmental policy, the economy initially uses fossil energy only (ignoring the niche markets), and switches to renewable energy once the fossil extraction costs have become higher than the backstop costs. Climate change and pollution build up as long as fossil energy is used. Also the cost of fossil energy supply increases with depletion. Initially the economy grows since the low cost of energy and the high marginal product of capital stimulate investment. But

¹¹ In this formulation, fossil fuel and the alternative energy are perfect substitutes and only one type of energy is used unless the cost is exactly the same. In reality, they are imperfect substitutes and there is simultaneous use even if costs differ greatly: there are always some niche markets in which the expensive type is used. Such niche markets can easily be incorporated in the model without affecting the messages we stress in our discussion. Denote total clean energy use by B_1+B_2 , of which B_1 is a perfect substitute for fossil and B_2 serves niche markets in which fossil and clean are imperfect substitutes. Then equation (7) must be modified into

$$\dot{K} = F(K, R + B_1, B_2, N) - [M(S)R + \beta B_1 + \beta B_2] - \delta K - C.$$

growth slows down with rising energy costs and diminishing returns to capital. Van der Ploeg and Withagen (2013a), who ignore the productivity effects of environmental quality, show that this is likely to result in overshooting: initially capital and consumption grow to high levels, but later start to decline if energy becomes costly and if eventually the economy switches to the expensive backstop economy.

A Green Growth policy could take different shapes, but would always require cuts in fossil energy use, so that less carbon emissions accumulate and a larger fossil resource stock is left in situ. The effects on growth follow the logic explained above. Either energy use is reduced, or energy supply is more expensive, so that GDP is lower. This causes a drag on growth since the return to capital falls. However, there is an opposite force since with less intensive fossil energy use, extraction costs rise less quickly over time. Depending on how the policy affects the timing of the energy saving and the timing of transition to the backstop, the growth dip can be concentrated in initial periods and resume quickly, or may be more spread out over time.

The socially optimal policy again trades off the nearer-term losses in production against the longer-term environmental gains. Formally, it involves maximization of (2) subject to (7), (8), and (9). A price on carbon emissions, through carbon tax or cap and trade system, would implement the policy, provided this tax reflects the net present value of marginal damages from carbon emissions. The resulting optimal growth path depends on the initial situation and two interesting cases have to be distinguished (here we leave out a third possibility in which the economy has so little fossil reserves and so much carbon in the atmosphere already that fossil use is immediately and forever banned).

The first case is a situation with an initial capital stock that is large relative to fossil reserves. This economy has a high demand for energy and will quickly face rising extraction costs. The optimal Green Growth policy requires substantial energy reductions and a faster transition to the renewable alternative. Since less fossil energy is used than without optimal policies, fossil energy costs rise less and the period of negative growth is partly mitigated.

In the second case, fossil energy is relatively abundant so that the cost of energy remains low as long as the economy continues using fossil energy. Although the optimal green policy requires less fossil energy use, measured cumulatively over time, and an earlier introduction of the backstop than in the market solution, initially it pays *increase* fossil energy and grow faster.

It is optimal to benefit from cheap energy in the near future for the economy that makes the fast transition, while the (market) economy that waits longer in making the transition has a longer “fossil energy epoch”. In this fossil-abundant world, optimal green growth is faster than brown growth, but only in terms of capital stock, not consumption. The economy unavoidably gives up consumption in exchange for a better environment. Man-made capital, however, can be cheaply built as long as fossil energy costs are still low and the higher capital stocks can still be benefitted from once the economy has made the transition to more expensive energy sources. Hence, fast capital accumulation (and reduced consumption) now prepares for higher consumption in the period of more expensive renewable energy.

How high should the carbon tax be? In principle, along the optimal growth path it equals the net present value of marginal damages, but what does this imply for its evolution over time? First of all we should note that the carbon tax increases over time if the economy grows. As a rule of thumb, the optimal carbon tax grows at approximately the same rate as GDP (Golosov et al, 2013; Gerlagh and Liski 2012). This is because marginal damages increase with income: marginal damages from climate change in production are larger if there is more capital to be affected and marginal damages to consumers increase with their consumption level since produced consumption goods and environmental quality are complements (the demand for both increases with income).

The key trade-off in green growth policies stems from the fact that at least initially non-fossil energy sources are more expensive in terms of GDP than fossil sources. Some authors have drawn attention to the fact that this higher cost is mainly because of the cost of installing capacity rather than the cost of producing the actual energy. Think of solar and wind of which the initial capacity needs to be built, but once it is installed the operating costs are low (US EIA 2010, Table 1). An analysis of its implications requires the distinction between two types of man-made capital, viz. production capital K , as above, and renewable energy capacity, K_B . Green growth policies now include policies to invest in alternative energy capacity, which comes at the cost of production capital and consumption. Hence, there is a timing decision: when to start

building renewable energy capacity and how quickly. It takes time to build capacity and it is efficient to smooth investment out over time.¹²

Tsur and Zemel (2011) analyze an economy with constant cost of fossil fuel (cf. μ above) and no scarcity of fossil energy; each unit of renewable energy requires a certain amount of renewable energy capacity, while the operating cost is negligible. An economy with a low capital stock invests its savings entirely in production capacity and runs on fossil energy: building renewable energy capacity is too expensive in terms of how it would crowd out production capacity, which is still scarce. However, with economic growth the return to investment in production capital falls and at some point gradual investment in renewable energy becomes profitable. Even if fossil and non-fossil energy are perfect substitutes in production and the latter has zero production costs, the capacity constraint dictates that the economy uses both fossil and non-fossil. Green growth in this economy would require building the renewable energy capacity earlier and faster, and since building this capacity requires production of man-made capital, this could go together with faster GDP growth – another example of green growth that is faster than brown growth, though we emphasize again the tradeoff between nearer-term and longer-term consumption possibilities.

In a market economy with perfect competition on all markets the implementation of this first best outcome requires setting a carbon tax, reflecting the marginal damage. However, if for political economy reasons introducing such a tax turns out to be infeasible, then the design of a second best policy is in order. One of the options is to subsidize the renewables. From a Green Growth perspective this might look promising and effective. However, such a policy can lead to adverse unintended effects. On the one hand, the subsidy will speed up introduction of renewables and to more fossil fuel being left in the crust of the earth. This would lead to a reduction of the climate damages, which might even more than compensate for the distortionary impact of the subsidy. On the other hand, resource owners will experience the subsidy as a kind

¹² Many small analytical models (including Van der Ploeg and Withagen, 2013a) assume perfect substitution between fossil and non-fossil energy and abstract from niche markets and capacity constraints. The result is that the market economy typically uses either fossil energy or non-fossil energy, which is at odds with reality. On the other end of the spectrum, applied models show that non-fossil energy resources are introduced long before fossil is phased out, due decreasing returns to scale in non-fossil and time to build. An early model of the latter type is Manne et al (1995).

of expropriation of their stock of fossil fuels and will, in light of this, extract more fossil fuel initially. The effect is detrimental for social welfare. This is an example of the green paradox.¹³ Hence, the model sketches a clear picture of the dangers of a Green Growth strategy that doesn't account for supply side effects of fossil fuel. This is not to say that policy makers should refrain from subsidizing renewables, but it gives a warning against a naïve approach to the development of green policies.

Since climate change is a negative externality, environmental policy is needed to implement the optimum in a market economy. Without environmental policy, the market doesn't take account of climate change and only trades off marginal extraction costs and costs of the renewables. Hence, there will be too much fossil fuel use, and less will be left unextracted. Since the only externality here is the climate externality by assumption, brought about by the use of fossil fuel, a carbon tax corresponding with marginal damage will do the job. The carbon tax is increasing in an economy that starts below the long-term carbon-free steady state, but it might decrease in an economy starting above the long-term carbon-free steady-state in order to sharply reduce incentives for fossil fuel use.

6. How does technical change interact with Green Growth?

So far we have considered growth mainly as the result of the accumulation of man-made capital and the maintenance of natural capital. With expansion of capital stocks, however, diminishing returns would cause the returns to capital fall, and in the absence of some other driver, growth would slow down. To explain steady sustained growth rates,¹⁴ we need to account for technical change that improves the productivity of inputs, including capital, mitigating diminishing returns to capital. Technical change can be represented in growth analysis as an increase over time in

¹³ This concept was introduced by Sinn (2008a, 2008b), to point at the danger of too fast increasing carbon taxes or subsidies on renewables. These policies might lead to faster extraction of fossil fuels, quite contrary to the intention of the policies. Studies that summarize the mechanisms behind the green paradox and its implications are Gerlagh (2010), Di Maria and van der Werf (2012), and van der Ploeg and Withagen (2013b).

¹⁴ Stable growth trends are observed in the US over the past century, and in the other OECD countries, as well as some fast growing developing countries (India, China) over the past few decades.

the availability of a stock of technical knowledge that allows producing more per unit of inputs. Output grows thanks to technical change, not only because it directly increases output, but also because it sustains capital accumulation. Growth accounting studies (see Caselli, 2005, and Crafts, 2010, for surveys) confirm that technological change is a main source of growth, often dominating other important sources like (physical as well as human) capital accumulation.

Not all possible forms of technological change are equally conducive to sustained economic growth when we take into account natural as well as man-made capital. Resource use is physically constrained: cumulative non-renewable resources are finite and become costlier to extract as they are depleted, and the flow of renewable resources is ultimately constrained by the natural regeneration or natural growth rate of the resource stock. Hence, to reconcile growing output with non-increasing resource use, the resource intensity of the economy has to fall over time. This requires some combination of resource substitution (including substitution towards backstop use, as discussed above), and input-augmenting technical change. A key consideration in the context of green growth is the impact of different types of technology change on use of natural resources and other inputs, and on incentives to accumulate man-made capital.¹⁵

To capture input-augmenting technical change in the growth model we have set out above, we introduce in our production function “factor-augmentation terms” A_i as follows:

$$(10) \quad Y = F(K, A_R R + A_B B, A_L L, N),$$

where we now make explicit labour inputs, L , to account for the fact that labour-related technical change is needed to sustain growth as well as interacting with other types of technical change. Input-augmenting technical change (increases in the A terms) makes it possible that effective inputs (e.g. effective energy inputs $A_R R$) grow, while the inputs themselves (e.g. R) do not grow. Examples in the context of energy inputs are electricity-saving measures, fuel-efficiency improvements, improved drilling techniques that increase effective economic reserves of

¹⁵ Incentives to innovate depend on the substitutability between production factors. If substitutability is low, it is desirable to increase the productivity of the depletable resource. With high substitutability, however, it is probably more efficient to increase the productivity of the substitute (e.g. physical capital) and increasingly substitute away from the depletable resource.

resources, or cost reductions in the production of alternative energy. These and other factor-augmenting measures will involve specific types of effort and associated costs.

Changes in resource use, in particular as part of green growth policies, can affect both costs and benefits of innovation activities and thus can change the rate and direction of technical change. This endogeneity of technical change adds another channel that shapes the relationship between growth and natural resources. On the one hand, increased scarcity of natural capital services will provide incentives for resource-augmenting innovation. On the other hand, because declining resource use in the face of growing scarcity will create a drag on growth, all else equal, it will crowd out innovation as well as physical capital accumulation (since knowledge is one particular form of man-made capital). For example, reduced energy use will reduce output and with it learning-by-doing, all else equal. Moreover, the returns to inventing new products will be lower since less energy is available to manufacture these products, which makes them more costly and lowers the market size for them.

This same mechanism would figure into the cost of environmental policy that limits use of other forms of natural capital. Various authors have identified this crowding out effect of environmental policy in growth models with endogenous technology (e.g., Stokey, 1998; Aghion and Howitt, 1998). However, the mechanism also implies an increase in technical change (and hence more growth) if the productivity effect of a cleaner environment or improved eco-service systems dominates the effect from reduced resource inputs (Bovenberg and Smulders, 1996). The more an economy relies on endogenously generated technical change generated domestically, the more sensitive its growth is to changes in resource and environmental variables, in both directions, since these changes indirectly affect home-grown innovation (Smulders, 2005). Growth in economies that mainly rely on imported (rather than home-grown) technologies and diffusion of technologies from abroad would be less affected by domestic resource and pollution policies.

Reduced use of natural resource or polluting inputs as a result of environmental policy crowds out “brown innovations,” that is, innovations in technology that is intensive in natural resource or polluting inputs (Smulders and Di Maria, 2012). These innovations have to be distinguished from new “green technologies” which are substitutes for polluting/resource

intensive inputs.¹⁶ Examples are improvements in abatement technologies (like scrubbers or carbon capture and storage), cost reductions in alternative (cleaner) energy production, and (under some circumstances¹⁷) energy efficiency improvements. Reduction in resource use and emission cuts can be expected to stimulate the demand for these technologies, which implies crowding *in* of such innovation.

Models that incorporate opportunities for innovations of both types, green and brown, allow for the possibility of “Directed Technical Change” (DTC) based on the relative economic rewards from the different types of innovation (e.g., Smulders and De Nooij, 2003; Hart, 2008; Grimaud and Rouge, 2008; Di Maria and Valente, 2008; Gerlagh, 2008; Gans, 2011; Andre and Smulders, 2014). The issue here is which forces affect innovators’ choices regarding the types of technical change they pursue, and the resulting impacts on overall technical change and growth. We identify several lessons from this literature.

We first consider that an economy that depends on investment in less resource-intensive (less pollution-intensive) green technologies to sustain growth in the long run. Then it is necessarily more difficult to substitute man-made inputs for resource inputs while sustaining growth. To illustrate, suppose man-made capital and resource inputs are complements. If man-made capital grows while resource inputs are constant or declining (due to rising natural scarcity or environmental policy), the return to investment in man-made capital stocks – including the return to brown innovation – falls until growth stops. If the cost of green innovation becomes relatively high, moreover, the incentives to innovate in the long run peter out. However, because green technologies provide growth benefits in this case from the reduction of pollution and resource use, this in itself stimulates productivity improvement and growth at the aggregate level. Indeed, in these types of models, a balanced growth path arises along which both

¹⁶ Formally, consider the general production function $Y = f(K, L, R, A)$, where A is the vector of technology variables (or knowledge stocks) A_i . A technology i is defined to be brown if $f_{A_i R} > 0$. Similarly, capital is defined to be brown if $f_{KR} > 0$. Technology i and capital are green if $f_{A_i R} < 0$ and $f_{KR} < 0$. While in general we can distinguish as many technology stocks as we have inputs in the production function (as in our equation (10)), each of these stocks can be classified as either brown or green according to this definition. Our discussion therefore focuses on this contrast between green and brown technologies.

¹⁷ The exception is when the “rebound effect” occurs: higher energy efficiency might lower prices so much that demand for energy increases.

innovations take place, but the rate of green innovation is faster than the rate of brown innovation so that the drag of reduced resource use is exactly offset by relatively green innovation (Smulders and De Nooij, 2003).

A second insight from DTC literature is that environmental policy is less costly if there are relatively low-cost opportunities for green as well as brown innovation as compared to brown technology only, insofar as environmental policy redirects innovation to green technologies. Unfortunately, in a second-best world there is no guarantee that the direction of innovation responds to environmental policy in the socially desired way. For example, if intellectual property rights are not well defined and protected across countries, green technology development in countries that implement stringent environmental policies may be more than offset by technical development in the opposite direction in other countries (see Di Maria and Van der Werf (2008) and Di Maria and Smulders (2004) for DTC in the context of transboundary pollution problems).

An economy might get locked into a pollution-intensive model of production. Acemoglu et al. (2012) illustrate this in a model with green and brown sectors, which both produce a similar final good. In both sectors innovation can take place that enhances productivity. Without environmental taxes, goods from the brown sector are initially cheaper because they have a longer history of cost-reducing R&D; and only brown firms undertake R&D since they have a larger market. Even with the introduction of environmental taxes, Acemoglu et al. show that firms in the brown sector can continue to become even more productive over time and capture an even larger market share: the economy becomes locked into a more polluting industry structure and the productivity gap between brown and green goods becomes wider. An additional policy instrument – a subsidy for green R&D – is needed to close the gap.

For the long-run it seems reasonable to expect that both green and brown innovation opportunities are available. However, in the medium-run, past technological developments might favour brown over green innovation. This leads to a further insight from the DTC literature, namely that there are well defined circumstances under which technology policy needs to focus more on green technologies than on conventional technologies. This is not an obvious conclusion when one takes externalities as the rationale for technology policies. As is well accepted, the reward an innovator gets by marketing her invention does not reflect the social benefits or costs

of her invention: she does not get compensated for knowledge spillovers that are created, and she does not bear the cost of premature obsolescence of other assets due to the capture of business from other firms. Most empirical studies find that the positive knowledge-spillover externality dominates the negative externality from business stealing, so that a subsidy to research is needed to correct underinvestment in innovation. However, there are no reasons to expect that these imperfections are systematically different for brown and green innovations, except for the impact of environmental policy failures from inadequate internalization of the environmental costs of brown technologies. As Newell et al. (2005) point out, environmental policy (and hence green growth) is a problem of two interacting externalities: knowledge and environmental externalities.

R&D subsidies for green technology should be bigger if the ideas that they generate create greater benefits but these benefits cannot be appropriated by the innovator. Larger subsidies for green R&D can partly offset inadequate incentives for switching to greener technology when environmental policy is not efficient. However, even with efficient environmental policy, the optimal R&D subsidy for green technologies is larger than the brown R&D subsidy (Hart, 2008; Gerlagh et al, 2014). Since environmental policy induces substitution to greener methods of production, a more stringent policy to correct externalities also increases the spillover benefits from green R&D. Hence, the total value of spillovers increases with environmental policy. For R&D related to polluting sectors, the opposite happens.

7. Empirical regularities in the light of growth theory: decoupling, growth drag and EKC

Growth theory provides many insights about mechanisms and possibilities, but cannot give insights into the magnitude of effects without being systematically confronted with data. Although extensive quantification is beyond the scope of our conceptual review, we want to point out the links between growth theory and the main empirical approaches to growth and environment.¹⁸

¹⁸ For illuminating and more elaborate discussions see Hepburn and Bowen 2013, Sorrell 2010.

We start from a simple operational definition of green growth: GDP growth without emission growth. This requires that the ratio of emissions per unit of GDP falls at a rate (at least) equal to GDP growth. This is referred to as “absolute decoupling”, with relative decoupling meaning decreases in the emissions-GDP ratio but at a slower pace than GDP growth. Calculating historical rates of decoupling as GDP growth minus emissions growth, we find relatively small numbers for CO₂. IPCC (2014) concludes that worldwide since 1970 CO₂ emissions per unit of GDP have declined at about the same rate as population growth, so that per capita emissions have been constant on average. Hence, there has been relative but not absolute decoupling.

It would be overly pessimistic to conclude that CO₂ decoupling is not feasible, however, since the observed worldwide development has been the result of market forces without that much in the way of explicit environmental policies for CO₂ limitation. The theory suggests that once policies are in place, more decoupling could be expected. How effective these policies can be in reducing emissions and simultaneously maintain growth depends on the possibilities for technical change (which seem to be abundant), substitution possibilities (which seem to be limited) and rebound effects (which tend to often offset technical emissions savings, see Sorrell 2010).

One way to quantify the effect of emissions reduction, in particular through energy reductions, on growth is through growth accounting. In a competitive economy the output elasticity of energy equals the cost share of energy in production, which is typically small at the aggregate level. Hence a back-of-the-envelope calculation suggests that a ten percent reduction in energy use reduces output at most by 1 percent. This type of growth drag calculation (see also Brock and Taylor, 2005) are optimistic, as indicated by our theoretical discussions. The calculations are often based on comparison of the steady states of a resource-dependent economy and a non-resource dependent economy. However, the relevant calculation compares a brown growth path with increasing emissions to a green growth path with substantially lower and non-growing emission levels. Moreover, the growth drag calculation typically assumes a given cost share for energy, which effectively implies Cobb-Douglas production with good substitution

while in reality substitution is more difficult. Lower levels of energy and emissions go together with a higher cost share of energy, which magnifies the growth drag.

The Environmental Kuznets Curve (EKC) literature has looked for evidence of an inverted U-shaped relationship between GDP and pollution levels. According to this hypothesis, the development path of the economy might display a deterioration in the quality of nature in the early stages of economic development, but with increasing income the quality of nature would improve again. Copeland and Taylor (2003) make a distinction between the scale effect (more production leads to more pollution), the composition effect (growth leads to changing, cleaner, consumption patterns), and technology effects (the need for cleaner technologies induced by preferences giving higher weight to a clean environment).

Mechanisms from growth theory may generate this type of path, in particular the fact that a low capital stock triggers both high investment and growth with growing demand for polluting inputs in production, while low income and consumption can imply that demand for environmental quality also is limited. Nevertheless, once endogenous technology is brought into the picture, an inverted-U-shaped pattern is no longer the natural outcome. Process innovations could increase the demand for polluting inputs and product innovations may shift consumption to energy-intensive sectors (Smulders et al 2011).

The empirical literature on the EKC (starting with Grossman and Krueger (1995)) is huge and far from unambiguous. It typically looks at how *levels* of income and pollution are related across countries, which makes it difficult to deal with technical change and growth issues as well as with linkages across countries. From the perspective of growth theory it seems better to think in terms of growth rates of pollution and income (cf. Wagner, 2008). For some pollutants or patterns of natural resource degradation no inverted U-shape is found, while for others the turning points differ across countries. The only thing that might be concluded is that the EKC provides some support for the claim “that environmental degradation is not an inevitable consequence of economic growth” (Levinson, 2008).

8. Further reflections: Green growth and the search for positive spillovers

Although the models we have explored are stylized representations of growth with natural capital, there are several important basic conclusions relevant to green growth that we can draw from them:

(i) When and how a country still in the stage of building up its capital stock makes a transition away from environmentally damaging inputs depends on a variety of empirical economic efficiency considerations that do not readily reduce to simple guidelines for sustainable growth. For example, “overshooting” – growth beyond the “green” steady state with reversion to that state thereafter – can occur along an optimal path (depending on the nature of the damage function among other influences). The greenness of an optimal growth path may depend heavily on initial conditions related to physical as well as natural capital.

(ii) Transition to a green economy has costs as well as benefits, and the efficient transition may be gradual, even when the level of environmental degradation is high and irreversible. The specific model we have studied in Section 5 has only limited adjustment costs as the economy converges from above to the carbon-free steady state. In practice we can anticipate that there will be also adjustment costs that give rise to at least transitory under-employment of labor as well as premature obsolescence of some existing capital.

(iii) In the real world consisting of both more developed and developing economies, a variety of different adjustments can be occurring concurrently even along an optimal path – e.g. some countries may be reducing fossil energy use along an optimal path, even while it grows – albeit more slowly – in some developing countries. Even when the environmentally damaging inputs are globally traded and have a single real price, the environmental damages under consideration could be mainly country-specific. Even more heterogeneity of adjustments might be expected if the environmentally damaging inputs are locally produced non-tradeables.

(iv) There is no general presumption that longer-term environmental sustainability can be realized with minimal impacts, or even positive spillover effects, on nearer-term income growth. Reduced utilization of natural capital, whether due to increasing scarcity or policy to restrict over-depletion, exerts some drag on growth. When the rate of natural capital depletion is inefficiently large, then near-term costs of limiting its utilization will be offset by longer-term

productivity gains from maintaining and enlarging natural capital stocks. However, as vividly illustrated by the example of greenhouse gas mitigation policy, the timing of benefits relative to costs is an empirical matter (as is the extent to which benefits are realized in conventional income and product terms versus more intangible improvements in utility).

(v) Factor-augmenting technical change that offsets resource depletion is critical to sustaining long-term growth within natural limits on the availability of natural resources and environmental services. A case can be made for targeting public R&D investment toward green technology, either in concert with stricter environmental policies or to overcome path dependency problems that could lock in less sustainable (and ultimately lower-welfare) brown growth paths. However, the extent of need for targeting green R&D depends on the importance of alleviating resource constraints (as distinct from conventional capital accumulation) for economic growth, and the cost of green R&D relative to other options.

Our review of conventional growth-and-environment frameworks highlights again the central role of correcting inefficiencies in market prices for achieving efficient and sustained growth. It is well known that there are a variety of practical obstacles to implementing efficient environmental pricing, including political economy, enforcement, and information/cognitive issues that have been identified by behavioral economists (Kallbekken et al., 2011; Aalbers et al., 2009; see also Kahnemann 2003). A number of second-best alternatives to address these issues have been studied, and the reframing of debate over sustainable development in the context of green growth provides practical benefits in drawing attention to these issues. However, this does not obviate the importance of the role of pricing in guiding both efficient, sustainable use of natural capital and investment in green technology. While positive spillovers may arise, evaluation and management of tradeoffs through one or another form of pricing is essential.

Policies that increase the efficiency of resource allocation by correcting environmental or natural resource externalities also can have a positive effect on growth indirectly, if by increasing total output they also increase savings and capital accumulation. For example, policies that reduce degradation of natural environments also can beneficially reduce exposure of built capital to natural disasters, assuming disaster risk probabilities are not adequately reflected in private investment decisions or land-use policies. Policies to stimulate reforestation programs can slow

the rate of CO₂ accumulation in the atmosphere, reduce erosion and water contamination, and provide direct monetary and non-monetary benefits. From a definitional point of view, these are not spillover effects so much as a reflection of the full benefits of the environmental policy, including co-benefits or general equilibrium effects.

We suggest that it is more useful to define policy spillovers in a green growth context as arising when a policy intervention in one part of the economy more fundamentally changes the nature of tradeoffs in other parts of the economy. For example, policies to spur growth through broad-based strengthening of economic and social institutions also could increase the effectiveness of environmental monitoring and enforcement or reduce over-use of open access resources. Coordination of individual efforts to improve management of a common property resource also could spill over to better coordinated, more efficient allocation of different labor services (Gibson, Williams and Ostrom 2005).

Some observers point to a broader category of economy-wide “coordination problems” as hindering growth (Rodrik 2008). There may be path dependencies in technology development and diffusion as a consequence of different types of economies of scale and scope, leading to possibilities for multiple long-term equilibria. As already noted, innovation and technology adoption can depend on specific knowledge and human capital built up over the course of past innovation.

A question that has received scant consideration in discussions of green growth is the way that growth policies could (or might not) have positive spillovers for environmental sustainability. For example, could a growth-enhancing industrial policy (assuming one exists) have as a side effect a less costly path toward green innovation? “Clustering” of development across certain industries to promote economies of scope in cross-process innovation and supply chain development might also have reduced environmental waste products. Productivity spillovers from capital to energy arise when more modern equipment also has higher energy efficiency. However, these ideas remain almost entirely speculative. This points to an important knowledge gap for further research in understanding the technology-based drivers of green growth.

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