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ABSTRACT

The natural environment provides crucial inputs and services for economic development, but its role for productivity growth is insufficiently explored. Environmental scarcities can pose a drag on productivity growth and a risk for its sustainability. At the same time productivity growth is often seen as the solution to environmental challenges. Methodological problems abound, overall the literature suggests that environmental issues are a potentially important risk factor. Theoretical models tend to focus the role of resource-augmenting technical progress in the long run, in light of environmental constraints. Macroeconomic studies suggest the contribution of the natural environment to productivity growth has been modest overall. Microeconomic studies focus on partial equilibrium impacts, which in many cases have been found larger than expected. Finally, case-studies of historical civilisation collapses suggest the risks may be significant.

RÉSUMÉ

Le milieu naturel fournit des ressources et des services cruciaux pour le développement économique, mais son rôle dans la croissance de la productivité n'est pas suffisamment étudié. Les pénuries de ressources environnementales peuvent engendrer un frein à la croissance de la productivité et un risque pour sa pérennité. Dans le même temps, la croissance de la productivité est souvent considérée comme la solution aux défis environnementaux. Les problèmes méthodologiques abondent, mais dans l'ensemble, les rapports suggèrent que les questions environnementales sont un facteur de risque potentiellement important. Les modèles théoriques ont tendance à se concentrer sur l'impact du progrès technique et l'augmentation des ressources dans le long terme, à la lumière des contraintes environnementales. Les études macroéconomiques suggèrent que la contribution de l'environnement naturel dans la croissance de la productivité a été globalement modeste. Les études microéconomiques quant à elles se concentrent sur les impacts d'équilibre partiel, qui dans de nombreux cas se sont révélés plus importants que prévus. Enfin, des études de cas sur l'effondrement des civilisations historiques suggèrent que les risques peuvent être importants.

FOREWORD

This paper was authored by Alex Bowen (LSE/Grantham Research Institute on Climate Change and the Environment) under the oversight of Tomasz Kozluk (OECD). The author wishes to thank delegates to the Working Party for Integrating Environmental and Economic Policies (WPIEEP) for their insightful comments and suggestions, and Natasha Cline-Thomas and Katjusha Boffa (both OECD) for their editorial support.

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EXECUTIVE SUMMARY

The natural environment provides material inputs and services that support economic activities. Some material inputs are exhaustible natural resources while others are renewable to varying extents, with the supply of each renewable input dependent on the state of its supporting ecosystem. Environmental services include 'supporting services' (such as soil formation), 'regulating services', such as climate, that have pervasive but diffuse influences on economic activity and 'cultural services', such as culturally significant landscapes.

In order to take the environment into account in measuring productivity growth, one should in principle measure each environmentally related input along with capital, labour and other inputs. Otherwise, measures of total factor productivity growth will be biased by the exclusion of changes in environmental inputs. Similarly, on the output side, the production of environmental 'bads' such as pollution as well as goods and services should be taken into account. Although efforts are being made to move in this direction, for example, through the development of a System of Environmental and Economic Accounting under UN auspices and the measurement of different forms of 'natural capital', the role of the environment in economic activities is still neglected.

The environment can affect the growth rates of output and labour productivity directly through changes in the rate of use of natural resources and environmental services and indirectly through impacts on the quality and quantity of inputs from labour (e.g. via effects on health) and manufactured capital (e.g. through effects on depreciation) and on innovation (e.g. by affecting the returns to R&D).

Theoretical models draw attention to the challenge of sustaining productivity growth in the face of the limited stocks of some raw materials and the constraints on the flow of services from eco-systems. Many of these are not measured, priced in competitive markets or indeed priced at all, in part because many have the characteristics of public goods. One consequence is the tendency to over-exploit 'common pool' resources, increasing traditional measures of productivity growth in the short run at the cost of lower growth in the long run. Another problem is the adverse externalities from pollution and other waste products. Modelling points to the importance of resource-augmenting technical progress in sustaining output and productivity growth in the long run. The pattern of productivity growth over time also depends on whether society seeks to maximise the sum of suitably discounted individual utilities, to ensure sustainable development, or to leave individual behaviour as unfettered as possible.

Empirical evidence about the impact of environmental factors on productivity growth falls into broadly three categories: microeconomic evidence on environmental effects on productivity; more macroeconomic evidence about the environment and aggregate productivity measures; and more anecdotal and qualitative evidence from economic history. The evidence suggests that environmental factors can matter very much for long-run output and labour productivity growth. This is perhaps illustrated most clearly by the historical evidence of civilisation collapses. Rapid and severe global climate change threatens to provide a further demonstration.

Microeconomic studies have been drawing attention to the direct impact of the environment on labour productivity at a disaggregated level, particularly via pollution damages and extreme weather conditions, and to the contribution of the climate and ecosystem services to the production of marketed output in

narrowly defined sectors. In many cases, these impacts have been estimated to be larger than expected. But measurement problems abound.

Macroeconomic studies have been putting together estimates of broader measures of welfare than conventional GDP and broader measures of inputs than labour and manufactured capital alone. In many cases, the resulting estimates suggest that the contribution of natural resources and ecosystem services to labour productivity growth has been modest overall. In some times and places, however, the contribution has been significantly larger, most notably in resource-rich developing countries.

The scope for adaptation to cushion adverse impacts of environmental changes is not well understood and is empirically difficult to assess. Nor are the dynamics of many eco-systems fully understood; they are consequently very difficult to project outside their historical range.

There is scope for environmental policies to raise productivity in the broad sense and to improve the allocation of resources (and hence the profile of productivity growth) over time, primarily by internalising externalities. However, empirical research on the effects of environmental policies on traditional measures of productivity is largely inconclusive. The evidence for the strong version of the 'Porter Hypothesis', that the cost savings from environmental regulation of production processes are sufficiently large to increase firms' competitiveness, is mixed.

This review gives rise to a number of suggestions for further research, with respect to measurement, theory and empirical evaluation.

RÉSUMÉ

Le milieu naturel fournit des intrants matériels et des services qui alimentent l'activité économique. Certains de ces intrants sont des ressources naturelles épuisables ; d'autres sont renouvelables à des degrés divers, l'offre de chaque intrant renouvelable dépendant de l'état de l'écosystème dont il est tributaire. Les services environnementaux comprennent des « services de soutien » (formation des sols, notamment), des « services de régulation », comme le climat, dont les effets sur l'activité économique sont omniprésents mais diffus, et des « services culturels », tels que les paysages d'importance culturelle.

Pour mesurer la croissance de la productivité en tenant compte de l'environnement, il faudrait en principe mesurer, outre le capital, le travail et les autres intrants, chaque intrant lié à l'environnement. Si cela n'est pas fait, la mesure de la croissance de la productivité totale des facteurs se trouvera faussée par l'exclusion des modifications des intrants environnementaux. De même, s'agissant de la production, les « maux », environnementaux générés, notamment la pollution, devront être pris en considération en même temps que les biens et services produits. En dépit des efforts déployés pour progresser dans cette direction, dont on trouve par exemple une illustration dans le Système de comptabilité environnementale-économique (SEEA) mis au point sous les auspices des Nations Unies ou dans la mesure des différentes formes de « capital naturel », le rôle de l'environnement dans les activités économiques demeure négligé.

L'environnement peut influer sur les taux de croissance de la production et de la productivité du travail directement, à travers la modification du taux d'utilisation des ressources naturelles et des services environnementaux, et indirectement, à travers ses impacts sur la qualité et la quantité de travail fourni (effets sanitaires, par exemple) et de capital produit (effets sur l'amortissement, par exemple) et sur l'innovation (effets sur la rentabilité de la R-D, par exemple).

Les modèles théoriques attirent l'attention sur la difficulté de maintenir la croissance de la productivité compte tenu de la limitation des stocks de certaines matières premières et des contraintes pesant sur les flux de services fournis par les écosystèmes. Bon nombre d'entre eux ne sont pas mesurés, et il ne leur est attribué aucun prix sur des marchés concurrentiels, ni souvent aucune autre forme de prix, en partie parce qu'ils possèdent les caractéristiques de biens publics. On a tendance pour cette raison à surexploiter les ressources à gestion partagée, ce qui fait augmenter à court terme la croissance de la productivité, mesurée de façon classique, au prix d'une croissance plus faible à long terme. Les externalités négatives de la pollution et des autres résidus et rejets posent un autre problème. Les travaux de modélisation font ressortir l'importance d'un progrès technologique générateur d'économies de ressources si l'on veut maintenir la croissance de la production et de la productivité à long terme. Le profil de croissance de la productivité dépend également des choix de la société qui peut chercher, soit à maximiser la somme des utilités individuelles en appliquant un taux d'actualisation adéquat, pour assurer un développement durable, soit à laisser le plus de liberté possible aux comportements individuels.

Les données empiriques concernant l'impact des facteurs environnementaux sur la croissance de la productivité peuvent être regroupées en trois grandes catégories : données microéconomiques concernant les effets environnementaux sur la productivité ; données plus macroéconomiques concernant l'environnement et les mesures de la productivité agrégée ; et observations plus ponctuelles et qualitatives tirées de l'histoire économique. Les faits observés suggèrent que les facteurs environnementaux peuvent fortement conditionner la croissance de la production et la productivité du travail à long terme. L'histoire

de la chute des civilisations en est sans doute la meilleure illustration. Le changement climatique, compte tenu de sa rapidité et de son intensité, pourrait en offrir une nouvelle démonstration.

Les études microéconomiques ont attiré l'attention sur l'incidence directe de l'environnement sur la productivité du travail à un niveau plus détaillé, en particulier à travers les dommages causés par la pollution et les phénomènes météorologiques extrêmes, et aussi sur la contribution des services climatiques et écosystémiques à la production de biens et services commercialisés dans certains secteurs bien précis. Les estimations ont fait souvent apparaître des impacts plus importants que prévus. Toutefois les problèmes de mesures sont légions.

Les études macroéconomiques ont regroupé des estimations du bien-être plus larges que la mesure classique du PIB et des estimations des intrants allant au-delà du travail et du capital produit par l'homme. Dans bien des cas, les estimations obtenues semblent indiquer que la contribution des ressources naturelles et des services écosystémiques à la croissance de la productivité du travail a été généralement modeste. On trouve toutefois certaines situations dans lesquelles cette contribution a été bien plus marquée, principalement dans les pays en développement riches en ressources.

Le champ des possibilités offertes par l'adaptation pour amortir les effets négatifs des évolutions environnementales est mal connu et difficile à évaluer de façon empirique. La dynamique de nombreux écosystèmes n'est pas non plus vraiment comprise ; il est par conséquent très difficile de faire des projections.

Les politiques d'environnement peuvent permettre au fil des ans d'accroître la productivité au sens large et d'améliorer l'allocation des ressources (et partant le profil de la croissance de la productivité), principalement en internalisant les effets externes. Cependant, les études empiriques consacrées aux effets des politiques environnementales sur la productivité, mesurée de façon classique, ne donnent pas de résultats clairs. Les arguments en faveur de la version forte de « l'hypothèse de Porter », selon laquelle les économies réalisées grâce à la réglementation environnementale des procédés de production sont suffisamment importantes pour améliorer la compétitivité des entreprises, sont mitigés.

De cette étude émerge un certain nombre de suggestions pour la suite des travaux eu égard à la mesure, la théorie et l'évaluation empirique.

1. INTRODUCTION

This report reviews the role of the natural environment (including natural resources and ecosystem services) in influencing long-term productivity growth, an issue that has been brought to the fore by mounting concerns about the possible impacts of human-induced climate change. It also seeks to identify where further research is most needed to illuminate this issue.

The contribution of elements of the natural environment to economic activity has been long recognised. Classical economists such as Malthus (1798) and Ricardo (1817, 1911) were much concerned with the constraints on productivity imposed by the limited availability of agricultural land. Jevons (1866) in the nineteenth century worried about the exhaustion of coal deposits. Hotelling (1931) analysed the pricing of exhaustible resources. Nevertheless, the mainstream theories of economic growth developed by economists since have tended not to stress the roles of the environment and natural resource endowments. For example, Barro and Sala-i-Martin (2003) in their well-known text, "… use an empirical framework that relates the real per capita growth rate to two kinds of variables: first, initial levels of state variables, such as the stock of physical capital and the stock of human capital in the forms of educational attainment and health; and second, control for environmental variables … such as the ratio of government consumption to GDP, the ratio of domestic investment to GDP, the extent of international openness, movements in the terms of trade, the fertility rate, indicators of macroeconomic stability, measures of maintenance of the rule of law and democracy, and so on." But the list of 'state variables' does not include any related to the natural environment or natural resources and the term 'environmental variables' does not refer to the natural environment.[1] Galor (2011), in his exposition of 'unified growth theory', focuses on demographic factors, human capital and technology, although with an acknowledgement of the importance of initial 'biogeographical conditions' in the far distant past. The book's subject index does not include the word 'environment.' The recent work by Acemoglu and Robinson (2012) emphasises the divergent growth records of economies with very similar natural environments but different institutions (such as North and South Korea), thus downplaying the role of the former (see Diamond, 2012; for a critique). Dasgupta (2010) notes with dismay that "When asked, economists acknowledge nature's existence, but many deny she is worth much. I have heard professional colleagues remark at seminars that the services nature provides amount at best to 2-3% of an economy's output, which is the share of agriculture in the gross domestic product (GDP) of the United States. Why, they ask, should one incorporate a capital asset of negligible importance in macroeconomic models of growth and distribution?"

The lack of emphasis placed on environmental and resource factors in most of the growth theory of modern economics contrasts with the attention paid to the environment in some other disciplines such as economic history and geography. Diamond (2005), for example, examines several cases in which environmental factors were central to the collapse of economies. He stresses the risks to productivity in the long run from the interaction of economic activity with aspects of the natural environment such as soil, forest cover and water supplies. Diamond (2012) also remarks, "Countries that excessively deplete their resources—whether inadvertently or intentionally—tend to impoverish themselves, although the difficulty of estimating accurately the costs of resource destruction causes economists to ignore it." Ayres and Warr (2009), drawing on ideas from thermodynamics, argue for the central role of energy and resource inputs in economic activity and in particular the dependence of long-run growth on an ever-increasing flow of materials through supply chains, a theme common in the ecological economics literature.

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1 See pp. 515-516 and pp. 518-520.

However, more recently, economic policy-makers have been paying greater attention to the relationship between the environment and productivity growth. This probably reflects increasing demands for development in general to be sustainable and, in particular, the concerns due to human-induced climate change (Bowen, 2014). As Collier (2010) notes, "Since the Stern Review of the Economics of Climate Change of 2006 one aspect of the natural world – that it is warming – has suddenly slammed into the economic mainstream." A discourse around the theme of 'green growth' has developed, exemplified by the reports of the OECD (2011) and World Bank (2012). Efforts to measure and monitor the interaction of the environment and growth have increased, for example, in the efforts to measure 'natural capital' and changes therein (Arrow et al., 2012; World Bank, 2011) and to extend appropriately the standard national accounting framework (UN and others, 2014). Policy-makers have been able to draw on analytical work bridging the gap between ecological economics and more traditional economic analyses of growth (e.g. Simpson et al., 2005; Neumayer, 2013; Chapter 16 of Aghion and Howitt, 2009).

The policy discourse has drawn on various strands of the academic economic literature, both theoretical and empirical, which have also been evolving in recent years. This report gives a brief introduction to some of these strands, affirming the potential importance of environmental factors but also drawing attention to gaps in the empirical evidence base. The focus of this report is on the impact of the environment and environmental policies on long-run productivity growth and economic growth more generally. The relationship can run in the opposite direction as well, through the impact of productivity growth on income growth and hence on both the demand for natural resources and ecosystem services in production and the demand for environmental amenities, a link stressed in the analysis of the so-called Environmental Kuznets Curve (Stern, 1998; Stern, 2004). This makes it more difficult empirically to sort out cause and effect.

The report is organised as follows. In the next section, definitional and measurement issues are considered. In section (3), a typology of channels through which the environment may affect productivity growth is suggested, based on a production function framework. In section (4), some theoretical models of the relationship between the natural environment and growth are discussed. Then in section (5), empirical evidence on the impact of environmental and natural resources on productivity growth is considered. In section (6), the role of environmental policies in theory and practice is discussed. Section (7) concludes and offers some suggestions for future research priorities.

2. DEFINING AND MEASURING PRODUCTIVITY AND ENVIRONMENTAL INPUTS, OUTPUTS AND STOCKS

2.1 Defining productivity growth

It is helpful to start with a rehearsal of what is meant by productivity growth. The term is used in two broad ways. 'Productivity growth' is often used to describe the growth of output of some good or service relative to the growth in inputs. Given that typically labour income is still by far the largest component of national income classified by broad factor input (Dünhaupt, 2013), most attention has been paid to labour productivity growth – growth in output per unit of labour input – although measures of the growth of energy productivity, materials productivity and capital productivity are often reported, too.[2] Labour input is ideally measured in terms of hours of work but, as information on hours worked is not always available, it is often measured in terms of numbers of workers. Measurement issues include the treatment of the inputs of the self-employed, which are often incorrectly attributed to capital (Gollin, 2002). Labour productivity growth is often taken as a proxy for the growth of income per head and hence living standards, although its accuracy in this respect depends on the absence of changes in labour supply per head of the population, changes in the functional distribution of income, changes in the distribution of income across workers and changes in the terms of trade.

The concept of total factor productivity (TFP) growth or multi-factor productivity growth is used to refer to the growth rate of output after deducting some weighted average of the growth rates of all factor inputs – most commonly labour and manufactured capital. Conceptually, TFP growth is caused by technological and organisational progress, whether by innovation or learning from better practices elsewhere. If some factor inputs – such as raw materials – are ignored, changes in their contribution to production will be incorrectly ascribed to TFP growth and other inputs. Labour productivity growth depends not only on TFP growth but also on the growth of other inputs of production. Changes in the quality of labour inputs are sometimes attributed to the accumulation of 'human capital', assessed by measures such as years of schooling and educational qualifications obtained, rather than TFP growth.

2.2 The environment: inputs to and outputs from production

The natural environment provides useful inputs to economic activity in two ways: direct inputs and services. First, the environment can provide natural resources that are used up in production, such as fossil fuels or grain. Such resources are often classified as either exhaustible or renewable, where the supply of each renewable input depends on the state of its supporting ecosystem. The Millennium Ecosystem Assessment (2005) – see Box 1 – classifies such inputs as provisioning services (for example, fresh water). Second, the environment provides services. The Millennium Ecosystem Assessment refers to supporting services (such as soil formation). There are also more pervasive but diffuse influences on economic activity ('regulating services'), some of which can be thought of as facilitating production. The climate and the physical landscape, for example, influence economic production. Material inputs can be thought of as a 'flow' variable where the rate of flow depends on decisions made by producers. The flow of regulating services is usually determined largely by the 'stocks' of the relevant type of natural capital, which can be enhanced or damaged over time by economic activity.

[2] An inverse of the productivity measure such as energy per unit of output – 'energy intensity' – is perhaps more common for non-labour inputs, as in, for example, accounting decompositions of the drivers of CO_2 emissions into the energy intensity of output, the carbon intensity of energy, output per capita and population using the Kaya Identity (Kaya and Yokobori, 1998).

Box 1. The Millennium Ecosystem Assessment

The Millennium Ecosystem Assessment (2005) was an international synthesis by over 1000 of the world's leading biological scientists of research that analysed the state of the Earth's ecosystems.

The Assessment found that:

- Over the past 50 years, humans have changed ecosystems more rapidly and extensively than in any comparable period of time in human history, largely to meet rapidly growing demands for food, fresh water, timber, fibre and fuel. This has resulted in a substantial and largely irreversible loss in the diversity of life on Earth.

- Approximately 60% (15 out of 24) of the ecosystem services examined were being degraded or used unsustainably, including fresh water, capture fisheries, air and water purification, and the regulation of regional and local climate, natural hazards and pests.

- There was evidence that pressures on ecosystems are increasing the likelihood of nonlinear changes (including accelerating, abrupt and potentially irreversible changes). Examples of such changes include disease emergence, abrupt alterations in water quality, the creation of 'dead zones' in coastal waters, the collapse of fisheries and shifts in regional climate.

- The harmful effects of the degradation of ecosystem services were being borne disproportionately by the poor, contributing to growing inequities and disparities across groups of people. The degradation of ecosystem services could grow significantly worse during the first half of this century and is a barrier to achieving the Millennium Development Goals.

Source: Millennium Ecosystem Assessment (2005)

In practice, there is a spectrum rather than a simple dichotomy between exhaustible resources and renewable resources. The extent of reserves of usable oil, for example, depends on past geological exploration and the state of extractive technology. Physical reserves may exceed economically recoverable reserves because the costs of exploiting some reserves may be prohibitive given relative prices and technology. Reserves may be replenished over time but only very slowly, as for example with fossil fuel deposits. As Ayres and Warr (2010) point out, given the first law of thermodynamics postulating the conservation of mass-energy, material inputs are not strictly speaking used up in production but transformed. Some can be recycled relatively easily and economically (e.g. aluminium once it has been extracted from bauxite), others not (e.g. coal burnt to produce heat). As Ayres and Warr (p.171) explain, "In a finite planetary environment, the concentration of a scarce metal can never fall below the average. This means that recycling will become more difficult over time, but it will never become impossible… perfect recycling is theoretically possible given a flow of exergy from outside the system (for example, from the sun). But zero emissions can be ruled out as a practical matter, if only because there is always a point at which the benefits of more complete waste treatment (or recycling) are less than the costs."[3] Hence exhaustibility is partly an economic question. So is renewability. The rate at which some natural input to production can be renewed depends on the size and health of the ecological system producing it, both of which are influenced by economic activity and the relative prices facing economic agents. In certain circumstances, potentially renewable resources may be exhausted, as with the extinction of species used for food production.

On the output side, some of the activities that the Millennium Ecosystem Assessment describes as regulating services (such as breaking down pollutants into safer compounds) include ways in which the natural environment accommodates some outputs of economic activity – waste materials and pollution – rather than supplies inputs directly. These outputs can be regarded as environmental 'bads' that can reduce

[3] The 'exergy' of a system is the maximum useful work possible during a process that brings the system into equilibrium with its environment. Thus exergy is the energy that is available to be used.

productivity by adversely affecting not only environmental inputs but other inputs such as labour (e.g. by increasing morbidity) or manufactured capital (e.g. by increasing corrosion). Regulating services often have the characteristics of public goods (goods that are both 'non-excludable' and 'non-rivalrous' – i.e. individuals cannot be effectively excluded from use and use by one individual does not reduce availability to others). They can be regarded as providing an environmental service – providing a sink or recycling – as an input to the production of output broadly defined (i.e. a definition including environmental benefits to consumers or future producers). There are also aspects of the environment that promote well-being directly, for example by providing culturally significant landscapes and leisure opportunities. These include those services that the Millennium Ecosystem Assessment calls cultural services – also often 'public goods'. It is a moot point whether these involve economic activity; one might think in terms of aspects of the environment being combined with social activities (such as religion) to produce well-being.[4]

Many of these environmental inputs and outputs are not marketed, although material inputs usually are, as long as ownership and control of the relevant ecosystem or stock of material has been established. The 'public goods' nature of many aspects of the natural environment makes pricing in competitive markets difficult even where property rights are established. Some of the inputs are not under the control of the producer. Some of the outputs are jointly produced with the output(s) that are the objective of economic activity, with limited technological options to adjust the ratio in which they are produced. The economic agent producing them usually regards them as subject to free disposal unless regulation internalises what is otherwise an externality of production (although in some cases, such as with some forms of waste, the environmental bads may affect the producer directly by taking up space or reducing the efficiency of production). The widespread existence of externalities leads to a divergence of private and social costs.

Environmental factors may affect the level of output (and hence measured labour or total factor productivity) without affecting its long-run rate of growth. For example, a one-off fall in ambient temperature may trigger a one-off fall in the levels of labour productivity and output in a factory (and hence short-run measures of growth across the time interval in which the fall takes place) without affecting their subsequent rates of growth, which are dependent instead on technical progress and investment in plant and machinery.

2.3 Measurement issues

In order to take the environment into account in measuring productivity growth, one should in principle measure each environmentally related input along with capital inputs and labour inputs. Otherwise, measures of TFP growth will be biased by the exclusion of changes in environmental inputs. For example, productivity growth will be overestimated if the growth rates of inputs of energy or raw materials are higher than the growth rates of other inputs and are not counted. Any attempt to identify the sources of labour productivity growth in these circumstances will be misleading.[5]

Similarly, on the output side, the production of environmental 'bads' as well as goods and services should be taken into account. An important issue is the extent to which the measure of output is intended to

[4] According to some ethical perspectives, the utilitarian approach to valuing the environment is anyway inappropriate and excessively anthropocentric. Hence the philosophical debates about animal rights (Regan, 1983; Singer, 1993) and differing 'shallow' or 'deep' ecological perspectives (Naess, 1973, 1986).

[5] The problem is sidestepped to some extent if output is measured in terms of valued added, netting off the value of material inputs, but this does not help if the material inputs are not valued properly – or, indeed, at all. Also, the conditions that need to be met for a value-added production function to be well defined are more demanding than for a production function for output (see Cobbold (2003) and OECD (2001) for discussions of the relative merits of gross output and value-added methods of productivity estimation).

capture well-being or utility. At the aggregate level, this issue is reflected in the debate about the adequacy of GDP as a measure of economic activity, let alone of national well-being (see, for example, Stiglitz et al., 2009). Non-marketed outputs (e.g. housework, own-account agricultural production) are often ignored or measured by inadequate proxies. Valuation is very difficult when there are no marketed analogues to provide a yardstick. Banning a process generating toxic by-products may reduce measured GDP and hence measured labour productivity even though, overall, welfare is increased (if the removal of toxic outputs outweighs the reduction in GDP). More generally, an economy may find it desirable to use more inputs to adapt to environmental threats, increasing welfare by reducing environmental damage (e.g. 'tail-pipe' filters on car exhausts, scrubbers to treat waste gases), while reducing the volume of final output (and changing its composition).

Nevertheless, economists' growth accounting exercises can in principle be extended further to encompass more aspects of the interaction of the environment and the economy. For example, Caselli (2008) notes that, "[b]ecause of the well-known shortcomings of standard measures of value added as indicators of the 'want-satisfying' capacity of the economy, some attempts have been made to augment such measures by estimates of non-market outputs, chiefly the output of the education sector. Accounting for the effects of economic activity on the natural environment is very likely the next frontier." This assessment is borne out by the evolution of the concept of 'green GDP' to measure the non-market (flow) benefits of nature (Boyd, 2006). The UN's work in developing its System of Environmental and Economic Accounting (SEEA) is likely to be helpful in this regard, by providing a consistent and coherent framework for national statistical offices to collect and organise data about the economy and aspects of the environment, including energy, water, fisheries, land and ecosystems, and agriculture.[6]

The standard production function approach can be used to illustrate how a wider range of inputs and outputs than is conventional can be taken into account in calculating measures of productivity growth. In the standard textbook exposition, a production function is defined of the form $Y = Y(A, K, L)$, where K and L are capital and labour inputs respectively and A denotes the state of technology (or, as Abramovitz (1956) puts it, "a measure of our ignorance"). This formulation can be extended to introduce more inputs and joint outputs, including those related to the natural environment, as explained in Brandt et al. (2013 and 2014). Thus one can write down an expression for a more general transformation curve $H = H(A, Y_i, B_j, X_k) = 1$, where i indexes the number of 'good' outputs, j the number of 'bad' outputs and k the number of inputs. TFP growth can then be defined as a weighted sum of the rates of growth of 'good' outputs less a weighted sum of rates of growth of 'bad' outputs less a weighted sum of rates of growth of inputs. With constant returns to scale and perfectly competitive markets for all inputs and outputs, the weights on the growth rates of outputs would be the shares of each output in the total value of output, counting the value of 'bad' outputs as negative, while the weights on the growth rates of inputs would be the shares of each input in total input costs. If some outputs or inputs are excluded from the calculation, the weights assigned to the growth rates of the remaining outputs and inputs will in general be incorrect, even though the weights used for the remaining outputs would add up to one as would the weights used for the remaining inputs.[7]

The impact of environmental bads on the production of marketed output (for example, via the impact of pollution on plant productivity), as opposed to wellbeing, will in principle be captured by a GDP

[6] The SEEA was first proposed by the UN in 1993 and was adopted as an international statistical standard for official statistics by the Statistical Commission of the United Nations at its 43rd session in 2012.

[7] This framework can be used with heterogeneous inputs and outputs. In practice, at industry or national level, data on inputs and outputs represent aggregates. In general, the process of aggregation does not take account of either bad outputs or many environmental inputs. The conditions for the existence of a well-behaved aggregate production function given well-behaved production functions for the constituents of the aggregate measure are not discussed here. Neither are those for the existence of a well-behaved production function for value added.

measure, but the impact on non-marketed output (e.g. in the household sector of the economy) will not be. Nor will, at least directly, the impact of environmental bads on other aspects of welfare (e.g. health). Reilly (2012) writes, "While environmental effects are often considered to be 'non-market,' many of the impacts of environment are often reflected in market accounts through damages that might include, for example, less labour (due to environment related health problems), reduced productivity of agroecosystems, or damage to infrastructure and other produced assets. The challenge is to make the environmental connection explicit so as to provide a guide to where changes in policies could provide benefit. However, some damages do not enter the accounts at all, and mainly this is because household labour and leisure time are generally not valued in traditional accounts." Other approaches have tried to value 'bads' directly using a variety of valuation approaches, in principle allowing a more comprehensive value-weighted measure of productivity growth to be derived (e.g. Brandt et al., 2013 and 2014), or have used data envelopment analysis to identify how a form of production frontier has moved over time, taking account of multiple inputs (including some forms of natural capital) and multiple outputs (including physical measures of some 'bads') (e.g. Färe et al., 2012a and 2012b).

GDP is designed as a measure of the flow of goods and services in a given period. It does not attempt to account for the depreciation of capital stock, the depletion of exhaustible natural resources or any change in the sustainable size of ecosystems as a result of that economic activity. The concept of green GDP is subject to the same shortcoming. But concepts of net production, after allowing for changes in potentially productive stocks, exist and can be more useful for assessments of the sustainability of economic activity. The World Bank has developed measures of adjusted net saving that account for changes in some of the stocks of various types of capital – manufactured, human and natural (World Bank, 2011). However, these measures assume that different types of capital – manufactured, human and natural – are perfect substitutes for each other, so that changes in the composition of the capital stock do not matter as long as total capital is being augmented. This is an implausible assumption, at least for non-marginal changes (see the discussion in Neumayer, 2013). It is unusual and conceptually difficult to use measures of output or value added net of dissaving in measures of productivity growth. Nevertheless, the depletion of natural capital may adversely affect the conventional (gross) measure of productivity growth in the long run by making current levels of environmental inputs impossible to sustain (see section 4, which refers to theoretical models that support this point).[8]

[8] There is an extensive literature bringing together growth theory, the Hartwick Rule (that sustainability requires that resource rents along the optimal growth path are reinvested) and guidelines for improving National Accounts to obtain better welfare and sustainability measures. See Weitzman (1976), Weitzman (2007), Asheim (2002), Dasgupta (2008) and Hamilton (2014).

3. CHANNELS THROUGH WHICH THE ENVIRONMENT CAN AFFECT PRODUCTIVITY GROWTH

The discussion of the previous section suggests a simple typology of the proximate channels through which the environment can affect conventionally measured productivity growth, based on a production function framework. Thus, for labour productivity growth, the channels include:

- the quality and quantity of environmental inputs (use of natural capital and eco-system services)
- the quality and quantity of human capital inputs
- the quality and quantity of manufactured capital input
- impacts on innovation and technological progress in its broad sense (including organisational improvements)
- impacts on X-efficiency (proximity to the technological frontier).

For multi-factor productivity growth, the first three channels do not apply.

Changes in environmental inputs may be induced by changes in other factor inputs and relative price changes, depending on the substitutability or complementarity of the various inputs. Hence their proximate contribution to productivity growth may mask the ultimate cause of changes in the latter. Both types of productivity growth measured at an aggregate level can also be influenced by the re-allocation of production from less to more productive sectors. Environmental factors could in principle also affect aggregate productivity growth through such general equilibrium effects, as production and consumption decisions lead to changes in the composition of output.

3.1 The environmental inputs channel

Starting with environmental inputs, increases (decreases) in the growth rate in the use of environmental services and natural resource inputs, both renewable and non-renewable, will tend to increase (decrease) labour productivity growth (but not properly measured multifactor productivity growth, which accounts for these environmental inputs). In the case of 'environmental sink and recycling' services, their growth may substitute for the use of manufactured inputs for pollution abatement and waste disposal, freeing them up to produce higher final output, boosting labour productivity.

Hence both actual and measured productivity growth can slow if, for some reason, environmental inputs become less easily available. What factors might lead to slower or negative growth in environmental inputs – natural (material) resources, energy or ecosystem services – and therefore give rise to adverse impacts on labour productivity growth?

Physical exhaustion of non-renewable natural resources

In the long or very long run, growth in the supply and use of non-renewable resources will necessarily be reduced and then reversed as their stocks approach exhaustion; input growth rates must turn negative. On the one hand, this tendency may be offset to some extent by improvements in recycling technologies and other means of increasing the supply of supposedly limited resources (e.g. by finding ways of extracting minerals from progressively less concentrated deposits). Moreover, environment-augmenting technological progress may reduce demand – more output can be achieved using a constant amount of (environmental) inputs. But, on the other hand, maintenance of the growth rate of the quantity of such resources may be offset to some degree by falls in the quality of the inputs (e.g. switching from anthracite coal to lignite, which produces more pollutants than anthracite when burnt).

The question of how long is the very long run is an empirical one. In the case of solar energy, the sustainable rate of harvesting for power generation is likely to be very much higher than current levels, so that there is no absolute supply constraint on the growth rate of energy inputs from this source in the foreseeable future (although the cost may act as an economic constraint). There is considerable debate about other environmental inputs, as illustrated by the famous wager between Paul Ehrlich and Julian Simon about whether the price of five key commodity metals would rise or fall between 1980 and 1990, and the debate that this bet engendered (see Sabin, 2013; Grantham, 2011).[9] Ayres and Warr (2009) argue that "opportunities for further technological improvements in the energy- and materials-conversion stages of the economic system are simultaneously reaching exhaustion." However, while that may be true of some mature technologies, advances in the efficiency of solar photovoltaic cells and in the recovery of natural gas from shale, reflected in the prices of solar energy and U.S. natural gas, raise some doubts about the generality of this conclusion.

Increasing scarcity of non-renewable resources

In a perfectly competitive market economy with full property rights in exhaustible natural resources, the rent charged for an exhaustible natural resource should increase at the real rate of interest (Dasgupta and Heal, 1979). Thus the price of natural resources is likely to rise relative to the general price level over time, reducing demand and the growth rate of their use in production. This effect is likely to be exacerbated by an increase in real extraction costs as producers develop successively more difficult-to-exploit resources. Shocks to estimates of remaining reserves (e.g. new oil-field discoveries, new technologies such as fracking and news about geological conditions) will affect prices and hence the growth rate of natural resource inputs. So will natural-resource-augmenting technological progress, which may be stimulated by the rise in the relative prices of natural resources (the direction of innovation appears to respond to changes in relative prices (Popp, 2002).

The time profile of exploitation of natural resources is likely to be affected by absence of competitive markets and full property rights, as a result of which market prices will not incentivise the optimal rate of depletion. Insecure property rights are likely to increase the rate of use of natural resources initially (with a lower real price in the market) but result in a faster slowdown later (e.g. as with oil fields with competing oil drillers drawing on a common pool of oil). Monopoly power over supply is likely to slow the exploitation of the resource in question. Hence the time profile of the impact on labour productivity growth will depend on market structure and property rights as well as endowments and technological progress. Faster labour productivity growth in the short term may entail a sharper slowdown in growth in the longer term. In the absence of full information about these factors, it is difficult for policy-makers to design extraction regulation and taxation to bring about the welfare-maximising path of labour productivity growth.

Limited capacity of renewable eco-system services

Moving from non-renewable resources to renewable ones, it is evident that increases in the rate at which renewable resources are harvested may damage the sustainability of their supporting eco-systems, in

[9] Simon argued that a resource's relative price is the best measure of its scarcity. He bet Ehrlich that the inflation-adjusted value of a basket of five commodity metals – copper, chromium, nickel, tin and tungsten – would fall over the period 1980-1990. He won – the price of each of the five fell in inflation-adjusted terms. But the result of the bet would have been the reverse for several other decades.

which case the growth rate of the use of renewables would tend towards zero.[10] The growth rate could become negative if over-harvesting reduces the level of harvesting sustainable in the long run (in which case the degree of renewability is affected, illustrating that renewability may best be thought of as varying according to the resource considered and circumstances). This tendency may be offset to some extent by technological progress that enables a higher rate of harvesting (e.g. innovations in agricultural practices that allow higher yields per hectare to be sustained).

A lack of the relevant markets and property rights is likely to be associated with different time profiles of the rate of change of inputs. This is likely to be a more pervasive problem than with material resources, given the 'common pool' properties of many renewable resources and ecosystems. Thus, for example, the lack of property rights in shoals of fish leads to overfishing in the absence of regulation, with more rapid growth of fish production initially but ultimately lower production and higher fishing costs for a given size of catch. In some cases, it may be possible to organise collective action to remedy 'common pool' problems and externalities, although the difficulties have been evident at least since Olson (1965). Thinking about climate change, Ostrom (2009) writes, "The classic theory of collective action predicts that no one will change behavior and reduce their energy use unless an external authority imposes enforceable rules that change the incentives faced by those involved." However, she suggests that "[t]wo broad grounds exist for doubting whether sole reliance on the conventional theory of collective action is a wise scientific strategy. The first is the weakness of empirical support for the conventional theory of collective action... The second is the existence of multiple externalities at small, medium, and large scales within the global externality that has been of primary concern in the academic and policy literature." At smaller scales, the difficulties may be less acute than often feared. However, for transborder and global problems, the problems remain great.

Some ecosystem services, unlike material inputs, are 'non-rival' in their use. Climatic conditions, defined by TEEB (2010b) as a 'regulating service', are an example. Changes in climate can affect output directly (e.g. in agriculture and tourism) and via their impact on the efficiency of other factors of production (e.g. via impacts on human health and buildings). Such 'public goods' are not amenable to competitive pricing and could in principle allow for continuing growth of use as an input over time. However, as the case of greenhouse gas emissions and anthropogenic climate change makes clear, economic activities can damage the provision of the public good just as they can harm the supply of environmental goods and services that are rival in their use.

Complexity and non-linearities in eco-systems

Many eco-system services are generated by eco-systems that are complex and not fully understood. Some are best thought of as chaotic systems without determinate long-run equilibria, as with some animal populations (May, 1974). Others are subject to tipping points, irreversibilities and hysteresis (e.g. climate). In some cases, a normally renewable resource may not be renewed and ultimately disappear, either because of harvest rates in excess of rates of renewal or the passing of some minimum size for the sustainability of the relevant system (e.g. trees on Easter Island). The changing underlying functioning of an eco-system may not be immediately evident and hence have a delayed impact on labour productivity growth as environmental services initially continue to be used more intensively. One source of complexity is that increasing economic demands on some eco-system services may adversely affect the provision of others (e.g. greenhouse gas concentrations may affect the oceans' capacity to absorb carbon dioxide but also kill off coral reefs because greenhouse gases are making the oceans more acidic).

[10] Sustainability can be defined in different ways. De Groot et al. (2000) defines ecological sustainability as "the natural limits set by the carrying capacity of the natural environment (physically, chemically and biologically), so that human use does not irreversibly impair the integrity and proper functioning of its natural processes and components." Neumayer (2013) discusses economic concepts of sustainability.

3.2 The labour inputs channel

The environment can also affect human capital. Environmental factors affect morbidity and mortality (e.g. through harmful air pollution), altering the quality and quantity of labour supply and hence measures of labour productivity growth unadjusted for hours and quality of labour inputs. By impairing cognitive ability, some forms of pollution may reduce the production of new ideas, thereby harming growth in the long run by slowing the accumulation of knowledge capital, which is sometimes argued to be subject to increasing returns and therefore a key foundation for continuing endogenous growth. They can also affect workers' choices about labour supply, depending on the complementarities among the environment, benefits from leisure and income from employment. That would in turn affect labour productivity growth per head (e.g. unusually good weather may encourage absenteeism (Shi and Skuterud, 2015), temporarily reducing measured labour productivity growth; global warming may harm health, especially in the Tropics, reducing measured labour productivity growth over a longer period (World Bank, 2014)).

If productivity growth in the production of human capital (in human growth or in education, for example) slows because of a reduction in the growth rate of environmental inputs, that may slow the accumulation of such capital, thus slowing labour productivity growth (e.g. if increases in disposable income, which promote health, are accompanied by increases in pollution, which harm health). Similarly, if the rate of return to investment in human capital falls, because declining returns set in as the ratio of labour inputs to environmental inputs rises, the accumulation of human capital may slow. This type of effect will be more pronounced if labour and environmental inputs are strong complements (e.g. if material inputs increase with the size of the labour force – plausible with a given technology but not necessarily the case across an economy as a whole).

3.3 The capital inputs channel

Manufactured capital depreciates over time. The natural environment can affect the rate of depreciation, both by eroding the efficiency of the capital in a given task and by accelerating its obsolescence by changing the tasks that need to be undertaken. An example of the first effect would be faster corrosion of machinery in a damp atmosphere or more frequent destruction of roads in areas with more frequent earthquakes. An example of the second would be the obsolescence of existing sea defences as sea level rises because of climate change. More indirectly, the production of manufactured capital usually requires environmental inputs (such as material inputs, energy and water).

As with human capital, the degree of substitutability matters. If productivity growth in the manufacturing of physical capital slows because of a reduction in the growth rate of environmental inputs, that may slow the accumulation of such capital, thus slowing labour productivity growth. Similarly, if the rate of return to investment in physical capital falls, because of declining returns as the ratio of capital inputs to environmental inputs rises, the accumulation of capital may slow. In contrast, models assuming so-called 'weak sustainability' treat manufactured capital and natural capital as perfect substitutes, so ruling out this effect.[11]

[11] 'Weak' sustainability requires that some suitably defined value of aggregate capital, including man-made capital and the initial endowment of natural resources, must be maintained intact over time, so that the "generalized production capacity" of an economy does not decline (Solow, 1974; 1986); the composition of aggregate capital is not treated as important. 'Strong sustainability' in contrast requires that certain specific elements of natural capital are preserved, because there are certain functions that the environment performs that cannot be duplicated by humans or manufactured capital e.g. the ozone layer. See the discussion in Neumayer (2013) and Hediger (2006).

3.4 The innovation channel

Finally, the environment can affect growth holding other factor inputs constant, including via the pace of technological progress. The analogy with physical and human capital is obvious if innovation is seen as the output of a production process (measured, for example, by patents) subject to declining returns to any single factor of production. Falling growth rates of environmental inputs could slow the production of knowledge capital, while the accumulation of knowledge capital relative to natural capital could blunt the incentives for further accumulation, unless knowledge growth was sufficiently 'resource-augmenting.' However, many theories of endogenous growth (see Aghion and Howitt, 2009) suggest that the production of knowledge is subject to increasing returns to scale, because of the public goods nature of many ideas. Thus TFP growth and labour productivity growth could be sustained in the face of slowing or even stalling growth rates of environmental inputs.

Aspects of these channels have been explored in at least three areas of the academic literature: first, long-run theoretical growth modelling incorporating environmental inputs of various kinds (but usually at a high level of abstraction); second, empirical studies of examples of particular channels; and, third, studies of the economic history of past societies. The literature on sustainability is also relevant to an understanding of some of the channels, even though ecological economists often argue against a focus on productivity growth, finding it inimical to achieving sustainability of consumption over the longer term (Jackson and Victor, 2011).

4. THEORETICAL MODELS RELEVANT TO THE RELATIONSHIP BETWEEN THE ENVIRONMENT AND PRODUCTIVITY GROWTH

Concern about the sustainability of growth in the long run has stimulated considerable theoretical research. Much of this is relevant to the impact of the environment and natural resources on long-run productivity growth. The relevant literature has been surveyed by Smulders (1999), Brock and Taylor (2005) and Withagen and Smulders (2012). Smulders (2005) focuses on the role of exhaustible natural resources (energy and materials) and the limits to growth. Hepburn and Bowen (2012) discuss the scope for continuing long-run GDP growth, emphasising the importance of a growing role for what some call the ‘knowledge economy’ and others the ‘weightless economy’. Smulders et al. (2014) also discuss the relationship between growth theory and green growth, where longer-term investments in sustaining environmental wealth are balanced against nearer-term income growth to reduce poverty.

Theoretical growth models have been useful in identifying the assumptions and conditions under which output growth is sustainable – that is, under which there exists a path for strictly positive output growth in the long run. They show that these assumptions and conditions are non-trivial. In the long run, environmental constraints may reduce labour productivity growth to zero or less, even with positive total factor productivity growth, as the latter may be insufficient to compensate for the reduction in output due to the depletion of natural resources and increases in pollution. Nevertheless, optimal growth models do have some drawbacks. In order to obtain analytical results, most theoretical modelling has concentrated on balanced growth paths (where key variables all grow at the same rate in the long run and structural change is absent) and the transition to such paths. It is also usually assumed that transformation possibilities among goods and services – in and over time – constitute a convex set. The latter assumption allows the price system to be an efficient allocation mechanism and thus points towards the use of Pigouvian taxes and subsidies as key policy instruments. Both these aspects of the models have been criticised as unrealistic in the context of natural resources (Ayres and Warr, 2010) and ecological systems (Dasgupta and Mäler, 2003). For example, physical constraints on the supplies of raw materials often induce structural change and ecological systems can produce positive feedbacks, discontinuities and hysteresis effects, implying non-convexities in transformation possibilities.

The basic Solow and Ramsey-Cass-Koopmans (RCK) models of optimal growth both use a production function for output comprising two inputs, capital and labour, with exogenous technical progress. Population growth is treated as exogenous but output can be either invested or consumed. In the Solow model, investment and saving rates are exogenous. In the so-called Green Solow model, different pollution abatement intensities can be chosen. As Brock and Taylor (2005) put it, “the Green Solow model forms a useful benchmark since this model predicts that a more strict pollution policy has no long-run effect on growth. In true Solow tradition, different abatement intensities create level differences in income but have no effect on the economy’s growth rate along the balanced growth path.” In the RCK model, by contrast, the investment and saving rate is endogenous. In the long run, the rate of capital accumulation tends to the rate of growth of labour inputs measured in efficiency units – that is, of labour inputs as augmented by technical progress. Labour productivity growth is equal to the exogenous rate of TFP growth. In this set-up, the optimal consumption growth rate is equal to the elasticity of intertemporal substitution multiplied by the difference between the marginal rate of return on investment and the rate of pure time preference. At first sight, this framework does not appear to be very propitious for analysing the impact of environmental factors on productivity growth, given the absence of explicit environmental inputs and the assumption that multi-factor productivity growth is given. However, Withagen and Smulders (2012) point out that if environmental externalities lead to the social rate of return on investment exceeding the private rate of return (as would be the case if some of the capital is natural capital), and if the social planner does not take account of this, the steady-state growth rate of consumption and output taking into account the impact of these externalities will be below the socially desirable rate. Hence failing to internalise positive environmental externalities such as the benefits from investing in improved pollution control will reduce the rate of long-run labour productivity growth (not just its level). Rejecting climate-change mitigation measures would be an example of such a failure.

This draws attention to the importance of considering what drives investment, an exogenous saving rate or intertemporal optimisation. In the latter case, if the returns to investment diminish over time for some reason, such as the increase in the ratios of manufactured capital to both natural capital and labour, this is likely to reduce capital accumulation and long-run productivity growth. Smulders (2005) considers the issue of diminishing returns in his discussion of natural resources and growth. He identifies what he calls the ‘neoclassical trinity’: diminishing returns, substitution and technical change. Substitution of manufactured capital for non-renewable resources (‘natural capital’) reduces the impact on growth of increasing resource scarcity but diminishing returns to investing in manufactured capital set in, which also impose a drag on growth. In the neoclassical model, both drags on growth can be offset if the exogenous rate of technical progress is sufficient.

Withagen and Smulders (2012) consider a simple special case of no population growth, technical change or depreciation of manufactured capital but with explicit use of exhaustible resources in production (implying that the assumption of balanced growth is relaxed). With these assumptions and a positive rate of time preference, consumption will necessarily decline to zero in the long run as natural resources are depleted. If depreciation of manufactured capital is then introduced in the model, growth is hit harder still, as more and more investment is used up simply to replace depreciated capital as the capital intensity of the economy increases. In this case, exogenous technical change is not necessarily a solution to the problem. It creates a substitution effect, with fewer depletable resources being used with a given amount of manufactured capital and labour. But it also creates an income effect, which, together with a desire to smooth consumption through time, encourages depletion. To sustain consumption growth and labour productivity growth, an adequate level of specifically resource-augmenting technical progress is needed (i.e. technical progress that multiplies the contribution to output of each unit of natural resources used). The more difficult it is to substitute manufactured capital and labour for natural resource flows, the faster this type of technical change has to be.

As Withagen and Smulders point out, ecosystem services can be treated in a similar way to non-renewable resource flows, by regarding the natural capital from which they are derived (the ecosystems themselves) as natural resources with some ability to regenerate (thus the degree of renewability can be regarded as variable, as pointed out above). Regeneration lessens the challenge of depletion but does not remove it. Reduced pressure on renewable resources use can increase the productivity of ecosystem services and that of the economic sectors that depend on them. But problems of sustainability can still arise if technical progress is insufficient or of the wrong sort. Smulders (2005) argues that in optimal growth models, under normal conditions, an environmental resource stock capable of regeneration should not be asymptotically depleted but should approach a non-zero steady-state level. Thus the problem of diminishing returns to investment in manufactured capital is still likely to arise unless offset by capital-augmenting and environmental-resource-augmenting technical progress. In contrast, labour-augmenting technical progress can exacerbate the problem through the income effect on the demand for output. The danger of an excessive run-down of the natural capital that supports ecosystem services is increased by the fact that many ecosystem services have the characteristics of public goods (as pointed out above in paragraphs 12 and 31). Thus they are unlikely to be priced efficiently (or at all in many cases), leading to over-use and a lack of market incentive to maintain the stock of natural capital. Non-renewable resources supplied by competitive owners are not subject to the same difficulty. Lopez (2011) analyses a competitive economy with common access to a renewable resource that can be harvested but that can be harmed by pollution from the industrial sector. He finds that sustainable development is possible, even without property rights having been established in the renewable resource. But sustainability cannot be guaranteed; it depends on the adverse effects of pollution on the resource not being too great.

Much of the theoretical work in this area has taken technical progress to be exogenous. As a result, it can inform debate about the prospects for labour productivity growth (as resources are depleted, the quantity of ecoservices used changes and investment alters the stock of manufactured capital, so that factor proportions change) but total factor productivity growth is a given. However, total factor productivity growth (and any factor-augmenting biases) may be endogenous, the result of devoting time, effort and factors of production to purposive research and development. Smulders (2005) points out that this does not necessarily imply that sustainability or long-run growth are easier to achieve. On the one hand, investment in 'knowledge capital' may be subject to the problem of diminishing returns, as knowledge capital substitutes more and more for natural resources (just as with returns to investment in manufactured capital). Thus the incentive to continue this substitution will be attenuated over time. On the other hand, relative prices may affect the direction of technical progress, so that if increasing resource scarcity drives up the real relative prices of non-renewable resources technical progress will become more resource-augmenting (see paragraph 27).

Smulders notes that the microfoundations for this 'induced innovation' hypothesis are not strong, but there does seem to be some empirical evidence for it (see, for example, Popp, 2002; and Sue Wing, 2003).[12] Also, 'knowledge capital' is unusual in that it is to some extent non-rival in use – so that returns to investment are larger, the larger the relevant production sector's market size – and is not always subject to diminishing returns – new ideas can make it easier to develop further knowledge in the same area, so that researchers can 'build on the shoulders of giants' (see Acemoglu (2002) and, for the case of 'clean' and 'dirty' technologies, Acemoglu et al.,2012). Once a bias towards resource-augmenting technical progress has been established, this direction is likely to be maintained unless powerful price signals lead to a re-allocation of research effort; the pattern of technological progress is likely to be path-dependent. The possibility of increasing returns to investment in knowledge capital is central to much of the 'endogenous growth' literature (Aghion and Howitt, 2009). A major problem is that the public goods nature of much innovation is likely to lead a market economy to under-invest in research and development without R&D subsidies and thus produce too little growth.[13] Natural resource depletion rates may be too high or too low, depending on the balance of income and substitution effects among factors of production, so it is difficult to work out a priori whether natural resource inputs and ecosystem services will enhance labour productivity growth more or less than is ideal. However, focusing on under- or unpriced environmental externalities, it seems clear that, without strong price signals to reflect pressure on environmental resources, the direction of R&D is likely to be insufficiently resource-augmenting and the contribution of the environment to productivity growth will be less than optimal.

So far, the theoretical insights discussed have been derived from variations on the theme of Solow-type or endogenous-saving-type neoclassical growth models. This may rule out some mechanisms by which environmental degradation can curtail productivity growth in the long run. Dasgupta and Mäler (2003) note that "…Despite the ecologist's strictures, we economists have remained ambivalent toward Nature's non-convexities." They flag the existence of various environmental positive feedbacks, for example, in ocean circulation and the world climate at a global level, eutrophication of lakes, salinization of soil, and biodiversity loss in forests at a local level and health and nutrition at a human level. These

[12] Technological change appears to have shown an energy-saving bias in periods of high energy prices, especially when there have been fears that the increase in relative prices will persist. But energy services are not an example of a non-renewable resource, thanks to the solar energy received by the Earth daily. This observation has led some modellers to invoke a backstop energy technology available at a higher price than fossil fuels, which *are* depletable. It is interesting that Jorgenson and Fraumeni (1981) find that the US economy has tended to experience technical change that saved on material inputs but used energy.

[13] One way to try to get around this problem is to establish intellectual property rights but this is difficult when the knowledge is difficult to codify. Also, it risks introducing a different market failure, monopoly power and lower-than-optimal levels of licencing use of proprietary ideas.

positive feedbacks can lead to step falls in productivity as a result of stresses on the environment that trigger the passage of ecosystems to lower-output or zero-output equilibria. Such changes in productivity are unlikely to be optimal. As Dasgupta and Mäler point out, “We now know that in such environments it may prove impossible to decentralise an efficient allocation of resources by means exclusively of prices.” Assignment of property rights in Coasian fashion, even if possible, is not guaranteed to produce an efficient outcome.[14]

Ecological economists have developed alternative models from a systems dynamics perspective that can generate a range of outcomes for output dynamics. Ecological models often violate standard neoclassical assumptions made in traditional economic growth models and downplay the potential of the price system to steer economies towards stable growth paths, but they tend to place more emphasis on non-convexities and production relationships that are more complex than typical neoclassical production functions. For example, Motesharrei et al. (2014), motivated by the observation that many past civilisations have collapsed as a result of endogenously produced pressures, use the HANDY model to investigate possible output patterns over time, noting the danger of overshooting a society’s ecological carrying capacity and running down accumulated wealth. The existence of social classes differentiated by their consumption and labour input is also important in the model. Depending on parameter values, output in their model may smoothly approach a stable equilibrium, oscillate around equilibrium, follow a cycle of prosperity, overshoot and collapse, or collapse irrevocably. They conclude that, in unequal societies, to avoid catastrophe, it is necessary to reduce inequality and keep population growth below critical levels. But resource depletion alone, if large enough, can trigger a societal collapse. Their model has some features similar to the Ricardo-Malthus-inspired model used by Brander and Taylor (1998) and applied to the collapse of Easter Island’s economy.

Yet another approach is to change the social objective assumed in optimal growth models. Theoretical modelling has usually adopted a simple social welfare objective to facilitate welfare analysis. Taking the perspective of a utilitarian social planner maximising discounted consumption streams has been popular, although other perspectives (such as the egalitarian objective of maximising the welfare of the least well-off generation) have also been investigated (Withagen and Smulders, 2012). Their implications can differ. For example, it is possible for the utilitarian perspective to imply that it is desirable to have a period of consumption growth (and labour productivity growth) followed by declining consumption (and falling labour productivity), whereas an egalitarian approach, applied to an economy with the same technological characteristics, would imply a steady-state no-growth economy (with constant labour productivity). Asheim (2013) shows that, “[T]here is a general relationship between implementing a path which keeps well-being constant (is egalitarian) and where well-being cannot be increased for some subinterval of time without being decreased at some other subinterval (is efficient), on the one hand, and Hartwick's rule for sustainability, on the other hand,” where Hartwick’s Rule is, “Invest all profits or rents from exhaustible resources in reproducible capital such as machines.” Hartwick’s Rule stops societies ‘over-consuming’ by running down their natural capital without replacing it fully with manufactured capital (thus ensuring ‘weak sustainability’). Technical progress of the appropriate sort can relax this requirement. Investment in R&D can be thought of as investment to augment the stock of knowledge capital (although, as discussed above, this sort of capital may have unusual properties compared with the conventional variety). But heterogeneity of capital, lack of substitutability among different types of capital and population growth can make sustainability more difficult to achieve. In particular, some forms of natural capital may need to be sustained above key threshold levels if levels of well-being and aggregate output are not to fall (‘strong sustainability’).

[14] However, it may be possible to characterise the efficient outcome and the associated shadow prices in the presence of threshold effects. See, for example, Boucekkine et al. (2013), who study the problem of the optimal management of natural resources under ecological irreversibility.

All the approaches discussed so far abstract from the problem of uncertainty. In practice, economic agents faced with changing scarcity of natural resource inputs and, in some cases, changes in prices have to decide whether these changes signify long-run developments or short-run fluctuations (for example, are episodes of extreme weather a reflection of long-run changes in the climate or simply bad luck?). As producers learn about the persistence of changes in the conditions they face, they are more likely to undertake costly adjustments in the mix of inputs and technologies that they use to adapt to long-run changes in environmental conditions. Hence adverse productivity effects from such changes may be more pronounced initially before learning has taken place. The economics of adaptation to environmental change has been studied extensively in the case of climate change (see, for example, Agrawala and Fankhauser, 2008 and Hallegatte, 2009).

What are the implications of this discussion of theoretical models for the impact of the environment on long-run productivity growth? First, the finite nature of the stocks of natural resources and constraints on the supply of ecosystem services, in the absence of the right sort of technological developments, may reduce productivity growth in the future. This is more evident for labour productivity growth than TFP growth, but the latter may be affected through falls in the returns to investment in the factors driving TFP, such as R&D and human capital. Manufactured capital, human capital and knowledge capital are likely to have to be substituted for natural resource inputs and ecosystem services over time, given the supply constraints on the latter two categories of factors of production. This may result in decreasing returns to investment that may slow the accumulation of manufactured, human and knowledge capital, depending on the degree of substitutability in production possible and the biases in technological change. The drag is likely to be greater on measures of productivity growth that take into account the production of ‘bads’. In a perfectly competitive economy with full information, property rights and futures markets, relative prices would signal the degree of scarcity. In the real world, price signals may help signal increasing scarcity of some resources but cannot be relied upon to allocate resource use across time efficiently. There is a risk of sharp changes in resource prices in response to new information and changes in market type, implying the possibility of sharp changes in productivity growth (as with the oil price hikes of the 1970s and 1980s). The uncertainty this possibility engenders may itself inhibit capital accumulation.

Second, increasing natural resource scarcity, including erosion of the capacity of the environment to act as a sink for waste outputs, may stimulate offsetting technological developments that can sustain long-run productivity growth. However, this is not guaranteed (Hepburn and Bowen, 2013). Technological change can help but has to be directed towards augmenting resources and ecosystem services. Price signals may not be sufficient to do this, particularly where ecosystems exhibit non-convexities and where environmental ‘bads’ are unpriced, as they will be without regulatory intervention. Lack of substitutability in production and consumption is likely to exacerbate the problem. The implications for productivity growth may be masked for some time, both by failures of prices to reflect pressure on the environment fully and by time discounting, which encourages consumption in the near term at the expense of consumption in the more distant future. However, non-linearities in eco-system behaviour may lead to sudden and disruptive changes in productivity.

Third, there are a number of different modelling strategies to help investigate the impact of the environment on long-run productivity growth. However, they each have significant drawbacks. The choice of objective matters: maximising discounted consumption growth (adjusted perhaps for equity considerations where consumption possibilities are unequally distributed) does not generally imply the same path as does sustainability for output and productivity over time. Traditional economic growth models do not deal well with unbalanced growth and non-convexities. This warrants scepticism about their applicability to the many historical examples of civilisations’ collapses exacerbated by environmental degradation and also to some current threats of environmental crises. However, ecological models downplay the potential roles of the price system and optimising behaviour by economic agents in preserving natural capital. There is, therefore, further scope for combining insights from neoclassical and ecological growth models.

5. EMPIRICAL EVIDENCE ABOUT THE IMPACT OF ENVIRONMENTAL FACTORS ON PRODUCTIVITY GROWTH

Empirical evidence about the impact of environmental factors on productivity growth falls into broadly three categories: microeconomic evidence on environmental effects on productivity; more macroeconomic evidence about the environment and aggregate productivity measures; and more anecdotal and qualitative evidence from economic history. The micro-level studies tend to be more rigorous in their analysis of causation but suffer the limitations of a partial equilibrium approach. The results may be difficult to generalise and extrapolate to different settings because of their context-specific setup. The data requirements are demanding. Macroeconomic studies address more directly the aggregate variables but tend to describe correlations and trends (e.g. using growth accounting methods) rather than test hypotheses rigorously. Studies in the third category tend to be more qualitative than quantitative. In all categories, there is a paucity of good-quality data. This is true of most of the relevant environmental factors but particularly so with respect to ecosystem services. It is striking, for example, how little can be said with confidence about prospective global climate-change damages in the event of exceeding a 2°C global temperature increase, despite the thorough work of the Intergovernmental Panel on Climate Change.

5.1 Microeconomic evidence

Among the sources of microeconomic evidence about the impact of the environment on productivity are studies of the contributions of material inputs to output, the value of ecosystem services, studies of the impact of weather on various measures of productivity (often motivated by a desire to understand the risks from anthropogenic climate change) and studies of the impact of pollution on productivity.

Natural resource inputs

As far as natural resource inputs are concerned, production function studies have often included energy and/or land at a high level of aggregation but other material inputs have tended to be disregarded, either because they have been small relative to the inputs from other factors of production or because data have not been available Identification is difficult in production function studies. Aggregation is often much greater than in engineering models of production processes. Even with energy, there is little consensus about how easy it is to substitute capital and/or labour for energy in the event of a rise in the real relative price of energy. There remains debate about whether energy should be seen as more complementary with capital or labour, and hence how energy should be treated in a nested production function. Shen and Whalley (2013) note that, "…nested CES production functions over multiple inputs have been widely used. Although lack of reliable estimates of substitution elasticities for nested structures has been acknowledged for a long time, the problem has not yet been solved satisfactorily." Hence, as far as production function studies are concerned, the prospective impact of substitution away from energy on measured labour productivity growth, as energy becomes relatively more expensive, is uncertain. The upward (but interrupted and non-uniform) trend in real relative energy prices signals greater scarcity but any adverse impact on long-run labour productivity growth appears so far to have been small.

Baptist and Hepburn (2013) argue that the role of material inputs in production needs to be better recognised. Their study of firm-level gross output finds, first, that there is a negative relationship between intermediate input intensity and TFP in the data for US industry sub-sectors and a sample of South Korean firms. Second, there is a positive relationship between labour intensity and TFP. Third, value-added measures of productivity may systematically overstate the output-based productivity of material-intensive sectors. These results suggest that substitution away from the use of natural resources towards the use of human capital may actually boost productivity growth, as would a structural change away from material-intensive sectors. The results suggest that sectors less dependent on materials inputs and more dependent on labour inputs may be better at generating technological improvements. It is not clear whether a firm in a sector currently more dependent on materials inputs would achieve higher productivity growth if it attempted to substitute labour for materials.

Ecosystem services

The contribution of ecosystem services to the economy has been explored extensively by the ongoing global study 'The Economics of Ecosystems and Biodiversity' (TEEB), which was initiated by environment ministers from the G8+5 countries in 2007. Key findings relating to the importance of ecosystem services for productivity have been reported in particular in TEEB (2009), TEEB (2010a) and TEEB (2010b). The case studies referenced are too numerous to review here but certain findings stand out.

First, many ecosystems are under stress, so there is a major concern that deterioration of ecosystem services will inhibit productivity growth in the long run. These effects could be large in particular sectors. For example, TEEB (2008) draws attention to the study by Worm et al. (2006), which concluded that all of the world's commercial fisheries are likely to have collapsed in fewer than 50 years unless current trends are reversed. It found that low species diversity is associated with lower fishery productivity, more frequent collapses, and a lower tendency to recover after overfishing than naturally species-rich systems. This draws attention to the potential for sudden changes in labour productivity and the importance of hysteresis effects. Similar problems arise with pollination services (Gallai et al., 2009).

Second, the outputs of agriculture, forestry and marine sectors are likely to be most directly affected. Poor countries depend on these sectors to a greater extent than rich countries. They are likely to remain more vulnerable to environmental degradation. For example, TEEB (2008) notes that in Haiti, forest degradation and its consequences have jeopardised water availability and agricultural productivity, to the point where the elimination of hunger and poverty has proved impossible, and have severely affected health and child mortality, with adverse consequences for labour productivity growth, not to mention broader measures of the change in human welfare.

Third, the impact of environmental degradation on output is often non-linear, as with the example of fisheries. Dynamics vary widely according to a large range of factors, making it difficult to generalise about the risks to ecosystem services delivery and hence to productivity growth. Simple 'predator-prey' models are prone to booms and busts but more complex models can have more stable outcomes (reminiscent of the 'civilisation' modelling by Motesharrei et al. (2014) mentioned above, which draws its inspiration from the 'predator-prey' literature).

Fourth, an increase in biological diversity often leads to an increase in ecosystem productivity due to complementarities among species in their use of resources (TEEB, 2010a). Increased diversity can also help make ecosystems more resilient to adverse shocks, and hence reduce shocks to ecosystem services and output (TEEB, 2010a).

Fifth, the way in which some ecosystem services are delivered may need to change sharply if the risks of sharp falls in productivity are to be lowered. TEEB (2010a) points out that "…in intensively managed and disturbed ecosystems, maximum productivity is typically achieved in systems of very low diversity, for example heavily fertilised monocultures. However, these systems require large inputs of resources, including fertilisers, biocides and water, which generally are not environmentally or economically sustainable." In contrast, "sustained high production without anthropogenic resource augmentation is normally associated with high levels of biodiversity in mature ecosystems." This raises a difficulty for policy-makers in deciding when to try to transition from a risky monoculture that may not be sustainable in the medium term to a high level of biodiversity, with the possibility of a disruption to productivity growth at the point when resource inputs have to be reduced. TEEB (2010a) notes the findings of Mader et al. (2002) that moving from traditional methods to organic farming systems may reduce crop yields by 20%, but inputs of fertiliser and energy may be reduced by 30-50% and pesticide input by more than 90%. Hence a switch might reduce measured labour productivity significantly but have much less of an effect (and possibly a positive one) on TFP. This echoes the argument of Kammen at al. (2004) and Wei et al. (2010) that renewable energy is more labour-intensive than traditional fossil-fuel based energy. Studies such as these raise the interesting question of whether a 'green growth' strategy would increase the relative demand for labour (at given factor prices) and therefore reduce labour productivity growth. Gallai et al. (2009) note that it is difficult to assess the likely market and policy responses to reduced provision of ecosystem services such as pollination services; this makes it all the more difficult to project the economic costs of their decline.

Sixth, few ecosystem services are traded in markets. That is one among several of the factors making valuation difficult. Working out how much such services contribute to measured final output, let alone broader measures of human welfare, is correspondingly difficult even at the micro level.

Pollution

A number of studies have focused on the impacts of pollution of various types on output and productivity. In some cases, these have been used to calibrate models to project longer-run impacts on productivity and productivity growth. For example, Reilly et al. (2007) investigate the consequences of changing climate, CO_2 and ozone concentrations on crops, pasture and forests. In terms of the typology suggested above, one can think of this as focusing on the direct ecosystems services channel to productivity growth. Drawing on previous literature, they note that climate and CO_2 effects on crop yields have generally been positive in the past, while ozone has been highly detrimental.[15] Farmers, pastoralists and forest users have shown the ability to adapt to changes, with Reilly et al. suggesting that the longer-run effect of these environmental changes on agricultural yields is only one fifth to one sixth of the initial impact on yields.[16] They conclude that, comparing a world with climate change, CO_2 and ozone effects with a counterfactual one in which the ozone effect is 'turned off,' the ozone effect is enough to reduce total global consumption by nearly 0.2 percentage points. Crop yields are affected more than pasture yields, which in turn are affected more than forest yields. In an integrated assessment model exercise, they find that, in the counterfactual world, crop yields would rise by nearly 70% between 2000 and 2100. That contrasts with a drop of over 30% in the high ozone pollution case (with no control of CO_2 emissions). These numbers may appear large but the impact on annual growth rates ranges from an increase of 0.53% per year to a fall of 0.4% per year. The impact on crop production is much less. This reflects the relative inelastic demand for crops because of a relatively inelastic demand for food, the ability to adapt by substituting other inputs (e.g. fertilisers) for land, and the ability to shift land into or out of crops. Reilly et al. also point out how important terms of trade changes can be. In their model, Africa benefits substantially (in terms of overall consumption possibilities) from ozone damage because the latter improves Africa's terms of trade in agricultural commodities, while China suffers disproportionately. This is a reminder that environmental changes can affect welfare through channels other than productivity.

Reilly et al. (2007) treat CO_2 emissions as broadly benign for agricultural productivity, because of the fertilisation effect. However, some other studies take a very different view, focusing on the damaging consequences of heat stress from climate change brought about by greenhouse gas emissions.

[15] The impact of increasing CO_2 concentrations is likely to differ in the future, especially in tropical latitudes, as other aspects of climate change assert themselves, reflecting other non-linearities.

[16] Empirical studies do not always distinguish between short- and long-run effects of changes in environmental conditions and it is sometimes unclear what is assumed about the scope for adaptation.

Deryng et al. (2014) suggest that, even with the CO_2 fertilisation effect, under a business-as-usual scenario for greenhouse gas concentrations, by the 2080s (relative to the 1980s) extreme heat stress could double global losses of maize yield, reduce projected gains in spring wheat yield by half and in soybean yield by a quarter. Schlenker et al. (2009) find that yields increase with temperature up to 29°C for corn, 30°C for soybeans and 32°for C for cotton but fall off sharply after those points. Holding current growing regions fixed, area-weighted average yields are predicted to decrease by 30-46% before the end of the century under the slowest (B1) scenario and by 63-82% under the most rapid warming scenario (A1FI) under the Hadley III climate model. They also find evidence of limited historical adaptation by farmers to high temperatures. However, the methods they use do not allow them to assess the role of the CO_2 fertilisation effect. This illustrates not only the potential quantitative importance of climate change on agricultural productivity but also the multidimensional nature of the impact of global warming on crop yields and the danger of ignoring some of the channels through which they take place.

A comprehensive review of modern studies of the influence of climate on economic performance has been carried out by Dell et al. (2013). They focus on recent empirical research that has exploited data about high-frequency changes in temperature, precipitation and other climatic variables to identify their effects. Some of the macro-level results reviewed are discussed in the next sub-section. They report the findings of Hsiang (2010) that unusually high temperatures have large negative effects on output for three out of six non-agricultural sectors. Non-agricultural output appears to decline by 2-4% per degree Celsius, with losses driven by heat shocks during the hottest season. Dell et al. (2012) also estimate significant output losses (2% for each degree Celsius), but only in poor countries. The greater vulnerability of production in poor countries is a recurring theme. Although these effects are substantial in level terms and extend beyond the sectors typically regarded as at risk from climate change, linear extrapolation does not suggest large impacts from the human-induced climate change likely over the coming century. Even a 5°C increase by the end of the century would only reduce output by 10%, implying a fall in the annual growth rate of the order of only 0.1 percentage points.

However, as Dell et al. (2013) point out, such an extrapolation does not allow adequately for adaptation, reducing the impact on productivity, or intensification, increasing the impact. Although the literature has paid attention to the possibility of adaptation over time, Dell et al.'s attention to the possibility of intensification is relatively novel. Their reading of the evidence suggests that intensification effects are likely to outweigh adaptation effects in poor countries. They note in particular that it is more difficult to adapt to climate change that exhausts particular types of natural capital (e.g. desertification, salination). Also, the effects of extreme weather events do not appear to be limited to those areas that experience them only rarely – areas more accustomed to such events still suffer from them.

Dell et al. (2013) also review empirical literature on the impact of temperature and precipitation on agricultural productivity. They conclude, like Reilly et al., Deryng et al. and Schlenker et al., that variations in these variables can have major effects on productivity, with high temperatures, low or abnormally deviant rainfall levels being particularly harmful in developing countries. They are critical of earlier 'production function' and 'Ricardian land value' approaches to estimating the size of such effects.

Working Party II of the IPCC Fifth Assessment Report has reviewed a voluminous literature on the potential impacts of climate change on variables of economic interest. The Box below highlights some of the key points relating climate change impacts to output and productivity. Not all of the supporting studies take the rigorous approach to empirical identification that Dell et al. (2013) emphasise is valuable. Although there is ample evidence of adverse consequences from extreme weather events, heat stress, changes in precipitation patterns and ocean acidification, the implications for overall productivity growth are uncertain. The Report suggests that there is medium evidence for and medium agreement with the statement that a global mean temperature increase of 2.5°C above preindustrial levels may lead to global aggregate economic losses between 0.2 and 2.0% of income (medium evidence, medium agreement), which would imply that, at a global level, such warming would have a trivial effect on productivity growth (even though some sectors such as tropical agriculture might be more heavily affected). The sub-section below on macroeconomic evidence returns to this issue.

Box 2. IPCC Fifth Assessment Report – Working Group II comments on the impacts on output and productivity

- Hypoxic areas ('dead zones') are increasing in number and size, with implications for fisheries productivity.
- There is a risk of loss of rural livelihoods and income of rural residents due to insufficient access to drinking and irrigation water and reduced agricultural productivity.
- The progressive redistribution of species and the reduction in marine biodiversity in sensitive regions and habitats puts the sustained provision of fisheries productivity and other ecosystem services at risk. Socioeconomic vulnerability is highest in developing tropical countries.
- Valuation of non-marketed ecosystem services and limitations of economic valuation models that aggregate across contexts pose challenges for valuing rural impacts.
- Climate-change-induced impacts on human health will generate risks from lost work capacity and reduced labour productivity in vulnerable populations. There will be increased risks of mortality, morbidity, and productivity loss among manual workers in hot climates.
- Without adaptation, local temperature increases of 1°C or more above pre-industrial levels are projected to negatively impact yields for the major crops (wheat, rice, and maize) in tropical and temperate regions, although individual locations may benefit. On average, adaptation improves yields by the equivalent of around 15-18% of current yields, but the effectiveness of adaptation is highly variable.
- In Africa, increasing temperatures and changes in precipitation are very likely to reduce cereal crop productivity with strong adverse effects on food security. In Asia, too, climate change will cause declines in agricultural productivity in many sub-regions, for crops such as rice. Climate change impacts on agricultural productivity are expected to exhibit large spatial variability in Central and South America, for example with sustained or increased productivity through mid-century in southeast South America and decreases in productivity in the near term (by 2030) in Central America, threatening food security of the poorest populations.
- Rising sea levels and storm surges, heat stress, extreme precipitation, inland and coastal flooding, drought and water scarcity, and air pollution pose widespread negative risks for people, health, livelihoods, assets, local and national economies, and ecosystems.
- Climate change may influence the integrity and reliability of pipelines and electricity grids.
- Climate change will affect tourism resorts, particularly ski resorts, beach resorts, and nature resorts, entailing gains for countries closer to the poles and countries with higher elevations and losses for other countries.
- Throughout the 21st century, climate change impacts will slow down economic growth and poverty reduction, further erode food security, and trigger new poverty traps, the latter particularly in urban areas and emerging hotspots of hunger.
- For most economic sectors, the impacts of drivers such as changes in population, age structure, income, technology, relative prices, lifestyle, regulation, and governance will be large relative to the impacts of climate change.

Source: IPCC

So far, this section has focused on the direct impact of natural resources and the environment on output and productivity. However, as the typology developed above suggests, productivity may be affected via intermediate impacts on other factors of production. There is little literature on the impact via the efficiency of capital. The IPCC AR5 WG2 Chapter 10 draws attention to various types of infrastructure that will need to be replaced or adapted as a result of climate change (e.g. coastal defences, water supply, pipelines, electricity grids, roads in permafrost areas) and plant, equipment, buildings and other structures are likely to suffer some increase in depreciation as a result of more days at higher temperatures than the anticipated operating range. However, the chapter notes that "Not all key economic sectors and services have been subject to detailed research. Few studies have evaluated the possible impacts of climate change on mining, manufacturing or services (apart from health, insurance and tourism). Further research, collection and access to more detailed economic data and the advancement of analytic methods and tools will be required to further assess the potential impacts of climate on key economic systems and sectors." Robust quantitative estimates are scarce. Terregrossa (1997) points out that, in any case, very little is actually known about economic depreciation. Studies of capital depreciation tend not to mention environmental factors. For example, Bu (2006) studies the economic depreciation rates of the fixed capital stock in developing countries and finds that the stocks of fixed capital may depreciate at higher rates in the seven developing countries considered (Cote d'Ivoire, Ghana, Kenya, Zimbabwe, Indonesia, Philippines and South Korea), as compared with the normal rates usually assumed for advanced industrial countries. But Bu focuses on political economy reasons why this might be so, with no mention of the possible role of differences in the natural environment. Unexpected increases in natural resource scarcity may entail the need to change production techniques and consequently lead to early retirement of plant and equipment, as seems to have been the case with oil (see Baily (1981) on oil price increases).

There has been more work on the channel from environmental factors to labour productivity. Graff Zivin and Neidell (2013) review the literature on environment, health and human capital, drawing particularly on quasi-experimental empirical economics studies. They place particular emphasis on the importance of allowing for agents' optimising behaviour in response to changes in environmental factors and the role of avoidance behaviour (an issue that also arises in studies of other channels through which the environment affects output, such as accounting for adaptation in studies of agricultural productivity). They also argue that economic research has expanded the focus of analysis beyond traditional health outcomes to measures of human capital, including labour supply, productivity and cognition. They conclude that "pollution does indeed have a wide range of effects on individual well-being, even at levels well below current regulatory standards," with results suggesting effects could be quantitatively important. These effects include significant impacts on labour productivity. However, they do not consider how adverse health impacts may give rise to increased spending on health services, a form of adaptation to environmental stress. Aggregate measures of productivity would include the marketed output of health services, not the improvements in health status that are the real output of the activities concerned, nor the residual impacts on individual well-being, except in so far as this is reflected in lower labour productivity in the production of marketed output. The shift of output towards health services would also affect aggregate productivity through composition effects.

Among the examples of studies investigating labour productivity is Graff Zivin and Neidell (2012), who explore the impact of ozone pollution on labour productivity in the agricultural sector – more specifically, the productivity of workers at a large farm in the Central Valley of California that pays its employees through piece rate contracts monitored by an electronic payroll system. This setting is very useful empirically because the pollution is clearly exogenous to the workers' activities and the labour supply of the workers is likely to be highly inelastic in the short run. Graff Zivin and Neidell find that ozone levels well below federal air quality standards have a significant effect on productivity. A 10 parts per billion (ppb) decrease in ozone concentration leads to a 5.5% increase in labour productivity, a quantitatively as well as statistically significant result given that the average ambient ozone level for the day is under 50 ppb. They note that, if the productivity effect they estimate for the Central Valley of California is extrapolated to the whole of the US agricultural sector, a 10 ppb reduction in the federal ozone standard (as being contemplated) would translate into annual cost savings of $700m in employment costs. They also point out that the possible global implications of this result are even more striking given that 35% of the global active labour force works in agriculture.

More recent work involving the same researchers, Chang et al. (2014), investigates the impacts of outdoor pollution on the marginal productivity of indoor workers. Again, the effects are significant. They study data on outdoor particulate pollution ($PM_{2.5}$) and the productivity of pear-packers in an indoor plant in northern California. Such pollution can affect indoor air quality. They find that once $PM_{2.5}$ exceeds a level of 15 µg/m^3, an increase of 10 µg/m^3 reduces the productivity of workers by $0.41 per hour, which is about 6% of average earnings. Chang et al. note that if these productivity effects are extrapolated to all manufacturing workers throughout the USA, the reductions in $PM_{2.5}$ that took place between 1999 and 2008 would have generated $19.5 billion in savings in labour costs.

Dell et al. (2013) report various studies that also find quantitatively and statistically significant effects of environmental factors on labour productivity. Temperature appears to be an important factor, which is noteworthy given concerns about climate change this century. Weather fluctuations can lead to substantial changes in labour supply, especially at the extremes of temperature, for workers in industries exposed to outdoor temperatures. Seppanen et al, (2003), reviewing experimental studies, find that human productivity in various cognitive tasks falls by about 2% per °C over a threshold of 25°C. Seppanen et al. (2006) undertake a meta-analysis of studies, concluding that increasing temperature from 23°C to 30°C reduces productivity by about 9%. More recently, Cachon et al. (2012), using weekly production data from 64 auto plants in the USA over a ten-year period, find that a week with more than five days of heat exceeding 90°F reduces production in that week by 8% on average and across the whole sample of plants, severe weather reduces production by 1.5% on average (with no rebound in the week after). The question remains how far, spatially, such focused US case studies can reasonably be extrapolated.

There appears to be a trade-off between rigour in identification and inference on the one hand and geographical reach of the data sample on the other. However, several other studies suggest that environmental factors can have widespread effects. For example, Hanna and Oliva find that the closure of a large oil refinery in Mexico City resulted in an average 8% reduction in SO_2 within a five-mile radius relative to other neighbourhoods. This appears to have stimulated a 5% increase in hours worked, controlling for other factors, thus increasing labour productivity in per head terms.

Even more extensive in terms of geographical scope, if less directly linked to labour productivity, Burgess et al. (2013) find large effects on mortality from extreme temperatures in India but not in the USA.[17] In India, one additional day with a mean temperature above 36°C, relative to a day with a mean temperature in the 22-24°C range, increases the annual mortality rate by 0.75%. Using climate change models to extrapolate these results over time, the authors conclude that there is likely to be an increase in the overall Indian mortality rate of around 12-46% by the end of the century (and more in rural areas) – compared with a rise of 2% in the USA on the same basis. Such a large increase in mortality is also likely to reduce labour productivity through related morbidity effects. The study is revealing about the mechanisms by which this environmental factor affects health and thus output. It appears that extreme temperatures reduce agricultural incomes by hitting agricultural production and employment in the growing season. Hot weather is associated with lower agricultural yields, lower agricultural wages (reflecting lower labour productivity) and higher agricultural prices. The effects are entirely concentrated in rural areas, suggesting that the agricultural sector is particularly vulnerable and urbanisation mitigates the adverse productivity effects. This study corroborates Graff Zivin and Neidell's conclusion that, looking across the growing empirical literature on the environment, health and human capital, the "findings underscore the role of environmental conditions as an important factor of production." Heroic extrapolations over time and/or space suggest that the results could be quantitatively significant as far as productivity levels are concerned. It is less clear so far what the impact might be on long-run productivity growth, an issue meriting further empirical investigation.

[17] However, Deschênes and Moretti (2009), using high-frequency data from the USA, find that both extreme heat and cold result in immediate increases in mortality. Air pollution has also been shown to increase mortality (e.g. Chay and Greenstone (2003) for the USA; Greenstone and Hanna (2013) suggest that the evidence is less conclusive in India). It may also slow human capital formation (Currie et al., 2009).

5.2 Macroeconomic evidence

At the more macroeconomic level, there have been efforts to assess the importance of aggregate stocks of natural capital for output and productivity growth, and the overall contribution of non-renewable material inputs and eco-services, using approaches drawing on both growth accounting methods and growth theory. With respect to climate change, integrated assessment models have been used to assess the possible impact of higher global temperatures on output and case studies have illustrated the impact of climate variation on various aspects of economic performance.

Attempts to estimate the value of ecosystem services suggest that they may be large relative to the value of other factor inputs. Costanza et al. (1997) investigate the contribution of 17 major categories of ecosystem services, excluding non-renewable fuels and minerals and the atmosphere. Their approach is designed to estimate the contribution of the services valued at the margin. They conclude that "the annual value of these services is US$16-54 trillion, with an estimated average of US$33 trillion. The real value is almost certainly much larger, even at the current margin. US$33 trillion is 1.8 times the current global GNP." About 63% of the estimated value is contributed by marine systems, the rest by terrestrial systems. However, the authors point out that most of the value is outside the market. More recent work by de Groot et al. (2012) confirms that the value of ecosystems may be very large – extremely so in certain geographic settings such as coral reefs. Alexander et al. (1998) focus on marketed output, treating ecosystem services as one input to an aggregate global production function, together with labour and manufactured capital. Their estimates of ecological services range from US$3.4 trillion to US$17.6 trillion per year, between 44% and 88% of total world output in their data. The link to productivity growth is not made explicitly but the numbers are large enough that sharp changes in the supply of ecosystem services due to some ecological catastrophe would clearly have sizeable adverse impacts on labour productivity.

World Bank (2006) investigates the role of the stocks of various, often unmeasured, forms of capital in supporting production and discusses the concept of adjusted net saving ('genuine saving'), which they argue contributes to growth. If genuine saving is negative, output growth is unsustainable on the Hartwick criterion that all resource rents be reinvested and the long-run implications for productivity growth are adverse. One of the most striking features of the World Bank's empirical results is that several countries, particularly among oil-rich countries and in sub-Saharan Africa, appear to be sustaining GDP growth only by running down their various forms of capital (i.e. they have negative genuine saving). At some stage, aggregate labour productivity growth will be reduced, in large part because the output of extractive industries will decline without other industries more dependent on manufactured and human capital having been built up. However, this approach is silent on when this slowdown might occur. Box 3 discusses the World Bank approach in more detail.

Box 3. The World Bank's concept of genuine saving

The World Bank's measure of genuine saving is derived from gross national saving by subtracting an estimate of depreciation – the consumption of fixed capital – to give the conventional measure of net national saving; then adding the accumulation of human capital (current operating expenditures on education); and then subtracting an estimate of natural resource depletion (energy, metals, minerals and net forest depletion) and an estimate of damages from pollution (local particulate pollution and each country's share of the global emissions of carbon dioxide). This measure attempts to capture elements of both natural resource use and ecosystem use. Intangibles capital and R&D capital are not included in the calculations.

The World Bank categories of natural capital are not as comprehensive or as detailed as in the studies of eco-system natural capital mentioned in the text, reflecting both the problems of measurement and the heterogeneity of natural capital. Aggregating changes in different types of natural capital can be misleading, as the scope for substituting among forms of natural capital is limited, as is the scope for substituting between natural and manufactured capital.

The inclusion of two forms of pollution that have direct impacts on welfare as well as effects through conventional productivity suggests that ideally a measure of output more comprehensive than aggregate GDP should be used. The inclusion of CO_2 emissions at the national level is open to criticism, as the impact of climate change on each individual country is a function of the global stock of greenhouse gases, not the country's own share. There is also room for debate about the way in which natural and human capital stocks have been valued.

Genuine saving appears to be inversely correlated with countries' resource shares (mineral and energy rents as a percentage of Gross National Income). As the World Bank notes, "Countries such as Nigeria, Angola, Uzbekistan, and Azerbaijan all have growing economies, but negative genuine saving rates may be imperilling future generations." The latter two countries appeared to be suffering negative genuine saving rates of 40% or more in 2003. The two World Bank regions most at risk of having negative genuine saving are the 'Middle East and North Africa' and 'Sub-Saharan Africa'. Hamilton and Ley (2010) note a downward trend in the adjusted saving rate in Sub-Saharan Africa, with negative rates after 2002, despite the resource boom in the period.

Hamilton et al. (2005) ask the question, "How rich would resource-abundant countries be if they had actually followed the Hartwick Rule (invest resource rents in other assets) over the last 30 years?" Their answer is striking. Using time series data on investment and rents on exhaustible resource extraction for 70 countries, they find that Venezuela, Trinidad and Tobago, and Gabon would all be as wealthy as South Korea, while Nigeria would be five times as well off as it now is.

The OECD's recent work on productivity and natural capital (Brandt et al., 2013 and 2014) also highlights the importance in many countries of natural capital endowments. Brandt et al. (2013) use the World Bank's data set of natural resources – oil, gas, bauxite, copper, lead, nickel, phosphate, tin, zinc, gold, silver, iron ore, soft and hard coal and timber – and value their contribution at (an estimate of) their unit rents. The granularity of the data is thus greater than in the World Bank work but water, soil and renewable resources such as fish stocks are not covered. The authors find that the traditional multifactor productivity (MFP) growth measure needs to be adjusted significantly for countries with significant natural capital endowments. The adjustment can go in either direction and tends to be positive when natural capital growth is negative (e.g. in the UK and Netherlands as their fossil fuel resources dwindled), but is not necessarily negative when and where there are resource booms (e.g. if the inputs of other factors of production grow even more rapidly, as sometimes happens in resource booms). The authors note that the typical size of the correction increased in the most recent years of the data sample, reflecting a strong and generalised increase in commodity prices and hence estimated unit rents. The need to adjust MFP growth estimates arises despite the fact that the share of natural capital in overall production costs is no more than around 5%, even in resource-rich countries. The growth contribution of natural capital rarely reaches 0.25 percentage points. One can speculate that, as some ecosystem services are already under stress, the direction of adjustments might be more often downwards.

The World Bank's work suggests that, for some resource-rich and some poor countries, productivity growth is likely to be unsustainable unless genuine saving rates are raised substantially. But this threat is not universal, perhaps because of 'technical progress' in other countries or, thinking in stock terms, the accumulation of knowledge capital and other intangibles. Weitzman (1999) comes to a similar conclusion – resource depletion is an important issue but not as important as assessing the potential for technological advances. He uses Hotelling pricing theory and standard neoclassical growth theory to make an estimate of the aggregate costs of the non-renewability of 14 minerals, drawing on estimates of the Hotelling rents charged on them. He finds that the costs of these minerals being exhaustible instead of being capable of ever-continuing extraction at a constant rate (equal to the current rate in his data) is around 1% of average consumption each year (Weitzman focuses on the annuity value of discounted consumption per capita over time) – not enough to imply that depletion by itself has much of an effect at the aggregate level on productivity growth. In contrast, the adjustment to Weitzman's annuity measure of consumption necessary to take account of technical change (not considered in the base case) is 40 times larger. Of course, this relies on Hotelling rents being a good guide to future scarcity and neoclassical growth modelling being an appropriate framework within which to consider long-term growth.

The modelling framework in Weitzman (1999) does not take into account risk and uncertainty about resource depletion. Yet in the context of climate change, Weitzman has emphasised the importance of the small risks of catastrophic outcomes (Weitzman, 2009). The long-run impacts of climate change are highly uncertain, yet this is not reflected in most of the integrated assessment models that bring together climate models and aggregate 'damage functions'. Working Party II of the IPCC Fifth Assessment Report in the Technical Summary concludes "Global mean temperature increase of 2.5°C above preindustrial levels may lead to global aggregate economic losses between 0.2 and 2.0% of income (medium evidence, medium agreement). Losses increase with greater warming, but little is known about aggregate economic impacts above 3°C. Impact estimates are incomplete and depend on a large number of assumptions, many of which are disputable, and aggregate impacts hide large differences between and within countries." Damages of this magnitude over a timescale of several decades would have a trivial impact on global output and productivity growth.

Fankhauser and Tol (2005) take into account the possible feedbacks of climate change damages on capital accumulation and saving rates in a range of simple calibrated growth models, including some endogenous growth models. Thus they begin to take on board some of the implications of the growth theory discussed in section 4 above, often ignored in applied IAMs. They find that feedbacks via capital and, in the endogenous growth models, labour productivity and technical progress, can indeed exacerbate the impact of climate change on growth, but the effects are small. (This is in the context of calibrations that lead to projections of steadily declining per capita income growth over time in all scenarios anyway, as capital accumulation slows towards its long-run 'balanced growth' rate.) Fankhauser and Tol conclude that "for most climate change scenarios and most countries, negative climate change impacts are likely to reduce the rate of economic growth, but unlikely to reverse a long-term path of increasing per capita income. However, the possibility of negative growth cannot be fully excluded." They note that, "The dynamic effects are more important, relative to the direct effects, if climate change impacts are moderate overall." Dietz and Stern (2014), however, show that the implications for growth depend heavily on how models are parameterised. They argue that if the analysis is extended to take more strongly into account three essential elements of the climate problem – the endogeneity of growth, the convexity of damages, and uncertainty about the true sensitivity of climate to the concentration of greenhouse gases – the effects of emissions on growth risks being catrastrophic.

Case studies illustrate the fact that climate variation, via changes in the incidence of extreme weather events, can reduce growth rates in the short run.[18] Mechler (2004), for example, reports that Hurricane Mitch, which hit Honduras in 1998, reduced the country's GDP growth rate by as much as five percentage points. Raddatz (2009) found that natural disasters, especially climatic ones, have had a moderate but

[18] This paragraph draws on Bowen et al. (2012).

significant negative effect on real GDP per capita over the past four decades. He calculated that, at a conservative estimate, the macroeconomic cost of a climatic disaster affecting at least half a per cent of a country's population reduced real GDP per capita by 0.6%. Hallegatte and Ghil (2008) pointed out that economies may be able to respond more effectively to natural disasters if they have underutilised resources available. Hence, perhaps surprisingly, the costs of climate change and adaptation may be reduced by the presence of Keynesian unemployment or surplus labour. They argued that this is why some reviews of the costs of natural disasters have not found them to be particularly high (see, for example, Hochrainer, 2009). Landon-Lane et al. (2009) found that at the time of the great Dust Bowl in the USA in the 1930s, climatic stress hit the banking system, impairing financial intermediation and recovery for a prolonged period. Thus climate-related disasters can have long echoes through the financial system. Lis and Nickel (2009) showed how natural disasters tend to have an adverse impact on government budgets. Hornbeck (2009) drew attention to another aspect of the great Dust Bowl: adjustment happened primarily through migration out of the affected regions, not through inward capital flows, changes in agricultural practices or a movement of resources into industry. Migration can help adaptation to climatic change and extreme weather events. However, "the fewer choices people have about moving, the less likely it is that the outcomes of that movement will be positive" (Barnett and Webber, 2010).

Larger changes in global temperature could trigger tipping points, both in greenhouse gas feedbacks and impact processes, that could have much larger effects on productivity than the types of impact considered by Fankhauser and Tol. More generally, Stern (2013) argues that existing climate-change damage models are much too narrow in their coverage and fail to take account of risk. In similar vein, Pindyck (2013) writes, "A plethora of integrated assessment models (IAMs) have been constructed and used to estimate the social cost of carbon (SCC) and evaluate alternative abatement policies. These models have crucial flaws that make them close to useless as tools for policy analysis: certain inputs (e.g. the discount rate) are arbitrary, but have huge effects on the SCC estimates the models produce; the models' descriptions of the impact of climate change are completely ad hoc, with no theoretical or empirical foundation; and the models can tell us nothing about the most important driver of the SCC, the possibility of a catastrophic climate outcome."

Overall, the evidence seems to suggest that the impact of environmental factors is often quantitatively significant and, if taken into account properly, would lead to changes in estimates of productivity growth. But existing modelling suggests that the adjustments would not generally need to be large. A similar message emerges from the climate-change integrated assessment model literature, which attempts to take into account the impact of aggregate climate-change damages on output and productivity. Some researchers have sharply criticised the latter, however, in terms that also bring into question the use of estimates of the past impact of environmental factors on output and productivity in projections of the future. The effort to recognise the contributions of all forms of natural capital, particularly ecosystem services, has not yet been fully reflected in empirical estimates of productivity growth. Major challenges lie ahead in attempting to project changes in these contributions over time.

5.3 Evidence from economic history

A thorough assessment of the contribution of economic history to understanding the impact of environmental factors on long-run productivity growth is beyond the scope of this review. However, it is important to note that a number of studies reinforce the concerns discussed above that 'balanced growth' models and the extrapolation of trends in recent data could be seriously misleading.

For example, Burke and Pomerantz (2009) present one collection of studies that take a long historical perspective on the role of environmental factors in economic development. The increasing exploitation of land and other natural resources is a common theme, with changing land use often substituting new eco-systems for old ones. New forms of social organisation and agricultural technologies permitted increases in labour productivity. Collective action or statecraft often played an important role. Some widespread environmental problems threatening economic activity, such as massive deforestation, were sidestepped by exploiting new resources, in particular, fossil fuels. The studies are a reminder that the malleability of natural capital for social ends has been a very long-term feature of development. Also, climate change is not the only environmental phenomenon that can have society-wide adverse impacts on economic activities. Soil exhaustion and deforestation have had calamitous effects in the past.

Several of the chapters in Burke and Pomerantz note periods when technological advance failed to overcome environmental challenges to productivity. Pomeranz (2009), for example, draws attention to the problems of managing waterways due to sedimentation. He notes that, "Between 1820 and 1850, annual repairs to the Yellow River and Grand Canal were consuming perhaps 12 per cent of central-government depending in addition to heavy expenses borne by local people. Many ancient regime states spent less than this on all projects combined, other than war, debt service, and maintaining the court." Flooding nevertheless became a more and more serious problem during the nineteenth century. The Chinese economy suffered. Burke (2009) discusses 'the Middle East environmental crisis, 1450-2000', drawing attention to the impacts of deforestation, land degradation, spoilage of fisheries, depletion of aquifers and pollution of water sources, but also suggests that "the assumption that modern people are unique in their capacity to adversely affect the environment seems questionable." Although the author does not assess the quantitative impact of these environmental problems on GDP, it is clear that he sees them as central to the development challenge of the region and to the capacity of governments to promote growth. He concludes that, "Like the proverbial canary in the miner's cage, the Middle East provides a warning for the rest of the planet."

Motesharrei et al. (2014) similarly note that, "It is common to portray human history as a relentless and inevitable trend toward greater levels of social complexity, political organization, and economic specialization, with the development of more complex and capable technologies supporting ever-growing population, all sustained by the mobilization of ever-increasing quantities of material, energy, and information. Yet this is not inevitable. In fact, cases where this seemingly near-universal, long-term trend has been severely disrupted by a precipitous collapse – often lasting centuries – have been quite common." They argue that environmental factors have often made major contributions to collapses. One may conclude that use of a production function that obeys the standard regularity conditions may be an acceptable simplification when considering marginal changes in inputs and outputs but misleading in certain circumstances. Hence making long-run projections of productivity growth is fraught with uncertainty. Unfortunately, the relevant systems are not well enough understood to identify with any confidence when variables are approaching tipping points and discontinuities.

Diamond (2005) reinforces this argument. He details in a well-known study the role of environmental factors in past societal crises from Greenland to Guatemala. In the Maya civilisation of Central America, for example, drought, interacting with population pressures and agricultural methods, seems to have changed the dynamics of growth and decline amongst major Mayan settlements, ultimately leading to the disappearance of between 90% and 99% of the Maya population after 800 AD. Deforestation impoverished Easter Island. The fragility of Iceland's soils made them unsuitable for the land-use practices imported from Scandinavia and Britain, where, unknown to the migrants, the geology and soils were very different. As a result, Icelanders for a long time lived on the margins of subsistence in the poorest country in Europe. McDaniel and Gowdy (2000) document how the island nation of Nauru failed to observe the requirements of weak sustainability in exploiting the island's phosphate reserves.

Although environmental costs have been particularly high in agricultural societies, they have not been restricted to them. At the moment, long-term growth models incorporating environmental factors, particularly calibrated ones such as those used in climate-change policy debates, do not meet the analytical challenge laid down by historical studies such as these.

6. THE IMPACTS OF ENVIRONMENTAL POLICIES

Well-designed environmental policies hold out the promise of raising economic performance and improving well-being. The key reason is that policies can correct environmental externalities ignored in pure market economies (in Pigouvian fashion), giving rise to a better allocation of goods and services across different individuals at different times and places, with the possibility of improving the well-being of some individuals without reducing anyone else's (a 'Pareto-superior' outcome). The production frontier (generalised to take account of non-marketed inputs and bad outputs as well as the conventional inputs and outputs) can be moved outwards. A second, more speculative, possibility is that environmental regulation can induce reductions in inefficiency, allowing firms to move out towards the efficient frontier – in other words, shock therapy promoting more managerial effort to adopt best practices. This possibility is often associated with the hypothesis of Porter (1991), that "Strict environmental regulations do not inevitably hinder competitive advantage against rivals; indeed, they often enhance it."

The first mechanism – internalising externalities – is elaborated in standard environmental economic textbooks. Ricci (2007) presents a systematic review of the channels by which environmental policy could be transmitted to economic growth, reviewing the implications of the types of theory discussed in section 4 above, which invoke growth dynamics, not simply comparative statics. He points out that the potential for 'Pareto improvements' exists with respect to welfare in the broad sense, not narrowly defined GDP. It may still be the case that optimal environmental policies slow productivity growth as it is conventionally measured by imposing more costs on sectors producing marketed outputs, thus engineering a rebalancing from marketed outputs to reductions in environmental 'bads'. The extra costs may reduce the productivity of manufactured capital, directly and by requiring more investment in abatement activities, and consequently may reduce investment and the rate of growth.

However, appropriate policies may allow conventional labour productivity growth to be higher in the future by avoiding premature depletion of natural resources and damage to ecosystems providing valuable inputs to production. Also, there may be regions of increasing returns to scale to abatement activities that policy can exploit to reduce the flow of 'bads' and increase the return to conventional capital at the same time (Smulders, 1995). Policy can also reduce the adverse impact of pollution on human capital, labour productivity and capital depreciation. If consumption and environmental quality are complements, the introduction of well-designed environmental policies can increase saving rates, generating a (temporary) increase in output and labour productivity growth. Environmental policy could also shift firms' factor demand from the services of manufactured capital towards human capital (if pollution is associated with the size of the conventional capital stock), while encouraging households to substitute human capital accumulation for leisure to maintain incomes. A similar argument could be put forward for knowledge capital, with the added advantage (in the view of some economists) of exploiting further the increasing returns to scale of investments in (some forms of) knowledge capital, thus increasing conventional multi-factor productivity. However, Ricci notes that this argument depends on the existence of effects that are in some cases speculative – and the effects have to be strong enough to offset the standard result. This seems to be most likely to happen in the case of pricing hitherto unpriced resources and ecosystem services.

Koźluk and Zipperer (2015), in a comprehensive survey of the empirical evidence on the impact of environmental policies on productivity, note some other potential channels by which environmental policies could promote traditionally measured productivity growth, such as by fostering the creation of 'green' industries that would otherwise not exist or not benefit from economies of scale. But that depends on those industries displaying more rapid productivity growth than the non-green activities that would otherwise have taken place. There is some evidence that that might be the case. Dechezleprêtre et al.

(2013) find that knowledge spill-overs from ‘clean’ technologies are significantly greater than the spill-overs from ‘dirty’ technologies (although they find the same for spill-overs from innovation in the IT sector). However, Koźluk and Zipperer conclude that, “Empirical research on the productivity effects of environmental policies is largely inconclusive.” One problem is that “results are usually very context-specific and hence of little use for policy makers deciding on which tools to choose to tackle a particular environmental issue.” Another is that past empirical work has focused on assessing short-term impacts, yet longer-term effects can be very different, as the discussion of learning and adaptation above indicates.

Koźluk and Zipperer find broad support for the weak version of the Porter Hypothesis, that that environmental regulation leads to an increase in environmental innovation, but it is not clear that innovation overall necessarily increases. The evidence for the strong version of the Porter Hypothesis, that the cost savings from improved production processes are sufficiently large to increase firms’ competitiveness, is mixed. Brännlund and Lundgren (2009) and Ambec et al. (2013) come to similar conclusions. Koźluk and Zipperer point out that the mix of results is somewhat surprising given the pronounced scepticism expressed about the strong version by many economists, based on a priori reasoning. Some rigorous quasi-experimental studies lend mild support to the concept. For example, Martin et al. (2009) find that the UK Climate Change Levy reduced energy intensity and energy expenditures by firms subject to it (compared with those subject to the lower tax associated with UK Climate Change Agreements), but without any adverse impact on employment, gross output or total factor productivity. Having to respond to environmental regulation may overcome managers’ ‘rational inattentiveness’ (see Sims (2003) for a discussion of this concept and its importance in a macroeconomic context). Dechezleprêtre and Sato (2014), surveying empirical work relating to the competitiveness effects of green policies, note that recent studies tend to find evidence for negative productivity impacts on regulated businesses, at least in the short run. In the longer run, however, the evidence is thinner, more mixed and inconclusive, and more work is needed to investigate long-run effects. Estimated costs are relatively small with respect to the size of the economy, but can be significant in some pollution-intensive or energy-intensive sectors. Recent work by Albrizio et al. (2014) tends to find only short-term productivity effects of environmental policies, but these depend on firms’ and industries’ technological advancement. They find that the impact on productivity growth is positive for the most advanced firms and industries, while negative for firms that are less productive. Nearly all of the empirical work surveyed has been carried out in a partial equilibrium context and therefore may miss costs imposed elsewhere in economies through general equilibrium adjustments. The empirical results nevertheless suggest that further investigation of some of the theoretical channels identified by Ricci (2007) and Koźluk and Zipperer is warranted.

7. CONCLUSIONS AND RESEARCH PRIORITIES

Environmental factors can matter very much for long-run output and labour productivity growth. This is perhaps illustrated most clearly by the historical evidence of civilisation collapses. Rapid and severe global climate change threatens to provide a further demonstration. Analytical models of economic growth suggest that the size of stocks of non-renewable resources and the sustainable levels of outputs from eco-systems may have significant effects on the very long-run trajectories of output and labour productivity growth, the timing of these effects depending in part on the extent of market failures and the prevalence of externalities. But technological progress of the right type can mitigate these effects. The environment can alter labour productivity levels, with the impact spread out over time and therefore affecting labour productivity growth too. Theory suggests that it can also affect growth processes, including saving rates, the rate of accumulation of manufactured, human and knowledge capital and the rates of depletion of exhaustible resources and potentially renewable resources and pollution sinks.

However, assessing just how big these effects are and could be in practice is difficult. The hard evidence about the impact of the environment on productivity, especially in the longer term, is scant. One reason is the paucity of relevant data. This is true of most of the relevant environmental factors but particularly so with respect to ecosystem services. The fact that most environmental goods and bads (beyond material non-renewable resources) are not marketed means that markets do not generate the information needed. The small contribution of environmental inputs to output at the margin in most industries means that business people and economists have not much studied the relevant processes. The dynamics of many eco-systems are not fully understood and are even more difficult to project outside their historical range.

Nevertheless, many advances are being made in measurement and in characterising the processes linking the environment and long-term growth. Microeconomic studies have been drawing attention to the direct impact of the environment on labour productivity at a disaggregated level, particularly via pollution damages and extreme weather conditions, and to the contribution of the climate and ecosystem services to the production of marketed output in narrowly defined sectors. In many cases, these impacts have been estimated to be larger than expected.

Macroeconomic studies have been putting together estimates of broader measures of welfare than conventional GDP and broader measures of inputs than labour and manufactured capital alone. In many cases, these estimates suggest that the contribution of natural resources and ecosystem services to labour productivity growth (raising or lowering estimates compared with productivity growth as conventionally calculated) has been modest overall, although sufficient slightly to alter quantitative estimates. In some times and places, the contribution has been significantly larger, most notably in resource-rich developing countries. Some extreme weather events and other large environmental shocks have been shown to have persistent adverse effects on macroeconomic performance However, more attention has been paid to effects in the relatively short run (such as in studies of the effects of sharp oil price increases) than to effects on long-run productivity growth. The scope for adaptation to cushion adverse impacts of environmental changes is not well understood.

The impacts on TFP growth have been explored much less than the impacts on output and labour productivity growth, although possible mechanisms have been described in theory and there have been several studies of how environmental policies may have affected innovation and hence TFP growth. The role of ecosystem services over time at an aggregate level has also been neglected.

A major problem is determining how to project the possible impacts of the environment on productivity growth into the long run. It is difficult to gauge the extent to which careful microeconomic case studies can be generalised to national or global levels. They often abstract from economic variables that in practice may cushion or amplify the effects of environmental impacts on the wider economy through general equilibrium effects. Similarly, it is difficult to gauge how far ahead it is safe to project those recent macro trends that can be measured, however approximately (such as the World Bank's measure of genuine saving rates). Analytical growth models can be used to structure the process, as they have been in integrated assessment models for climate change. But it is not clear that economists' models adequately take on board the non-linearities and non-convexities that are pervasive in many aspects of environmental change. Again, the climate change literature provides a good illustration. Unfortunately, alternative systems dynamics approaches have tended to neglect economic adjustment mechanisms. Some researchers (e.g. the authors of the E3MG model)[19] have placed more weight on econometrically estimated relationships than traditional growth theory. However, it is not clear that these empirically observed relationships will be sustained a long way out of sample either.

What does this imply for research priorities? The following proposals draw on the review above:[20]

- Measurement:
    - Continuing to develop and refine National Income Accounting concepts to encompass environmental factors and to provide supplementary measures related to aggregate welfare and sustainability (Reilly (2012) notes how US efforts to establish an Integrated Environmental and Economic Satellite Account System have dissipated)
    - Developing time series for ecosystem services estimates of the kind that Costanza et al. (1997) have made
    - Disaggregating measures of inputs and outputs further to allow for better analysis of opportunities for and constraints on substitutability of different types of capital, including natural capital
- Theory:
    - Introducing more non-linear processes (e.g. tipping points, predator-prey models) and resultant tail risks into economists' growth models
    - Introducing more price mechanisms, agent adaptation and forward-looking behaviour into systems analysis approaches
- Empirics:
    - Setting up experiments, or identifying natural quasi-experiments, to assess rigorously the impacts of a wider range of environmental factors, and environmental policies, on productivity in different settings
    - Preparing for rigorous ex post investigations of the impact of environmental policies in advance of their initial implementation (e.g. with elements of randomisation)
    - Devising more robust ways of drawing inferences about the scope for adaptation to environmental changes over the long run (for example, as proposed by Dell et al., 2013)
    - Drawing complementary inference from effects of the environment and environmental policies on potential determinants of longer-term productivity growth – innovation, investment, health.

[19] See *www.tyndall.ac.uk/macroeconomic-modelling* for a description of the different modelling approach taken by E3MG. The 'environment to productivity' link is not as developed as the analysis of mitigation costs.

[20] Koźluk and Zipperer (2013) offer a complementary list of suggestions for future research into the impact of environmental policies (pp. 21-22).

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